26/09/2020

CERN Press Release 12/02/2018

- Measured W boson mass 80370 ± 19 MeV
- PAPER: ATLAS Collab, EPJC, 78, 2, 1, 2017 ⇒
- 14 million W bosons in 2011, LHC @ 7 TeV
- Matches measurements at LEP & Tevatron
- Consistent with SM predictions
  → mass can be predicted by SM w/ higher precision than direct measurement ∴ deviation ⇒ new physics
- "The measurement relies on a thorough calibration of the detector and of the theoretical modelling of the W boson production. These were acheived through the study of Z boson events & several other ancillary measurements".

Project Description Notes

- LHCb allows small angles not seen in other experiments
- Study production of electroweak sector bosons (W & Z)
- W boson mass precisely predicted using fine structure constant & Z boson mass.
- High precision measurements required to test for physics beyond SM. eg. supersymmetry, extra dimensions, additional matter generations

- Begin project by selecting a sample of SINGLE MUON EVENTS from the LHCb data that we ENRICHED IN W BOSON DECAYS.
- Develop model of transverse momentum distribution of the muon sample, inc main background process.
  → Code in C++ or python, or mixture.
- TERM 1: → Reasonable model of physics processes contributing to muon sample.
  → Initial estimate of W boson production cross section.
- Later goals → developing a fitting code in which W boson mass is a free parameter, building towards parameter measurement.

Eur. Phys. J. C (2018) 78:110

Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector.

- ATLAS detector 2011, centre of mass energy 7 TeV
  $\simeq 4.6\ fb^{-1}$ of integrated luminosity
- 7.8×10^6 $W \to \mu\nu$ & 5.9×10^6 $W \to e\nu$
- Mass from fit of reconstructed distributions of charged lepton transverse momentum & W boson trans mom^{ntm}

$\Rightarrow m_W = 80370 \pm 7\ (\text{stat}) \pm 11\ (\text{exp-syst.}) \pm 14\ (\text{mod. syst})$ MeV
$= 80370 \pm 19$ MeV

↑ experimental systematic ↑ modelling systematic

- Mass diff W^+ & W^- $\Rightarrow$ $m_{W^+} - m_{W^-} = -29 \pm 28$ MeV.

Introduction

ELECTROWEAK THEORY

→ Electroweak interactions mediated by W boson, Z boson & photon
→ Gauge theory based on $SU(2)_L \times U(1)_Y$ symmetry.
→ W & Z gain mass through a symmetry breaking mechanism
  ⇒ Higgs boson
    → "mechanism relies on interaction of gauge bosons w/ a scalar doublet field & implies the existence of an additional physical state" → H Boson.
→ W&Z bosons confirmed @ CERN SPS, 1983
  Higgs boson confirmed @ LHC collabs ATLAS & CMS, 2012
→ Lowest order EW theory, $m_W = f(m_Z, \alpha, G_\mu)$
  α = FINE STRUCTURE CONSTANT
  G_μ = FERMI CONSTANT
  Higher order corrections inc dependence on gauge couplings & masses of heavy particles in SM. ⇒ Δr

(Using SM parameters)

$$m_W^2\left(1 - \frac{m_W^2}{m_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}\,G_\mu}(1 + \Delta r)$$

SM → Δr sensitive to top quark & Higgs boson masses.

Extended theories, Δr has contributions from additional particles & interactions.

→ effects can be probed by comparing measured & predicted M_W.

→ CONSTRAINTS ON PHYSICS BEYOND SM LIMITED BY M_W MEASUREMENT PRECISION [16] in paper.

PREVIOUS MEASUREMENTS

centre of mass energy

- CERN SPS $p\bar{p}$ → UA1 $\sqrt{s} = 546$ GeV
  - UA2 $\sqrt{s} = 630$ GeV
- Tevatron SPS $p\bar{p}$ → CDF $\sqrt{s} = 1.8$ TeV
  - D0 $\sqrt{s} = 1.96$ TeV } both expts @ both $\sqrt{s}$
- LEP $e\bar{e}$ $\sqrt{s} = 161 - 209$ GeV (4 expts)

⇒ World average $M_W = 80385 \pm 15$ MeV, dominated by CDF & D0

α, G_μ, M_Z & M_t M_H ⇒ SM prediction $M_W = 80358 \pm 8$ MeV [16] in paper
$= 80362 \pm 8$ MeV

⇒ 8 MeV uncertainty is measurement precision target.

[16] in paper worth reading → link saved.

The paper then goes into detail of the specific decay paths observed & lists the sections of the paper. Come back to this after reading other Mika papers?

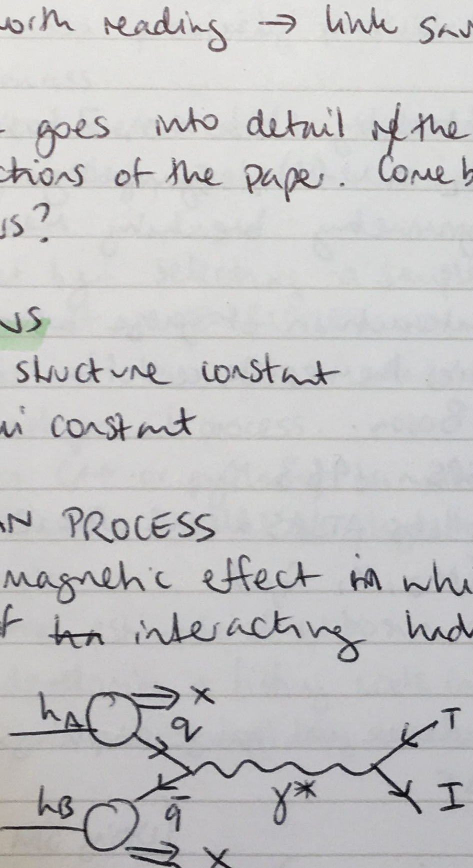
DEFINITIONS

α = Fine structure constant

G_μ = Fermi constant

DRELL-YAN PROCESS

→ electromagnetic effect ~~in~~ which a quark & antiquark from a pair of ~~ha~~ interacting hadrons annihilate to give a lepton pair.



(Kenyon ~~Kenyon~~ paper gives process or Drell, Yan paper)

⇒ Paper → "at Hadron colliders, W-boson mass can be determined in Drell-Yan production from $W \to l\nu$ decays where l is an electron or muon.

Eur. Phys. J. C (2015) 75:601

Prospects for improving the LHC ~~mass~~ W boson mass measurement with forward muons.

- Charged lepton transverse momentum p_T^l
- ~~Parton~~ distribution functions PDFs Parton

Parton — generic description for particle constituent within a hadron

PDF

Consider frame where target nucleon ~~has~~ has a v large momentum.
⇒ parton momentum is almost collinear with nucleon momentum
⇒ nucleon is a stream of ~~part~~ partons each with a fraction x of longitudinal momentum.

PDF = momentum distribution functions of ~~partons~~ partons within the hadron (spin of partons not considered).
= probability density for finding parton with longitudinal momentum fragment x at resolution scale Q^2.
↳ squared energy scale.

Determined experimentally by fitting observables to experimental data. Cannot be calculated using perturbative QCD.

$f_i(x, Q^2)$ → probability of finding in the hadron, a parton of flavour i, carrying a fraction ~~of~~ x of the hadron momentum, with Q being the energy scale of the hard interaction.

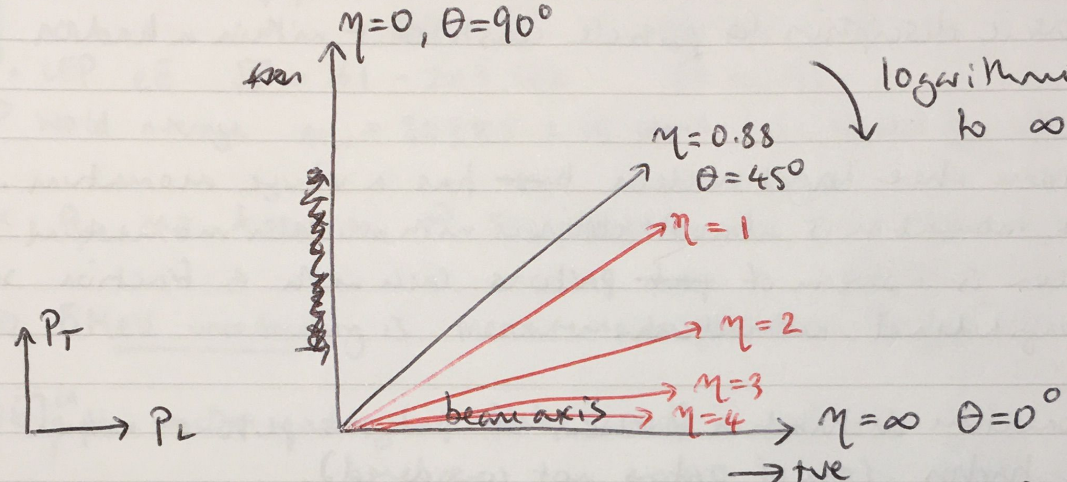
Eur. Phys. J. C (2015) 75:601 continued

- Discussion of current / in process measurements at Tevatron & LHC. & reduction of uncertainties.

- pseudorapidity η
  → Spatial coordinate describing angle of particle relative to beam axis

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

$\theta = \angle$ particle 3 momentum $\underline{p}$ & positive direction of beam access. "polar angle"



Longitudinal momentum p_L = along beam axis (p_z)
Transverse momentum $p_T = \sqrt{p_x^2+p_y^2}$ = perpendicular to beam axis

Particles w/ high pseudorapidity generally lost → very shallow scattering angles. ↓ detectors achieved $|\eta| \sim 3$

Hadron colliders measure physical momenta in terms of:
- transverse momentum p_T
- polar angle in the transverse plane ϕ
- pseudo rapidity η

pseudorapidity = "longitudinal angle of emerging particle ~~jet~~ jet"
→ Lorentz invariant under longitudinal boosts.

- $E^2 - |\underline{p}|^2 = m^2$ $\quad m$ = rest mass, $c=1$

LHCb → W production rate smaller due to
i) limited angular acceptance $2 < \eta < 5$
ii) lower instantaneous luminosity
→ Only available observable = p_T^l

LHCb can select pure sample of $W \to \mu\nu$ decays w/o requirement on $\not{E}_t$
($\not{E}_t$ = missing transverse energy)
⇒ only requires knowledge of muon reconstruction

Study chooses to focus on Run II data 2015-2016 at $\sqrt{s} = 13$ TeV
→ expected to record at at least $7 fb^{-1}$ Will this be our data?

fb^{-1} = per femtobarn, inverse femtobarn
→ unit used to measure #particle collision events per femtobarn of target cross section
→ conventional unit of time-integrated luminosity
(indicate particle collider productivity)
b = barn, unit of area $= 10^{-28} m^2$

2) PDF uncertainties
• Uses data from previous paper, Ref 16, Phys. Rev. D 91 (11), 113005 (2015)

Previous LHC measurements / proposed of type $pp \to W \to l\nu + X$ @ $\sqrt{s} = 13$ TeV

& suggestions of requirements eg. $p_T^l > 25$ GeV

Kinematic acceptance, GPD (general purpose detector eg LHC)
GPD • $|\eta| < 2.5$ $p_T^l > 25$ GeV $p_T^\nu > 25$ GeV $p_T^W < 15$ GeV
LHCb • $2.0 < \eta < 4.5$ $p_T^l > 20$ GeV ($W \to \mu\nu$)

PDF4LHC recommendation? Sets? → seems to be PDFs calculated by experimental groups to give sets & PDF4LHC is recommended sets.

PDFs lead to uncertainties & uncertainties of m_W (MeV) have been calculated using 3 sets of PDFs.

There's a lot of statement of values with no explanation of calculation.
→ Summary → LHCb measurements (PDFs) are anticorrelated to LHC sets ∴ reduce uncertainties by 20-30%

3) LHCb experimental sensitivity to the W mass.

→ Can LHCb measure M_W w/sufficient experimental precision to exploit this anticorrelation in PDF uncertainties?

Extrapolate projected Run I & Run II signal yields ($W \to \mu\nu$) & estimate M_W measurement uncertainty.

PDF uncertainties motivate separate analyses for W^+ & W^-

3.1) BACKGROUND PROCESSES

Dominant → ① $Z/\gamma^* \to \mu\mu$

where one μ escapes ~~due to~~ the limited angular acceptance of LHCb

② "QCD" background

muonic decays of pions & kaons, at lower p_T^{ℓ}

Simulated data given in graphs → FIG 3 } Calculate statistical uncertainties

→ Events per 0.5 GeV vs Muon p_T (GeV)

⇒ $\delta_{stat} \simeq 10\ (13)$ MeV for $W^+\ (W^-)$

3.2) Momentum scale calibration

Quarkonium → flavorless meson whose constituents are a heavy quark, & its own antiquark ⇒ neutral particle

• LHCb has excellent momentum resolution 0.2 – 0.8%

What does momentum scale mean ~~than~~ & how does it affect uncertainties?

3.3) Other source of uncertainty is muon reconstruction efficiency.

→ sub-dominant source of uncertainty.

4) Prospects for an LHC M_W combination

"The idea of this study is not to make a precise estimate of the LHC sensitivity, but rather to estimate the relative impact of the proposed LHCb measurement"

"Total uncertainty improved by 80% when LHCb included"

"It seems that in any realistic scenario, excluding extreme cases, LHCb would reduce the total uncertainty on the LHC average by 20-40%"

"LHCb has a more ~~…~~ impact than a second GPD"

→ Table of values to confirm (Table

5) Uncertainties stemming from the p_T^W modelling.

→ source of theoretical uncertainty

→ not discussed in paper, suggestion of further study.

→ affects templates used to fit data to extract M_W

6) Summary

- "LHCb ~~…~~ Run II using $W \to \mu\nu$ reduces total uncertainty on the LHC average by 20-40% depending on the assumptions on the experimental uncertainties."
- "It remains to be demonstrated that the p_T^W model uncertainties can be controlled at the necessary level of precision"

Action: Read 2nd Mika Paper, Eur Phys J C 79, 6, 2 2019

→ Detailed analysis of PDFs

(Also revise error calculation w/ correlation) ✓

05/10/20

Error Revision - Tom Hase Book p. Chpt 6 & 7

Standard error in a parameter (a_j), in terms of CURVATURE of the error surface (AKA hyper-surface)

$\downarrow$

χ^2

$$\alpha_j = \sqrt{\frac{2}{\left(\frac{\partial^2 \chi^2}{\partial a_j^2}\right)}}$$

$$\chi^2 = \sum_i \left(\frac{(y_i - y(x_i))^2}{\alpha_i^2} \right)$$

$y(x_i)$ = theoretical model

y_i = data α_i = error bars.

→ Develop matrix methodology for describing the ~~the~~ variation of the χ^2 surface (around minimum value χ^2_{min}) & determining the uncertainties of fit parameters.