Efficacy of technology-aided monitoring for early childhood vaccination coverage: Evidence from a Natural Experiment

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Abstract

Achieving population-wide vaccination coverage against vaccine-preventable diseases (VPDs) remains a challenge across the globe. A promising solution involves technology-aided monitoring, which can potentially improve vaccination rates. The current study estimates the impact of a similar intervention on early childhood vaccination rates in the province of Punjab, Pakistan. During late 2014, E-VACCS (an Electronic Vaccine Registration System) was implemented across the province of Punjab, one of the four provinces in Pakistan. We use yearly data (2010-2019) from Pakistan Social and Living Standards Measurement Survey (PSLM) in a difference-in-differences framework to exploit the natural across-province over-time variation offered to us by Punjab's adoption of E-VACCS. We analyze the impact of E-VACCS on complete vaccination coverage as well as antigen-specific vaccination rates. Treatment effects on vaccination coverage are largely driven by specific sub-populations. The intervention led to a 2.2 percentage points increase in the proportion of children having received at least 1 dose of vaccination. Across urban households, we find a 6.2 percentage points increase in vaccination coverage on the intensive margin. These treatment effects in urban areas are limited to mid-high income households. Our estimates for antigen-specific rates of vaccination coverage confirm similar trends. Among urban mid-high income households, improvements occurred in the antigen-specific coverage rates for vaccines administered towards the end of the childhood vaccination cycle (.e.g D-Tap-3 or Hep-B-3). However for rural low-income households, we find negative treatment effects for antigen-specific vaccine coverage rates, particularly for the three hepatitis doses. The results suggest that the increase in vaccination coverage across urban mid-high income households came at the expense of a significant decrease in coverage across low-income rural households, signaling redirection of critical resources. Our estimates remain robust to several variations in the specifications. Further robustness is also confirmed through event study estimation methods.

Keywords: Pakistan; Vaccination; Digital Vaccination Registry; Vaccine Information Systems; Health Information Systems; Immunizations; Immunization Information Systems; E-VACCS

JEL Codes: I1, I14, I18

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1 Introduction

Vaccination against preventable diseases stands as one of the most significant public health interventions globally (Ehreth, 2003). The implementation of routine childhood vaccination has played a crucial role in mitigating the risks of under-five mortality by curtailing the spread of communicable diseases worldwide (World Health Organization, 2021). Despite the fact that vaccines prevent 3 million deaths and 750,000 cases of disabilities annually among children, approximately 23% of children born globally lack access to vaccines. In Pakistan, routine vaccination coverage has consistently fallen below the global average, exposing children to the threat of disabilities and death from communicable diseases (Umer et al., 2020; Wain et al., 2016). It is estimated that communicable diseases, easily controllable through routine childhood vaccination, contribute to approximately 50 percent of deaths under the age of five in Pakistan (Umer et al., 2020). As of 2016, rates of complete vaccination[1] have remained below 50-60% for many districts[2] (Umer et al., 2020). Notably, clusters of districts with low coverage persist in the country, despite decades of vaccination efforts funded by the government and supported by international allies and institutions (Obregón et al., 2009).

A number of barriers have made it challenging to attain population-wide vaccination coverage across Pakistan. Market dynamics for childhood vaccination include different demand and supply mechanisms (Muzumdar and Cline, 2009), which could potentially lead to market failures. In Pakistan, the demand for childhood vaccination has traditionally remained low (Riaz et al., 2018; Wain et al., 2016; Bugvi et al., 2014). The reasons for lower demand and vaccine hesitancy can be attributed to lower literacy levels (Riaz et al., 2018), lower education levels (Murtaza et al., 2016; Bugvi et al., 2014; Ameen et al., 2018), and lack of information dissemination (Haq et al., 2019). In this scenario, even when the supply of vaccines is at the desired optimal levels of output and distribution, lower demand leads to lower vaccine consumption. In this context, supply and demand related interventions can potentially mitigate low demand for routine vaccination (Muzumdar and Cline, 2009).

Ensuring the efficient delivery and supply of routine vaccination in the country, however, has presented persistent

[1] Complete vaccination denotes the scenario in which an age-eligible child has received all vaccinations according to the country's schedule, encompassing one dose of Bacillus Calmette−Guerin (BCG) vaccine, 3 doses of D-TaP Vaccine (diphtheria, tetanus, and pertussis), 3 doses of Oral Polio Vaccines, 3 doses of Hep-B (Hepatitis-B) vaccine, and 2 doses of Measles Vaccines for a 2-year-old. Since 2016, children receive a pentavalent vaccine containing antigens for diphtheria, pertussis, tetanus, hepatitis B, and Haemophilus influenzae type b in lieu of D-TaP.

[2] Districts, serving as the second-tier administrative units within provinces, consistently display low vaccination coverage across all four provinces in Pakistan (Umer et al., 2020).

challenges over the past few decades. Given the significance of this public good, the government has the incentive to provide publicly funded vaccination services to the population (Muzumdar and Cline, 2009; Ehreth, 2003). The federal government fulfills this role by financing the Expanded Programme on Immunisation in Pakistan (EPI), heavily relying on aid from GAVI - the Vaccine Alliance and UNICEF (Haq et al., 2019). While GAVI and UNICEF predominantly fund the vaccine supply, the government of Pakistan covers EPI staff and operational costs[3] (Haq et al., 2019).

EPI receives funding from the federal government, yet its administration is overseen by provincial governments. The provinces facilitate service delivery by devolving responsibility to the district (sub-provincial) administration level[4]. At the district level, service delivery for vaccination is ensured through two channels. First, vaccination services are available at the district health office, major and minor hospitals, and basic health units[5]. Second, a local team of "vaccinators" or field staff is assigned to each basic health unit, conducting physical visits to households in the respective area. This second channel becomes crucial in the context of low demand for vaccination from the citizens themselves, necessitating the need for a service delivery push (Haq et al., 2019). This intricate service delivery infrastructure also poses several challenges related to monitoring, reporting, and communication among different layers of employees and management.

Ensuring an equitable supply of vaccines to the public poses a formidable challenge in the context of substantial socioeconomic inequities across and within provinces and districts, (Wain et al., 2016; Ameen et al., 2018; Bugvi et al., 2014; Murtaza et al., 2016; Raza et al., 2018). These socioeconomic disparities, to some extent, stem from the unmet need for information dissemination, particularly among the relatively uneducated and poorer segments of the population, who have the greatest information needs (Raza et al., 2018; Bugvi et al., 2014). According to estimates by Murtaza et al. (2016), 7.7% of children in Pakistan never receive a single vaccination shot, with more than 87.4% of these children residing in rural areas, where lower education levels and economic status are associated with a higher likelihood of low vaccination rates. Similar studies have identified that children born in specific low-income, rural areas, and provinces are more likely to experience low vaccination rates (Khan et al.,

[3]Haq et al. (2019) identified financial bottlenecks in meeting operational costs, noting that EPI had to reduce monitoring and evaluation expenses to stay within budget. As EPI funding is federally mandated, we can presume that these financial challenges are randomly distributed across the population. Haq et al. (2019) also suggest the same when explaining how federal EPI finances are allocated across provinces and, ultimately, districts, following legislative formulas.

[4]Typically under the supervision of a civil service officer in the general district administration or district health department.

[5]Basic health units are the primary level of health care at the union council level, the smallest administrative unit within Pakistan. Pakistan has four provinces. Each province has many districts, and each district is further divided into small union councils.

2017; Kols et al., 2018).

Existing research underscores the presence of workforce accountability issues within the EPI. Shaikh et al. (2018) identifies the lack of workforce accountability as a primary reason for the under-performance of the EPI. Naveed et al. (2021) attributes poor immunization performance in certain regions to demotivation, poor attendance, and suboptimal performance among the workforce. The literature also suggests that the absence of local-level data and the underutilization of available data contribute to inaccurate estimates of vaccination coverage and a lack of workforce accountability (Shaikh et al., 2018; Haq et al., 2019). Limited evidence indicates that technology-based solutions capable of generating real-time data and monitoring the performance of local workers[6] could potentially offer a successful remedy (Chandir et al., 2018; Zaidi et al., 2020).

In 2014, the province of Punjab initiated comprehensive e-governance programs, encompassing sectors such as education, health, infrastructure, and public safety. As part of this initiative, E-VACCS, an immunization information system[7], was introduced to enhance routine childhood vaccination rates (PITB, 2021). The intervention included a smartphone app mandated for use by each vaccinator. The app required vaccinators to log in, geo-tag their daily attendance, record details of each administered antigen, and capture demographic information of the child and household. Additionally, administrator-side data dashboards were implemented to facilitate tracking, visualization, and accountability of field-level employees/vaccinators (Ahmed et al., 2018). The intervention aimed to achieve two objectives: creating digital vaccination records and increasing vaccinator attendance. Digital records not only provided real-time granular data on geographical coverage but also enabled vaccinators to follow up on children who lapsed from their immunization schedules after being entered into the system. E-VACCS was launched across all 36 districts of Punjab in October 2014. Under this intervention, the treated cohort comprised children born during or after the first quarter of 2014[8].

The introduction of E-VACCS serves as a natural experiment, as no other province employed tech-based solutions for administering and monitoring vaccination efforts for children born in the birth-year cohorts of 2014 and 2015. This study leverages the natural across-province over-time variation resulting from the adoption of E-VACCS in Punjab province. We employ a difference-in-differences approach, designating the province of Punjab

[6] primarily vaccinators.

[7] or a Vaccination monitoring system: interchangeable terms from our perspective, the purpose is to monitor and progress vaccination in eligible populations.

[8] Usually, children receive their vaccinations from birth and complete their vaccination up to Measles-1 by 9 months of age (WHO, 2021).

as the treatment group and utilizing the other three provinces as a control group for identification purposes. Our dataset comprises microdata extracted from a nationally representative survey, providing detailed information on all antigens of early childhood vaccination for children under 5. The sample universe for this survey encompasses children in birth-year cohorts from 2007 to 2015, with children in Punjab born during and after the first quarter of 2014 exposed to the treatment[9]. We examine two key outcomes: (i) total vaccination coverage, a measure of the number of antigen-specific vaccines received out of the total possible number of antigen-specific vaccines for which a child is age-eligible (representing the intensive margin of vaccination), and (ii) the proportion of children ever immunized, indicating if a child has ever received any shot of vaccination (representing the extensive margin of vaccination).

The current literature on childhood vaccination rates, problems, solutions, and interventions in Pakistan exhibits several shortcomings. Existing studies often remain confined to descriptive evidence or review papers (Umer et al., 2020; Naveed et al., 2021; Wain et al., 2016; Khan et al., 2017; Murtaza et al., 2016; Husain and Omer, 2016). They tend to offer qualitative evaluations of very pilot projects based on limited sample sizes (Zaidi et al., 2020), rely on limited, short-run cross-sectional data (Raza et al., 2018; Imran et al., 2018; Asif et al., 2019; Bugvi et al., 2014; Ameen et al., 2018), apply simple methods (such as the bivariate analysis in (Kols et al., 2018)), or resort to anecdotal evidence in discussing issues and possible solutions (Haq et al., 2019; Ali and Altaf, 2021). Few quantitative studies on vaccination coverage in Pakistan attempt to draw causal estimates for different childhood vaccination-related interventions. Among these, Kazi et al. (2018) conduct a small randomized controlled trial testing the efficacy of SMS-based reminders, and Habib et al. (2019) report findings from a small-scale quasi-experiment involving a maternal, neonatal, and child health intervention package for one rural district.

Existing literature provides limited evidence, indicating that despite efforts to enhance overall vaccination coverage, the improvements are concentrated in urban settings, exacerbating the persistent urban-rural coverage gap in vaccination over the past couple of decades (Husain and Omer, 2016). Some evidence also suggests potential gender disparities in the increase of vaccination coverage (Khan et al., 2017). Raza et al. (2018) argue that neglecting income and regional disparities in formulating interventions related to vaccination coverage may exacerbate vaccination inequalities across sub-populations. In light of the existing literature, we carefully consider heterogeneity in

[9]Children born from Q1-2014 until Q4-2015. Children born in and after Q1-2016 might have been treated under different interventions that occurred later in the control group and are thus excluded from the sample universe for this paper.

vaccination coverage across urban and rural areas, low-income and middle/high-income households, and different levels of parental education.

Our paper makes three primary contributions. Firstly, it is the inaugural attempt, to the best of our knowledge, to derive a reliable causal estimate of the impact of E-VACCS on childhood vaccination rates in Punjab. Secondly, our study holds immediate policy implications within the local context, offering valuable insights for administrators to refine the targeting of the intervention. Thirdly, we add to the existing literature on the effectiveness of similar technology-aided resource monitoring interventions in analogous settings, with findings that hold particular relevance across the developing world amidst public health challenges. Our paper provides robust evidence on the effects of E-VACCS on childhood vaccination coverage across the province, with a specific focus on heterogeneity within relevant sub-populations.

2 Data Description

Microdata for this paper is derived from the Pakistan Social and Living Standards Measurements (PSLM) Survey, a nationally representative survey capturing a spectrum of social and economic indicators (Pakistan Bureau of Statistics, 2021). The PSLM survey operates on a biennial basis, alternating between a larger sample size of approximately 80,000 households and a smaller sample size of roughly 16,000 households each year. Our data is extracted from the years featuring larger sample sizes, enabling valid estimates at the district level[10]. The selected samples encompass the years 2010-11, 2012-13, 2014-15, and 2019-20 of the PSLM surveys[11]. Each PSLM survey incorporates a childhood vaccination component documenting antigen and dose-specific vaccination coverage for each child up to the age of 5 in the surveyed households. For instance, in PSLM 2010-11, children in birth-year cohorts of 2006, 2007, 2008, 2009, 2010, and 2011 reported their vaccination status for each antigen/dose[12]. To avoid potential contamination issues with pilot interventions initiated in our control provinces, we exclude children born during or after the birth-year cohort of 2016[13]. Considering the vaccination schedule under EPI Pakistan

[10] In contrast, the smaller sample sizes only permit reliable point estimates at the provincial level.

[11] No surveys were conducted in 2016-17 and 2017-18 due to the decennial census, which did not include health/vaccination components. 2018-19 constituted a short sample survey to maintain the alternating pattern, while 2019-20 featured the large sample.

[12] Similarly, in PSLM 2012-13, the vaccination status of children in birth-year cohorts of 2008, 2009, 2010, 2011, 2012, and 2013 was documented. In PSLM 2014-15, children in birth-year cohorts of 2010, 2011, 2012, 2013, 2014, and 2015 were surveyed, and in PSLM 2013-20, children in birth-year cohorts of 2015, 2016, 2017, 2018, 2019, and 2020 were documented.

[13] E-VACCS was later replicated in the provinces of KPK and Balochistan during late 2016 and 2017, and the province of Sindh initiated a similar intervention. At this point, we lack sufficient details on the specifics of these interventions to ensure homogeneous treatment.

(Table 1) and allowing for a few months of delays in immunizations, we exclude children from our sample who are between 0 and 4 months of age on the day of the survey. Our final dataset comprises 170,960 children born in birth-year cohorts from 2007 to 2015. The data structure of PSLM enables us to identify and link parental characteristics and the demographic, geographic, and socioeconomic variables of the household to each child.

2.1 Overall Vaccination Coverage

Our primary outcome of interest is a measure representing vaccination coverage, defined as the proportion of vaccines administered to a child out of the total vaccines for which the child is age-eligible at the time of the survey. This measure focuses on the intensive margin of vaccination coverage. Under this criterion, a child aged between 5 to 10 months[14] is eligible for a total of 10 vaccines (1 dose of the BCG vaccine, and 3 shots each of the D-Tap, Hep-B, and Polio vaccines). For instance, if a child in this age range has received 7 vaccines at the time of the survey, the total vaccination coverage for that child would be 0.7. For children older than 10 months, we include the first dose of the measles vaccine in the denominator, making them age-eligible for a total of 11 vaccines. Our coverage estimates exclude Polio-0 since our data did not record this vaccine for birth-year cohorts of 2010 and earlier. Additionally, Measles-2 is omitted from our calculations as it was added to the immunization schedule in 2009, and PSLM did not capture data for this vaccine before 2014-15.

District-level coverage estimates for pre-intervention and post-intervention birth-year cohorts are depicted in Figure 1a and Figure 1b, respectively. Consistent with prior literature, a nationwide decrease in vaccination coverage during 2014-2015 is evident across all provinces (Umer et al., 2020). Punjab exhibits a similar trend, although the extent of the decline in coverage is comparatively less pronounced than in other provinces. In the pre-treatment period across the control provinces, 14 districts had at least 90% of the population with full coverage, 24 districts had at least 75% of the population with full coverage, 30 districts had at least 50% of the population with full coverage, and 13 districts had less than 50% of the population with full coverage[15]. Post-treatment, the control provinces experienced 15 districts with at least 90% of the population fully vaccinated, 23 districts had 75-90% of the population fully vaccinated, 22 districts had 50-75% of the population fully vaccinated, and 24 districts had

[14] Although the child becomes eligible for Measles-1 after 9 months, we allow for an additional month of delayed vaccination.
[15] excluding FATA.

less than 50% of the population fully vaccinated[16]. Summarizing the post-treatment changes in control provinces, 8 more districts had less than 50% of the population fully vaccinated. Similar trends were observed across Punjab, although the magnitude of the coverage decreases was much smaller. Over the pre-treatment years, the province of Punjab had 33 districts where at least 90% of the age-eligible population had full vaccination coverage, and the remaining 3 districts had at least 75% of the population fully vaccinated. Post-treatment, only 24 districts in Punjab maintained at least 90% full vaccination coverage among the age-eligible population. In 12 districts, full coverage dropped below 90% of the population, with one district having less than 75% of the population fully vaccinated out of these 12.

The decline in vaccination coverage across all provinces during 2013-15 is corroborated by Umer et al. (2020), utilizing administrative data from the Expanded Programme on Immunisation (EPI). This verification ensures that analogous trends in our data during the same years are not a result of measurement or survey errors. Several country-level factors may contribute to this coverage drop, including increased rural-to-urban migration (Umer et al., 2020) and, to some extent, reductions in GAVI-supported funding at the national level (GAVI, 2021). Notably, country-wide GAVI funding decreased from around 150 million USD in 2013 to 120 million USD in 2014, further reducing to 70 million USD in 2015. The termination of health-systems strengthening aid in 2014, along with the removal of support for DPT vaccine procurement in 2015, were significant changes in funding at the country level, impacting provinces uniformly. While rural-to-urban migration is often associated with missed vaccinations (Basra et al., 2018; Kusuma et al., 2010), an examination of migration rates from the Pakistan Labor Force Survey and a province-wise comparison of coverage rates across the years (2013-14 and 2014-15) reveal no correlation between migration and changes in provincial vaccination coverage (Pakistan Bureau of Statistics, 2015). Notably, Balochistan, with the highest rural-to-urban migration, maintained a constant vaccination coverage of around 62% over 2014-15, while Punjab indeed had lower rates for rural-to-urban migration when compared with Balochistan[17]. The argument that higher urban vaccination rates could be related to the province with the highest rural-to-urban migration is not supported by our descriptive analysis[18]. Detailed urban and rural trends across the treatment and control provinces are provided in Appendix Table A1, indicating that the decline in vaccination

[16]This includes 2 new districts carved out post-2013, and excludes FATA.
[17]Balochistan's vaccination coverage remained constant at around 62% over 2014-15.
[18]Our district fixed effects should be able to purge any remaining short-run time-invariant differences in rural-urban migration rates across provinces, as short-run migration trends remain consistent across provinces

coverage was universal, affecting both urban and rural areas. All these factors suggest that the declines in coverage resulted from exogenous, country-level shocks. Existing literature, extensive research, and local knowledge about EPI in Pakistan do not provide evidence of these shocks having heterogeneous effects on any single province.

Table 2 provides mean vaccination coverage rates for both control and treatment provinces. In the control provinces, mean vaccination coverage increased from 79.3% for the birth-year cohort of 2007 to 84.5% for the birth-year cohort of 2011. However, a nominal seasonal drop is observed for the birth-year cohort of 2014, and in 2015, the ongoing country-wide shock leads to a reduction in coverage rates to 70.2%. Conversely, in the treatment province, coverage rates remained closer to 90% for all birth-year cohorts, with some seasonal variations. Despite significant drops for the birth-year cohorts of 2014 and 2015 following the systematic shock in coverage rates post-2013, a notable recovery in vaccination coverage rates is observed during the post-treatment period, specifically in the province of Punjab, in contrast to other provinces[19].

Panel A in Figure 2 compares quarterly vaccination coverage trends across the treatment and control provinces for children born between the first quarter of 2007 and the last quarter of 2015[20]. Vaccination coverage across the treatment province consistently outpaced that of the control provinces, and the pre-treatment coverage trends in treatment and control provinces are quite similar. Panels B and C display coverage trends separately for rural and urban areas, respectively. Both rural and urban pre-intervention trends closely mirror the overall coverage trends, and display no signs of pre-trends that could potentially conflate our estimates are observed.

2.2 Vaccination Outreach

Over the pre-treatment years (2007-2013), an average of 2.22% of children under 5 in Pakistan had never received a single dose of any antigen. While this fraction may seem small, it corresponds to approximately 0.66 million children in absolute numbers, given that the total under-5 population in Pakistan is around 30.24 million (Pakistan Bureau of Statistics, 2017). Existing literature (Bugvi et al., 2014; Haq et al., 2019) suggests that most of these children live in difficult-to-reach areas, impoverished households, and displaced families, facing significant socioeconomic disadvantages. E-VACCS aimed to encompass such children within the scope of immunization coverage. We gauge this extensive margin of vaccination (or immunization) by defining our measure of "Proportion of Children Ever

[19]Similar descriptive data comparing rural and urban areas are discussed in Appendix-A

[20]To smooth out seasonal quarter-over-quarter variation in these graphs, we take a moving average of preceding and following quarters.

Immunized" as a binary variable, taking a value of 1 if a child has ever received any dose of any antigen from the childhood vaccination regimen of the country, and 0 if a child has never been given any dose of any antigen in the vaccination schedule. Mean vaccination outreach levels, as measured by the variable "Ever Immunized," are presented in Table 3. There is little variation in the incidence of children being ever immunized across control provinces and the province of Punjab. For birth-year cohorts from 2007 through 2013, 97-98% of the population received at least one dose for one antigen from the EPI schedule in Pakistan, and these trends remain consistent across Punjab and other provinces.

2.3 Antigen-Specific Vaccination Coverage

Our overall measure of vaccination coverage might mask antigen-specific trends that could be independent of the overall vaccination coverage. To address this, we assess antigen-specific coverage for each dose of every antigen on EPI Pakistan's schedule.

Quarterly trends in antigen-specific coverage and associated discussions are provided in Appendix B.

2.4 Household Characteristics

We link household and parental characteristics to each child's vaccination record. This ensures that all our specifications incorporate controls for household demographics, including the child's gender, the total number of other under-18 members in the household, and parental information such as age, education, work status of both parents, as well as household income levels.

3 Empirical Strategy

The introduction of E-VACCS establishes a natural experiment, as no other province in Pakistan implemented a technology-aided monitoring program for childhood vaccination during that period. We leverage this variation within a difference-in-differences framework, designating Punjab as the treatment province and Sindh, Khyber Pakhtunkhwa (KPK), and Balochistan as control provinces. According to the EPI's schedule in Pakistan (Table 1),

childhood vaccinations are administered up to 9 months of age[21]. Consequently, any child aged 9 months or younger in October 2014 was exposed to treatment in Punjab. Therefore, our identifying assumption is that changes in vaccination coverage post the first quarter of 2014 would have been similar across all provinces in the absence of the treatment.

Under the assumption that most children adhere to the EPI schedule, children born in the first two quarters of 2014 (Q1-2014 and Q2-2014) are only partially exposed to the treatment, having completed most of their vaccination routine before October 2014. Children born in Punjab between Q3-2014 and Q4-2015 are fully exposed to the treatment. Even allowing for the possibility that some percentage of children are a month or two late on their vaccination schedule, our identification assumption provides some margin to accommodate this likelihood. For instance, even if we assume that 10 percent of children are late by 2 months on the EPI schedule, a child born in the first quarter of 2014 would still have completed 10 out of 11 required vaccines by October 2014 and would only be partially exposed to the treatment, receiving only the Measles-1 vaccine under E-VACCS, despite being two months late from the schedule. In contrast, a child born in December 2013 would have minimal chance of any treatment, even with a 2-month delay, as they would have received all vaccines (10 out of 11) before June 2014. Any children born in October 2013 or earlier can never be exposed to the treatment, even if we allow for a 2-month delay in the vaccination schedule[22]. Combining these arguments, our identifying assumption will lead to lower-bound estimates, as a fair share of children born in the first two quarters of 2014 are only minimally exposed to the treatment[23,24].

Pilot programs of a similar nature commenced in other provinces starting in August 2016. We consider the possibility of children born in these provinces after the first quarter of 2016 being exposed to these treatments. Consequently, our analysis is confined to children born from the first quarter of 2007 to the last quarter of 2015, with the latter marking the final quarter and year of birth included in the sample.

[21] Measles-2 is excluded, as mentioned earlier.

[22] Children complete vaccinations up to Measles-1 by 9 months of age. Even if this age is raised to 11 months by a 2-month delay, a child born in October 2013 would already be over 11 months before October 2014

[23] Even when allowing for a 2-month delay in vaccinations (an extremely unlikely, outlying occurrence), children on a delayed schedule born in November or December of 2013 in Punjab are at most exposed to one out of 11 vaccines being administered under E-VACCS. Even if we assume that 10% of children are on a delayed schedule with a 2-month delay, children born in November or December of 2013 would only be 10% of a very small fraction of children born during pre-treatment years (2007-2013) in Punjab, and those still would have only received the last vaccine, i.e., Measles-1, under E-VACCS. Our antigen-specific estimates for Measles-1 vaccine, however, are not at all different from our other antigen-specific estimates, further validating our assumption.

[24] A total of 878 children in our sample were born in November or December of 2013 in Punjab. Even if, say, 100 of them were late on schedule and received 1/11 treatment (at most receiving 1 out of 11 vaccines after initiation of E-VACCS, 10 before the initiation), this number cannot bias our estimates at all, given our substantial total sample size of 170,960 children.

3.1 Estimating Equations

We begin our analysis by examining overall vaccination coverage on the intensive margin, with a specific focus on variations across urban and rural areas, low-income and middle-to-high-income households, and different levels of parental education. Our most stringent difference-in-differences specification is represented by the following equation:

$$Y_{idt} = \gamma(p_{idt} \times e_{idt}) + \beta X'_{idt} + \zeta_{yb} + \xi_{qb} + \eta_{d\times r} + \varepsilon_{idt} \tag{1}$$

In Equation (1), Y_{idt} denotes the outcome variable, which is the vaccination coverage for child i in district d, within the year-of-birth cohort t. The binary variable p takes the value 1 if the child resides in a district within the province of Punjab and 0 otherwise. The post-EVACCS treatment indicator e assumes the value 1 for the year-of-birth cohorts 2014 or 2015 and 0 for cohorts in 2013 or earlier. The coefficient of interest, γ, is the interaction term between the indicator for the province of Punjab (p) and the post-treatment indicator (e). The vector X' includes demographic controls such as the gender of the child, the number of household members under 18, household income, as well as the age, work status, and education level of both parents. ζ and ξ represent year-of-birth and quarter-of-birth fixed effects, respectively, while ε indicates district $\times$ region fixed effects. Standard errors are clustered within province $\times$ year-of-birth cells.

The inclusion of year-of-birth fixed effects control for time invariant unobserved factors shared by birth cohorts, such as macroeconomic conditions, national-level health spending, and infrastructure specific to the birth-year cohort. Quarter-of-birth fixed effects control for unobserved heterogeneity and seasonal variation seasonal variation in the performance of the Expanded Program on Immunization (EPI) concerning vaccination. Region-specific district fixed effects[25] control for time-invariant factors like local and regional health infrastructure, local variations in beliefs and cultures, district-specific elements such as the local economy, weather conditions, and political ideologies, among others. Our reliance on this comprehensive set of fixed effects leads us to assert that the estimate captured by our coefficient of interest γ isolates the effect of exposure to the treatment in the districts of the Punjab province.

[25] Districts are much smaller administrative units than provinces and hence controlling for district fixed effects should remove all province-specific unobserved heterogeneity as well. Regions in PSLM are designated on a smaller level than districts, which signals if an area within a district is a rural union council or not.

Figure 2 might create the impression among readers that our results could be influenced by a reduction in vaccination coverage in other provinces, particularly in urban areas. Essentially, these graphs might suggest that time-variant, province-specific macroeconomic or policy shocks in other provinces could be responsible for the decline in vaccination coverage, exhibiting variations across the treatment and control provinces. Notably, Martinez-Bravo and Stegmann (2022) reported that Taliban influence in rural Khyber Pakhtunkhwa (KPK) province might have led to a decrease in vaccination coverage during 2010-2012. However, this is not applicable to later years. Firstly, Martinez-Bravo and Stegmann (2022) solely focused on KPK since it was the province most likely to be influenced by the Taliban geopolitically. Moreover, our findings reveal that vaccination coverage rates in KPK province display increases comparable to our treatment province throughout the study period. Secondly, Pakistan's military operation, Zarb-e-Azb, against these outfits in KPK was largely concluded by the start of our study period, substantially reducing the influence of the Taliban in the province. A third reason is that even if Taliban influence were to impact estimates, it would be more likely in the rural areas of KPK province, not in the urban region, given that the Taliban are more likely to be present in rugged, tribal, rural regions of KPK. We do not perceive any credible identification threat from Taliban influence in KPK; nonetheless, we conduct a restricted set of analyses excluding KPK from the sample, and our estimates are even stronger[26].

Following our baseline estimations in equation (1), we employ various specifications to estimate heterogeneity across different sub-populations. To achieve this, we split our sample into urban and rural areas, using a similar specification to equation (1) but substituting district fixed effects for district $\times$ region fixed effects. Recognizing that low-income households are particularly vulnerable to low vaccination coverage, we conduct similar specifications for low-income and middle-to-high income households, separately for rural and urban regions. This approach allows us to investigate any heterogeneous treatment effects based on the interaction of low-income levels with urban and rural households in our sample. We conclude our analysis on overall vaccination coverage by testing for heterogeneity in treatment effects on the interaction of parental education levels with urban and rural households. To achieve this, we classify a household as having less than high school education if both parents have less than a high school education. All other families are considered to have higher than high school education, even if only one parent has education beyond high school. Even with this strategy to identify families with less than high school

[26] available with us.

education, we found that 114,928 children were living in families where neither parent had a high school certificate.

We then shift our focus to our measure of immunization on the extensive margin, where the outcome variable is a child's status of ever being immunized. Our estimating equations for this outcome, "ever immunized," mirror the specifications discussed earlier following equation (1). Similar to our analysis for overall vaccination coverage, we initiate by estimating the probability of a child being ever immunized in the overall sample. Subsequently, we explore the possibility of treatment heterogeneity across regions and socioeconomic subgroups. We conduct separate estimations for low-income and middle-to-high income households, both in rural and urban samples. Additionally, we run distinct estimations for households with "less-than-high-school" and "higher-than-high-school" education levels, again across rural and urban samples.

Turning our attention to antigen-specific coverage estimates, we aim to discern if trends in antigen and dose-specific coverage differ from our overall coverage estimates. Employing a similar estimation approach to the first two outcomes, we use the exact specification from equation (1) to estimate the outcomes across the entire sample. This specification incorporates individual and household-level demographic controls, year and quarter-of-birth fixed effects, and district × region fixed effects. Subsequently, we split our sample into rural and urban areas and conduct further estimations for specific income and education levels within these samples[27].

4 Main Results

4.1 Overall Vaccination Coverage

The table 4 provides the DID estimates for overall vaccination coverage using equation (1). In our baseline specification (column 1), we include individual-level demographic controls, year-of-birth fixed effects, and district fixed effects. Column (2) augments the model with individual controls for household income-bins and introduces region fixed effects. In column (3), quarter-of-birth fixed effects are added, and column (4) incorporates the most stringent set of fixed effects, including region × district fixed effects. The DID estimate for overall vaccination coverage remains robust across these specifications, reflecting a modest 1.9 percentage points increase, which is

[27]Consistent with our approach for the first two outcomes, we substitute district fixed effects for district × region fixed effects in our split-sample region-specific analysis.

statistically insignificant[28].

To explore the possibility of heterogeneous treatment effects, we conduct a rural-urban split in columns (5) and (6), substituting district fixed effects for region-specific district fixed effects. Column (5) indicates no treatment effect on overall coverage for rural households, while column (6) shows a statistically significant increase of 6.2 percentage points in vaccination coverage for urban households. The inclusion of a gender control across columns (1) to (6) does not affect our treatment estimate, whereas the inclusion of a control for low-income households consistently attenuates our estimates from column (2) to column (6).

The attenuation of treatment effects resulting from the inclusion of a control for low-income status suggests the possibility of heterogeneous treatment effects between low-income and mid-high income households. To investigate this potential heterogeneity, we further divide our sample into low-income and mid-high income households[29] in Table 5. The DID estimates in columns (1), (2), and (4) of Table 5 are all statistically insignificant and of small magnitude. However, in column (3), we observe a statistically significant 10.2 percentage points increase in vaccination coverage among mid-high income households within urban regions. In summary, the positive treatment effects of the intervention on the extensive margin of vaccination coverage are not only limited to urban households but are also concentrated within mid-to-high income households. Treatment effects on the extensive margin do not extend to low-income households, irrespective of the urban/rural heterogeneity in treatment effects observed in Table 4.

As discussed in the introduction, E-VACCS was designed as a supply-driven intervention to address the lack of parental demand for vaccination. However, the observation that treatment effects did not extend to low-income households raises questions about this premise. Typically, reduced demand for vaccination is associated with lower socioeconomic status and is influenced by parental education levels. We examine this hypothesis by analyzing heterogeneity across parental education levels in Table 6[30].

There are nearly no treatment effects for children born in rural regions, irrespective of their parents' education

[28]It is essential to note that these effect sizes, relative to the mean pre-treatment coverage levels in Punjab, might be misleading. We clarify that these effect sizes are mathematically plausible considering the country-wide decline in vaccination coverage in 2015, as discussed in the data description (see Table 2).

[29]based on household income falling below or above the low-income thresholds of the country, as measured by monthly/annual minimum wages in Pakistan.

[30]We divide our sample into two groups based on household characteristics. The "less than HS" group includes children with both parents having less than a high school education, while the "HS or more" group comprises children with at least one parent holding a high school diploma or higher. We make this distinction as more than 50 percent of our sample consists of children born to parents without a high school diploma, reflecting the overall low education levels in the country.

levels. In column (1) of Table 6, the point estimate indicates no treatment effect for children in rural regions with at least one parent holding a high school or higher degree. In column (2), for children in rural regions with both parents educated less than high school, there is a slightly positive treatment effect, but it is imprecisely estimated and statistically insignificant. The estimates in column (3) for children in urban areas reveal a 5.4 percentage points treatment effect on vaccination coverage when at least one parent has a high school or higher degree. The coefficient magnitude in column (4) for children with both parents having less than a high school education is similar (5.1 percentage points) but statistically insignificant.

Considering the results from our main regressions in Table 4 in combination with estimates in Table 5 and Table 6, we find evidence that any treatment effects from E-VACCS on the intensive margin of vaccination coverage failed to reach rural areas. Even when observing some positive treatment effects in urban areas, these effects are not evident for low-income or less-educated households.

4.2 Vaccination Outreach

We extend our examination beyond total vaccination coverage to assess the extensive margin of immunization, indicated by a binary variable denoting whether a child has ever been immunized. The DID estimates for our "ever immunized" outcome are presented in Table 7. The specifications in columns (1) through (6) are analogous to those in Table 4, with the outcome variable modified to the indicator for being ever immunized. Our DID estimates on this extensive margin of immunization remain consistent and robust across various demographic controls and fixed effects. In the most stringent specification in column (4), the DID estimate reveals a 2.2 percentage points increase in the likelihood of children being ever immunized[31]. In contrast to our estimates on the intensive margin of vaccination, both the magnitude and statistical significance of this treatment effect on the extensive margin persist when we split our sample across rural and urban households in columns (5) and (6) respectively. With the exception of rural households, low-income levels still appear to attenuate the treatment effects, although the coefficients' magnitudes are relatively small compared to those in Table 4.

Next, we explore heterogeneity across low-income and mid-high income households in both rural and urban areas regarding this measure of being ever immunized. The DID estimates in Table 8 are positive and statistically

[31] As noted earlier, this implies that the child has received at least one dose of any vaccine on the day of the survey.

significant across all presented sub-populations in columns (1) to (4). The treatment effect's magnitude is slightly higher for children born in low-income households, both in rural and urban populations. For children born in low-income rural households, the treatment led to a 2.1 percentage points increase in the likelihood of being ever immunized compared to a 1.6 percentage points increase for those born in mid-high income rural households. Similarly, for children born in low-income urban households, the treatment led to a 2.7 percentage points increase in the likelihood of being ever immunized compared to a 1.3 percentage points increase for those born in mid-high income urban households.

In Table 9, we investigate whether treatment effects on the likelihood of being ever immunized are homogeneous across children born to parents with different education levels. Regardless of parental education levels across different sub-populations in columns (1) to (4), the treatment effects are positive and significant. Across rural and urban households, treatment effects for children born in households with both parents having less than high school education are nearly homogeneous with treatment effects for children born in households with at least one parent having a high school diploma or higher. For children born in rural households to both parents possessing less than high school education, the treatment resulted in a 2.6 percentage points increase in the likelihood of being ever immunized compared to a 2.1 percentage points treatment effect for children born in rural households with at least one parent having a high school diploma or higher. Similarly, for children born in urban households to both parents possessing less than high school education, the treatment resulted in a 2.2 percentage points increase in the likelihood of being ever immunized compared to a 1.7 percentage points treatment effect for children born in urban households with at least one parent having a high school diploma.

Three key observations summarize these estimates on the extensive margin. First, the magnitude of treatment estimates in Table 4 may be small, but they are meaningful when considering the context of 98% mean pre-treatment levels of "ever-immunized" children. The robustness of the treatment effect across all specifications on the extensive margin underscores the reliability of the estimate, particularly when rejecting the hypothesis of no treatment effect is statistically challenging with such high pre-treatment levels. Second, these estimates on the extensive margin are significant and stronger for rural areas. This informs us about the outreach of the EPI under E-VACCS: although the intervention did have an impact across rural Punjab, it was just about enough to be detectable on the extensive margin, but not strong enough to make a significant difference on the intensive margin. Third, the estimates on

the extensive margin are stronger in magnitude for low-income, low-educated households across rural and urban samples. This provides further evidence that treatment effects for vulnerable segments of the population were minimal. It is likely that any positive treatment effects for children across rural areas, low-income households, and low-educated parents might be confined to specific antigens or doses. We return to this argument later in the discussion section.

4.3 Antigen Specific Vaccination Coverage

To conclude our analysis,we examine treatment effects on antigen and dose-specific vaccination coverage. Our baseline specification for the overall sample mirrors equation (1), utilizing indicator variables for disease and dose-specific coverage for various vaccines. DID estimates for antigen and dose-specific coverage are presented in Table 10. For the overall sample, 7 out of 11 vaccines on the EPI schedule show no treatment effects. Statistically significant treatment effects are observed for the first dose of the Hep-B vaccine and the three polio doses (Polio-1, Polio-2, and Polio-3). Specifically, the Polio-1 vaccine sees an 8.4 percentage points increase in coverage, Polio-2 shows a 9.9 percentage points increase, and Polio-3 exhibits a 10 percentage points increase. Conversely, the first dose of the Hepatitis-B (Hep-B-1) vaccine experiences a negative treatment effect on coverage. Low-income status attenuates treatment effects for the coverage of almost all antigens and doses[32]. Gender disparities in antigen-specific coverage are not evident.

Table 11 presents antigen and dose-specific coverage estimates separately for rural and urban areas, revealing heterogeneous treatment effects. In rural areas, the treatment results in a 6.1 percentage points decline in the coverage rate for the first dose of the hepatitis (Hep-B-1) vaccine. For urban areas, no treatment effect is observed for the Hep-B-1 vaccine. Similarly, the Hep-B-2 vaccine shows a statistically significant decline of 4.7 percentage points in rural areas, but no treatment effect in urban areas. For the Hep-B-3 vaccine, rural areas see a significant decline of 3.3 percentage points, while urban areas experience a significant positive effect of 4.8 percentage points.

To conclude our analysis, we examine treatment effects on antigen and dose-specific vaccination coverage. Our baseline specification for the overall sample mirrors equation (1), utilizing indicator variables for disease and dose-specific coverage for various vaccines. DID estimates for antigen and dose-specific coverage are presented in Table 10.

[32]With the exception of the Polio-1 vaccine/dose.

For the overall sample, 7 out of 11 vaccines on the EPI schedule show no treatment effects. Statistically significant treatment effects are observed for the first dose of the Hep-B vaccine and the three polio doses (Polio-1, Polio-2, and Polio-3). Specifically, the Polio-1 vaccine sees an 8.4 percentage points increase in coverage, Polio-2 shows a 9.9 percentage points increase, and Polio-3 exhibits a 10 percentage points increase. Conversely, the first dose of the Hepatitis-B (Hep-B-1) vaccine experiences a negative treatment effect on coverage. Low-income status attenuates treatment effects for the coverage of almost all antigens and doses[33]. Gender disparities in antigen-specific coverage are not evident.

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The D-Tap 2 vaccine exhibits similar trends. Urban areas show a positive, statistically significant treatment effect of 6.1 percentage points, while rural areas show no treatment effect for the D-Tap 2 vaccine. For the D-Tap-3 vaccine, urban areas see a positive, statistically significant treatment effect of 7.1 percentage points, while rural areas exhibit no treatment effect for D-Tap 3.

Treatment effects for the Polio-1 vaccine in rural households are positive (7.3 percentage points) but imprecisely estimated and hence statistically insignificant. Conversely, urban households show not only a larger magnitude (10.1 percentage points) but also a statistically significant treatment effect for the Polio-1 vaccine. Although treatment effects for the Polio-2 vaccine are positive and statistically significant for both samples, the effect's magnitude and significance in urban areas (11.4 percentage points, significant at the 5% level) surpass rural areas (8.8 percentage points, significant at the 10% level). Similarly, for the Polio-3 vaccine, although treatment estimates are positive and statistically significant for both samples, the magnitude of the effect in urban areas (11.0 percentage points, significant at the 5% level) is higher than in rural areas (9.2 percentage points, significant at the 5% level).

Regarding Measles-1, the treatment effect is negative (though statistically insignificant) across rural households,

[33] With the exception of the Polio-1 vaccine/dose.

while urban households exhibit a strong 11.3 percentage points positive effect, significant at the 1% level.

In summary, there are clear contrasts between urban and rural households regarding heterogeneity in treatment effects, except for the case of Polio-2 and Polio-3, where the estimates for rural households (Panel-A) are either insignificant or negative when statistically significant. Conversely, for urban households (Panel-B), all estimates are positive when statistically significant. These results suggest that, except for the three polio doses, increases in antigen-specific coverage across urban areas come at the expense of decreases in rural areas. Specifically, this is evident across all three doses of the hepatitis vaccine. However, when treatment effects are observed, they are usually sizable. For example, the treatment effects across the three doses of polio range from 8.8 to 11.4 percentage points across rural and urban households. Similarly, although the positive treatment effects for D-Tap-2, D-Tap-3, Hep-B-3, and Measles-1 vaccines are concentrated only in urban areas, their magnitudes range from 4.8 to 11.3 percentage points, which are considerable given the high pre-treatment coverage levels in Punjab.

Lower household income in Table 11 is negatively associated with vaccination coverage across many antigens, and the attenuation effect of low-income status appears stronger for rural households. To explore this further, we examine heterogeneity across low-income and mid-high income households in rural and urban areas regarding our antigen-specific measures. The DID estimates for low-income and mid-high income households across rural areas are presented in Table 12, while the DID estimates for low-income and mid-high income households across urban areas are presented in Table 13.

The DID estimates on antigen-specific measures for rural areas (Table 12) reveal income disparities in treatment effects. When antigen-specific treatment effects are positive and statistically significant (e.g., Polio-2, Polio-3), they occur across mid-high income households. In Panel A of Table 12, positive treatment effects for Polio-2 and Polio-3 are observed across mid-high income households, while in Panel B, the treatment effects for Polio-2 and Polio-3 across low-income households are statistically insignificant.

However, when antigen-specific treatment effects are negative and statistically significant (e.g., for the three hepatitis doses), they occur across low-income households. Table 11 displayed negative treatment effects for the three doses of the hepatitis vaccine across the overall sample of rural households. Estimates from Table 12 show that these negative treatment effects on the three doses of the hepatitis vaccine across the overall rural sample are mainly concentrated across low-income households. In Panel A of Table 12 for mid-high income households, the

negative point estimates for the three hepatitis vaccines are statistically not distinguishable from zero. In Panel B, however, the treatment has a statistically significant, negative effect on all three hepatitis doses across low-income households, with effect sizes ranging from -6.2 to -4.4 percentage points. The only statistically significant negative effect across mid-high income households in rural areas is observed for the BCG vaccine, with a comparatively small reduction of 2.9 percentage points.

Table 13 presents antigen-specific DID estimates across low-income households and mid-high income households in urban areas. For mid-high income households in urban settings, estimates across the 11 vaccines are positive and statistically significant. The treatment effect sizes are quite large, ranging from 5 to 14 percentage points. For 7 antigens/doses, the effect size is higher than 10 percentage points. On the other hand, with the exception of Measles-1, there are no treatment effects for any other antigen across low-income households in urban settings.

Our findings, combined with the observations from Table 11, indicate that antigen-specific coverage increases across urban areas actually come at the expense of antigen-specific decreases in vaccination coverage across rural areas. This information, when considered alongside our findings regarding heterogeneous treatment effects across household income levels in rural and urban settings in Table 12 and Table 13, provides additional insights. First, antigen-specific coverage increases across urban areas are limited to only mid-high income households. Second, these increases across urban mid-high income households indeed come at the expense of decreases in coverage across rural households. Third, the antigen-specific coverage declines across rural areas, however, are only concentrated across low-income households. In essence, based on our antigen-specific coverage estimates, we find that positive treatment effects across mid-high income urban households come at the expense of negative treatment effects across low-income rural households.

5 Robustness

Our estimates across the three sets of outcomes[34] remain robust to the inclusion of a variety of individual and household level demographic controls, and a set of fixed effects that include district fixed effects, year-of-birth fixed effects and quarter-of-birth fixed effects. In the most stringent of our specifications, we include district $\times$ region fixed effects. The breadth of these controls and fixed effects should be able to purge any threats to the identification

[34] i.e. the measure for overall vaccination coverage on the intensive margin, the measure of "ever immunized" on the extensive margin and the measures of antigen specific coverage

that could potentially arise from time-invariant unobservables.

5.1 Event Study Plots

We provide further evidence to mitigate any remaining identification threats to our estimates by estimating an event study model. To start with, we regress overall vaccination coverage on lags and leads in a quarter-of-birth by province event study design, normalized to the provinces that were not impacted by the treatment. Our estimating equation for the event study model is as follows:

$$Y_{ipt} = \sum_{j=-28}^{8} \gamma_{t+j} q_{pt0+j} + \beta X_{ipt}^{'} + \zeta_{yb} + \xi_{qb} + \delta_{d} + \phi_{r} + \varepsilon_{ipt} \tag{2}$$

Where q_{pt0+j} is a set of indicator variables centered around the quarter in when children in each province were exposed to the treatment. The event study model includes controls for individual and household level demographics as well as year-of-birth, quarter-of-birth, district and region fixed effects. For the case when many control units are never treated, a similar approach to setting up an event study model is suggested by Clarke and Schythe (2020).

The estimates from equation (2) are presented in figure 3. As shown in the event study there are no pre-trends across the quarters-of-birth before the enactment of E-VACCS. Apart from a small decline in vaccination coverage around the second quarter-of-birth in the year-of-birth 2012, there are no visible trends in the event study. In contrast, we see a distinct increase (2 to 3 percentage points) in vaccination coverage for 6 out of 8 quarters post-treatment. It was expected that most of the treatment effects are concentrated in the later part of the treatment, as children born in the first few quarters of 2014 were only partially exposed to the treatment.

In figure 4, we estimate separate event study models for rural and urban areas. In panel A, the event study for rural areas confirms that there are no pre-trends in the quarters-of-birth before the treatment, and we see slightly negative post-treatment effects in the year of 2015, though they are not distinguishable from zero. Event study for urban areas in panel B also confirms that there are no pre-trends in the quarters-of-birth prior to the treatment. However, for the post-treatment 4 quarters-of-birth in 2015, we see a markedly different treatment effect of 7 to 10 percentage points in vaccination coverage.

Taken together, the three event-study graphs provide support to our identification strategy and confirm the

accuracy of our previous estimates in section 4. We present evidence that no pre-trends existed before the treatment, and E-VACCS had a distinct positive treatment effect on the intensive margin of vaccination coverage, limited to the extent of urban areas.

6 Conclusion

Technology-enabled solutions, such as real-time data generation, human resource monitoring, and smartphone-based tracking of vaccination status for eligible populations, have demonstrated promise in similar situations and populations (Uddin et al., 2016; Katib et al., 2013). Developing and maintaining such information systems incurs both fixed and variable costs[35]. For this intervention, an information system was designed, developed, and implemented province-wide, along with additional costs for creating a connected smartphone application. All vaccinators in Punjab were equipped with smartphones, representing the fixed costs of the project. Variable costs encompassed human resource training, maintaining a centralized database server, and human resource staff at different levels, with some administrative burden on district-level health officers. These financial costs are substantial within the context of a struggling economy.

In this paper, we present consistent and robust estimates of the treatment effects resulting from the intervention. Our findings reveal heterogeneous treatment effects, aligning with existing literature suggesting that such effects are typically confined to urban areas (Husain and Omer, 2016). Additionally, income and parental education levels, identified as major determinants of childhood vaccination rates by Raza et al. (2018), remain significant factors in determining the success of the intervention. Despite the intervention's objective to target vulnerable segments of the population, our results indicate an exacerbation of existing regional and income-level disparities.

Overall vaccination coverage estimates indicate that any positive treatment effects are concentrated in urban households with relatively higher income and education levels. This observation aligns with the channels through which E-VACCS purportedly operated. While the intervention may have enhanced accountability for human resources at the district level, it appears that this accountability was not directed towards addressing within-district disparities. District-level teams, achieving progress on vaccination targets at the aggregate level, may claim performance gains, regardless of disparities within sub-populations. This suggests that the intervention, while

[35] Unfortunately, we are unable to provide an exact dollar value for these costs.

increasing vaccination coverage, primarily targeted urban, easily accessible, and informed populations, potentially neglecting harder-to-reach and less-informed rural segments.

Treatment effects on the extensive margin of immunization show relatively more homogeneous patterns. Estimates for treatment effects across rural and urban populations on the extensive margin (Table 7) are identical. While this implies some positive effects of the treatment, possibly sufficient to make a difference on the extensive margin if not on the intensive margin of vaccination coverage, caution is warranted. Positive effects on the extensive margin could mean increased vaccination for some antigens/doses and decreased vaccination for others. Our results, detailed in Table 10, confirm that positive extensive margin vaccination coverage estimates are not driven by gains in early doses like BCG, DPT-1, or Hep-B-1 but rather by gains across the three polio doses.

For rural households, antigen-specific estimates corroborate this observation. Positive extensive margin estimates for rural households are solely driven by the three polio vaccine doses and are limited to mid-high income households in rural regions. Notably, low-income rural households do not exhibit positive treatment effects; instead, negative effects on hepatitis vaccine doses are observed.

Similarly, positive treatment effects in urban areas are primarily limited to mid-high income households, with almost no effects for low-income households in urban regions. This supports our hypothesis that E-VACCS, by introducing accountability and mobilization at the district level, inadvertently diverted attention away from hard-to-reach, remote households, which are more likely to have low-income and low-educated members. These households, less informed about the significance of childhood vaccination, might actively resist or hesitate to vaccinate their children.

Finally, our findings should be interpreted considering that our treatment effects are lower-bound estimates. We include children born in the first two quarters of 2014 in our "treated" sample, but their actual exposure to the treatment was minimal. A key limitation is the absence of long-run estimates, a gap we aim to address in future research by collecting information on the policy environment beyond 2016.

In conclusion, our findings suggest that E-VACCS had the potential to increase vaccination coverage and outreach, but its targeting may have been sub-optimal. The intervention possibly redirected vaccination and human capital resources away from rural and poor households towards affluent and urban households. Our policy recommendation is to enhance the precision of the intervention's targeting. A more granular approach to accountability

mechanisms could be beneficial, looking beyond aggregate numbers at the district level. Given the wealth of data generated and monitored by E-VACCS, a nuanced examination of sub-populations might yield valuable insights. This paper offers the initial causal estimate of E-VACCS's impact on childhood vaccination rates in Punjab, with potential generalizability to similar settings in resource-constrained developing economies.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used [OpenAI/GPT3.5] in order to [proofread and improve style of the paper]. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

References

Ahmed, M., Mazhar, S., Tabassum, E., Razzak, A., and Akbar, S. (2018). E-VACCS: Assessment of barriers and enablers using the Consolidated Framework for Implementation Research in Punjab. In Shahabuddin, A., Sharkey, A., and Hasman, A., editors, *Pakistan Implementation Research for Immunization A compilation of project objectives, results and recommendations*, pages 96–105. UNICEF IRDF UNIT, New York.

Ali, S. A. M. and Altaf, S. W. (2021). Citizen trust, administrative capacity and administrative burden in Pakistan's immunization program. *Journal of Behavioral Public Administration*, 4(1).

Ameen, M., Rasul, S., Haq, M. A., and Mahmood, Q. K. (2018). Determinants of factors associated with childhood immunization in Punjab, Pakistan: evidence from the multiple indicator cluster survey. *Journal of Public Health*, 26(5):495–499.

Asif, A. M., Akbar, M., Tahir, M. R., and Arshad, I. A. (2019). Role of maternal education and vaccination coverage: evidence from Pakistan demographic and health survey. *Asia Pacific Journal of Public Health*, 31(8):679–688.

Basra, A. M., Mushtaq, N., and Raza, A. B. (2018). Causes of Poor Vaccination Coverage in Children Under 5 Years of Age Presenting to a Tertiary Care Hospital. *Pakistan Journal Of Medical & Health Sciences*, 12(2):870–873.

Bugvi, A. S., Rahat, R., Zakar, R., Zakar, M. Z., Fischer, F., Nasrullah, M., and Manawar, R. (2014). Factors associated with non-utilization of child immunization in Pakistan: evidence from the Demographic and Health Survey 2006-07. *BMC public health*, 14(1):1–7.

Chandir, S., Siddiqi, D. A., Dharma, V. K., Shah, M. T., Turab, A., Khan, M. I., Habib, A., and Khan, A. J. (2018). Zindagi Mehfooz (Safe Life) Digital Immunization Registry: leveraging low-cost technology to improve immunization coverage and timeliness in Pakistan. *Iproc*, 4(2):e11770.

Clarke, D. and Schythe, K. T. (2020). Implementing the panel event study. Discussion Paper 13524, IZA Institute of Labor Economics.

Ehreth, J. (2003). The value of vaccination: a global perspective. *Vaccine*, 21(27-30):4105–4117.

GAVI (2021). Gavi Pakistan Country Information. https://www.gavi.org/programmes-impact/country-hub/eastern-mediterranean/pakistan. [Online; accessed 26-October-2021].

Habib, A., Black, K. I., Greenow, C. R., Mirani, M., Muhammad, S., Shaheen, F., Khadka, M. C., Vondeling, A., Ariff, S., and Soofi, S. B. (2019). Evaluation of a maternal, neonatal and child health intervention package in a rural district of Pakistan: A quasi-experimental study. *International Journal of Community Medicine and Public Health*, 6(11):4682.

Haq, Z., Shaikh, B. T., Tran, N., Hafeez, A., and Ghaffar, A. (2019). System within systems: challenges and opportunities for the Expanded Programme on Immunisation in Pakistan. *Health Research Policy and Systems*, 17(1):1–10.

Husain, S. and Omer, S. (2016). Routine immunization services in Pakistan: seeing beyond the numbers. *EMHJ-Eastern Mediterranean Health Journal*, 22(3):201–211.

Imran, H., Raja, D., Grassly, N. C., Wadood, M. Z., Safdar, R. M., and OâReilly, K. M. (2018). Routine immunization in Pakistan: comparison of multiple data sources and identification of factors associated with vaccination. *International Health*, 10(2):84–91.

Katib, A., Rao, D., Rao, P., and Williams, K. (2013). Jeev: a low-cost cell phone application for tracking the vaccination coverage of children in rural communities. In *2013 IEEE International Conference on Healthcare Informatics*, pages 115–120. IEEE.

Kazi, A. M., Ali, M., Zubair, K., Kalimuddin, H., Kazi, A. N., Iqbal, S. P., Collet, J.-P., and Ali, S. A. (2018). Effect of mobile phone text message reminders on routine immunization uptake in Pakistan: randomized controlled trial. *JMIR Public Health and Surveillance*, 4(1):e7026.

Khan, R. E. A., Aslam, I., et al. (2017). Child immunization in Pakistan: Socio-institutional and regional aspects. *Asian Journal of Economic Modelling*, 5(1):49–56.

Kols, A., Gorar, Z., Sharjeel, M., Midhet, F., Nazir, R., Kumar, D., and Fareed, A. (2018). Provincial differences in levels, trends, and determinants of childhood immunization in Pakistan. *Eastern Mediterranean Health Journal*, 24(4).

Kusuma, Y. S., Kumari, R., Pandav, C. S., and Gupta, S. K. (2010). Migration and immunization: determinants of childhood immunization uptake among socioeconomically disadvantaged migrants in Delhi, India. *Tropical Medicine & International Health*, 15(11):1326–1332.

Martinez-Bravo, M. and Stegmann, A. (2022). In vaccines we trust? the effects of the ciaâs vaccine ruse on immunization in pakistan. *Journal of the European Economic Association*, 20(1):150–186.

Murtaza, F., Mustafa, T., and Awan, R. (2016). Determinants of nonimmunization of children under 5 years of age in Pakistan. *Journal of Family & Community Medicine*, 23(1):32.

Muzumdar, J. M. and Cline, R. R. (2009). Vaccine supply, demand, and policy: a primer. *Journal of the American Pharmacists Association*, 49(4):e87–e99.

Naveed, Z., Saeed, A., Kakar, A., Khalid, F., Alnaji, N., and Kumar, G. (2021). Understanding the accountability issues of the immunization workforce for the Expanded Program on Immunization (EPI) in Balochistan: An exploratory study. *Journal of Global Health*, 11.

Obregón, R., Chitnis, K., Morry, C., Feek, W., Bates, J., Galway, M., and Ogden, E. (2009). Achieving polio eradication: a review of health communication evidence and lessons learned in India and Pakistan. *Bulletin of the World Health Organization*, 87:624–630.

Pakistan Bureau of Statistics (2015). Labor Force Statistic 2014-15. https://www.pbs.gov.pk/content/labour-force-survey-2014-15-annual-report. [Online; accessed 26-October-2021].

Pakistan Bureau of Statistics (2017). Decennial Census 2017. https://www.pbs.gov.pk/sites/default/files/population_census/ncrpcr/NCR%20Pakistan.pdf. [Online; accessed 26-October-2021].

Pakistan Bureau of Statistics (2021). Pakistan Social Living Standard Measurement Survey (PSLM): 2010-11, 2012-13, 2014-15, 2019-20 [dataset]. https://www.pbs.gov.pk/content/pakistan-social-and-living-standards-measurement.

PITB (2021). Tracking Vaccinators (E-VACCS). https://pitb.gov.pk/tracking_evaccs. [Online; accessed 26-October-2021].

Raza, O., Lodhi, F. S., Morasae, E. K., and Majdzadeh, R. (2018). Differential achievements in childhood immunization across geographical regions of Pakistan: analysis of wealth-related inequality. *International Journal for Equity in Health*, 17(1):1–8.

Riaz, A., Husain, S., Yousafzai, M. T., Nisar, I., Shaheen, F., Mahesar, W., Dal, S. M., Omer, S. B., Zaidi, S., and Ali, A. (2018). Reasons for non-vaccination and incomplete vaccinations among children in Pakistan. *Vaccine*, 36(35):5288–5293.

Shaikh, B. T., Tran, N., and Hafeez, A. (2018). Health system barriers and levers in implementation of the Expanded Program on Immunization (EPI) in Pakistan: an evidence informed situation analysis. *Public Health Reviews*, 39(1):1–10.

Uddin, M. J., Shamsuzzaman, M., Horng, L., Labrique, A., Vasudevan, L., Zeller, K., Chowdhury, M., Larson, C. P., Bishai, D., and Alam, N. (2016). Use of mobile phones for improving vaccination coverage among children living in rural hard-to-reach areas and urban streets of Bangladesh. *Vaccine*, 34(2):276–283.

Umer, M. F., Zofeen, S., Hu, W., Qi, X., and Zhuang, G. (2020). Spatiotemporal clustering analysis of Expanded Program on Immunization (EPI) vaccination coverage in Pakistan. *Scientific reports*, 10(1):1–11.

Wain, Z. N., Masood, R. A., Ali, R. W., and Bashir, I. (2016). An overview of immunization practices in Pakistan. *International Current Pharmaceutical Journal*, 5(11):94–96.

WHO (2021). Vaccination schedule for Pakistan. https://immunizationdata.who.int/pages/schedule-by-country/pak.html. [Online; accessed 26-October-2021].

World Health Organization (2021). Vaccines and immunization. https://www.who.int/health-topics/vaccines-and-immunization. [Online; accessed 26-October-2021].

Zaidi, S., Shaikh, S. A., Sayani, S., Kazi, A. M., Khoja, A., Hussain, S. S., and Najmi, R. (2020). Operability, acceptability, and usefulness of a mobile APP to track routine immunization performance in rural Pakistan: interview study among vaccinators and key informants. *JMIR mHealth and uHealth*, 8(2):e16081.

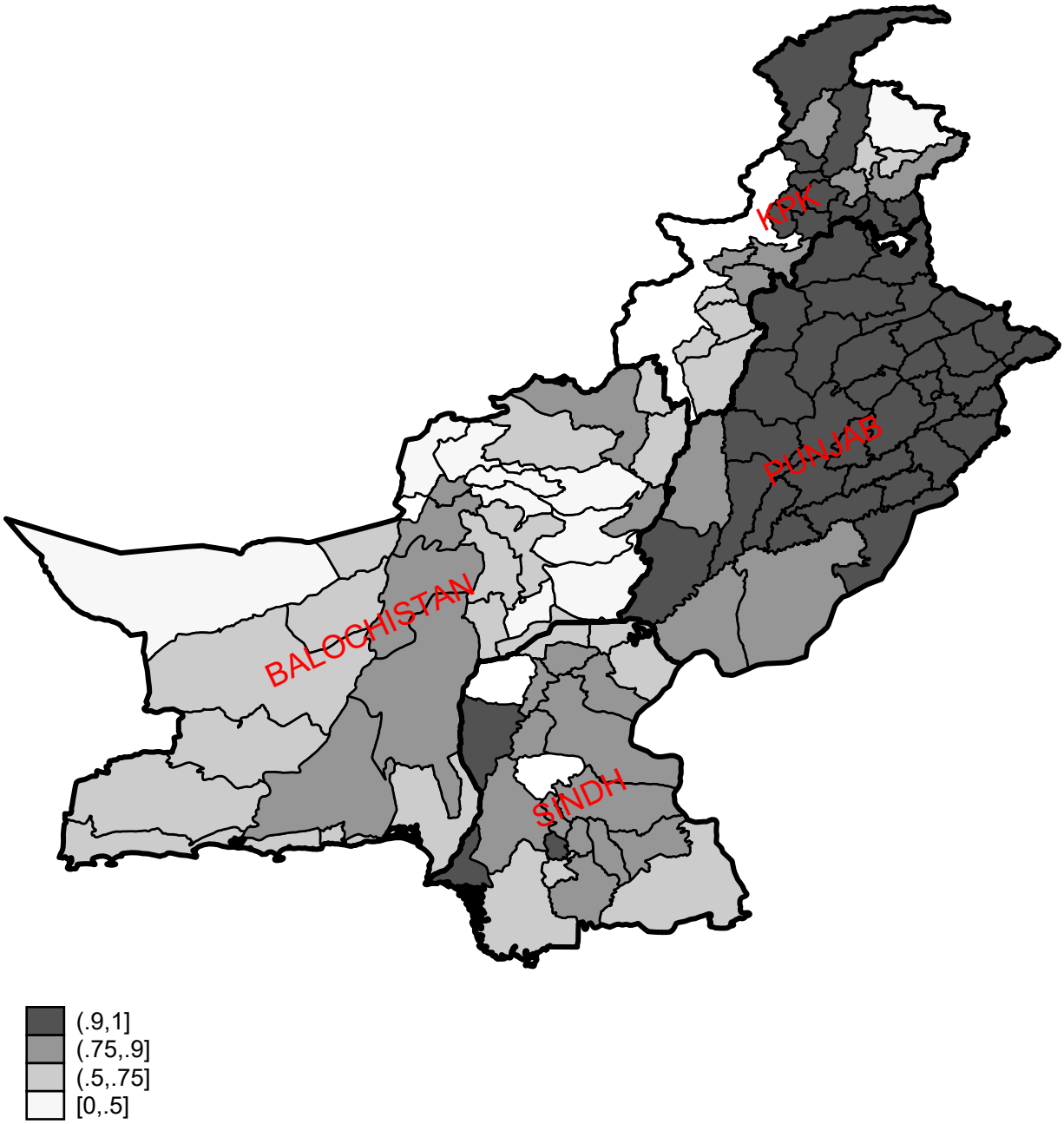
Figures and Tables

Table 1: Pakistan Childhood Vaccination Schedule

Age	Antigen	Dose No.
At Birth	Bacillus Calmette-Guerin(BCG), Polio	0
6 Weeks	D-TaP, Hep-B, Polio	1
10 Weeks	D-TaP, Hep-B, Polio	2
14 Weeks	D-TaP, Hep-B, Polio	3
9 Months	Measles	1
15 Months	Measles	2

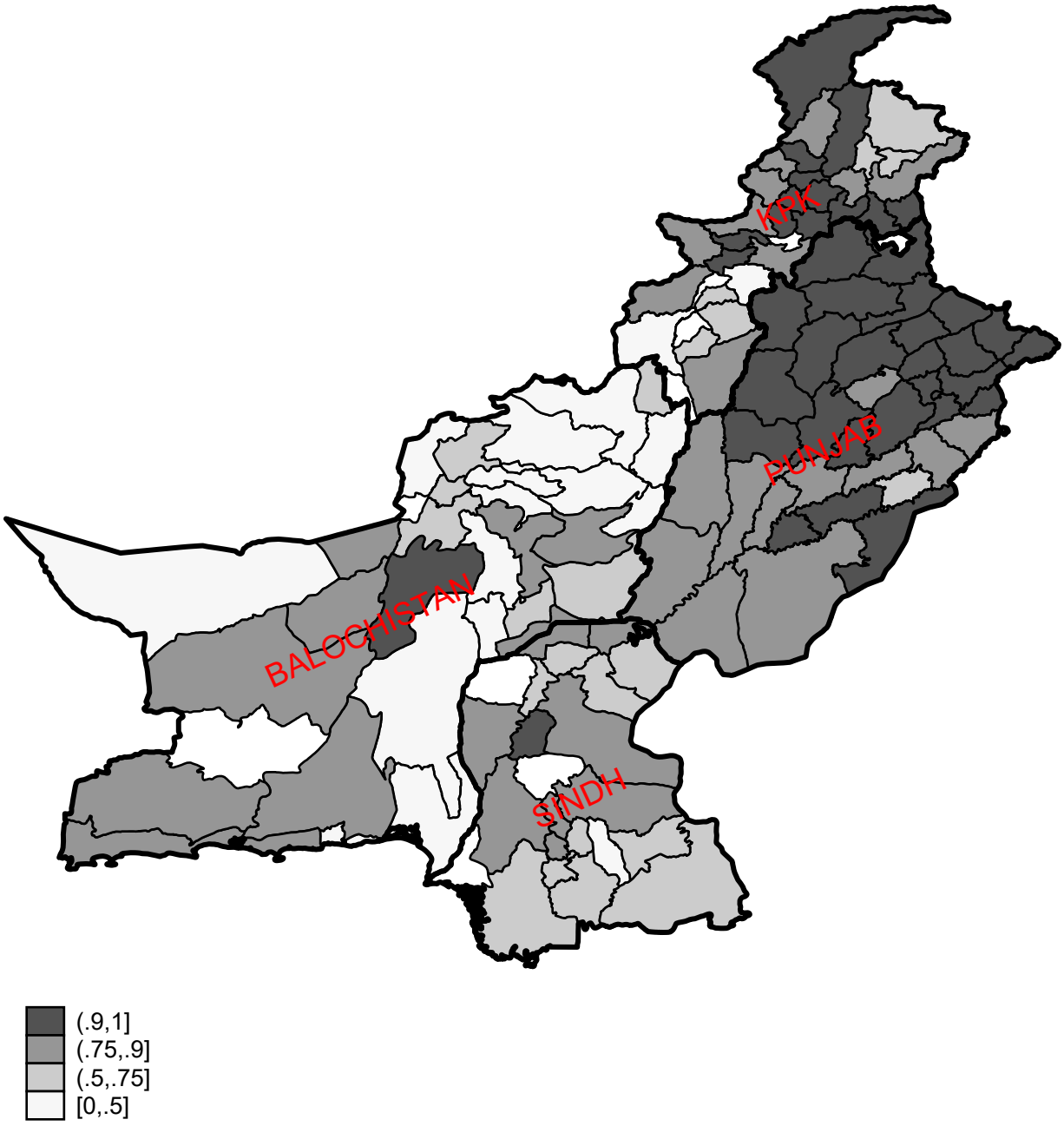
Source. World Heatlh Organization, http://www.emro.who.int/pak/programmes/expanded-programme-on-immunization.html. The table shows the age eligibility, name of antigen and sequence of childhood vaccination schedule under EPI Pakistan.

Figure 1a: Pre-treatment Vaccination Coverage by District



Source: PLSM, 2021. Figure 1 shows province and district-specific mean pre-treatment vaccination coverage for children in year-of-birth cohorts 2007-2013. The thin black borders are district boundaries while the thick black boundaries indicate the provincial boundaries for the provinces of Punjab, KPK, Balochistan and Sindh. All observations are weighted for survey weights.

Figure 1b: Post-treatment Vaccination Coverage by District



Source: PSLM, 2021. Figure 2 shows province and district-specific mean post-treatment vaccination coverage for children in year-of-birth cohorts 2014-2015. The thin black borders are district boundaries while the thick black boundaries indicate the provincial boundaries for the provinces of Punjab, KPK, Balochistan and Sindh.All observations are weighted for survey weights.

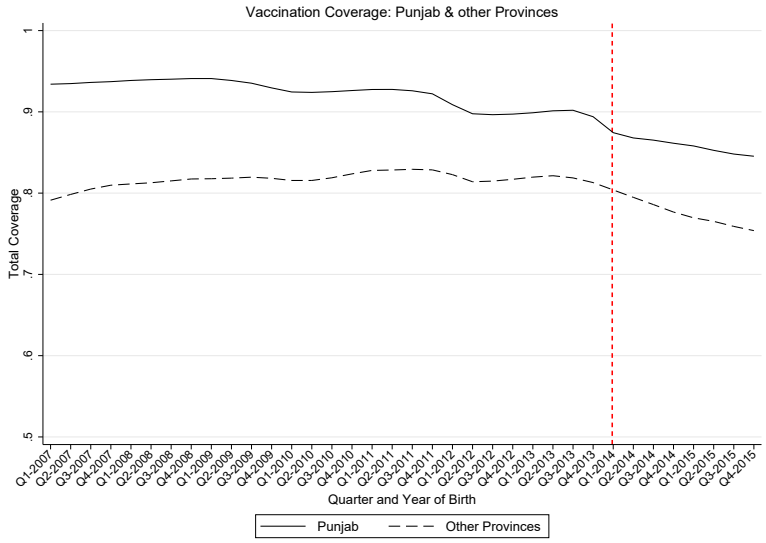
Table 2: Overall Vaccination Coverage: Summary Statistics

	Other Provinces	Punjab
2007	0.793	0.934
	(0.312)	(0.226)
2008	0.832	0.943
	(0.300)	(0.207)
2009	0.832	0.946
	(0.303)	(0.195)
2010	0.809	0.873
	(0.318)	(0.280)
2011	0.845	0.948
	(0.304)	(0.188)
2012	0.814	0.866
	(0.314)	(0.273)
2013	0.814	0.902
	(0.324)	(0.253)
2014	0.752	0.787
	(0.331)	(0.319)
2015	0.702	0.879
	(0.394)	(0.253)
Total	0.809	0.904
	(0.320)	(0.247)

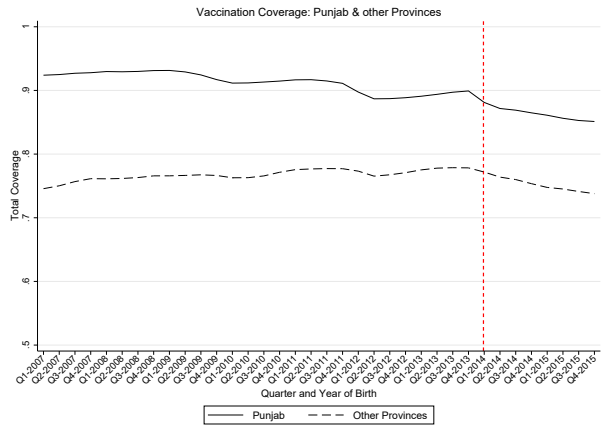
Source. PSLM Survey 2010-2020—The table shows means and standard deviations of total vaccination coverage for children in year-of-birth cohorts 2007-2015. Observations weighted for sampling weights. Total vaccination coverage for a child is measured as the total number of vaccine doses administered divided by the total number of vaccine doses for which a child is eligible at the time of survey.

Figure 2: Vaccination Coverage by Province(s): Trends over time

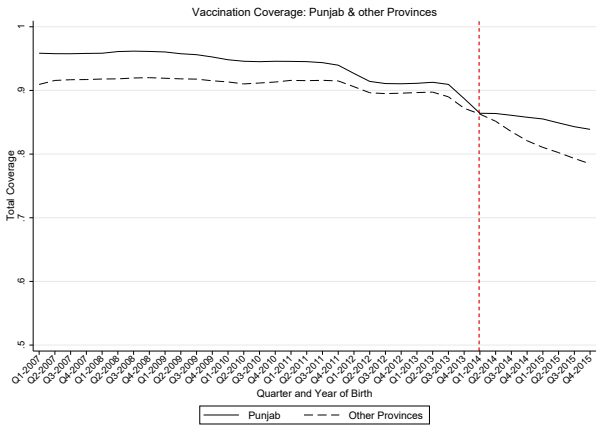
((a)) Panel A: Vaccination Coverage Trends: Overall



((b)) Panel B: Vaccination Coverage Trends: Rural Areas



((c)) Panel C: Vaccination Coverage Trends: Urban Areas



Source: PSLM, 2021. Panel A shows vaccination coverage trends for children in year-of-birth cohorts 2007-2015. The dotted line presents mean vaccination coverage trend for the three control provinces (provinces other than Punjab), while the solid line presents mean overall vaccination coverage for the province of Punjab, the treatment province. The vertical dotted line (red) presents the approximate start-date of E-VACCS. All observations are weighted for survey weights. The left hand side of Panel B shows analogous graphs to Panel A, but the sample is restricted to rural areas. The right hand side of Panel B shows analogous graphs for urban areas.

Table 3: Proportion of Children "Ever Immunized" by Province

	Other Provinces	Punjab
2007	0.977	0.967
	(0.149)	(0.178)
2008	0.974	0.975
	(0.159)	(0.159)
2009	0.976	0.977
	(0.155)	(0.149)
2010	0.979	0.976
	(0.141)	(0.155)
2011	0.980	0.988
	(0.142)	(0.110)
2012	0.982	0.986
	(0.133)	(0.118)
2013	0.980	0.988
	(0.139)	(0.107)
2014	0.978	0.991
	(0.146)	(0.097)
2015	0.957	0.984
	(0.203)	(0.131)
Total	0.976	0.980
	(0.152)	(0.140)

Source. PSLM Survey 2010-2020—The table shows means and standard deviations for the measure of a child being "ever immunized" in year-of-birth cohorts 2007-2015. Observations weighted for sampling weights.

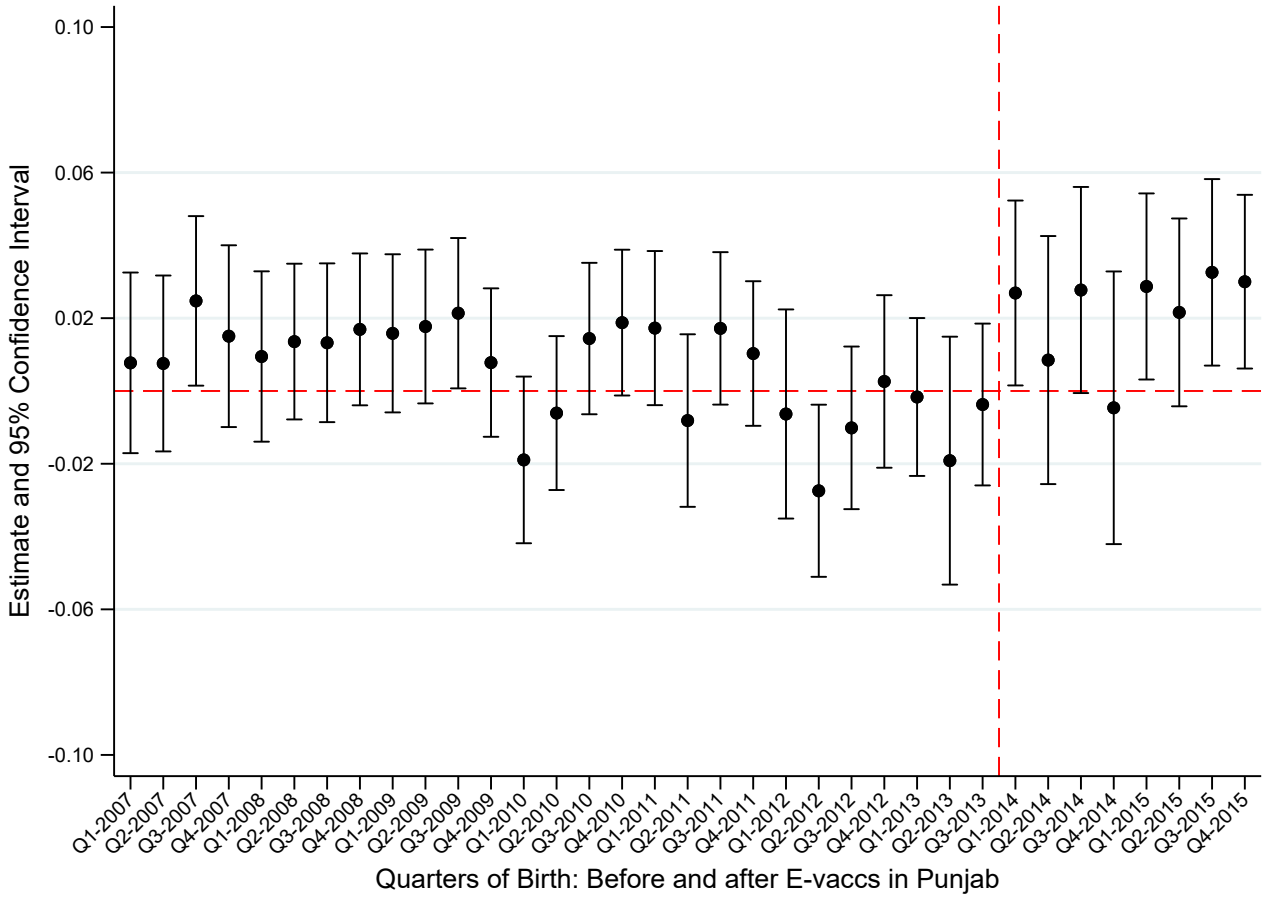
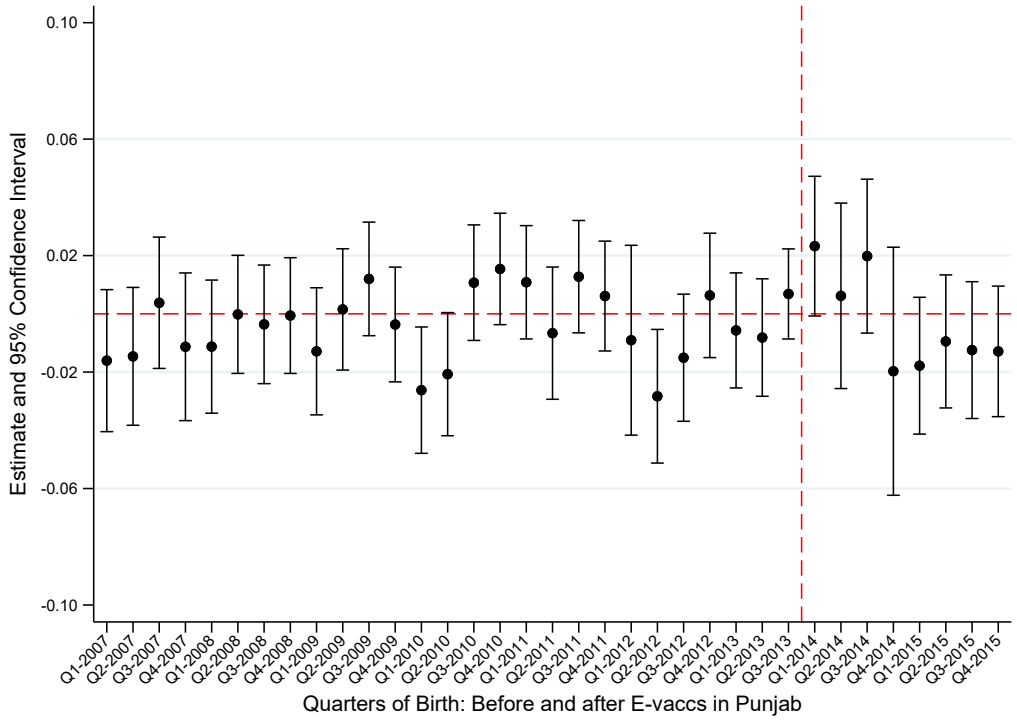
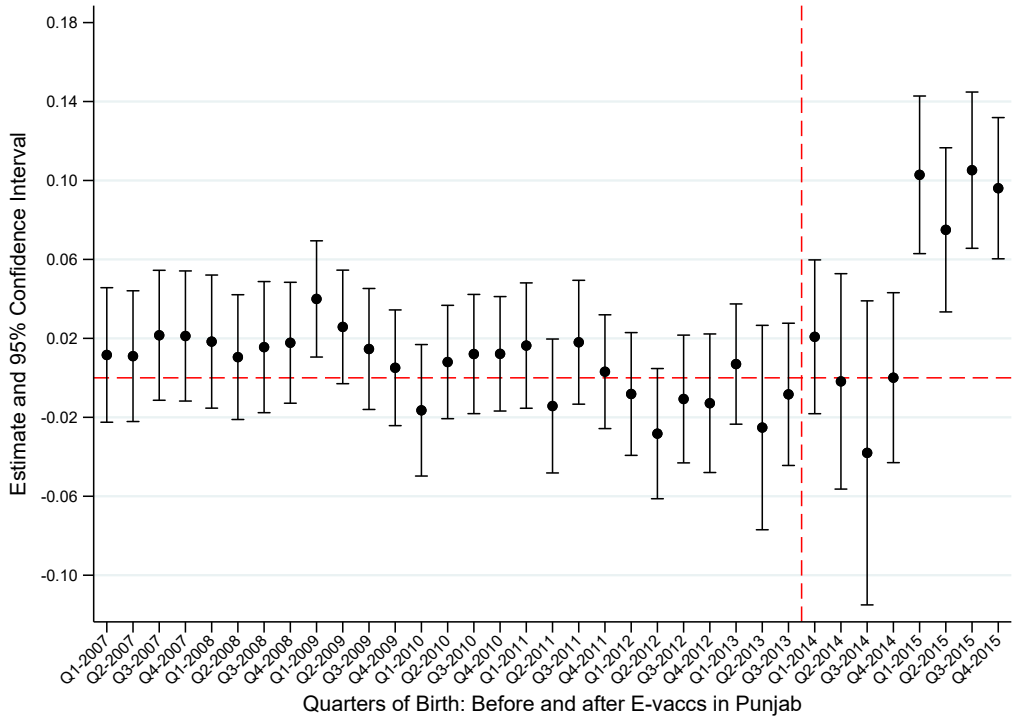


Figure 3: Testing Parallel Trends: Total Vaccination Coverage by Year and Quarter of Birth

Source: PSLM, 2021. The plot shows coefficients and confidence intervals associated with a measure of total vaccination coverage regressed on leads and lags of an indicator for treatment, i.e. the introduction of E-VACCS, conditional on controls for individual demographics, as well as district, year-of-birth, and region fixed effects. Individual demographic controls for father's and mother's ages, incomes, education level and school attendance. All observations are weighted for survey weights and report heteroskedasticity-robust standard errors.



((a)) Panel A: Rural Areas



((b)) Panel B: Urban Areas

Figure 4: Testing Parallel Trends: Rural and Urban Areas

Source: PSLM, 2021. The plot shows coefficients and confidence intervals associated with separate regressions for a measure of total vaccination coverage in urban and rural areas, regressed on leads and lags of an indicator for treatment, i.e. the introduction of E-VACCS, conditional on controls for individual demographics, as well as district, year-of-birth, and region fixed effects. Individual demographic controls for father's and mother's ages, incomes, education level and school attendance. All observations are weighted for survey weights and report heteroskedasticity-robust standard errors.

Table 4: Vaccination Coverage: Difference-in-Differences Estimates

	Vaccination Coverage					
	All regions				Rural Region	Urban Region
	(1)	(2)	(3)	(4)	(5)	(6)
Punjab x Treatment	0.020	0.019	0.019	0.019	0.001	0.062*
	(0.025)	(0.025)	(0.025)	(0.024)	(0.021)	(0.032)
Low−income==1		-0.013***	-0.013***	-0.013***	-0.018**	-0.009*
		(0.003)	(0.003)	(0.004)	(0.006)	(0.005)
Gender of the child	0.001	0.001	0.001	0.001	0.000	0.001
(Male==1)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.004)
Mean pre-treatment coverage	0.898	0.898	0.898	0.898	0.871	0.943
Sample Size	170,960	170,960	170,960	170,960	127,926	43,032
Individual Controls	Yes	Yes	Yes	Yes	Yes	Yes
Income-bin FE	No	Yes	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	No	No	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	No	Yes	Yes
Region FE	No	Yes	Yes	No	No	No
District X Region FE	No	No	No	Yes	No	No

Source.—PSLM 2021.
Notes.—The table reports the coefficients associated with regressions of a measure of total vaccination coverage on an indicator for interaction across the timing of E-vaccs and the observation lying in the Punjab Province (Punjab==0/1 × Post-Treatment==0/1). Each specification includes a matrix of individual-level demographic controls that include the gender of the child, age of both parents, education levels of both parents, employment status of both parents, and household income levels. Additionally, each specification includes year-of-birth and quarter-of-birth fixed effects. Additionally, specifications (1) to (3) and specifications (5)-(6) control for district fixed effects, while specification (4) includes district × region fixed effects. Standard errors are clustered at the province-year level and the observations are weighted for sampling weights.

Table 5: Vaccination Coverage: Heterogeneity Across Urban and Rural Areas By Household Income Levels

	Vaccination Coverage			
	Rural Regions		Urban Regions	
	Low-Income=0	Low-Income=1	Low-Income=0	Low-Income=1
	(1)	(2)	(3)	(4)
Punjab x Treatment	0.029	-0.006	0.102***	0.019
	(0.031)	(0.018)	(0.028)	(0.032)
Mean pre-treatment coverage	0.917	0.864	0.961	0.935
Sample Size	22,386	105,539	13,364	29,668
Individual Controls	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	Yes	Yes	Yes	Yes

Source.—PSLM 2021.
Notes.—The table reports the coefficients associated with regressions of a measure of total vaccination coverage on an indicator for interaction across the timing of E-VACCS and the observation lying in the Punjab Province (Punjab==0/1 X Post-Treatment==0/1). Each specification includes a matrix of individual-level demographic controls that include the gender of the child, age of both parents, education levels of both parents, and employment status of both parents. Additionally, each specification includes year-of-birth, quarter-of-birth and district fixed effects. Standard errors are clustered at the province-year level and the observations are weighted for sampling weights.

Table 6: Vaccination Coverage: Heterogeneity Across Urban and Rural Areas By Household Education Levels

	Vaccination Coverage			
	Rural Regions		Urban Regions	
	HS or more	Less than HS	HS or more	Less than HS
	(1)	(2)	(3)	(4)
Punjab x Treatment	-0.001	0.016	0.054*	0.051
	(0.018)	(0.012)	(0.029)	(0.031)
Mean pre-treatment coverage	0.916	0.855	0.968	0.926
Sample Size	32,684	89,660	16,793	25,268
Individual Controls	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	Yes	Yes	Yes	Yes

Source.—PSLM 2021.
Notes.—The table reports the coefficients associated with regressions of a measure of total vaccination coverage on an indicator for interaction across the timing of E-vaccs and the observation lying in the Punjab Province (Punjab==0/1 X Post-Treatment==0/1). Each specification includes a matrix of individual-level demographic controls that include the gender of the child, age of both parents, education levels of both parents, and employment status of both parents. Additionally, each specification includes year-of-birth, quarter-of-birth and district fixed effects. Standard errors are clustered at the province-year level and the observations are weighted for sampling weights.

Table 7: Ever Immunized: Difference-in-Differences Estimates

	Ever Immunized					
	All regions				Rural Region	Urban Region
	(1)	(2)	(3)	(4)	(5)	(6)
Punjab x Treatment	0.021***	0.021***	0.021***	0.022***	0.022***	0.022***
	(0.003)	(0.003)	(0.003)	(0.007)	(0.007)	(0.007)
Low−income==1		-0.004***	-0.004***	-0.004***	-0.003	-0.006**
		(0.002)	(0.002)	(0.002)	(0.002)	(0.003)
Gender of the Child	0.001	0.001	0.001	0.000	-0.001	0.003
(Male==1)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
Mean pre-treatment levels	0.979	0.979	0.979	0.979	0.976	0.983
Sample Size	170,960	170,960	170,960	170,958	127,926	43,032
Individual Controls	Yes	Yes	Yes	Yes	Yes	Yes
Income-bin FE	No	Yes	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	No	No	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	No	Yes	Yes
Region FE	No	Yes	Yes	No	No	No
District X Region FE	No	No	No	Yes	No	No

Source.—PSLM 2021.

Notes.—The table reports the coefficients associated with regressions of a binary variable indicating if a child ever received any dose of any childhood vaccines on an indicator for interaction across the timing of E-VACCS and the observation lying in the Punjab Province (Punjab==0/1 × Post-Treatment==0/1). Each specification includes a matrix of individual-level demographic controls that include the gender of the child, age of both parents, education levels of both parents, employment status of both parents, and household income levels. Additionally, each specification includes year-of-birth and quarter-of-birth fixed effects. Additionally, specifications (1) to (3) and specifications (5)-(6) control for district fixed effects, while specification (4) includes district × region fixed effects. Standard errors are clustered at the province-year level and the observations are weighted for sampling weights.

Table 8: Ever Immunized: Heterogeneity Across Urban and Rural Areas By Household Income Levels

	Ever Immunized			
	Rural Regions		Urban Regions	
	Low-Income=0	Low-Income=1	Low-Income=0	Low-Income=1
	(1)	(2)	(3)	(4)
Punjab x Treatment	0.016***	0.021***	0.013***	0.027*
	(0.006)	(0.004)	(0.003)	(0.015)
Mean pre-treatment levels	0.984	0.975	0.989	0.982
Sample Size	22,386	105,539	13,364	29,668
Individual Controls	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	Yes	Yes	Yes	Yes

Source.—PSLM 2021.
Notes.—The table reports the coefficients associated with regressions of a binary variable indicating if a child ever received any dose of any childhood vaccines on an indicator for interaction across the timing of E-VACCS and the observation lying in the Punjab Province (Punjab==0/1 X Post-Treatment==0/1). Each specification includes a matrix of individual-level demographic controls that include the gender of the child, age of both parents, education levels of both parents, and employment status of both parents. Additionally, each specification includes year-of-birth, quarter-of-birth and district fixed effects. Standard errors are clustered at the province-year level and the observations are weighted for sampling weights.

Table 9: Ever Immunized: Heterogeneity Across Urban and Rural Areas By Household Education Levels

	Ever Immunized			
	Rural Regions		Urban Regions	
	HS or more	Less than HS	HS or more	Less than HS
	(1)	(2)	(3)	(4)
Punjab x Treatment	0.021***	0.026***	0.017***	0.022**
	(0.003)	(0.005)	(0.006)	(0.008)
Mean pre-treatment levels	0.986	0.972	0.991	0.979
Sample Size	32,684	89,660	16,793	25,268
Individual Controls	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	Yes	Yes	Yes	Yes

Source.—PSLM 2021.
Notes.—The table reports the coefficients associated with regressions of a binary variable indicating if a child ever received any dose of any childhood vaccines on an indicator for interaction across the timing of E-VACCS and the observation lying in the Punjab Province (Punjab==0/1 X Post-Treatment==0/1). Each specification includes a matrix of individual-level demographic controls that include the gender of the child, age of both parents, education levels of both parents, and employment status of both parents. Additionally, each specification includes year-of-birth, quarter-of-birth and district fixed effects. Standard errors are clustered at the province-year level and the observations are weighted for sampling weights.

Table 10: Difference in Difference Estimates: Antigen-Specific Vaccination Coverage

	BCG	D-Tap-1	Hep-B-1	Polio-1	D-Tap-2	Hep-B-2	Polio-2	D-Tap-3	Hep-B-3	Polio-3	Measles-1
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Punjab x Treatment	-0.021	-0.007	-0.042**	0.084*	0.008	-0.025	0.099**	0.020	-0.011	0.100**	0.003
	(0.018)	(0.022)	(0.016)	(0.049)	(0.027)	(0.016)	(0.048)	(0.028)	(0.017)	(0.046)	(0.033)
Low−income==1	-0.011***	-0.010***	-0.013***	-0.004	-0.012***	-0.015***	-0.006*	-0.018***	-0.021***	-0.012**	-0.018***
	(0.003)	(0.003)	(0.003)	(0.002)	(0.004)	(0.004)	(0.003)	(0.006)	(0.006)	(0.005)	(0.004)
Gender of the Child	0.002	0.001	0.001	-0.002	0.001	0.001	-0.003*	0.001	0.002	-0.003*	0.004
	(0.002)	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.002)	(0.003)
Sample Size	170,958	170,958	170,958	170,958	170,958	170,958	170,958	170,958	170,958	170,958	158,460
Individual Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
District FE X Region FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Income-bin FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source.—PSLM 2021.
Notes.—The table reports the coefficients associated with regressions of a measure of dose-specific vaccination coverage on an indicator for interaction across the timing of E-VACCS and the observation lying in the Punjab Province (Punjab == 0/1 × Post-Treatment==0/1). Each specification includes a matrix of individual-level demographic controls that include the gender of the child, age of both parents, education levels of both parents, employment status of both parents, and household income levels. Additionally, each specification includes year-of-birth, quarter-of-birth fixed effects, and district × region fixed effects. Standard errors are clustered at the province-year level and the observations are weighted for sampling weights.

Table 11: Antigen-Specific Vaccination Coverage: Heterogeneity across Rural & Urban Areas

	BCG	D-Tap-1	Hep-B-1	Polio-1	D-Tap-2	Hep-B-2	Polio-2	D-Tap-3	Hep-B-3	Polio-3	Measles-1
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Panel A - Rural Areas											
Punjab x Treatment	-0.037	-0.024	-0.061**	0.073	-0.012	-0.047**	0.088*	0.001	-0.033*	0.092**	-0.038
	(0.023)	(0.024)	(0.023)	(0.047)	(0.025)	(0.020)	(0.047)	(0.025)	(0.018)	(0.045)	(0.027)
Low−income==1	-0.019***	-0.018***	-0.021***	-0.001	-0.021***	-0.023***	-0.002	-0.025***	-0.029***	-0.008	-0.027***
	(0.005)	(0.006)	(0.007)	(0.004)	(0.007)	(0.008)	(0.005)	(0.008)	(0.009)	(0.006)	(0.006)
Gender of the Child	0.003	0.002	0.001	-0.002	0.001	0.001	-0.003	0.000	0.001	-0.003	0.005*
(Male==1)	(0.002)	(0.002)	(0.002)	(0.001)	(0.003)	(0.003)	(0.002)	(0.003)	(0.003)	(0.002)	(0.003)
Sample Size	127,926	127,926	127,926	127,926	127,926	127,926	127,926	127,926	127,926	127,926	118,749
Individual Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Income-bin FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Panel B - Urban Areas											
Punjab x Treatment	0.023	0.037	0.008	0.101*	0.061**	0.033	0.114**	0.071**	0.048*	0.110**	0.113***
	(0.021)	(0.025)	(0.021)	(0.051)	(0.029)	(0.023)	(0.050)	(0.034)	(0.027)	(0.049)	(0.033)
Low−income==1	-0.005	-0.004	-0.006	-0.006**	-0.005	-0.007	-0.009**	-0.013	-0.015**	-0.016**	-0.010
	(0.005)	(0.006)	(0.005)	(0.003)	(0.006)	(0.006)	(0.004)	(0.008)	(0.007)	(0.006)	(0.008)
Gender of the Child	0.002	0.001	0.002	-0.003	0.001	0.002	-0.004	0.002	0.004	-0.003	0.003
(Male==1)	(0.004)	(0.004)	(0.005)	(0.003)	(0.004)	(0.005)	(0.004)	(0.005)	(0.006)	(0.004)	(0.007)
Sample Size	43,032	43,032	43,032	43,032	43,032	43,032	43,032	43,032	43,032	43,032	39,711
Individual Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Income-bin FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source.—PSLM 2021.

Notes.—The table reports the coefficients associated with regressions of a measure of dose-specific vaccination coverage on an indicator for interaction across the timing of E-vaccs and the observation lying in the Punjab Province (Punjab == 0/1 × Post-Treatment==0/1). Each specification includes a matrix of individual-level demographic controls that include the gender of the child, age of both parents, education levels of both parents, employment status of both parents, and household income levels. Additionally, each specification includes year-of-birth, quarter-of-birth fixed effects, and district fixed effects. Standard errors are clustered at the province-year level and the observations are weighted for sampling weights.

Table 12: Antigen-Specific Vaccination Coverage in Rural Areas: Heterogeneity across Income-Levels of Households

	BCG	D-Tap-1	Hep-B-1	Polio-1	D-Tap-2	Hep-B-2	Polio-2	D-Tap-3	Hep-B-3	Polio-3	Measles-1
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Panel A - Middle/High-Income Rural Households											
Punjab x Treatment	-0.029*	0.002	-0.027	0.088	0.017	-0.011	0.107*	0.045	0.016	0.130**	-0.016
	(0.015)	(0.027)	(0.016)	(0.058)	(0.031)	(0.019)	(0.059)	(0.033)	(0.021)	(0.059)	(0.029)
Sample Size	22,386	22,386	22,386	22,386	22,386	22,386	22,386	22,386	22,386	22,386	21,223
Individual Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Panel B - Low-Income Rural Households											
Punjab x Treatment	-0.027	-0.024	-0.062*	0.056	-0.014	-0.050*	0.068	-0.010	-0.044*	0.063	-0.036
	(0.027)	(0.025)	(0.031)	(0.040)	(0.023)	(0.025)	(0.041)	(0.022)	(0.022)	(0.038)	(0.027)
Sample Size	105,539	105,539	105,539	105,539	105,539	105,539	105,539	105,539	105,539	105,539	97,525
Individual Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source.—PSLM 2021.

Notes.—The table reports the coefficients associated with regressions of a measure of dose-specific vaccination coverage on an indicator for interaction across the timing of E-vaccs and the observation lying in the Punjab Province (Punjab == 0/1 × Post-Treatment==0/1). Each specification includes a matrix of individual-level demographic controls that include the gender of the child, age of both parents, education levels of both parents, and employment status of both parents. Additionally, each specification includes year-of-birth, quarter-of-birth fixed effects, and district fixed effects. Standard errors are clustered at the province-year level and the observations are weighted for sampling weights.

Table 13: Antigen-Specific Vaccination Coverage in Urban Areas: Heterogeneity across Income-Levels of Households

	BCG	D-Tap-1	Hep-B-1	Polio-1	D-Tap-2	Hep-B-2	Polio-2	D-Tap-3	Hep-B-3	Polio-3	Measles-1
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Panel A - Middle/High-Income Urban Households											
Punjab x Treatment	0.050***	0.079***	0.061***	0.128**	0.104***	0.085***	0.135**	0.120***	0.103***	0.140***	0.133***
	(0.016)	(0.019)	(0.016)	(0.049)	(0.027)	(0.023)	(0.050)	(0.030)	(0.026)	(0.046)	(0.030)
Sample Size	13,364	13,364	13,364	13,364	13,364	13,364	13,364	13,364	13,364	13,364	12,601
Individual Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Panel B - Low-Income Urban Households											
Punjab x Treatment	0.007	0.001	-0.040	0.053	0.026	-0.013	0.072	0.028	-0.004	0.058	0.089**
	(0.025)	(0.029)	(0.026)	(0.046)	(0.028)	(0.024)	(0.044)	(0.036)	(0.029)	(0.047)	(0.041)
Sample Size	29,668	29,668	29,668	29,668	29,668	29,668	29,668	29,668	29,668	29,668	27,110
Individual Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Quarter-of-Birth FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
District FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source.—PSLM 2021.

Notes.—The table reports the coefficients associated with regressions of a measure of antigen-specific vaccination coverage on an indicator for interaction across the timing of E-vaccs and the observation lying in the Punjab Province (Punjab == 0/1 × Post-Treatment==0/1). Each specification includes a matrix of individual-level demographic controls that include the gender of the child, age of both parents, education levels of both parents, and employment status of both parents. Additionally, each specification includes year-of-birth, quarter-of-birth fixed effects, and district fixed effects. Standard errors are clustered at the province-year level and the observations are weighted for sampling weights.

Online Appendix

A Rural and Urban Coverage Trends

In table A1, we decompose the vaccination trends across rural and urban areas. Across the provinces in the control group, mean rural vaccination coverage was 74.6% for the birth-year cohort of 2007, which increased gradually to 80.1% for the birth-year cohort of 2010, before declining to 69.6% for birth-year cohort of 2015. On the other hand, mean urban vaccination coverage across control provinces was 91.2% for birth-year cohort of 2007. This remained relatively stable till the birth-year cohort of 2011, and slowly dropped to 70.9% for the birth-year cohort of 2015. This would suggest that urban areas were in particular hit hard by the system-wide vaccination rate declines that the country underwent in 2015. On the other hand for the province of Punjab, mean rural vaccination coverage was 92.4% for birth-year cohort of 2007, which remained stable with some seasonal shocks till the birth-year cohort of 2013, before declining to 80.7% for birth-year cohort of 2014 and recovering back to 85.8% for birth-year cohort of 2015. Mean urban vaccination coverage for the province of Punjab was 95.8% for birth-year cohort of 2007, which roughly remains the same albeit with some seasonal variation, to the level of 90.1% till the birth-year cohort of 2013, and declines to 75.5% for the birth-year cohort of 2014. Then it goes back up to 91.3% during birth-year cohort of 2015. This goes on to show that the province of Punjab was not immune to the country-wide shock in mean vaccination coverage rates over the years 2014-2015, but the intervention helped to arrest the ongoing coverage decline that other provinces suffered, particularly so for the case of urban areas.

Table A1: Vaccination Coverage by Province: Rural & Urban

	Control-Rural	Control-Urban	Punjab-Rural	Punjab-Urban
2007	0.746	0.912	0.924	0.958
	(0.331)	(0.214)	(0.238)	(0.191)
2008	0.779	0.925	0.936	0.959
	(0.327)	(0.218)	(0.218)	(0.184)
2009	0.777	0.922	0.936	0.963
	(0.332)	(0.220)	(0.212)	(0.160)
2010	0.754	0.896	0.849	0.912
	(0.347)	(0.243)	(0.302)	(0.238)
2011	0.801	0.923	0.946	0.951
	(0.332)	(0.224)	(0.193)	(0.182)
2012	0.770	0.889	0.856	0.881
	(0.338)	(0.249)	(0.285)	(0.255)
2013	0.778	0.881	0.904	0.901
	(0.347)	(0.263)	(0.252)	(0.255)
2014	0.744	0.773	0.807	0.755
	(0.335)	(0.321)	(0.307)	(0.335)
2015	0.696	0.709	0.858	0.913
	(0.395)	(0.391)	(0.273)	(0.209)
Total	0.765	0.886	0.895	0.918
	(0.342)	(0.262)	(0.258)	(0.228)

Source. PSLM Survey 2010-2021—The table shows means and standard deviation of total vaccination coverage for children in year-of-birth cohorts 2007-2015, separately for urban and rural areas of Punjab, the treatment province and the urban and rural areas for other provinces. Observations weighted for sampling weights. Total vaccination coverage for a child is measured as the total number of vaccine doses administered divided by the total number of vaccine doses for which a child is eligible at the time of the survey.

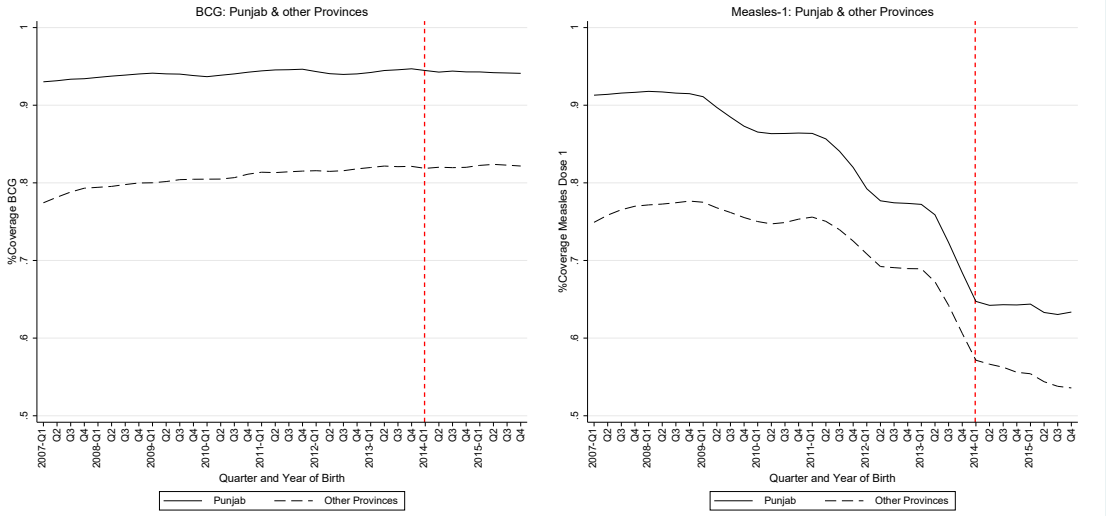
B Antigen Specific Coverage Trends

In appendix figures B1 and figure B2, we plot dose-specific coverage trends for each antigen of Pakistan's childhood vaccination schedule. Panel A of Figure B1 shows treatment and control trends for the first dose of Pakistan's vaccine regimen (the BCG vaccine) on the left, while analogous trends for the last dose of the regimen (the Measle-1 vaccine) are shown on the right hand side. The side by side comparison of the trends for first and last dose of the vaccine program confirms that the trends remain comparable across the treatment and control provinces throughout the routine vaccination cycle.

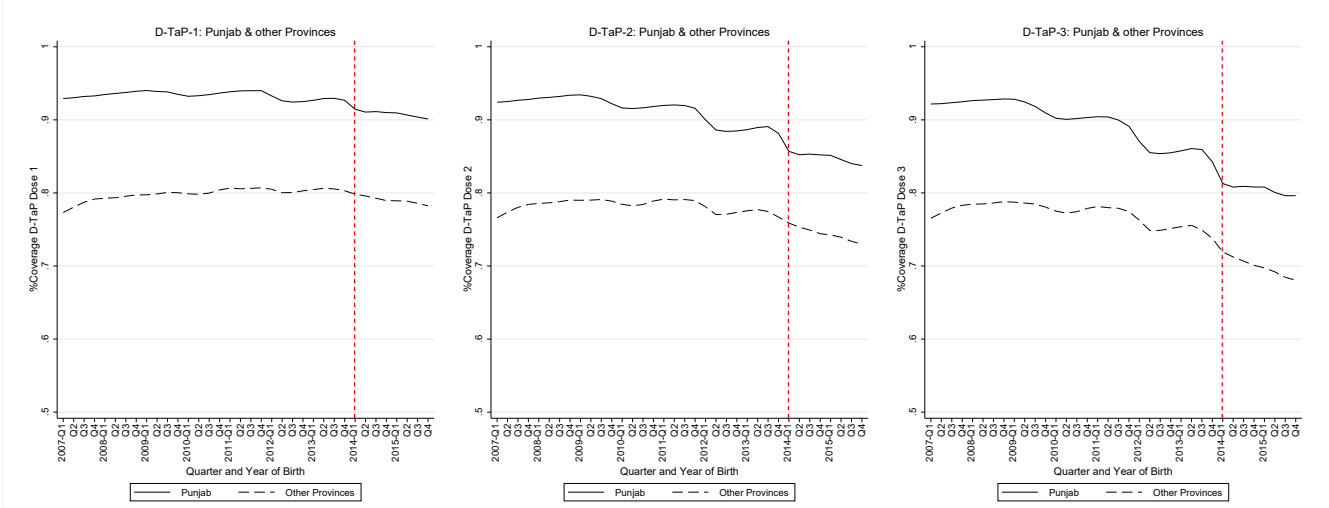
Panel B of Figure B1 plots coverage trends for the three doses of D-Tap vaccine, coverage trends for the three doses of Hepatitis-B vaccine are plotted in Panel A of Figure B2, and finally coverage trends for the three doses of Oral Polio vaccine are plotted in Panel B of Figure B2. The graphs show that no pre-treatment trends exist for the three doses of the D-TaP vaccine as well as the three doses of the Oral Polio vaccine. The control provinces do show signs of some increases in coverage for the three doses of the Hepatitis-B vaccine. Beginning the second quarter of 2013 however, these pre-trends also appear to flatten out. However, even if the pre-treatment increases in coverage for these three doses were to carry over to the post-treatment period, it is more likely that such pre-trends would only bias our estimates downwards for Hepatitis-B specific coverage.

Figure B1: Vaccination Coverage by Province(s): Bacille Calmette-Guerin (BCG), Measles-1, and Diphtheria, Tetanus, and Pertussis Vaccines (D-TaP)

((a)) Panel A: Bacille Calmette-Guerin-1 (BCG) & Measles-1 Vaccines



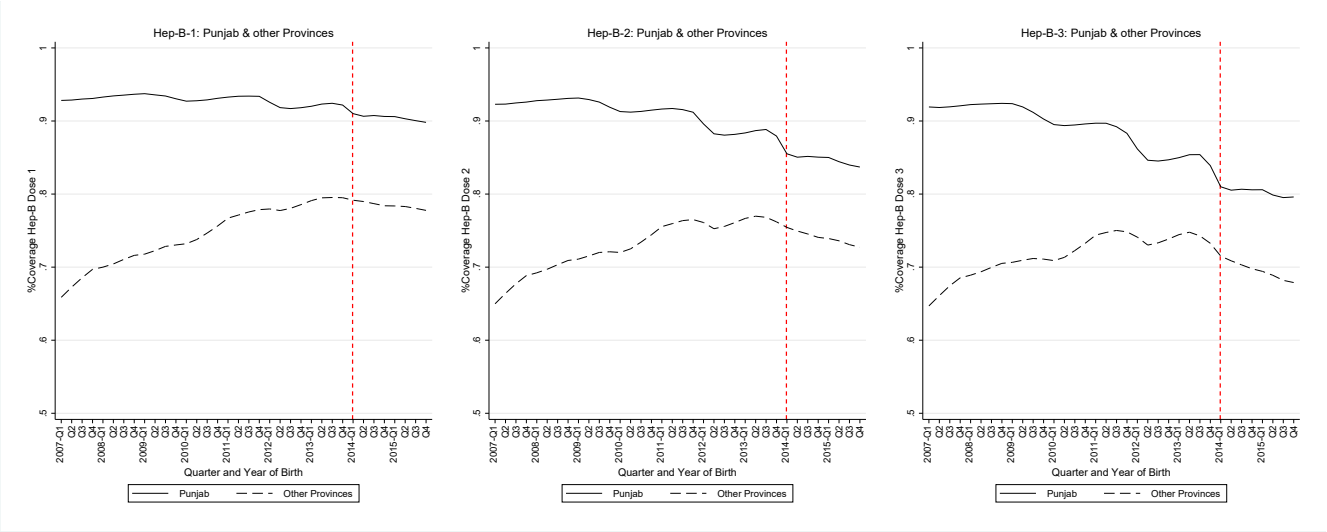
((b)) Panel B: Diphtheria, Tetanus, and Pertussis Vaccines (D-TaP)



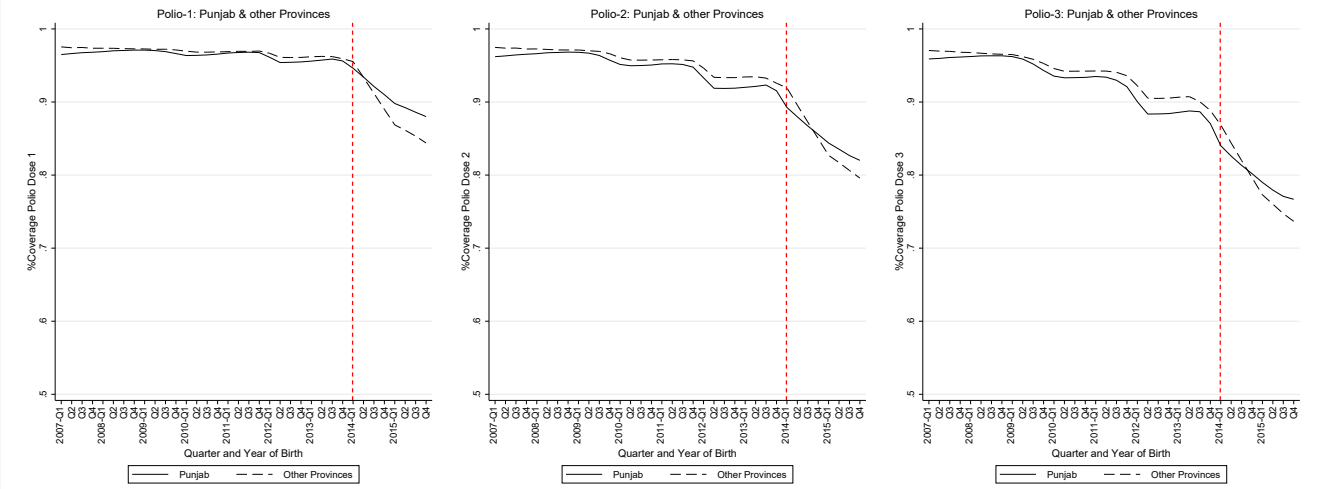
Source: PSLM, 2021. Panel A shows vaccination coverage trends for Bacille Calmette-Guerin-1 Measles-1 Vaccines for children in year-of-birth cohorts 2007-2015. The dotted line presents mean vaccination coverage trend for the three control provinces (provinces other than Punjab), while the solid line presents mean overall vaccination coverage for the province of Punjab, the treatment province. The vertical dotted line (red) presents the approximate start-date of E-VACCS. Panel B presents similar coverage graphs for the three doses of the Diphtheria, Tetanus, and Pertussis (D-TaP/DTP) vaccine. All observations are weighted for survey weights.

Figure B2: Vaccination Coverage by Province(s): Hepatitis (Hep-B) and Polio (OPV) Vaccines

((a)) Panel A: Hepatitis-B (Hep-B) Vaccines



((b)) Panel B: Polio (OPV) Vaccines



Source: PSLM, 2021. Panel A shows vaccination coverage trends for three doses of the Diphtheria, Tetanus, and Pertussis Hepatitis-B vaccine for children in year-of-birth cohorts 2007-2015. The dotted line presents mean vaccination coverage trend for the three control provinces (provinces other than Punjab), while the solid line presents mean overall vaccination coverage for the province of Punjab, the treatment province. The vertical dotted line (red) presents the approximate start-date of E-VACCS. Panel B presents similar coverage graphs for the three doses of the oral polio (OPV) vaccine. All observations are weighted for survey weights.