Search for the rare decays of Z and Higgs bosons to J/ψ plus photon at $\sqrt{s} = 13$ TeV

Hao-Ren Jheng
Thesis supervisor: Chia-Ming Kuo
National Central University
Department of physics and center of high energy and high field physics

14 Sep. 2018

Outline

- **Introduction**
  - Theoretical backgrounds and motivation of this search, previous results, the CMS detector
- **Analysis strategies**
  - Samples, event selection, background and signal models, systematic uncertainties, statistical method
- **Results & Conclusion**
  - Final results, projection, outlook

The standard model

- The standard model (SM) of particle physics describes the electromagnetic, weak, and strong interactions between all known particles

- These three interactions can be derived by requiring **local gauge invariance**: **the Lagrangian is invariant under the local phase transformation of the fields**

- The electromagnetic/weak/strong interaction can be associated with the transformation under the U(1)/SU(2)/SU(3) symmetry

The standard model

- The electromagnetic and weak interactions are unified in the GSW model, where the underlying symmetry group is **$U(1)_Y \times SU(2)_L$**
  - The masses of the W and Z bosons were predicted from this model. In 1983 UA1 and UA2 experiments lead by Carlos Rubbia and Simon van der Meer discovered the W and Z bosons

- However, there were some problems
  - Why do the four gauge bosons have so different masses, if they are manifestations of an electroweak interaction?
  - The unitarity violation of the WW scattering process
  - etc. ...

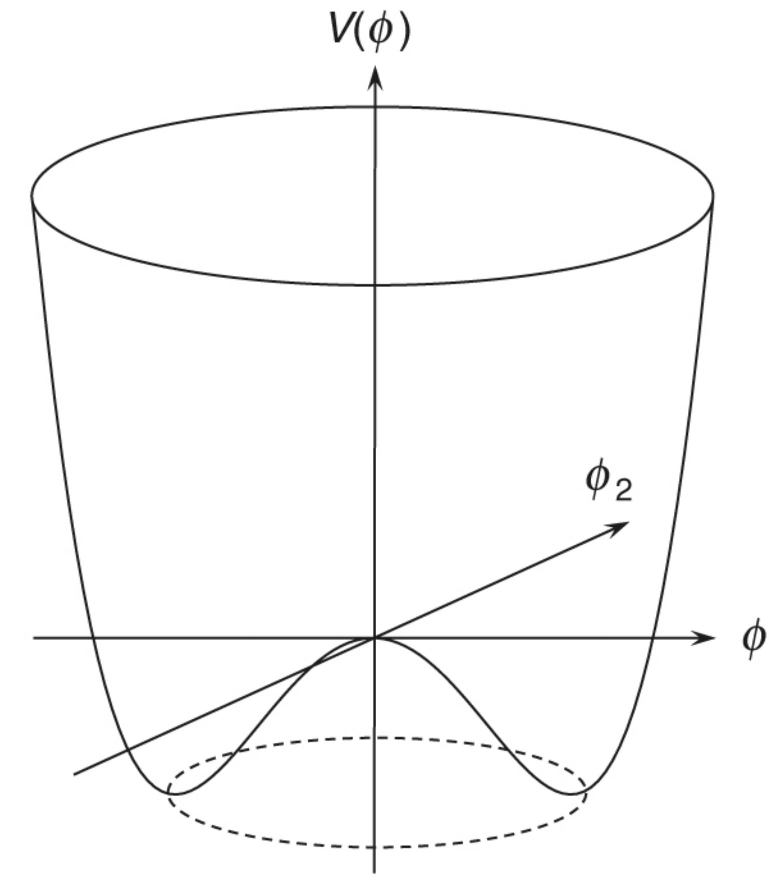
The BEH mechanism

- In the SM, the BEH mechanism is embedded in the $U(1)_Y \times SU(2)_L$ local gauge symmetry of the electroweak sector, and introduces two complex scalar fields in the doublet

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

with the Lagrangian

$$\mathcal{L} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi)$$



$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2, \mu^2 < 0$

- By choosing a particular vacuum state among infinite minima of the field and the unitary gauge, the doublet can be written in the form

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

- Expanding all the terms in the Lagrangian, the masses of gauge bosons can be identified as the coefficients of the quadratic terms in the gauge fields

The BEH mechanism

- It turns out that the couplings between the Higgs boson and the gauge bosons are proportional to the masses of the gauge bosons

$$g_{HWW} = g_W m_W, \; g_{HZZ} = g_Z m_Z$$

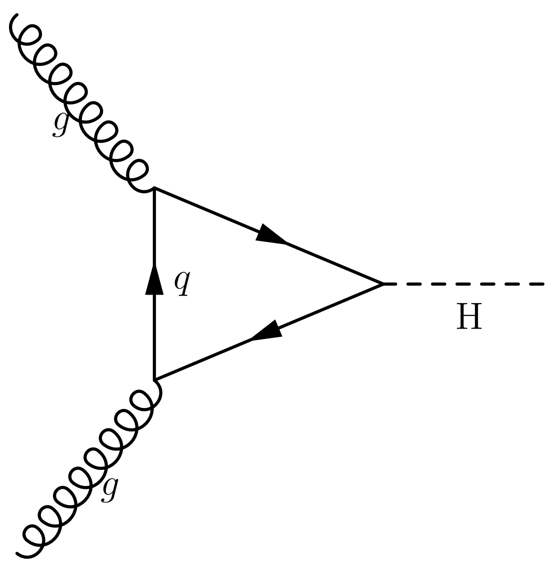
- The fermion masses can be accounted for by the Yukawa coupling

$$y_f = \frac{\sqrt{2} m_f}{v}$$

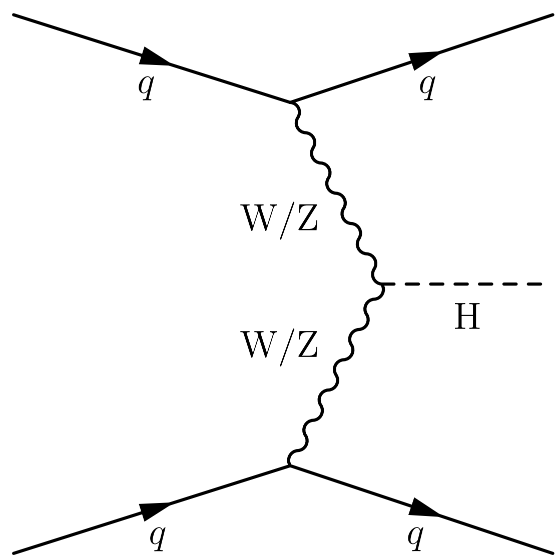
- A review of the Higgs boson production at the LHC will be introduced as follows

The Higgs boson production

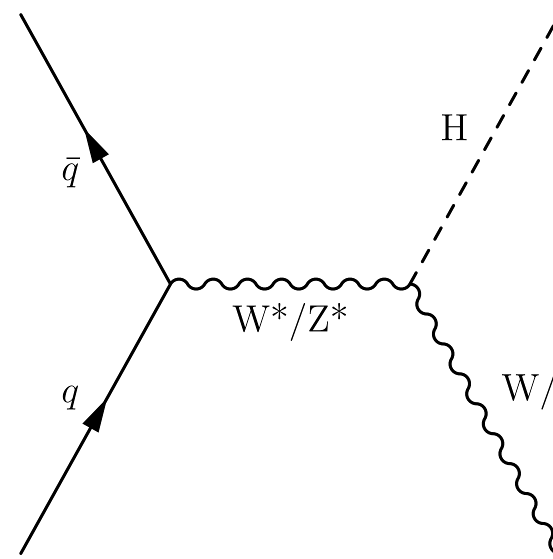
gluon-gluon fusion (ggF)



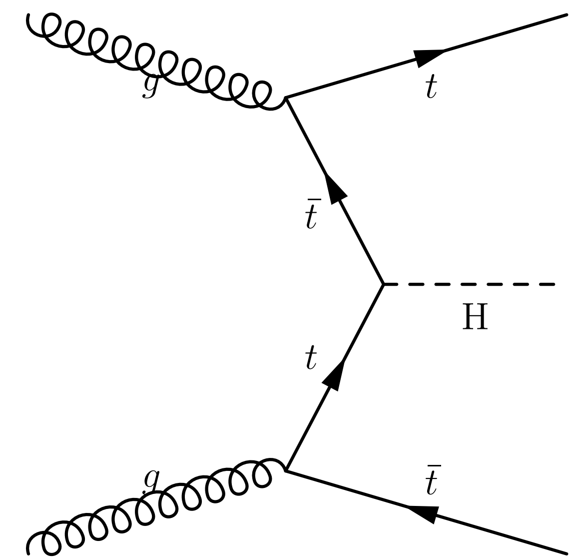
vector boson fusion (VBF)



associated vector boson production (VH)



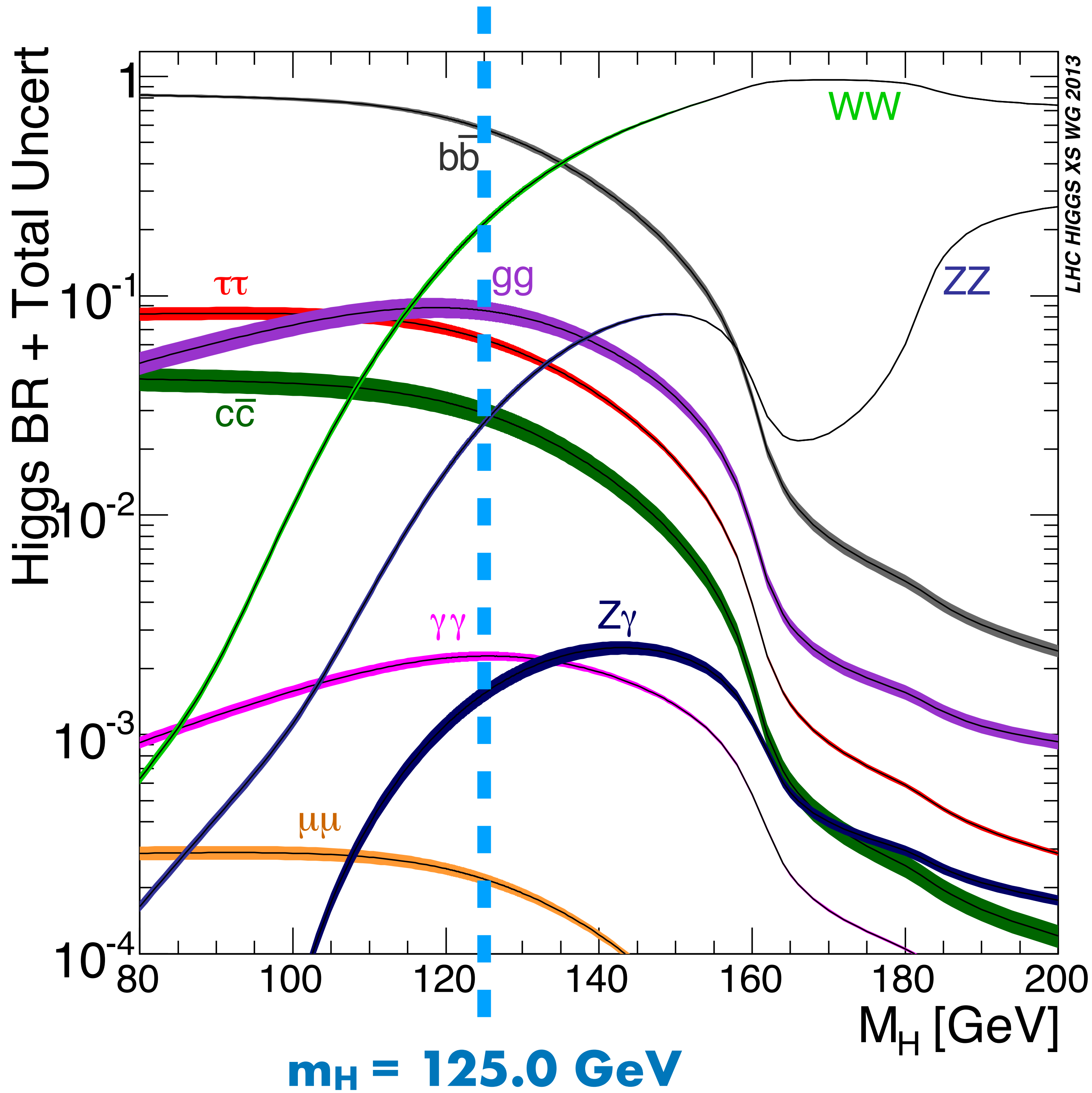
associated top quark pair production (ttH)



Production (m_H = 125.0 GeV)	**XS (pb)**
ggF	48.6
VBF	3.8
ZH	8.8E-01
WH (W^+H + W^-H)	1.4E+00
ttH	5.1E-01

Ref: LHCXSWG

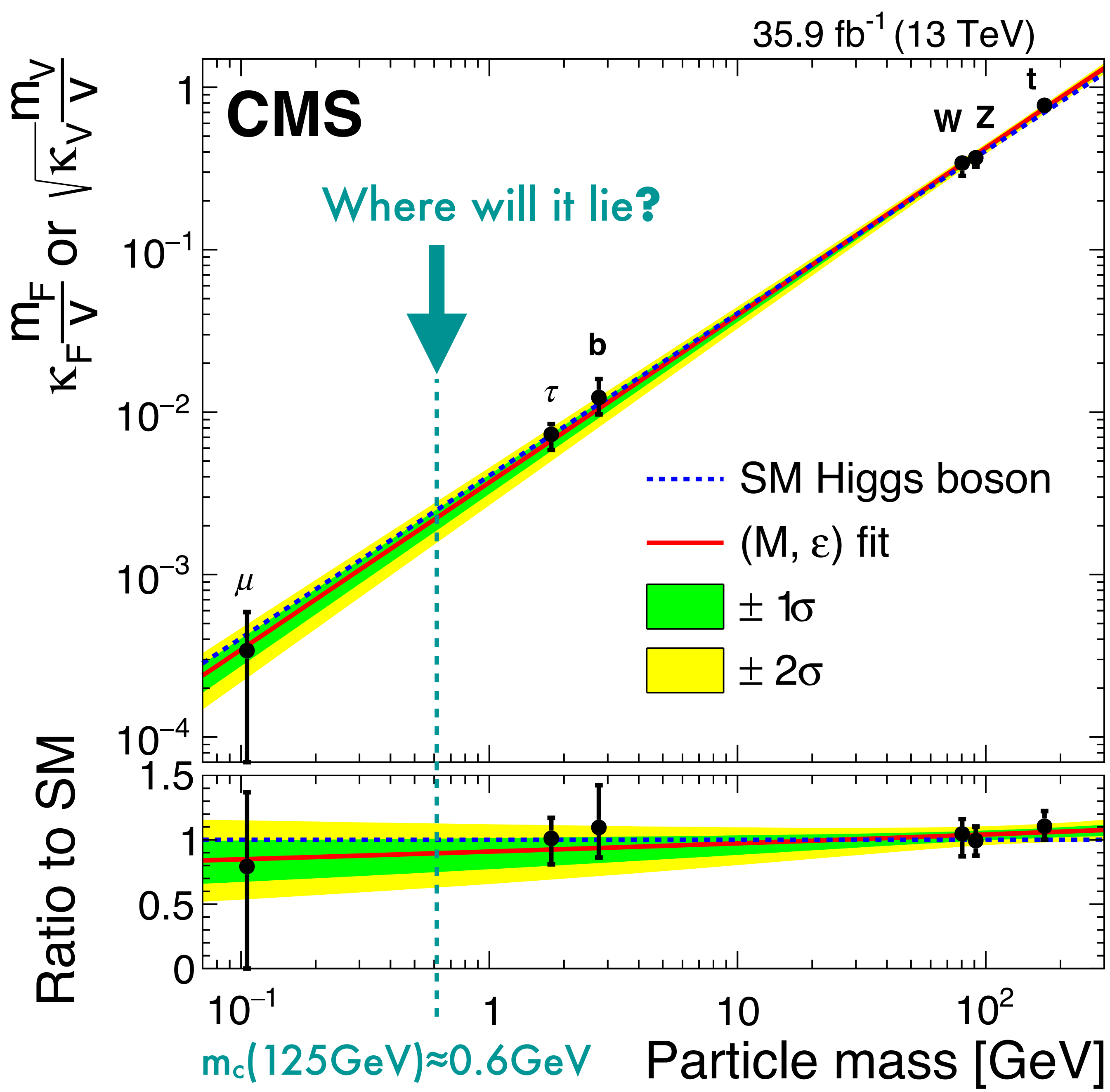
The decays of the Higgs boson



Channel (m_H = 125.0 GeV)	BR
$b\bar{b}$	0.5824
WW	0.2137
$\tau\tau$	6.3E-02
$c\bar{c}$	2.9E-02
ZZ	2.6E-02
$\gamma\gamma$	2.3E-03
$Z\gamma$	1.5E-03
$\mu\mu$	2.2E-04
$J/\psi\ \gamma$	3.0E-06

Ref: LHCXSWG

The coupling measurement



(The scale for the quark masses is set at $q^2=m_H^2$)

- So far, all the measurements suggest the Higgs boson is "SM-like"
  - The measurement of its couplings would provide solid evidence
- The couplings of these six particles to the Higgs boson are consistent within uncertainties with the SM predictions.

Ref: CMS-PAS-HIG-17-031

The Higgs-charm coupling

- There are ways to constrain the size of the coupling (coupling modifier κ_c)

Method		**constraint**
Recast the $VH\to b\bar{b}$ analysis with b- and c-tagging efficiency	Run1	$\kappa_c = 95^{+90}_{-95}$
Assuming the entire Higgs width is formed by $Hc\bar{c}$	Run1	$\kappa_c <$ 120 (CMS)/ 150 (ATLAS)
Using the relation between p_T^H distribution and κ_c	Run1	$-16 < \kappa_c < 18$
	Run2 2016 (CMS)	$-8.7 < \kappa_c < 10.6$
Rare exclusive decay $H\to J/\psi\ \gamma$	Run1	$\kappa_c < 220$
Direct search for $VH\to c\bar{c}$	Run2 2016 (ATLAS)	$\kappa_c < 150$

Ref: RPL. 118, 121801, PRD. 92, 033016

The Higgs-charm coupling

- There are ways to constrain the size of the coupling (coupling modifier κ_c)

Method
Recast the $VH \to b\bar{b}$ analysis with b- and c-tagging efficiency
Assuming the entire Higgs width is formed by $Hc\bar{c}$
Using the relation between p_T^H distribution and κ_c
Rare exclusive decay $H \to J/\psi\ \gamma$
Direct search for $VH \to c\bar{c}$

- Strongly depend on the b-/c-tagging efficiencies and associated mis-identified probabilities
- Large QCD multijets backgrounds in the LHC environment
- Only VH production can provide sensitive measurement

The Higgs-charm coupling

- There are ways to constrain the size of the coupling (coupling modifier κ_c)

Method	
Recast the $VH \rightarrow b\bar{b}$ analysis with b- and c-tagging efficiency	
Assuming the entire Higgs width is formed by $Hc\bar{c}$	• The Higgs width cannot be determined with high precision at the LHC.
Using the relation between p_T^H distribution and κ_c	
Rare exclusive decay $H \rightarrow J/\psi\ \gamma$	
Direct search for $VH \rightarrow c\bar{c}$	

The Higgs-charm coupling

- There are ways to constrain the size of the coupling (coupling modifier κ_c)

Method
Recast the VH→$b\bar{b}$ analysis with b- and c-tagging efficiency
Assuming the entire Higgs width is formed by H$c\bar{c}$
Using the relation between p_T^H distribution and κ_c
Rare exclusive decay H→J/ψ γ
Direct search for VH→$c\bar{c}$

- So far the most stringent constraint on κ_c
  - Neither suffers from small signal rates nor depends on the c-tagging performance
- The variation on the p_T^H distribution is marginal if κ_c varies within [-5, 5]

The Higgs-charm coupling

- There are ways to constrain the size of the coupling (coupling modifier κ_c)

Method
Recast the VH→$b\bar{b}$ analysis with b- and c-tagging efficiency
Assuming the entire Higgs width is formed by H$c\bar{c}$
Using the relation between p_T^H distribution and κ_c
Rare exclusive decay H→J/ψ γ
Direct search for VH→$c\bar{c}$

- Clean event signature
- Expected signal rate is too small
  - Only J/ψ→μμ is considered (the reason will be discussed later)

The Higgs-charm coupling

- A sensitive measurement of Higgs-charm coupling is challenging in the environment of the LHC

Method		constraint
Recast the $VH \to b\bar{b}$ analysis with b- and c-tagging efficiency	Run1	$\kappa_c = 95^{+90}_{-95}$
Assuming the entire Higgs width is formed by $Hc\bar{c}$	Run1	$\kappa_c < 120$ (CMS)/ 150 (ATLAS)
Using the relation between p_T^H distribution and κ_c	Run1	$-16 < \kappa_c < 18$
	Run2 2016 (CMS)	$-8.7 < \kappa_c < 10.6$
Rare exclusive decay $H \to J/\psi\ \gamma$	Run1	$\kappa_c < 220$
Direct search for $VH \to c\bar{c}$	Run2 2016 (ATLAS)	$\kappa_c < 150$

Ref: RPL. 118, 121801, PRD. 92, 033016

The Higgs-charm coupling

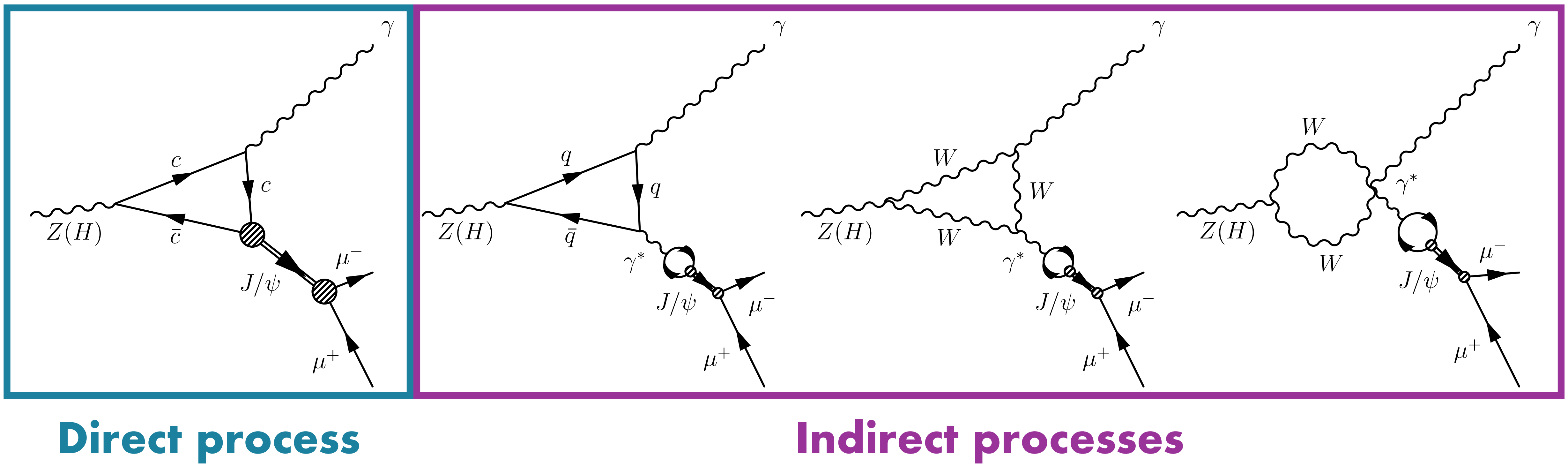
- In some extensions to the SM, modified $Hc\bar{c}$ coupling can arise.
    - In the context of the effective field theory, $Hc\bar{c}$ coupling is modified in the presence of dimension-six operator
        - An enhancement may occur at the cutoff scale Λ
    - Two-Higgs-Doublet model with minimal flavor violation
        - $Hc\bar{c}$ coupling is enhanced with other couplings not severely affected
    - The composite pseudo-Nambu-Goldstone boson model
        - Can be constrained by the direct search for the composite particles associated with the charm quark

Ref: PRD. 89, 033014

H (Z) $\rightarrow$J/ψ γ decay

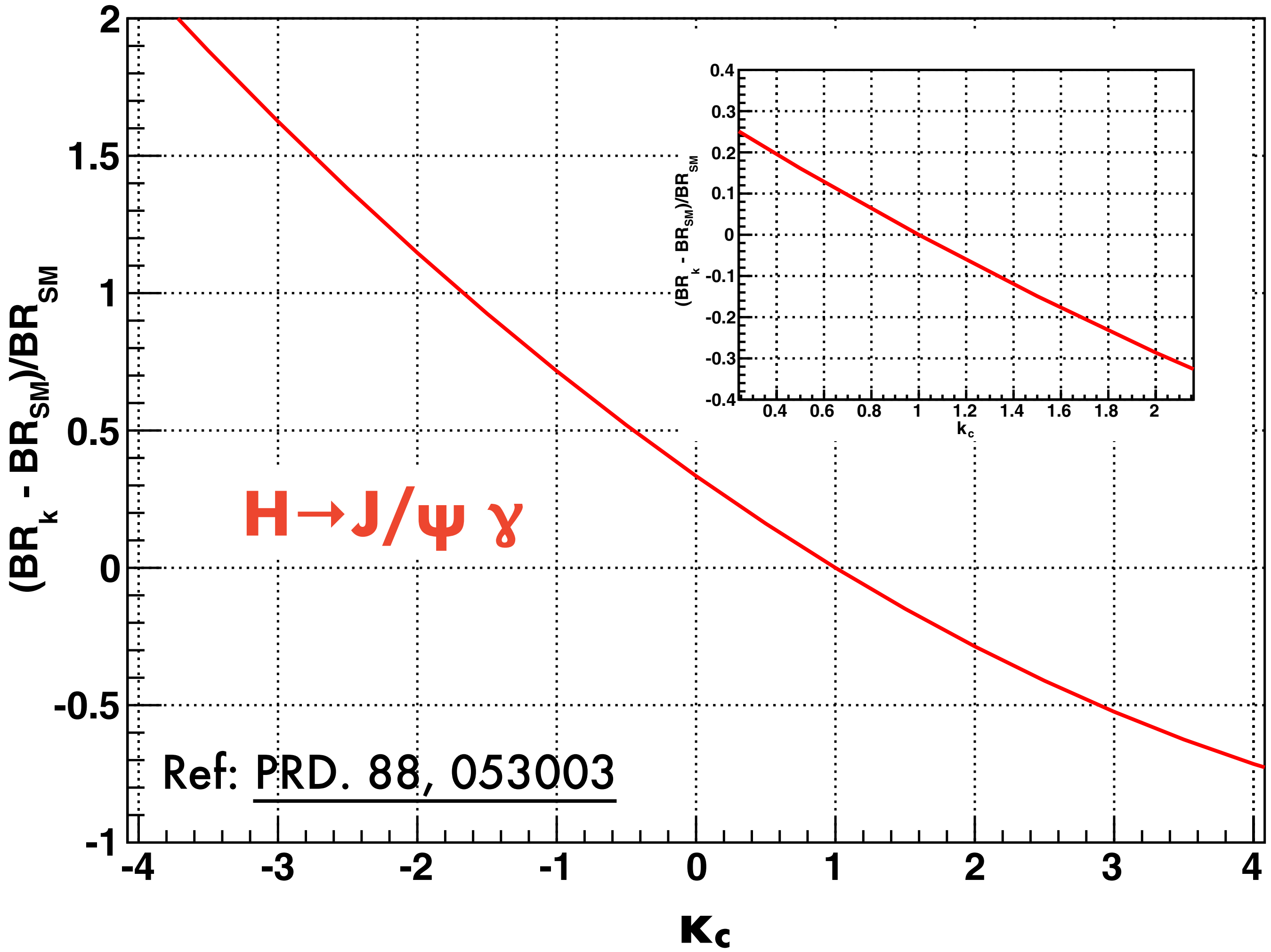
- This analysis focuses on the rare decay of H (Z) $\rightarrow$J/ψ γ
  - H$\rightarrow$J/ψ γ : probe the H$c\bar{c}$ coupling
  - Z$\rightarrow$J/ψ γ : experimental benchmark for the Higgs boson decay; benefit from the large production cross-section of the Z boson
- Test various QCD factorization approaches that are being used in the estimation of branching fractions for hadronic radiative decays of bosons

H (Z) →J/ψ γ decay



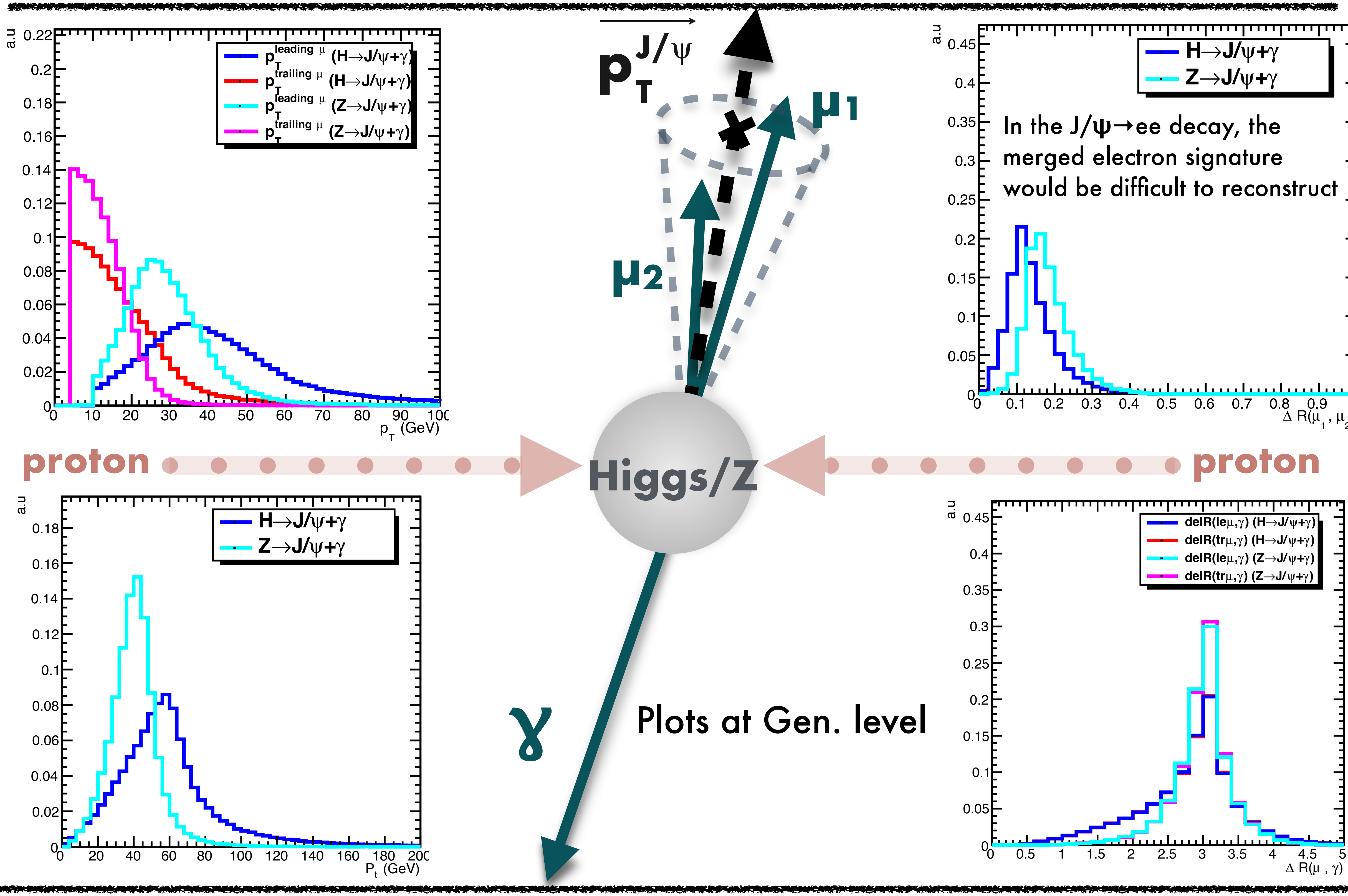
- Both decays have contributions from direct and indirect processes.
  - Interfere destructively in both decays
- BR(H→J/ψ γ)=3.0×10^{-6} ; BR(Z→J/ψ γ)=9.0×10^{-8}

BR(H→J/ψ γ) v.s κ_c

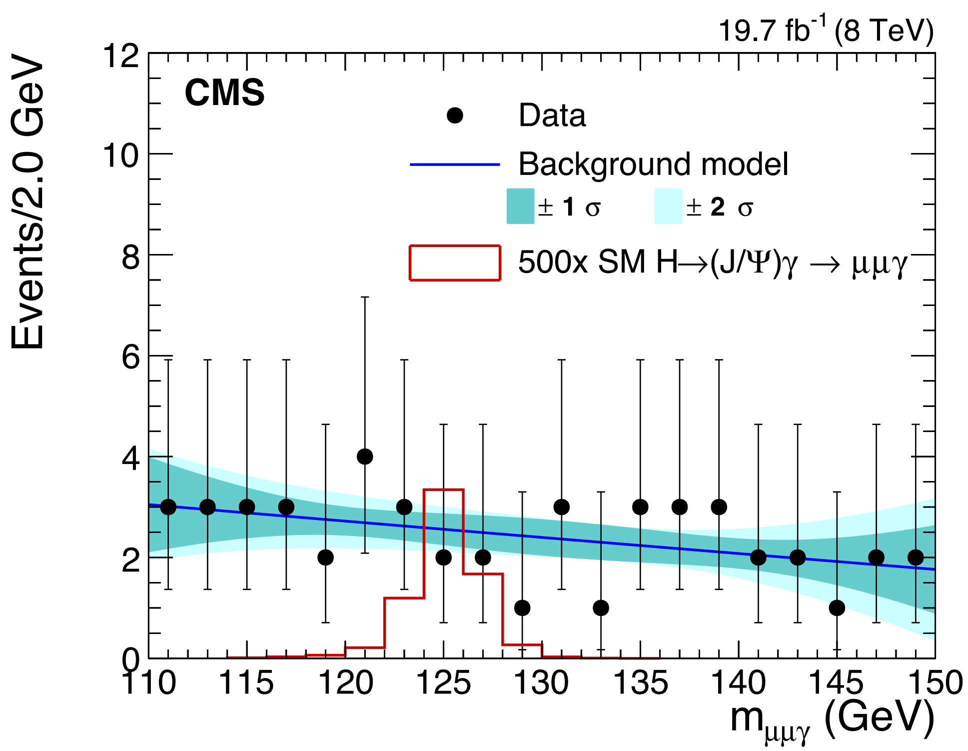


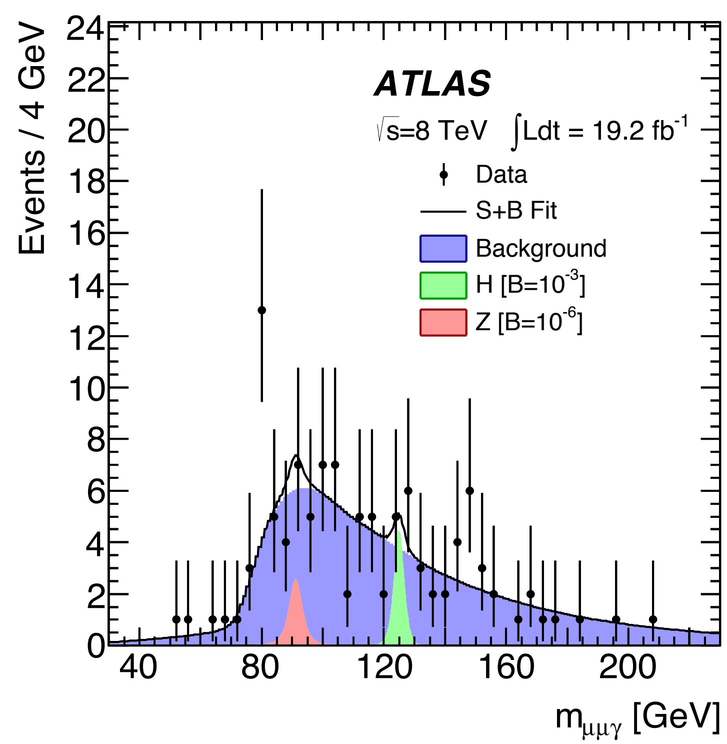
- Deviation from SM prediction for the couplings affects the interference terms and results in changes in the branching fraction.
  - $Hc\bar{c}$ coupling deviates 2 times from its SM value ➜ a shift in the branching fraction > 100%
- The interference can tell us more information
  - Which sign does κ_c have ?

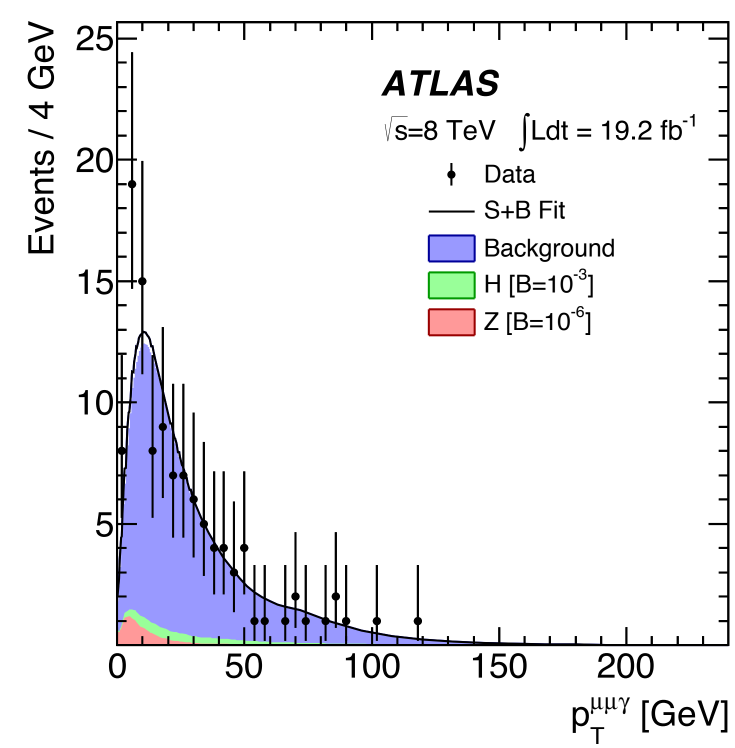
Features of the decay



Results in Run1



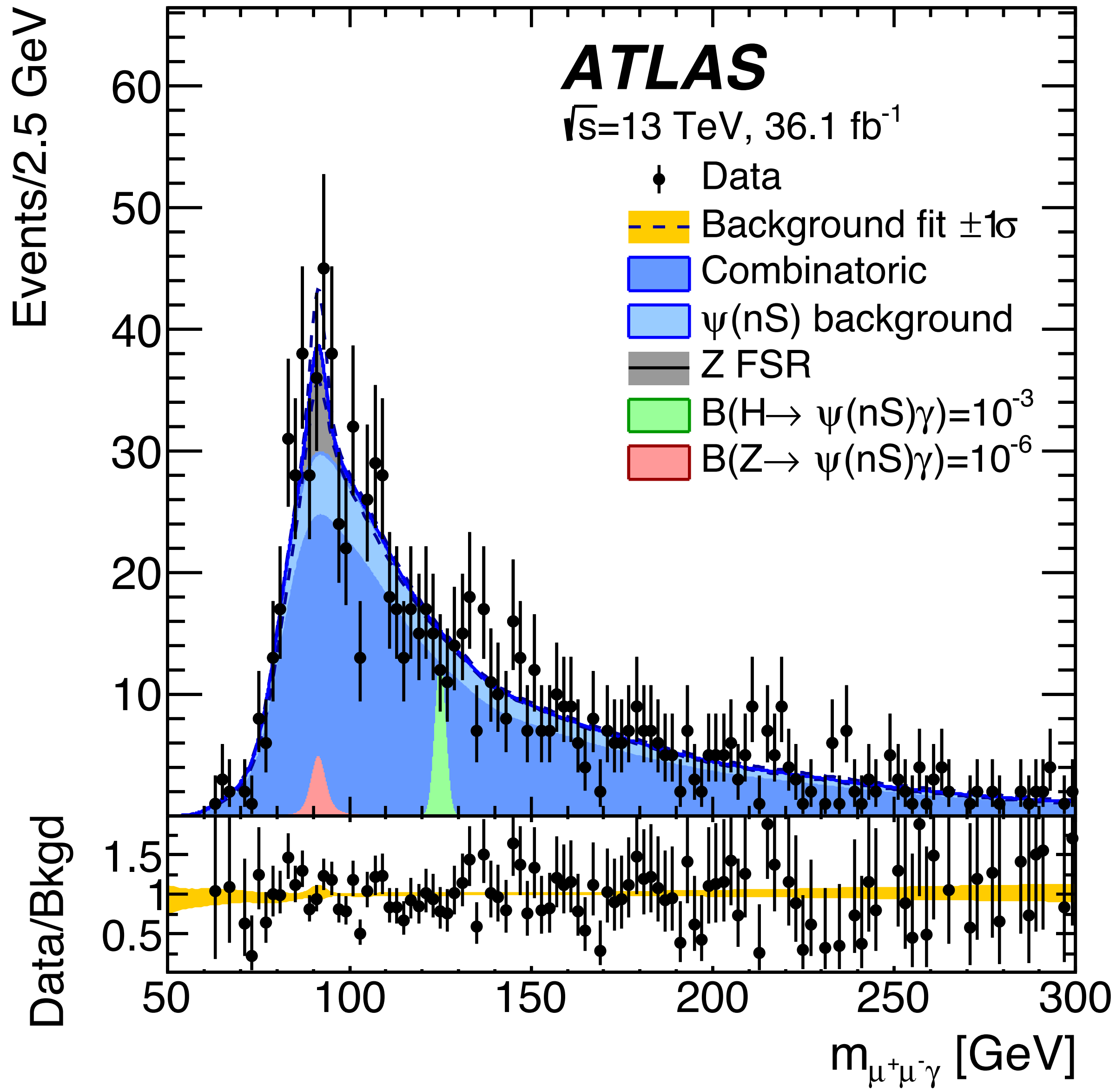


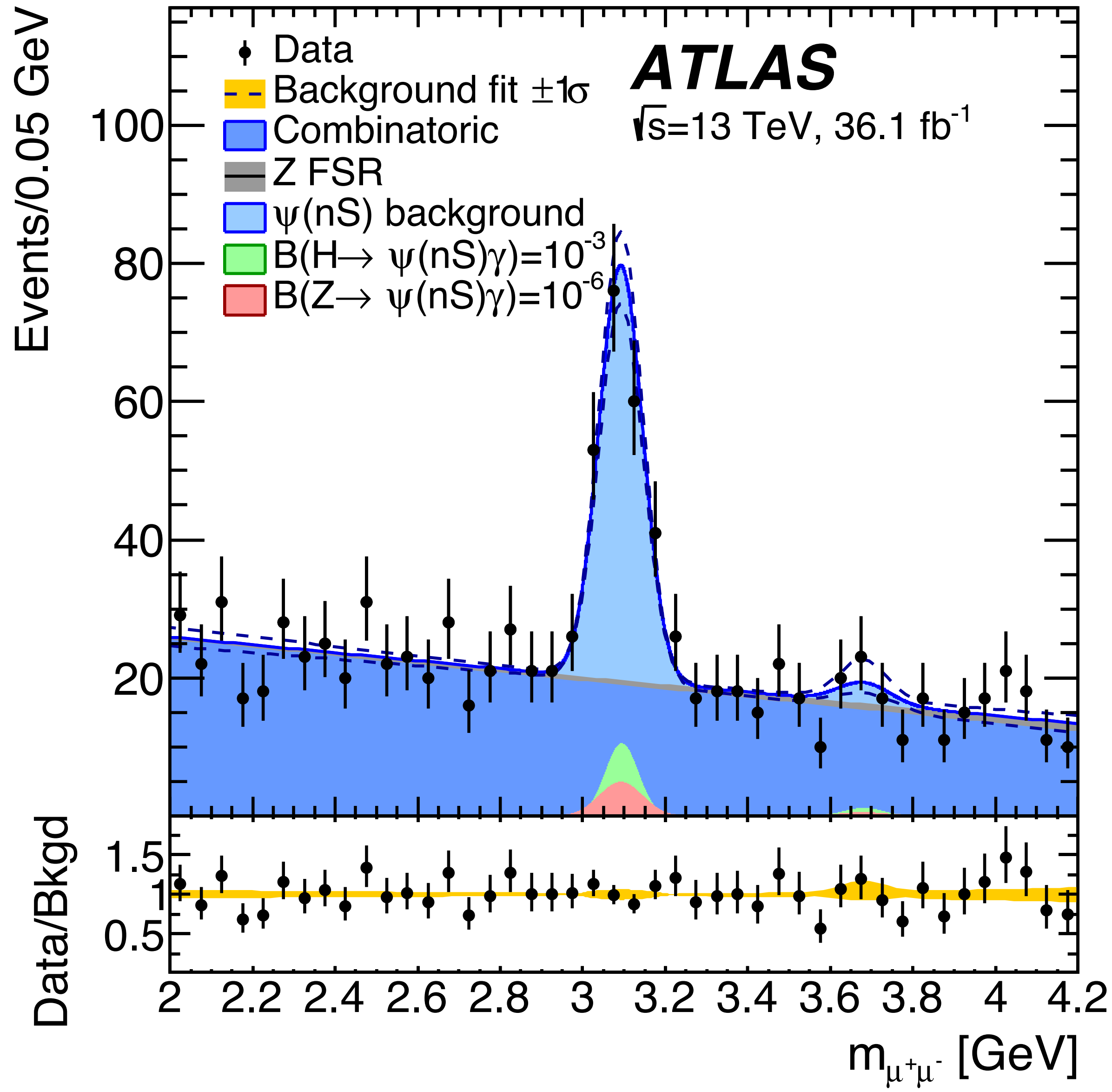


- Different approaches were exploited, but similar performances and results were obtained.
- Z decay has not yet been searched for in CMS.

95% C.L upper limits on BR			
	ATLAS		CMS
	$H \to J/\psi\ \gamma$	$Z \to J/\psi\ \gamma$	$H \to J/\psi\ \gamma$
Exp.	1.2×10^{-3}	2.0×10^{-6}	1.6×10^{-3}
Obs.	**1.5×10^{-3}**	**2.6×10^{-6}**	**1.5×10^{-3}**
σ/σ_{SM}	538	26.1	538

ATLAS results with 2016 data

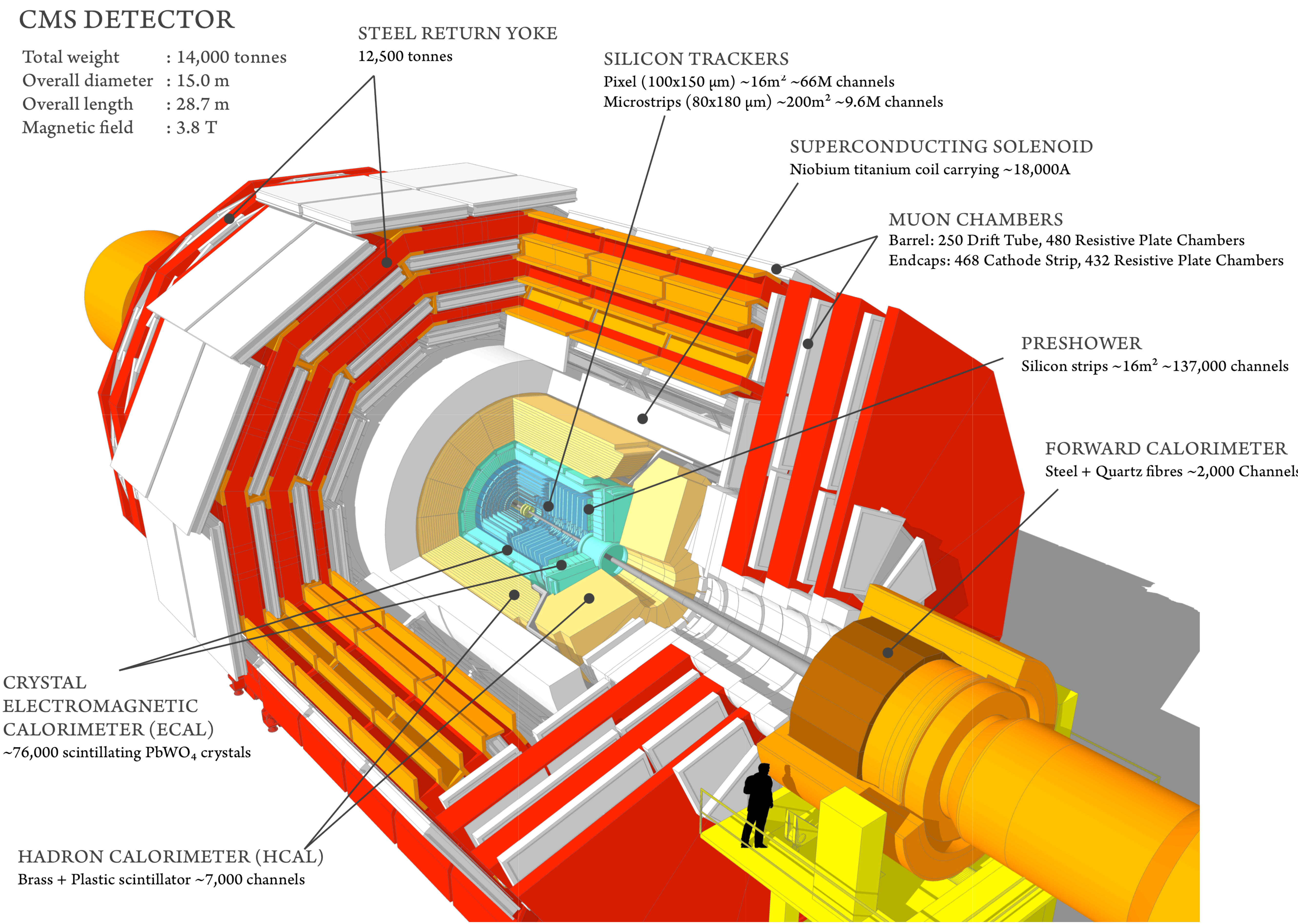




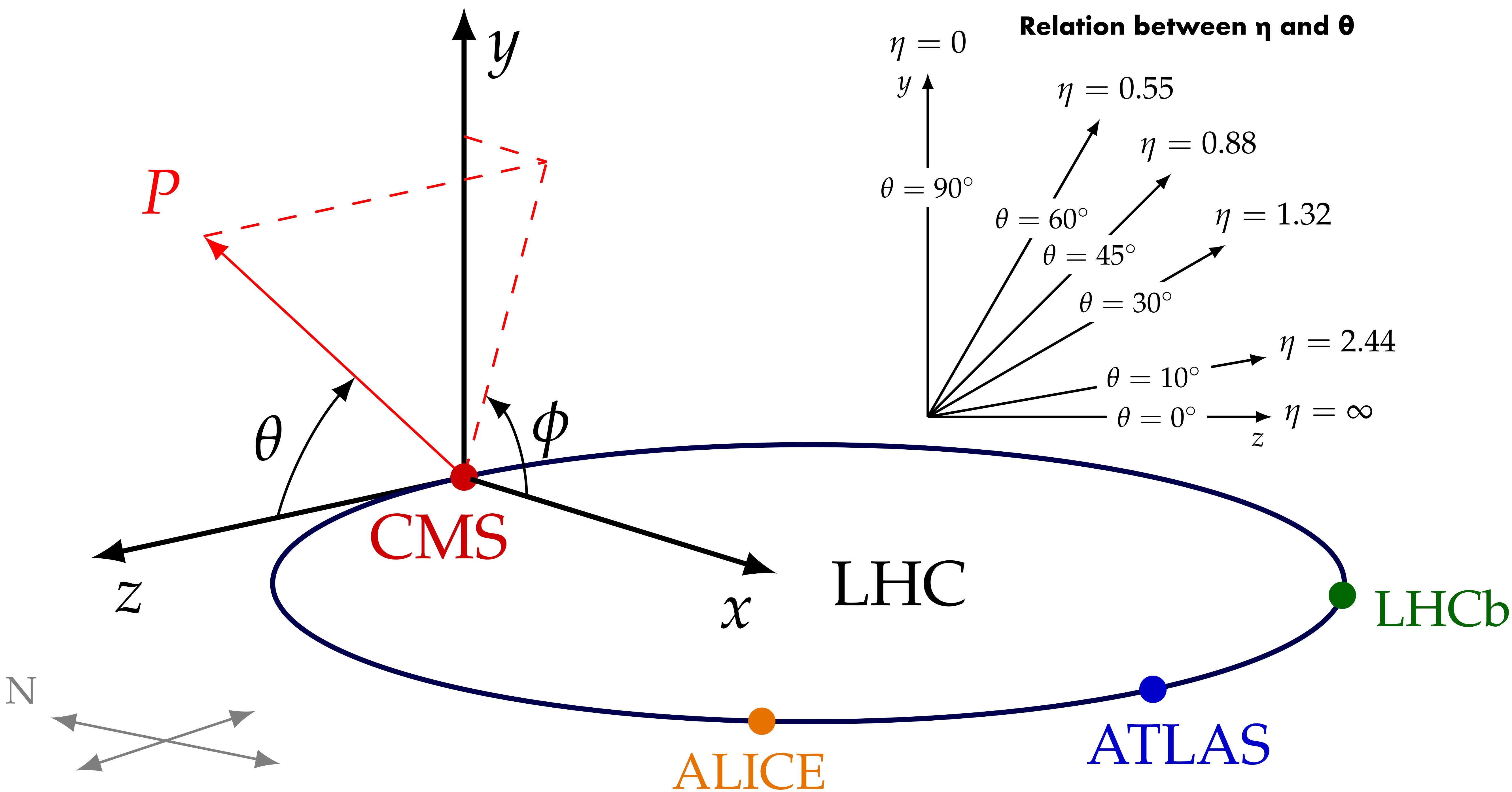
95% C.L upper limits on BR

	$H \to J/\psi\ \gamma$	$Z \to J/\psi\ \gamma$
Obs (Exp.)	$3.5\ (3.0) \times 10^{-4}$	$2.3\ (1.1) \times 10^{-6}$

Ref: ATLAS public results


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

The coordinate system



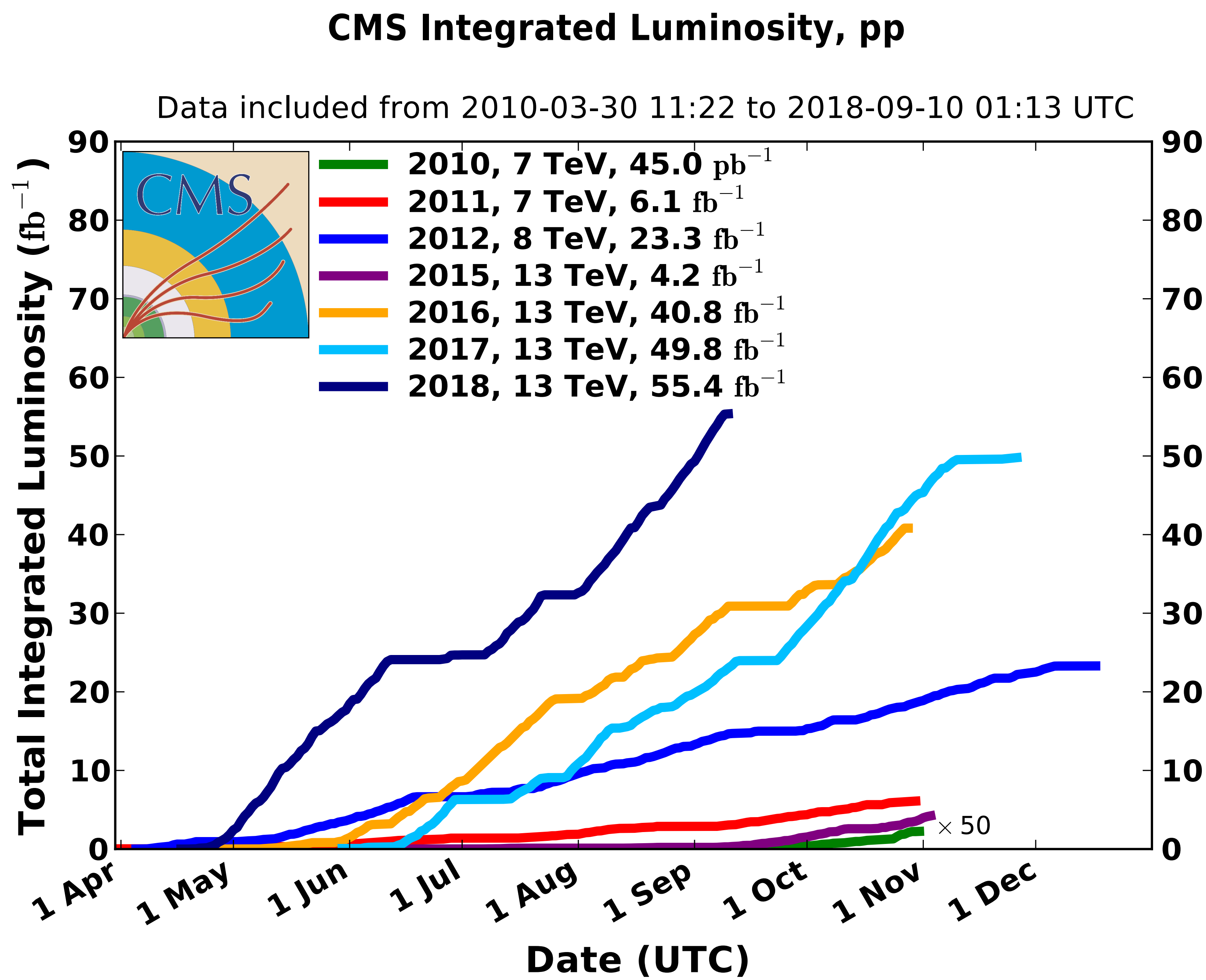
Luminosity

$$\frac{dN}{dt} = \sigma_{\text{event}} \frac{dL}{dt}$$

Event production rate

Interaction cross-section

Instantaneous luminosity



Ref: CMS luminosity

Overview of the analysis strategy

- Select 2 muons and 1 photon as the final state particles
- Mutually exclusive categories in the Z decay channel to enhance the sensitivity of the search
- Fit to $m_{\mu\mu\gamma}$ distributions in data as background models, while the signal is estimated from the simulation
- Statistical interpretation of the final results

Data & Signal samples

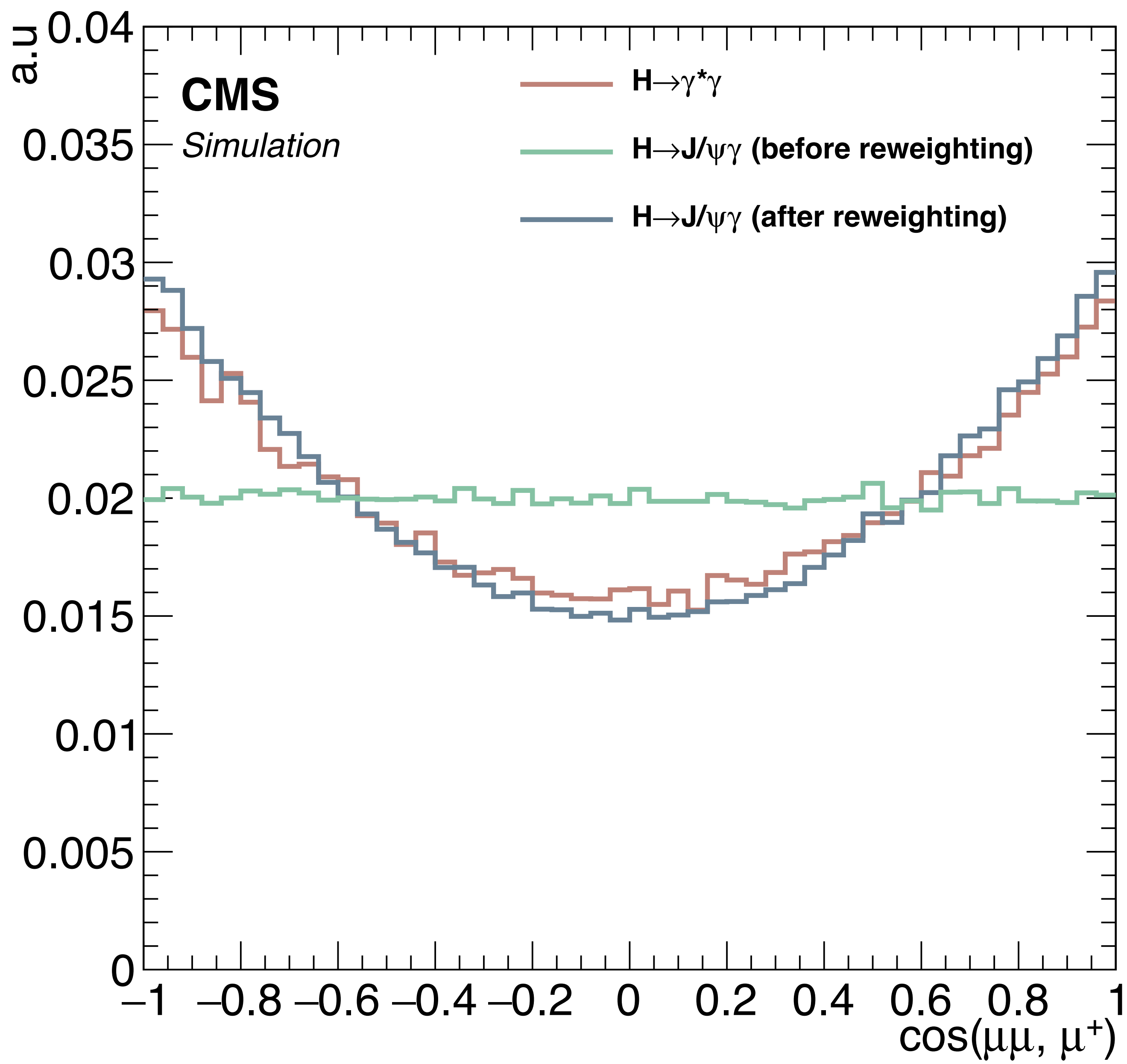
- **Data**
  - Corresponding to an integrated luminosity of 35.9 fb^{-1}
- **Signal simulated sample**
  - $Z \rightarrow J/\psi\ \gamma$ decay
    - Generated by PYTHIA8 for m_Z = 91.2 GeV
    - The Z boson production cross section includes NNLO QCD contributions, and NLO electroweak corrections
    - The Z boson pT is reweighted to match the NLO calculation

Data & Signal samples

- **Signal simulated sample**
  - $H \to J/\psi\ \gamma$ decay
    - Generated by POWHEG v2.0, with m_H = 125.0 GeV, for ggF, VBF, VH, and ttH productions

	XS (pb)	Order
ggF	48.6	N3LO QCD; NLO EW
VBF	3.8	
ZH	8.8E-01	NNLO QCD; NLO EW
W^+H	8.4E-01	
W^-H	5.4E-01	
ttH	5.1E-01	NLO QCD; NLO EW

J/ψ polarization - H→J/ψ γ



- The J/ψ meson from the Higgs boson decay must be fully transversely polarized, as the Higgs boson has spin 0 and the photon is transversely polarized.
- Reweighting factor is applied to each event via formula

$$w = 3/4\times(1+(\cos\theta)^2),$$

(θ is the angle between the μ⁺ and the direction of J/ψ in the frame of J/ψ).

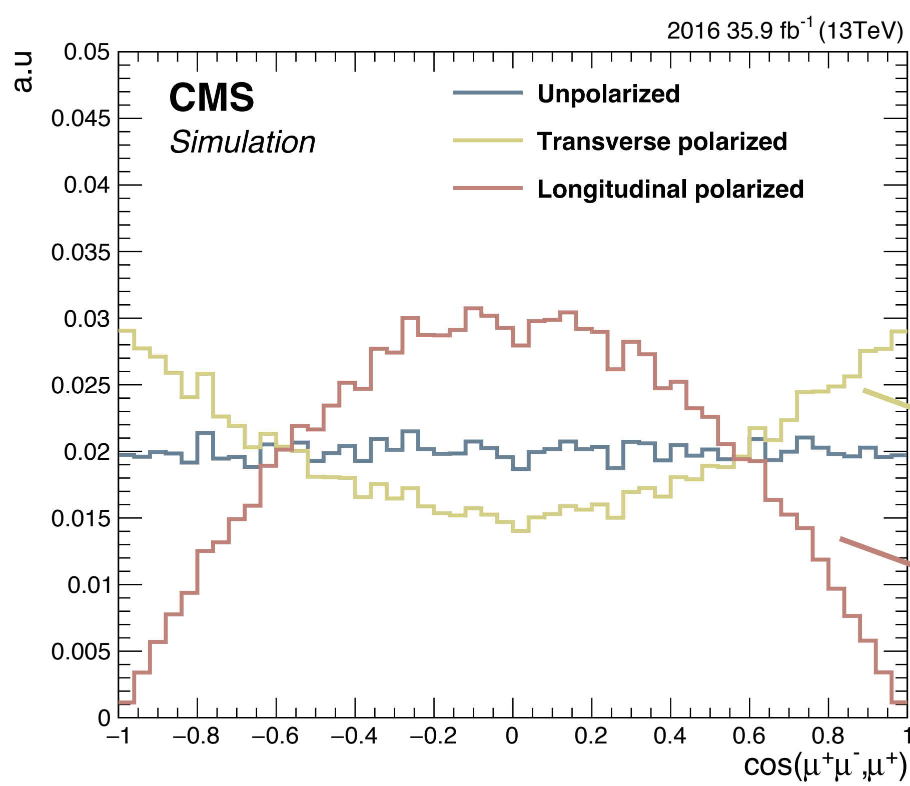
- The reweighting preserves the number of events

→ The acceptance decreases by ~7.0%

Ref: PRD 83, 031503(R)

J/ψ polarization - Z→J/ψ γ

- The polarization of the J/ψ depends on that of the Z boson (spin-1), which has J_z = ±1, 0
  - The results from the Z boson polarization measurement are not used to constrain the helicity of the J/ψ meson in this analysis
  - The signal acceptance is calculated for unpolarized J/ψ case and for two extreme scenarios (fully transverse and longitudinal)



J_z	polarization scenario	re-weight formula	effect on Acc.
±1	Transverse	3/4×(1+(cosθ)²)	-7.8%
0	Longitudinal	3/2×(1-(cosθ)²)	15.6%

Ref: PRD 83, 031503(R)

Resonant backgrounds

- Resonant background - Exhibit a peak in $m_{\mu\mu\gamma}$
  - For $Z \to J/\psi\ \gamma$ decay : $Z \to \mu\mu\gamma_{FSR}$ process
    - Produced with MadGraph generator and showered with Pythia8
  - For $H \to J/\psi\ \gamma$ decay :
    - $H \to \gamma^{*}\gamma$ (Higgs Dalitz decay) : with $\gamma^{*} \to \mu\mu$ ($m_{\mu\mu} < 50$GeV) produced with MadGraph and showered with Pythia8
    - $H \to \mu\mu + \gamma_{FSR}$: a photon radiated from one of the muons. After the event selection the contribution of this background is found to be negligible
- The resonant backgrounds are subtracted when deriving the limits

Non-resonant backgrounds

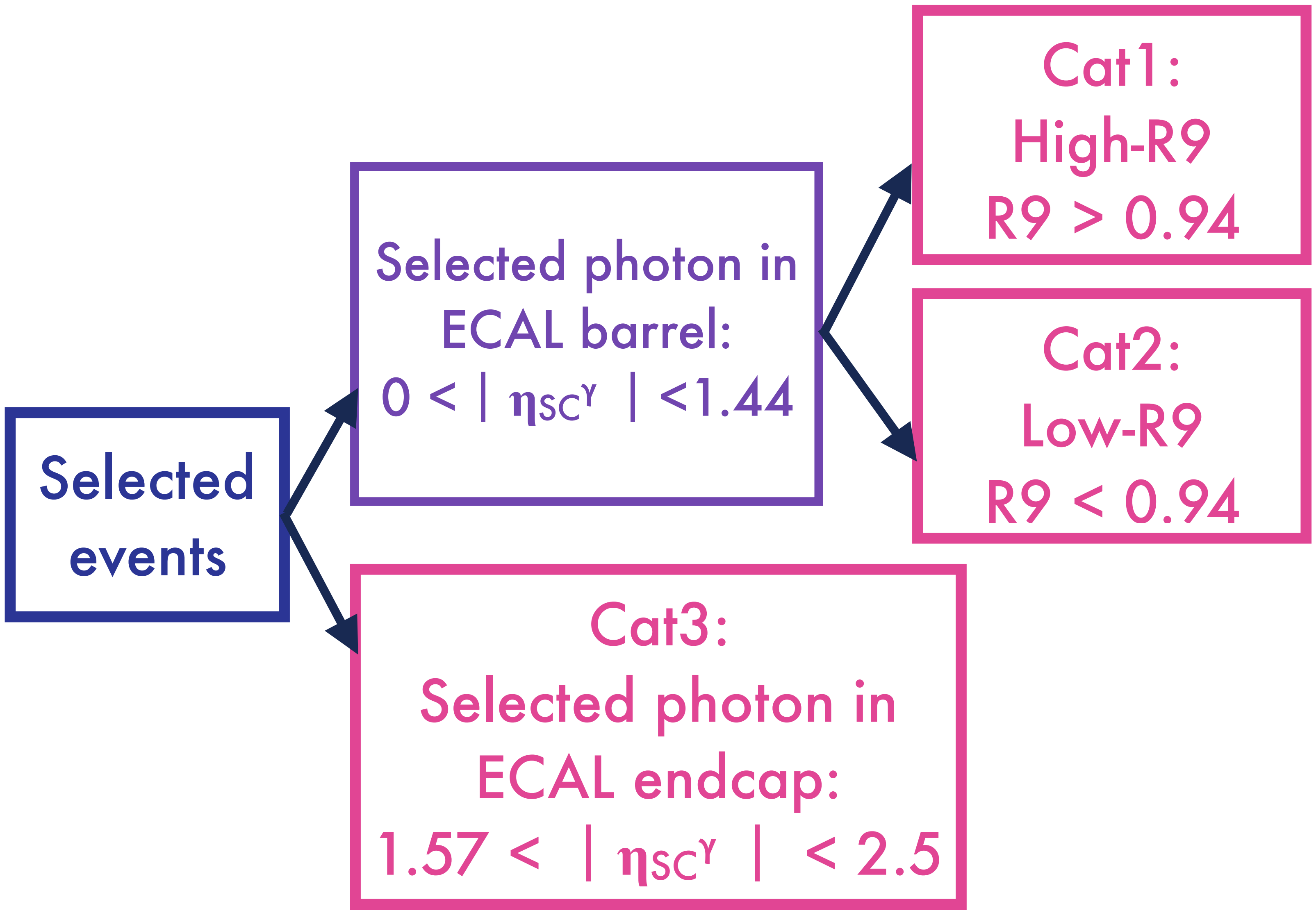
Process	Description
Inclusive Quarkonium + jets/γ	Muons come from the J/ψ, jet is misidentified as a photon
$pp \rightarrow Z/\gamma^{*}(\rightarrow \mu\mu)$+jets	A jet is misidentified as an energetic photon in the event
$pp \rightarrow \gamma$ + jets	The muons can come from the jets.

- These are background processes that do not give resonant peaks in the three-body invariant mass spectrum
- Samples are not available for this analysis (lack of statistics)
- Modeled using the fits to $m_{\mu\mu\gamma}$ in data (will be introduced later)

Event selection

Trigger	A muon with $p_T > 17$ GeV & a photon with $E_T > 30$ GeV
Muon selection	- $p_T > 20$ (4) GeV for leading (trailing) muon, $\lvert \eta^{\mu} \rvert < 2.4$ - Well reconstructed muons from event primary vertex - Isolation applied on μ_{lead} to reject decays of hadrons within jets
Photon selection	- $E_T^{photon} > 33$ GeV, $\lvert \eta_{SC}^{photon} \rvert < 2.5$ (exclude those in ECal transition region) - MVA ID (inputs include isolation, shower shape variables) - Electron-veto : photon is not from conversion
Kinematic selection	- $\Delta R(\mu,\gamma) > 1$: suppress Drell-Yan process - $\Delta R(\mu\mu,\gamma) > 2$, $\lvert\Delta\phi(\mu\mu,\gamma)\rvert > 1.5$: J/ψ candidates are well-separated from γ - $3.0 < m_{\mu\mu} < 3.2$ GeV : compatible with the mass of J/ψ meson - $p_T^{\mu\mu}, E_T^{photon} / m_{\mu\mu\gamma} > 35.0/125.0$ (35.0/91.2) for the Higgs (Z) decay : reject the γ^*+jet and γ+jet backgrounds

Event categorization - $Z \to J/\psi\ \gamma$



- <u>High-R9 value</u>
  - ➜ unconverted photon
  - ➜ better resolution (in $m_{\mu\mu\gamma}$)
  - ➜ better sensitivity
- No event categories in Higgs channel since it does not bring improvement

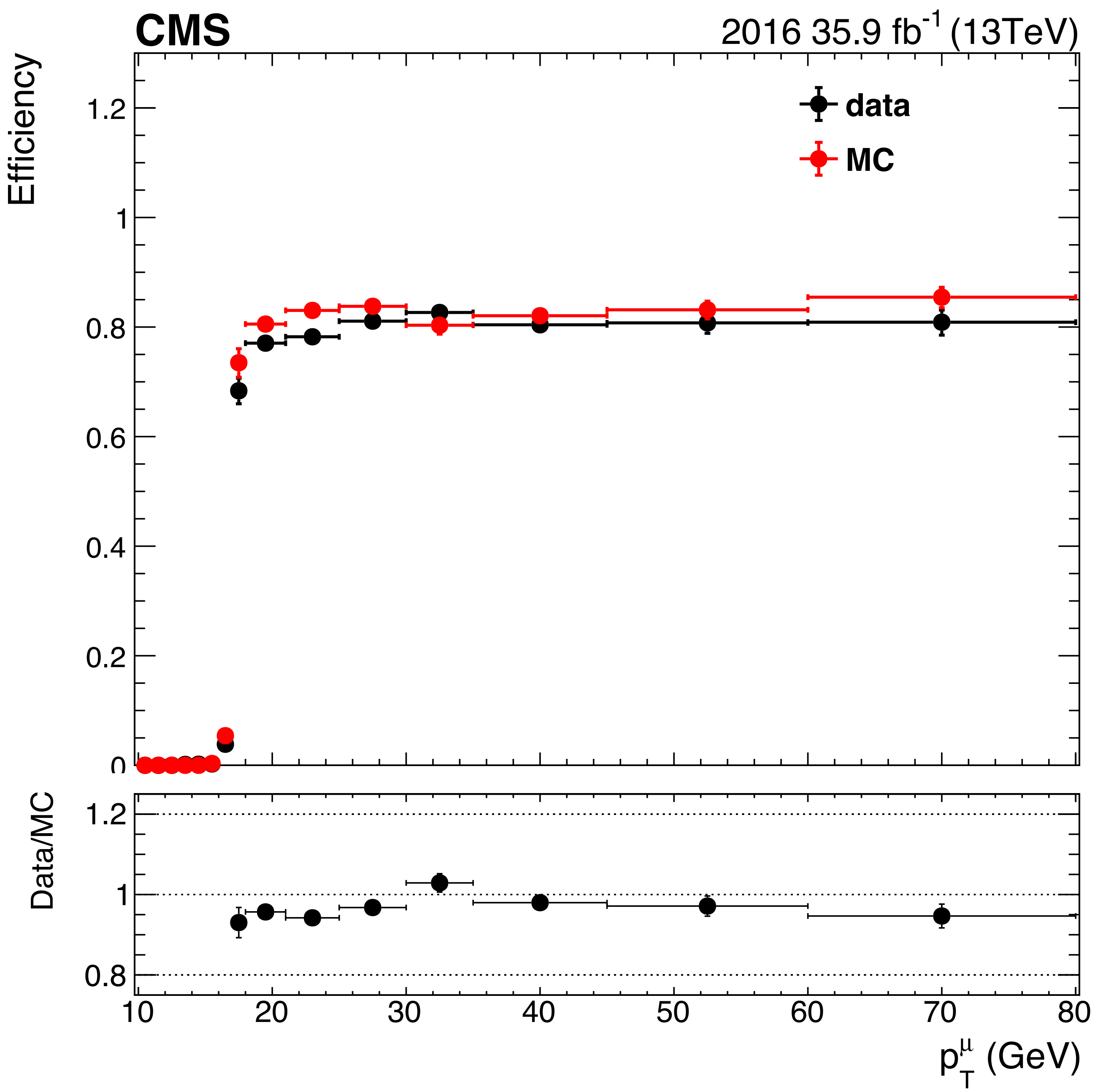
★R9 : The energy sum of 3x3 crystals centered on the most energetic crystal in the supercluster divided by the energy of the supercluster.

Summary of efficiencies

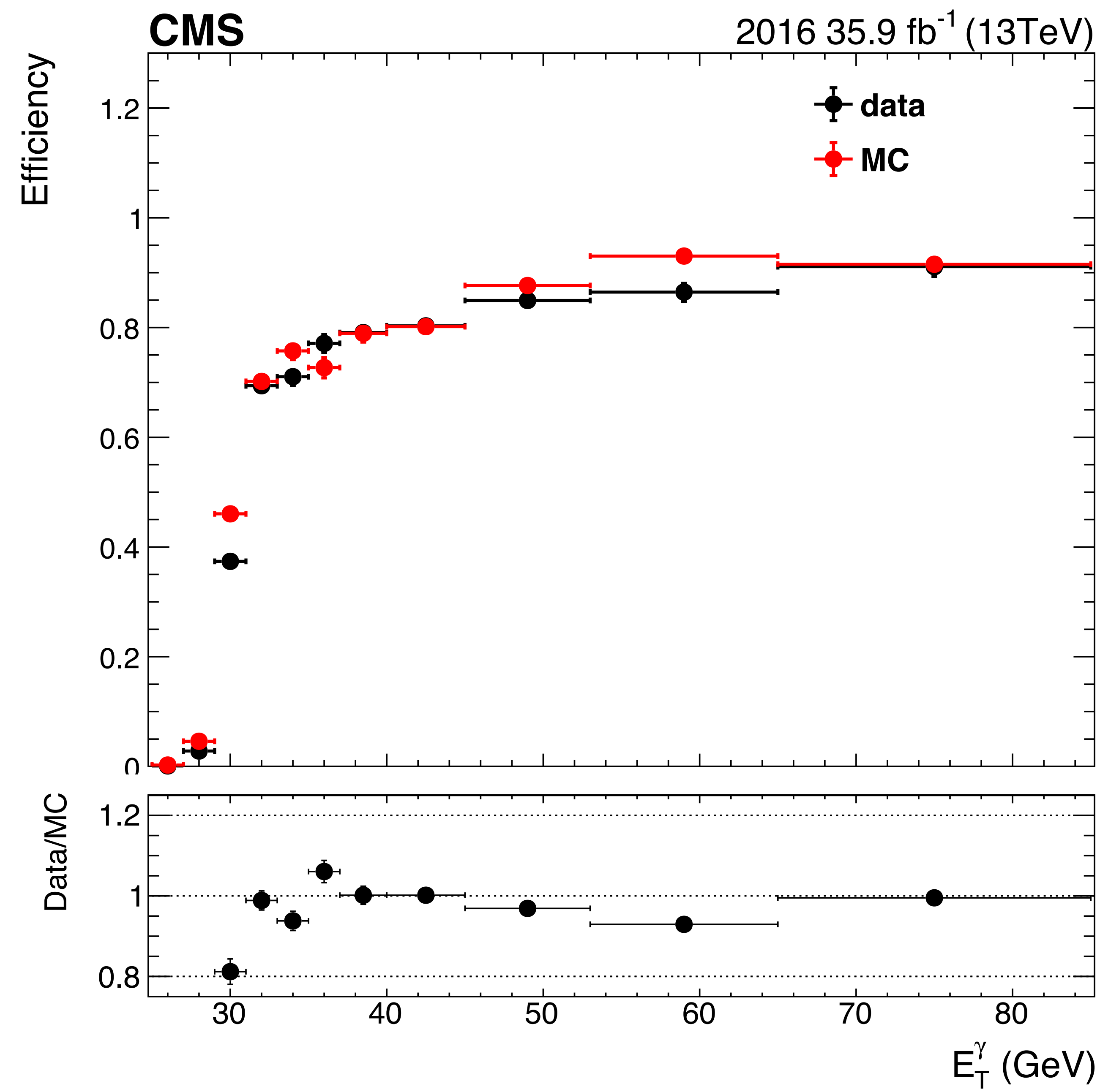
Object		Control sample	efficiency
Trigger		$Z \to \mu\mu\gamma_{FSR}$	82 (83)% in data (simulated) events
Muon	tracking	(p_T>20 GeV) $Z \to \mu\mu$ (p_T<20 GeV) $J/\psi \to \mu\mu$	94 - 98 % (barrel) 92 - 97 % (endcap)
	reconstruction and identification		
	impact parameters	$Z \to \mu\mu$	
	isolation		90 - 100 % (barrel) 92 - 100 % (endcap)
Photon	identification	$Z \to ee$	84 - 91 % (barrel) 77 - 94 % (endcap)
	electron-veto	$Z \to \mu\mu\gamma_{FSR}$	98% (barrel) 94% (endcap)

Trigger efficiency

eff. vs p_T^{μ}



eff. vs E_T^{γ}



Event yields

$Z \to J/\psi\ \gamma$ ($81 < m_{\mu\mu\gamma} < 101$ GeV)

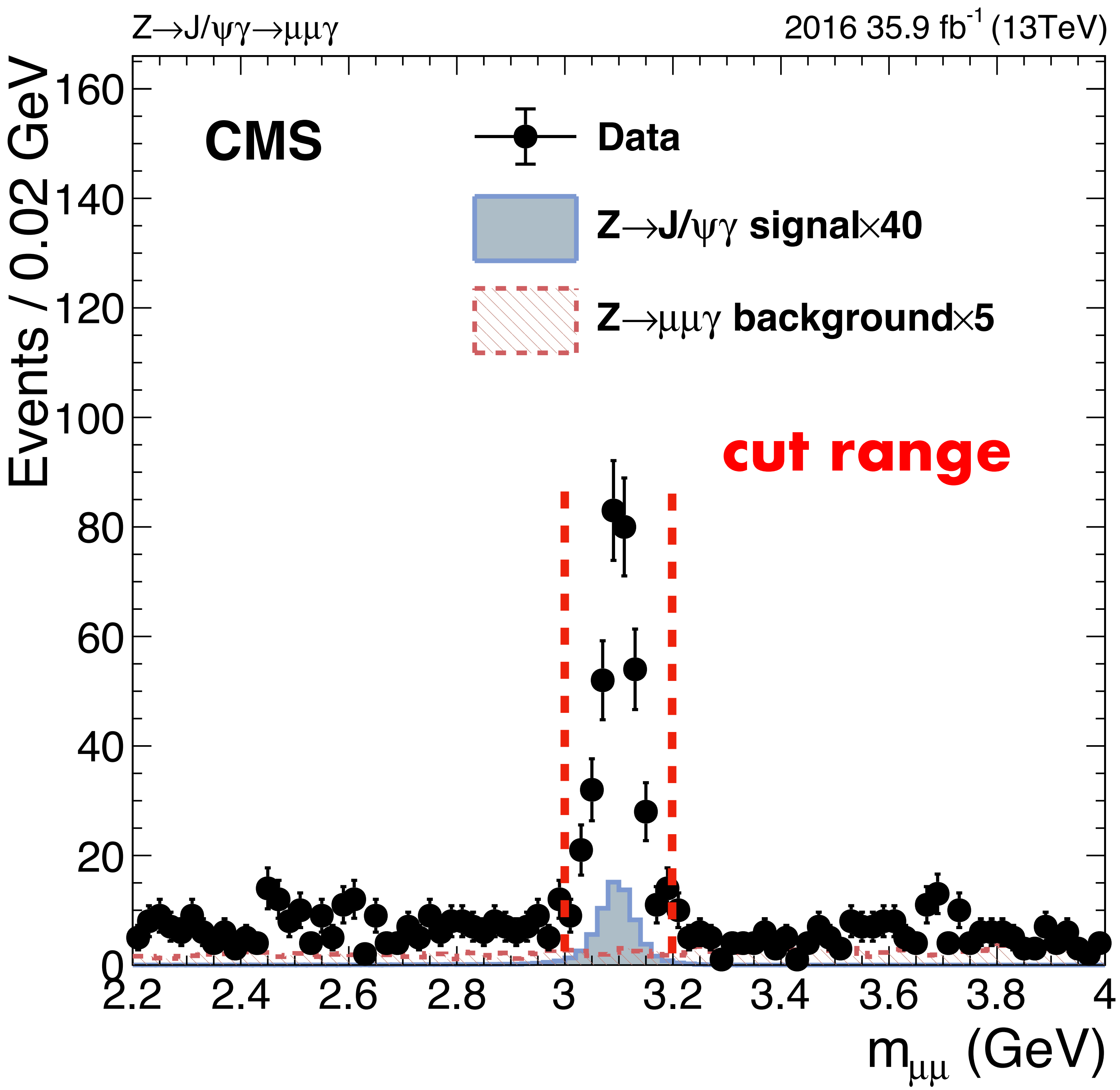
Category	Signal	Obs. (exp.) non-resonant bkg.	Exp. resonant bkg.
EB high R9	0.69	69 (66.9±4.9)	2.1
EB low R9	0.42	67 (62.6±4.6)	1.2
EE	0.30	47 (43.0±4.0)	1.0

$H \to J/\psi\ \gamma$ ($120 < m_{\mu\mu\gamma} < 130$ GeV)

Category	Signal	Obs. (exp.) non-resonant bkg.	Exp. resonant bkg.
Inclusive	0.076	56 (51.0±3.4)	0.20

- The total signal efficiencies for the $J/\psi\ \gamma \to \mu\mu\gamma$ final states are 22 and 14 % for the Higgs and Z boson decay, respectively
- The total signal efficiency for the Z boson decay is 13% if the J/ψ meson is fully transversely polarized and 16% if it is fully longitudinally polarized.

$m_{\mu\mu}$ distribution

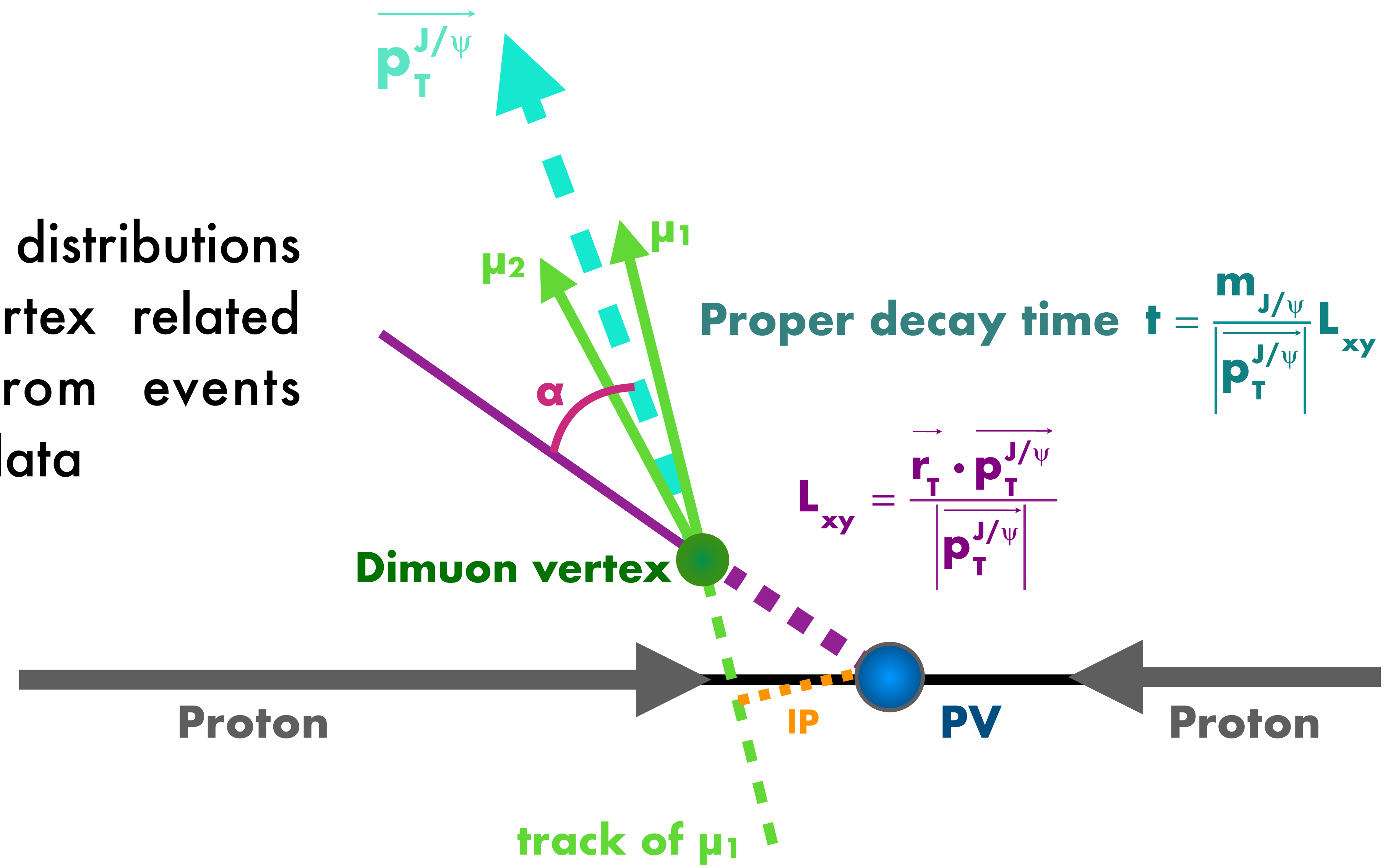


- Normalization of the distributions
  - Data : # of events
  - Signal: 40 times SM yields
  - Resonant background: 5 times SM yields
- **Real *J/ψ* is selected**
  - These events come from inclusive quarkonium production (not included in the distributions as no simulation is available for this analysis)

Vertex of the dimuon system

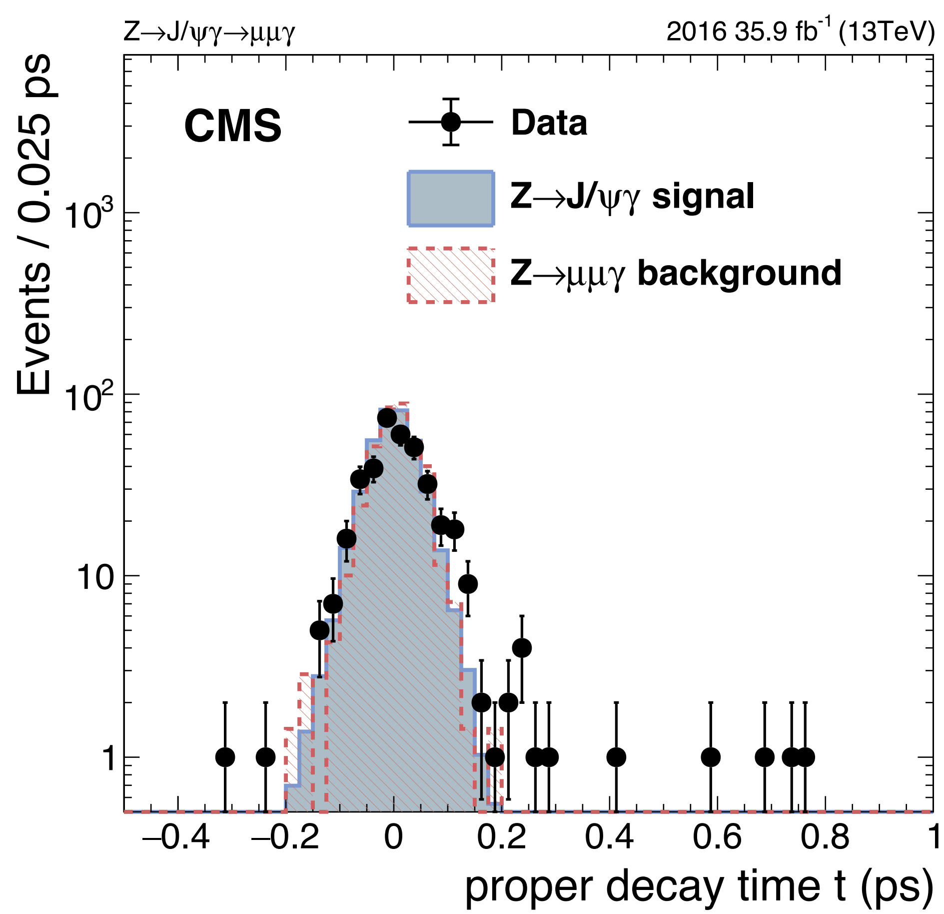
- The J/ψ meson from the Higgs/Z boson decay should be produced at the event primary vertex, not from the displaced heavy flavor hadron decays

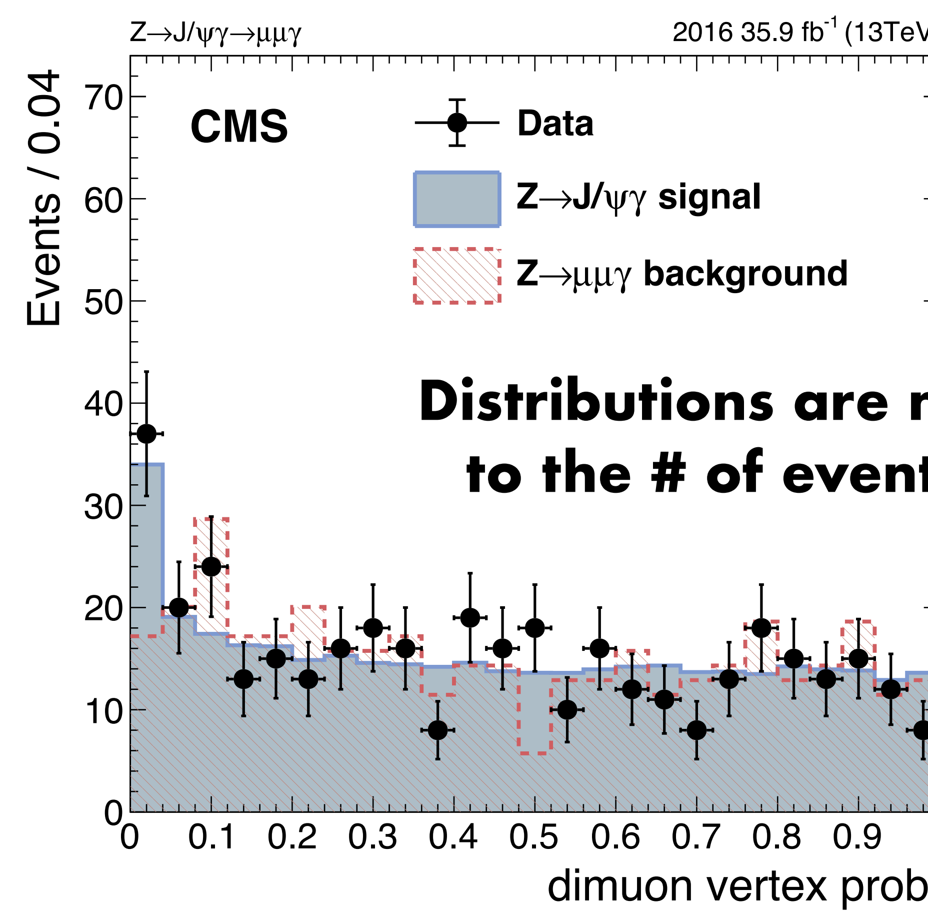
Examine the distributions of these vertex related variables from events selected in data



Vertex of the dimuon system

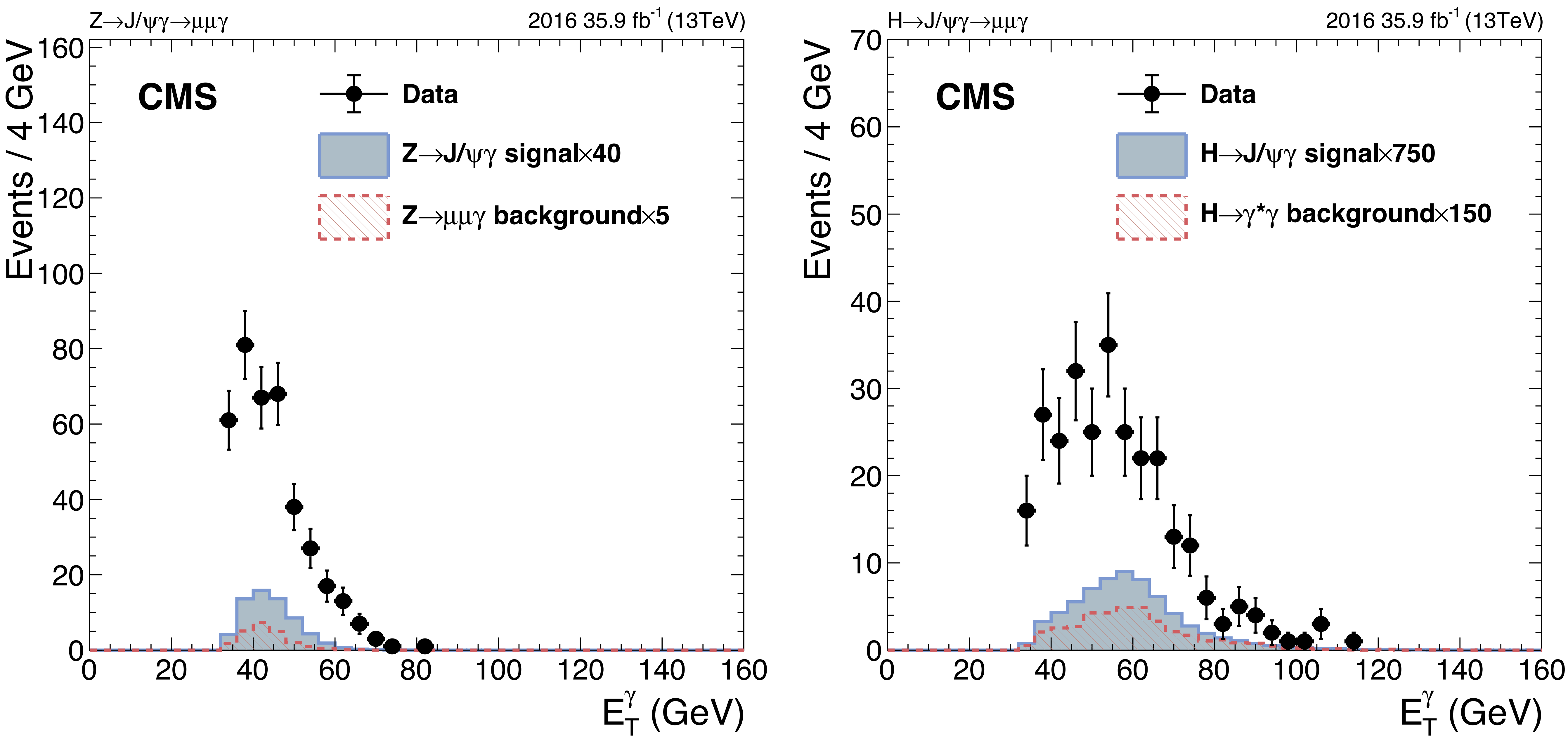
- The cuts on impact parameters implemented in the muon ID properly reject the J/ψ from heavy-flavor decays
  - The distributions suggest that the J/ψ candidates reconstructed in data, like the signal events, are produced promptly at the pp interaction point, rather than coming from displaced heavy hadron decays.





Distributions are normalized to the # of events in data

Photon E_T distributions



Non-resonant background model

- Determined from data by fitting a parametric function to the $m_{\mu\mu\gamma}$ distribution (maximum unbinned likelihood method)

- Four families of functions, referred to as true models, are considered

  ▲Bernstein polynomial ▲Power-law ▲Exponential ▲Laurent polynomial [<u>Parametrization in back-up</u>]

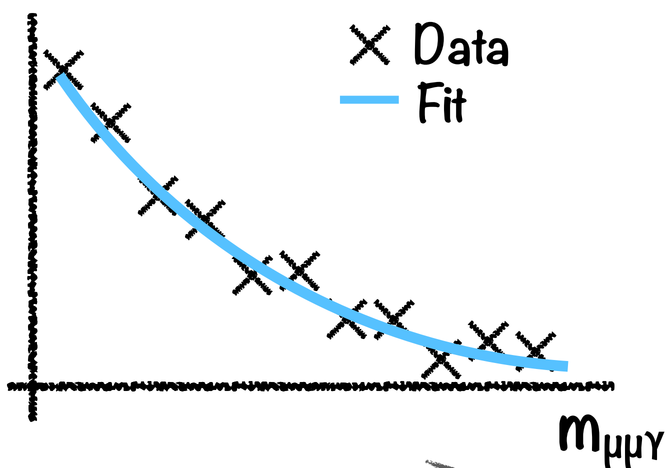
Non-resonant background model

- A function among the true models is chosen to fit the $m_{\mu\mu\gamma}$ distribution observed in data. Pseudo-events are randomly generated by using the resulting fit (referred to as the true function) as a background model to simulate possible experiment results.

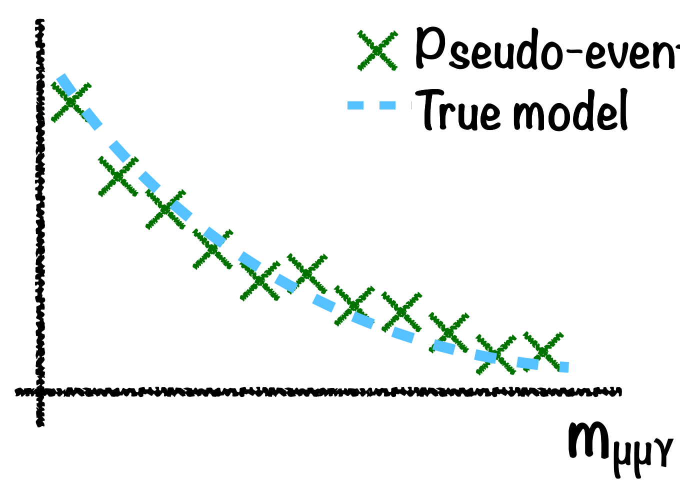
- Signal events with signal strength μ_{true} are introduced when generating the pseudo-events

  - μ_{true} = 1 corresponds to injecting 1 times the signal yield on top of the backgrounds

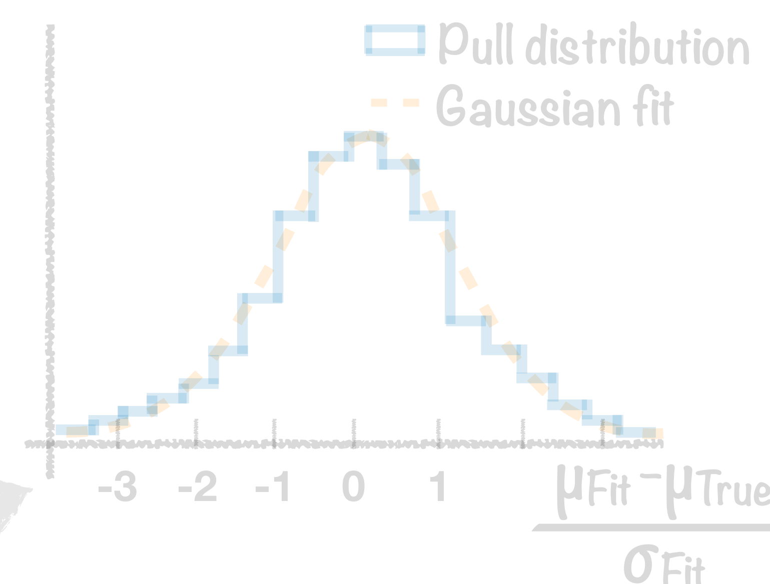
Non-resonant background model



Use the resulting fit as the true model to generate pseudo-events (μ_{true}=0)



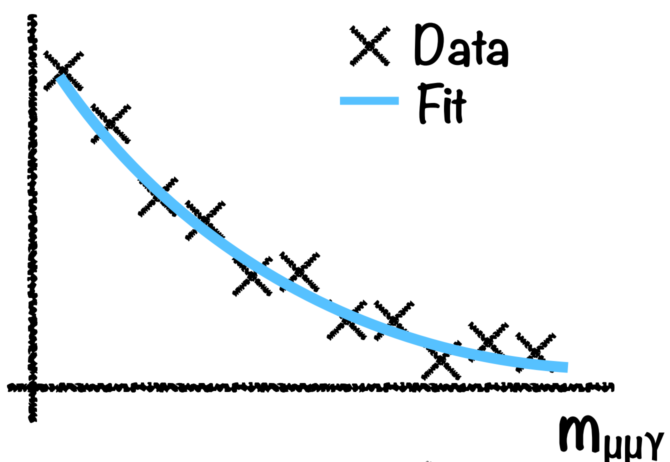
Find a function that gives a mean value for the μ_{Fit} consistent with μ_{true}.



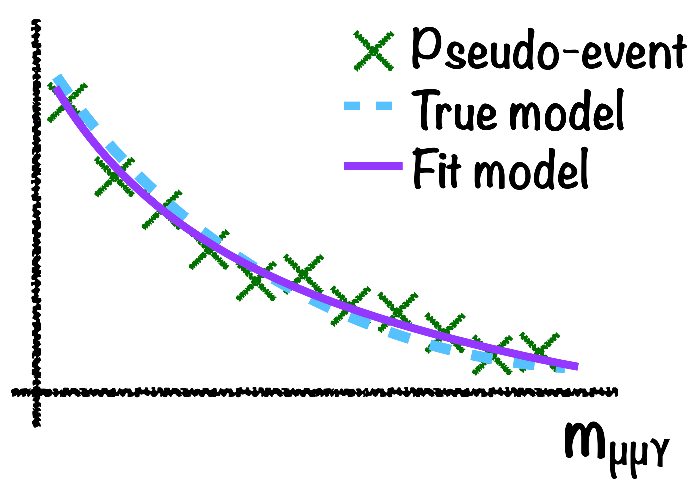
Fit the pseudo-data (with fit model) and extract the signal strength(μ_{Fit})

Non-resonant background model

- A fit is made to the pseudo-events distribution using one of the functions in the four families combined with a signal model, where the normalization of the signal in this step is allowed to be negative

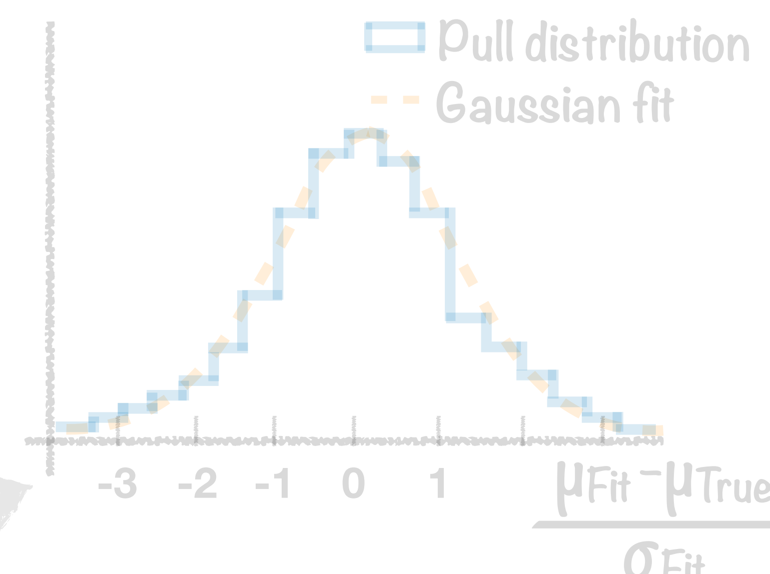


Use the resulting fit as the true model to generate pseudo-events (μ_{true}=0)



Fit the pseudo-data (with fit model) and extract the signal strength(μ_{Fit})

Find a function that gives a mean value for the μ_{Fit} consistent with μ_{true}.



Non-resonant background model

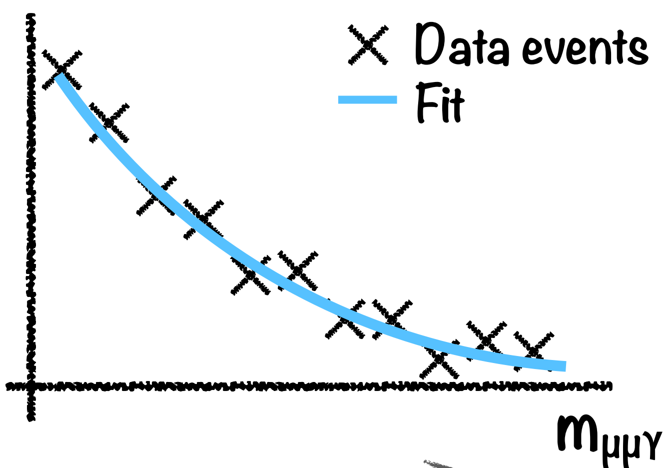
- The order of the function for each of the families is determined by increasing the number of parameters until an additional increase does not result in a significant improvement in the quality of the fit to the observed data.

- The improvement is quantified by the differences in the negative log-likelihood between fits with two consecutive orders of the same family of functions

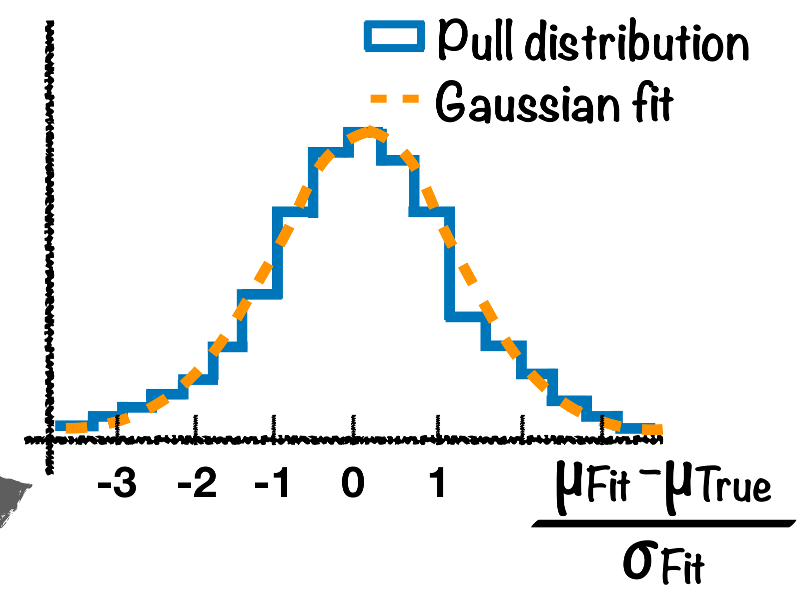
Non-resonant background model

- This procedure is repeated 5000 times and for each of the functions
  - Ideally, on average the signal strength predicted by the fit μ_{fit} will be equal to μ_{true}.
- The deviation of the mean fitted signal strength μ_{fit} from μ_{true} in pseudo-events is used to quantify the potential bias.
- The distribution of the pull values $(\mu_{fit} - \mu_{true})/\sigma_{fit}$ is examined.

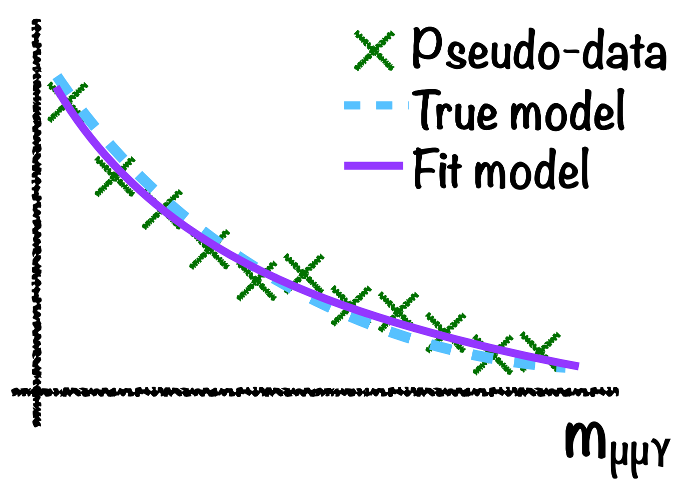
Non-resonant background model



Find a function that gives a mean value for the μ_{Fit} consistent with μ_{true}.



Use the resulting fit as the true model to generate pseudo-data ($\mu_{true}=0$)

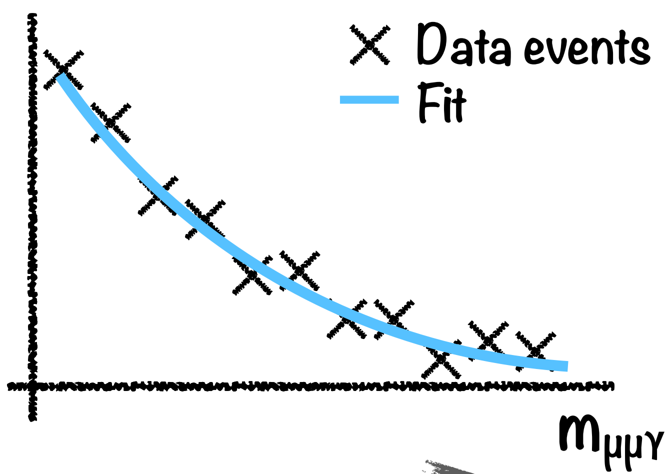


Fit the pseudo-data (with fit model) and extract the signal strength(μ_{Fit})

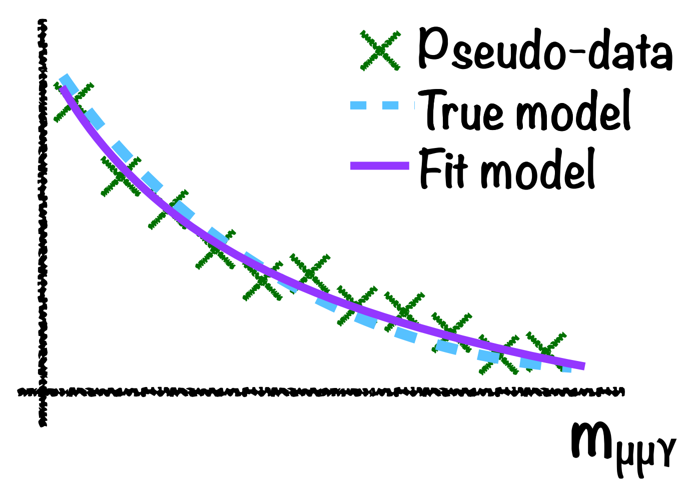
Non-resonant background model

- This procedure is repeated 5000 times and for each of the functions, and it is expected that ideally on average the signal strength predicted by the fit μ_{fit} will be equal to μ_{true}.
- The deviation of the mean fitted signal strength μ_{fit} from μ_{true} in pseudo-events is used to quantify the potential bias.
- The distribution of the pull values $(\mu_{fit} - \mu_{true})/\sigma_{fit}$ is examined.
- The criterion for the bias to be considered negligible is that the deviation must be at least five times smaller than the statistical uncertainty in μ_{fit}.
    - The mean value of the pull value distribution should be less than 0.2
- <u>No additional systematic uncertainty in background model is introduced</u>

Non-resonant background model

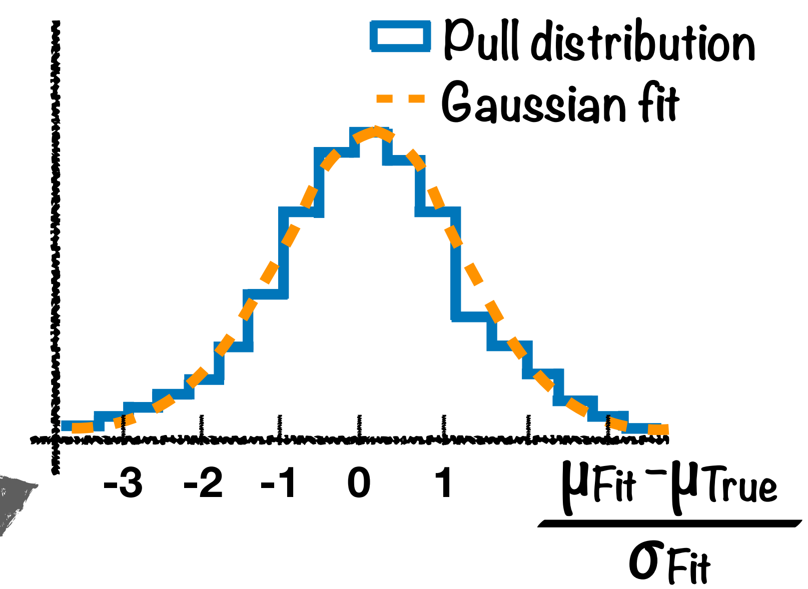


Use the resulting fit as the true model to generate pseudo-data (μ_{true}=0)

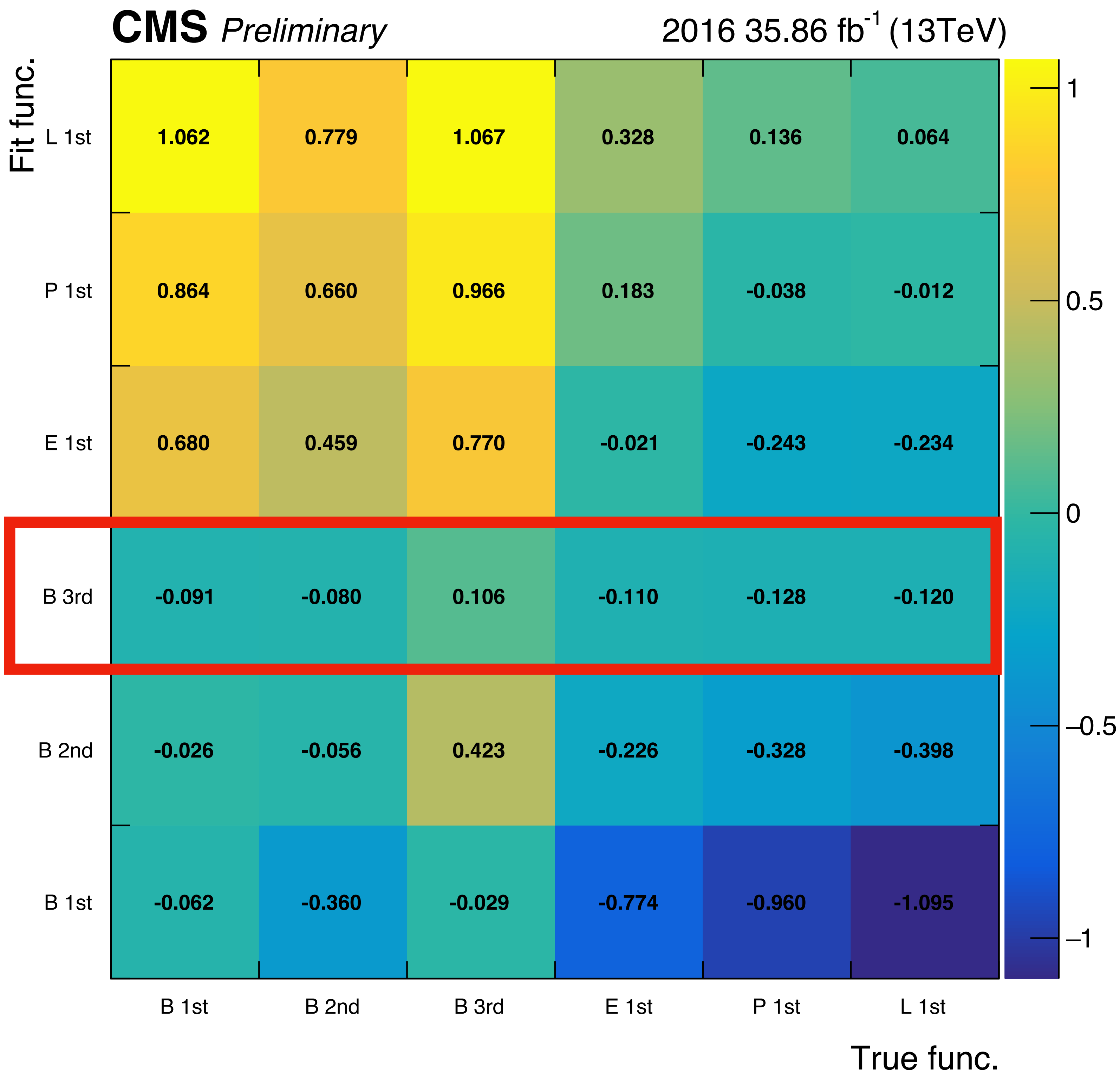


Fit the pseudo-data (with fit model) and extract the signal strength (μ_{Fit})

Find a function that gives a mean value for the μ_{Fit} consistent with μ_{true}.

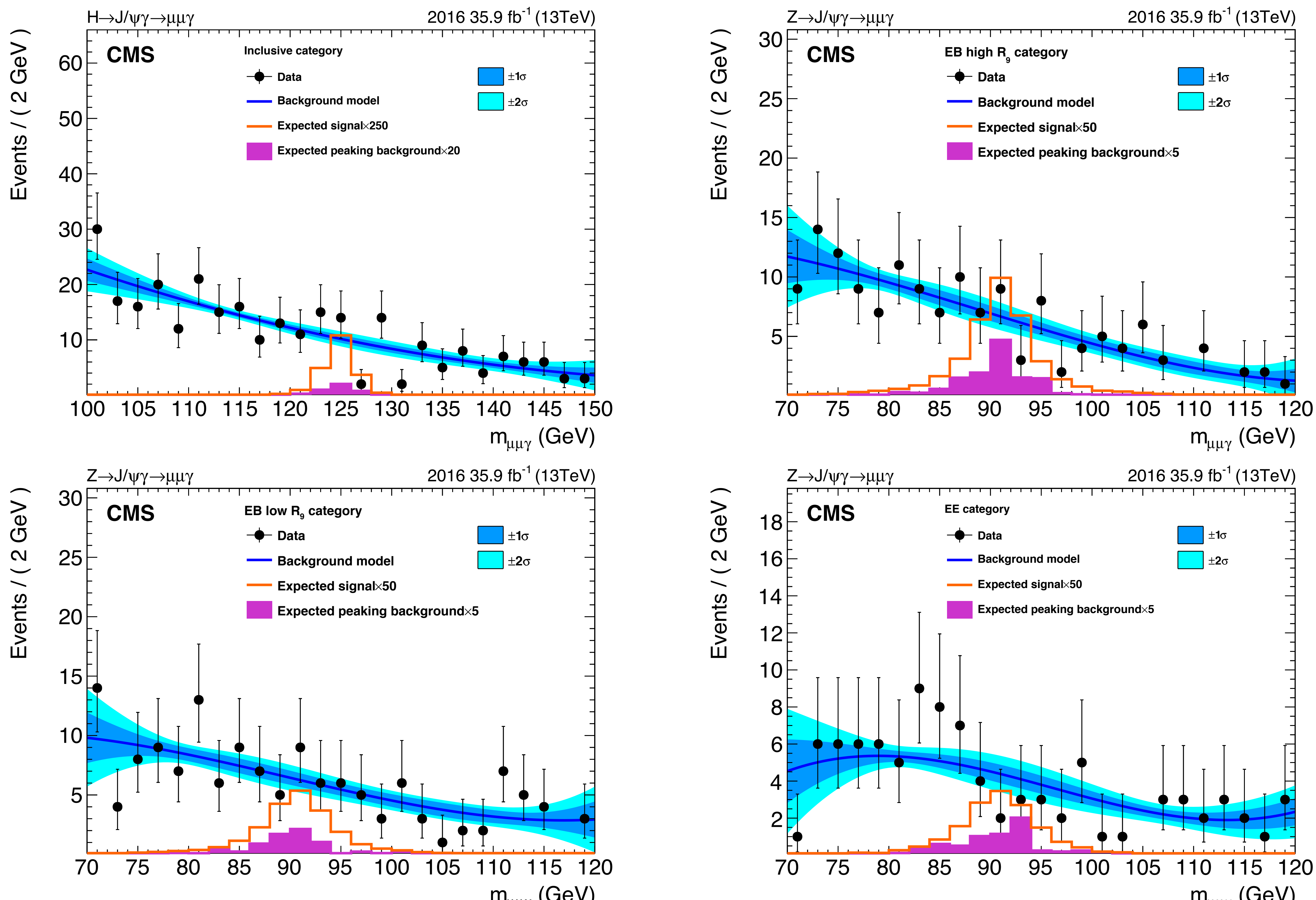


Non-resonant background model



- The bias table of $Z \to J/\psi\ \gamma$ EB high R9 category is shown on the LHS
- The numbers shown are bias of each combination of true&fit function
- As can be seen, Bernstein 3rd function satisfies the bias requirement
- As a result, Bernstein 3rd function is chosen as best fit function for all 3 categories in the Z decay, while Bernstein 2nd function is chosen for the Higgs decay

Non-resonant background model



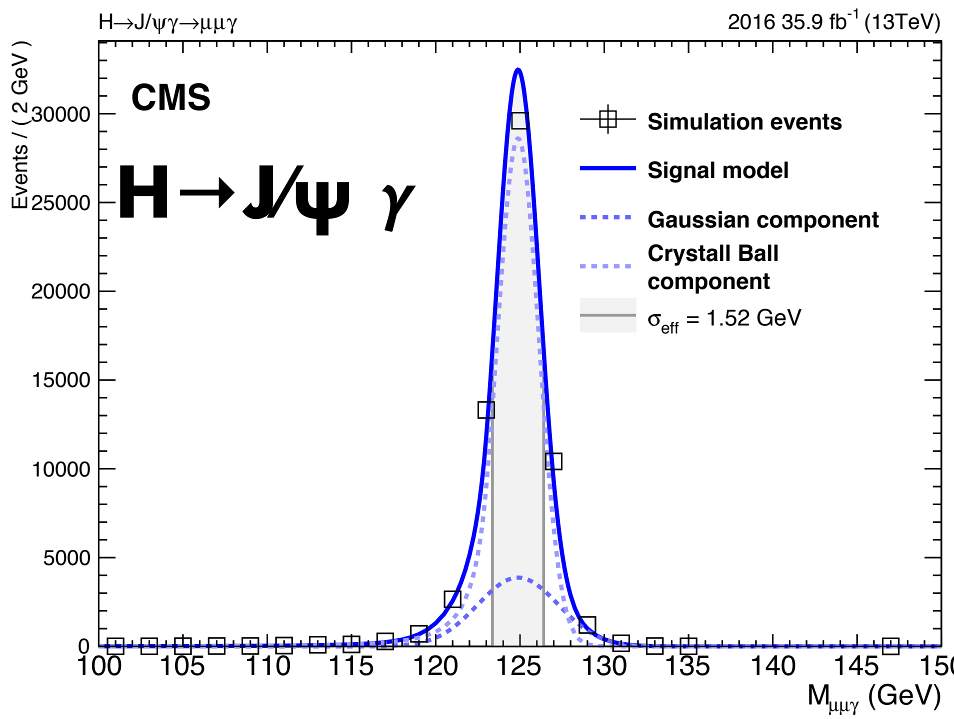
Resonant background & Signal model

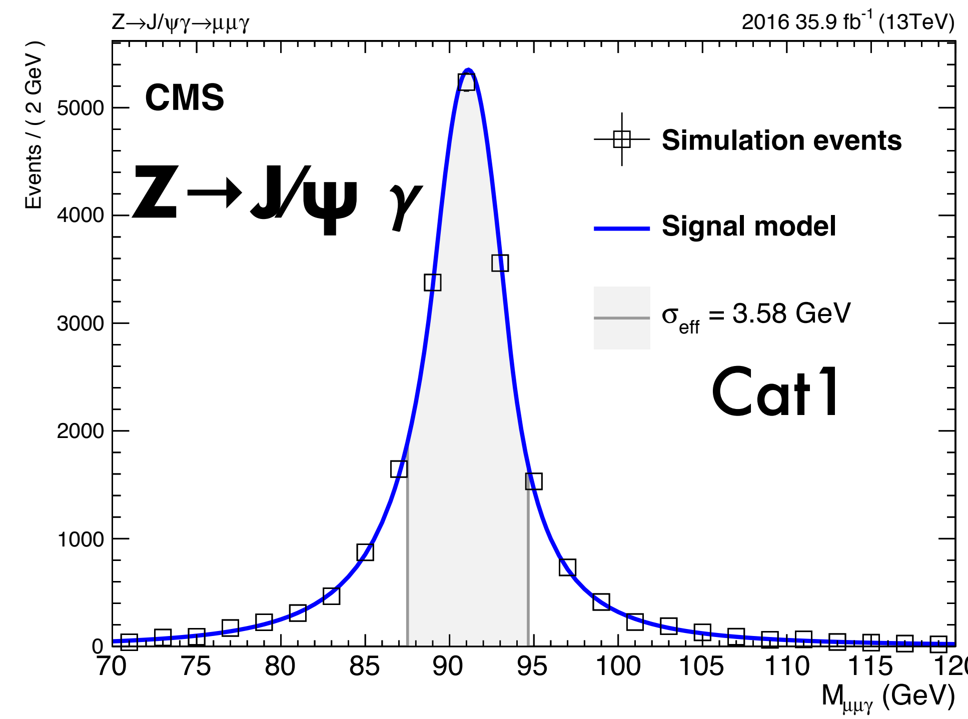
- The resonant bkg. and signal models for each case is obtained from an unbinned maximum likelihood fit to the $m_{\mu\mu\gamma}$ distributions of the corresponding sample of simulated events.

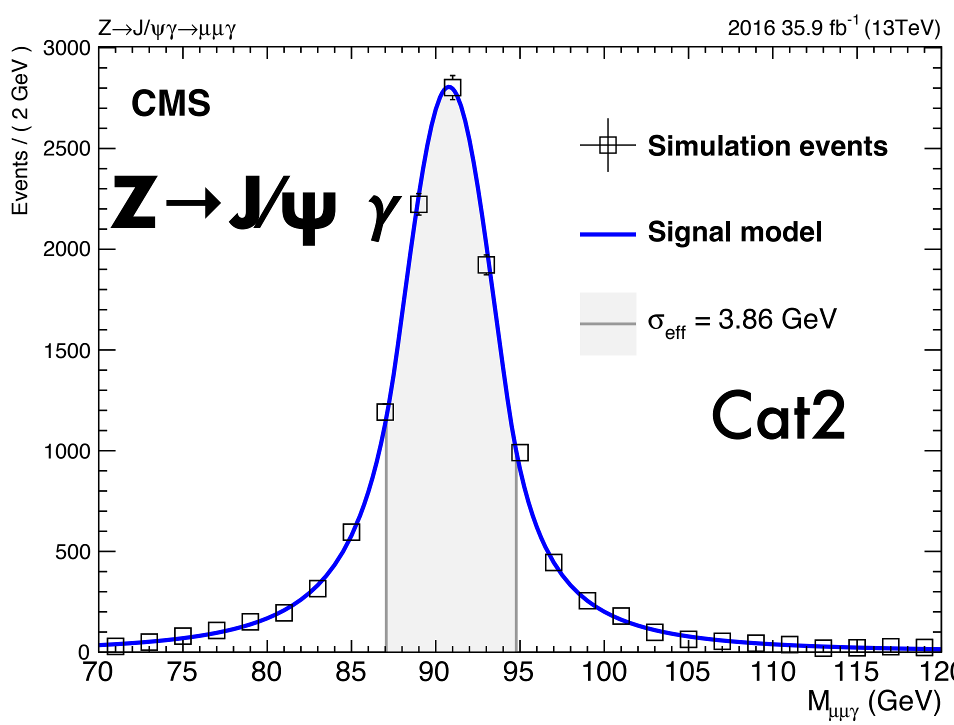
- For the Z boson decay, a double-sided Crystal Ball function is used for both signal and resonant bkg models.

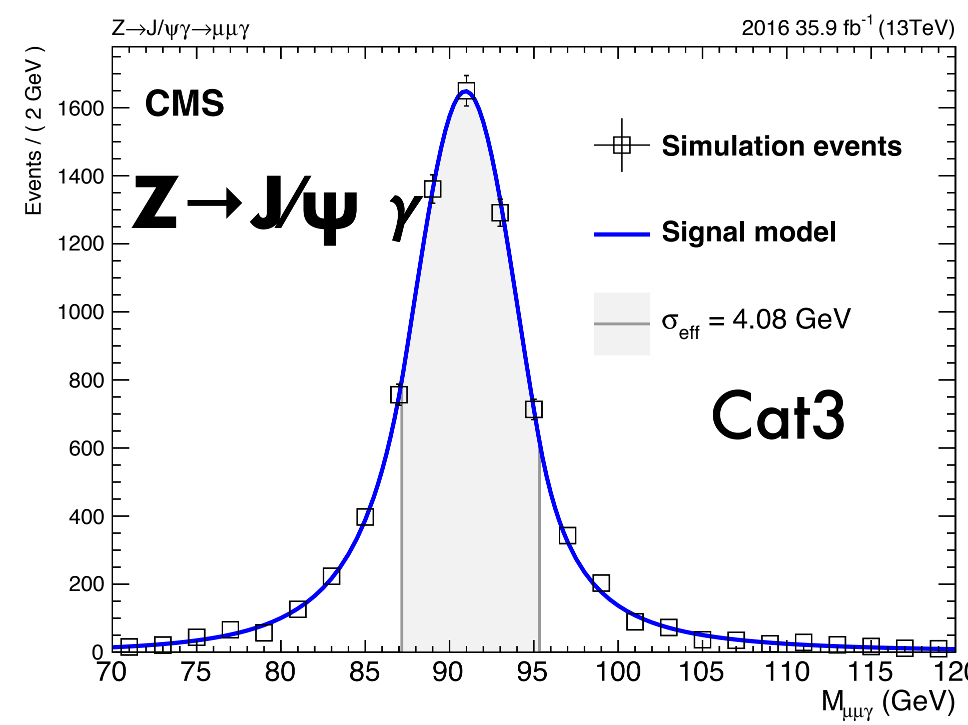
- For the Higgs boson decay, a Crystal Ball function plus a Gaussian with a common mean value is used for signal model, while a single Crystal Ball function is used for resonant bkg. model.

Signal model









Systematic uncertainty

- **Uncertainties in the predicted signal yields**
  - Luminosity measurement
  - Pile-up model in the simulations
  - The corrections applied to the simulated events in order to compensate for differences in trigger, object reconstruction, and identification efficiencies
  - Theoretical uncertainties
    - The effect of parton density function on the signal cross-section
    - The lack of higher-order calculations for the cross-section
    - The prediction of decay branching fractions

Systematic uncertainty

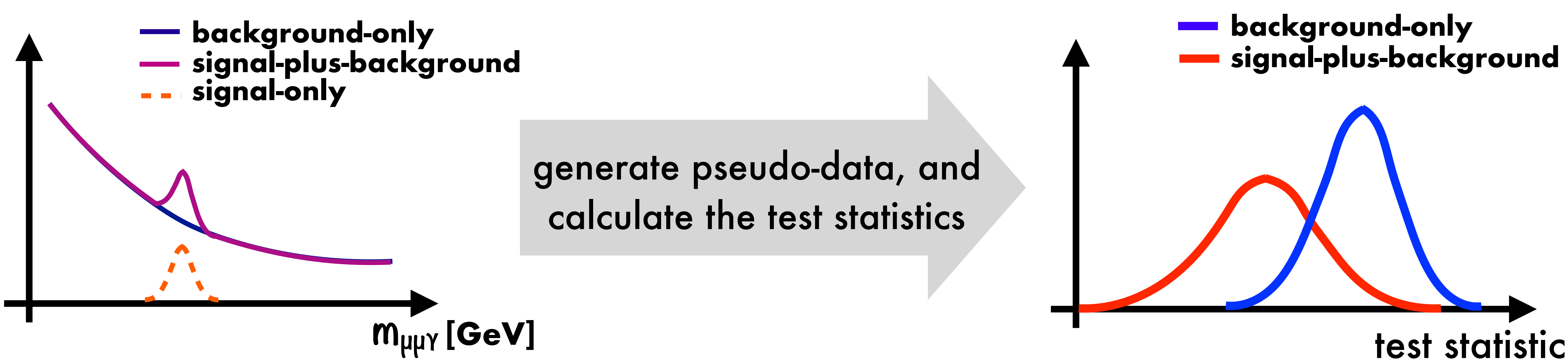
- **Uncertainties in the shapes of the signal models**
  - The momentum (energy) scale and resolution for muons (photons)
  - These effects are incorporated in the mean and width of the Gaussian component of the signal models, and introduced as shape nuisance parameters

Systematic uncertainty

Source	(Numbers are in %)			
	$Z\to J/\psi\ \gamma$ (average all cat.)		$H\to J/\psi\ \gamma$	
	Signal	Resonant background	Signal	Resonant background
Luminosity		2.5		
Theoretical uncertainty				
cross-section (scale)	3.5	5.0	+4.6 -6.7	
cross-section (PDF + α_S)	1.7		3.2	
branching fraction	–		–	6.0
Detector simulation, reconstruction				
pile-up description	0.8	1.8	0.7	1.6
trigger	4.0	4.0	3.9	4.0
Muon ID/Iso	3.0	3.4	2.0	2.5
Photon ID	1.1	1.1	1.2	1.2
electron veto	1.1	1.1	1.0	1.0
Signal model				
$m_{\mu\mu\gamma}$ scale	0.06	–	0.1	–
$m_{\mu\mu\gamma}$ resolution	1.0	–	4.8	–

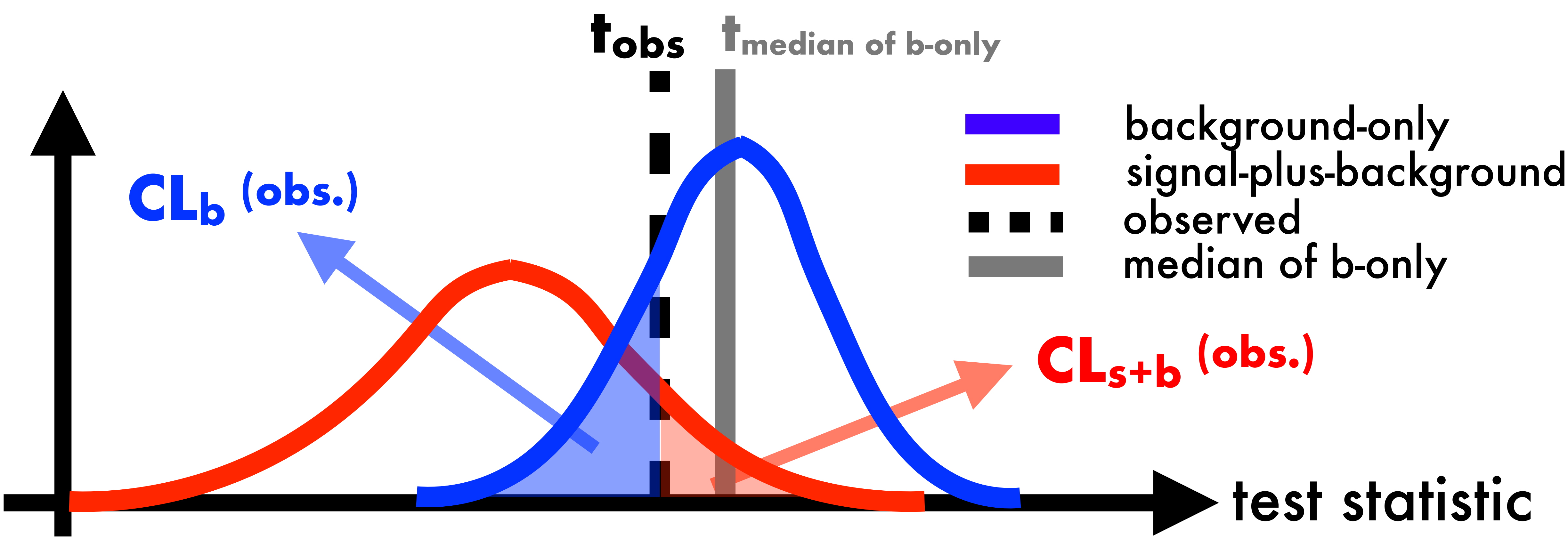
Statistical method

- Define *background-only* and *signal-plus-background* hypotheses in the unbinned likelihood calculation
- Choose a proper test statistic, which represents the sample in the hypothesis test
  - The profile likelihood ratio is used
- Construct expected distributions of the test statistic



Statistical method

- Determine the observed (expected) significance
  - CL_b : the probability that one gets value of t less than t_{obs} ($t_{\text{median of b-only}}$) under b-only hypothesis
  - CL_{s+b} : the probability that one gets value of t larger than t_{obs} ($t_{\text{median of b-only}}$) under s+b hypothesis



Statistical method

- In this analysis, the expected signals from the SM prediction are too small, the distributions from b-only and s+b hypotheses cannot be well distinguished (not sensitive)
- Exclusion upper limits are set
  - Introduce additional signal in the likelihood calculation with amount of μ times its SM value (μ: signal modifier)
  - Scan the μ until $CL_s \equiv CL_{s+b}/CL_b < 0.05$. Then we interpret the result as *"the signal model is excluded, with an upper limit of μ, at 95% confidence level"*

Results

Exclusion observed (expected) upper limit at 95% C.L		
Channel	σ(pp→Z/H)×BR(Z/H→J/ψ γ→μμγ)	BR(Z/H→J/ψ γ)
Z→J/ψ γ	$< 4.6(5.3^{+2.3}_{-1.6})$ fb	$< 1.4(1.6^{+0.7}_{-0.5})\times10^{-6}$ (~15 (18) times the SM prediction) SM prediction = 9.0×10^{-8}
H→J/ψ γ	$< 2.5(1.7^{+0.8}_{-0.5})$ fb	$< 7.6(5.2^{+2.4}_{-1.6})\times10^{-4}$ (~260 (170) times the SM prediction) SM prediction = 3.0×10^{-6}

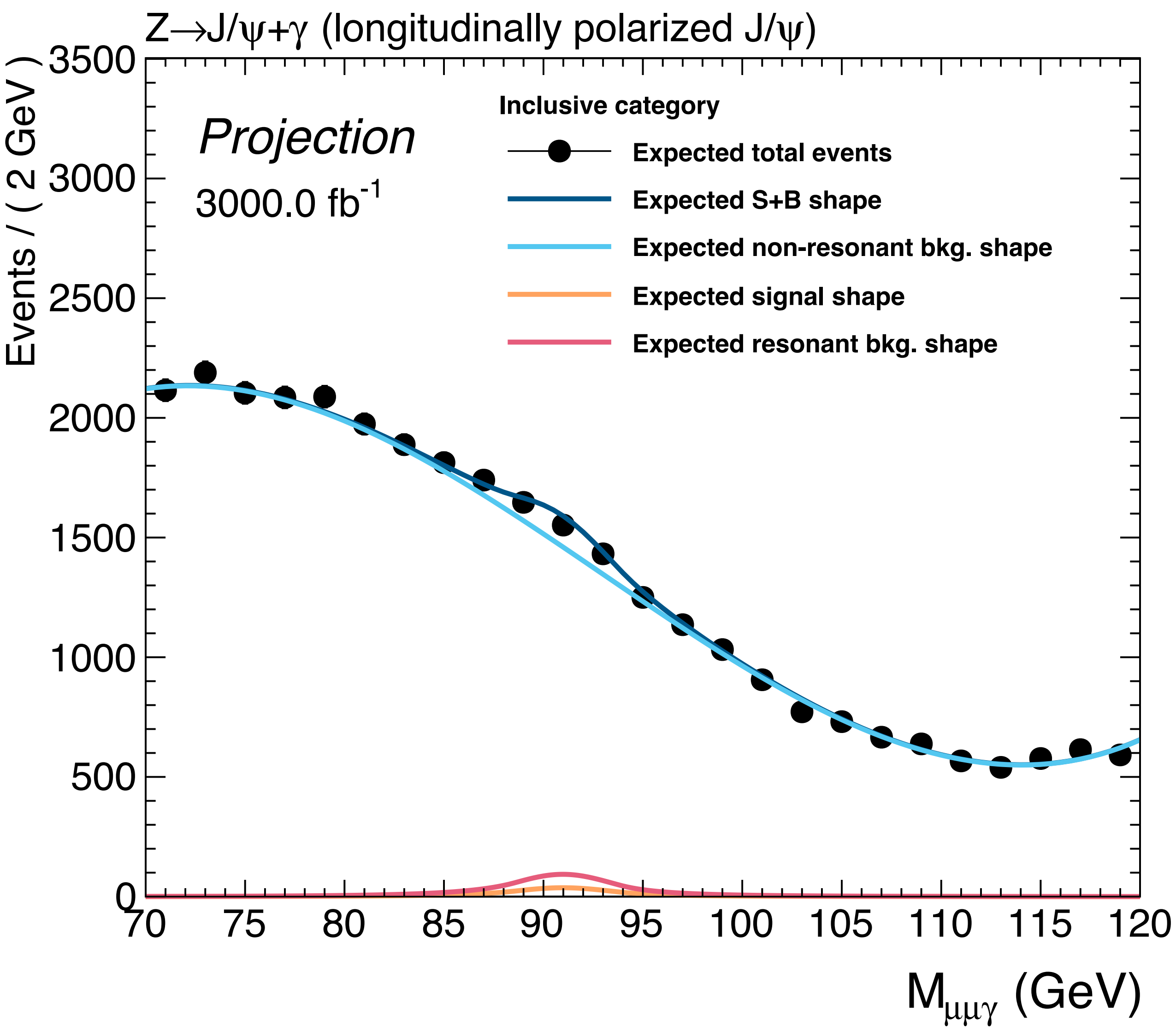
Variations from different polarization scenarios in the Z boson decay

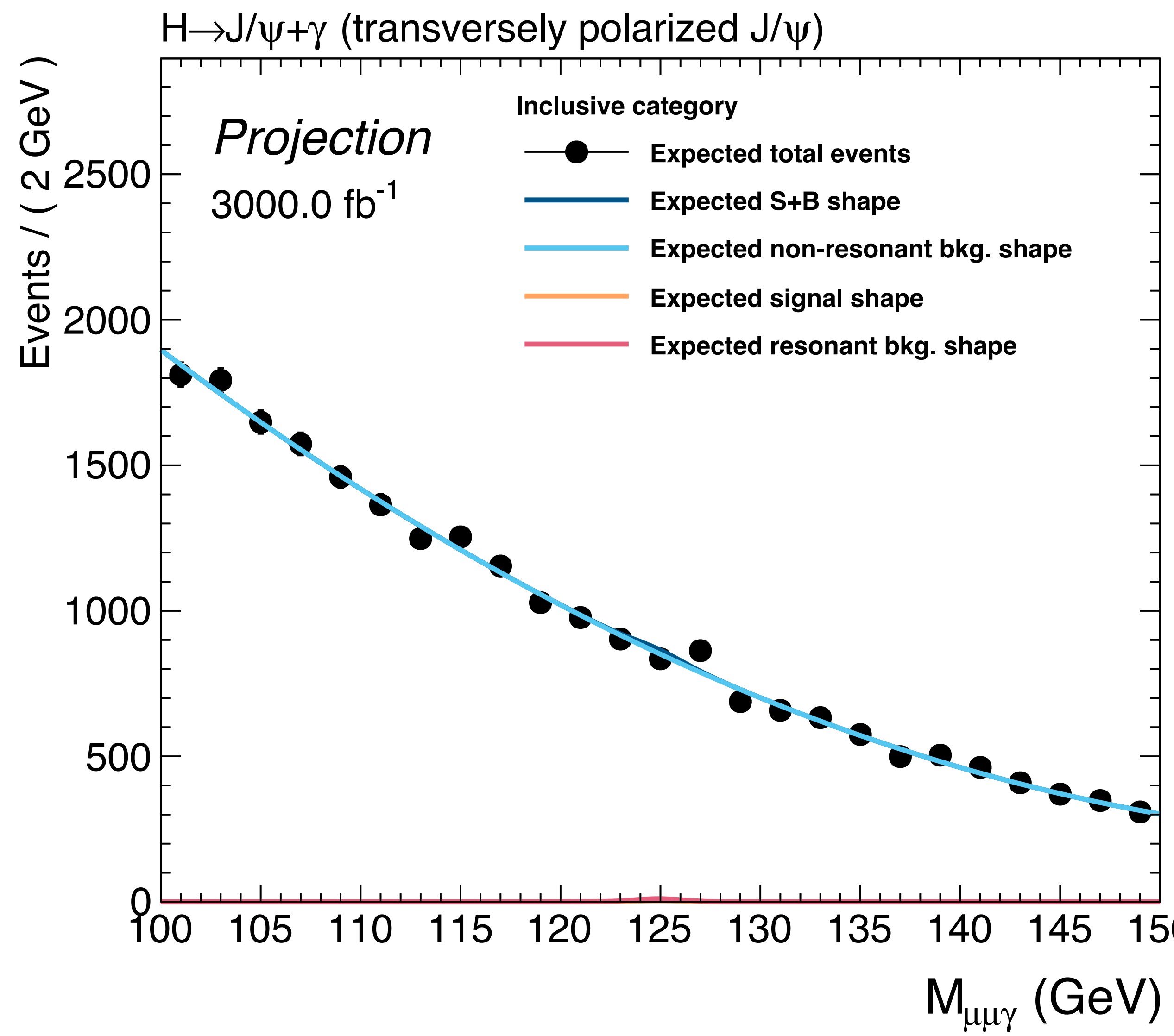
Polarization scenarios	Obs. (Exp.) limit	Difference
Transverse	$1.5\ (1.7)\times10^{-6}$	8.6 (8.2)%
Unpolarized	$1.4\ (1.6)\times10^{-6}$	-
Longitudinal	$1.2\ (1.4)\times10^{-6}$	-13.6 (-13.5)%

Conclusion

- A search for decay of the $Z/H \to J/\psi\ \gamma$ using full 2016 data with integrated luminosity of 35.9 fb^{-1} collected by the CMS detector is performed.
- The upper observed (expected) limits of 95% C.L on branching fraction
  - **$H \to J/\psi\ \gamma$: 7.6 ($5.2^{+2.4}_{-1.6}$)×10^{-4}, which is 260 (170)×SM**
  - **$Z \to J/\psi\ \gamma$: 1.4 ($1.6^{+0.7}_{-0.5}$)×10^{-6}, which is 15 (18)×SM**
  - In the Z boson decay, extreme polarization scenarios give variations of -13.6~+8.5 (-13.5~+8.2)% w.r.t the central observed (expected) value, assuming the unpolarized scenario
- The paper has been approved and gone through the collaboration wide review. The final reading is scheduled on Oct. 5th. The target journal is EPJC.
  - The public PAS (physics analysis summary) can be found here.

Projection





- Based on current sensitivity, the upper limit on the Z boson decay is expected to be around 2×SM and on the Higgs boson decay to be less than 20×SM with 3000fb^{-1} of data

Outlook

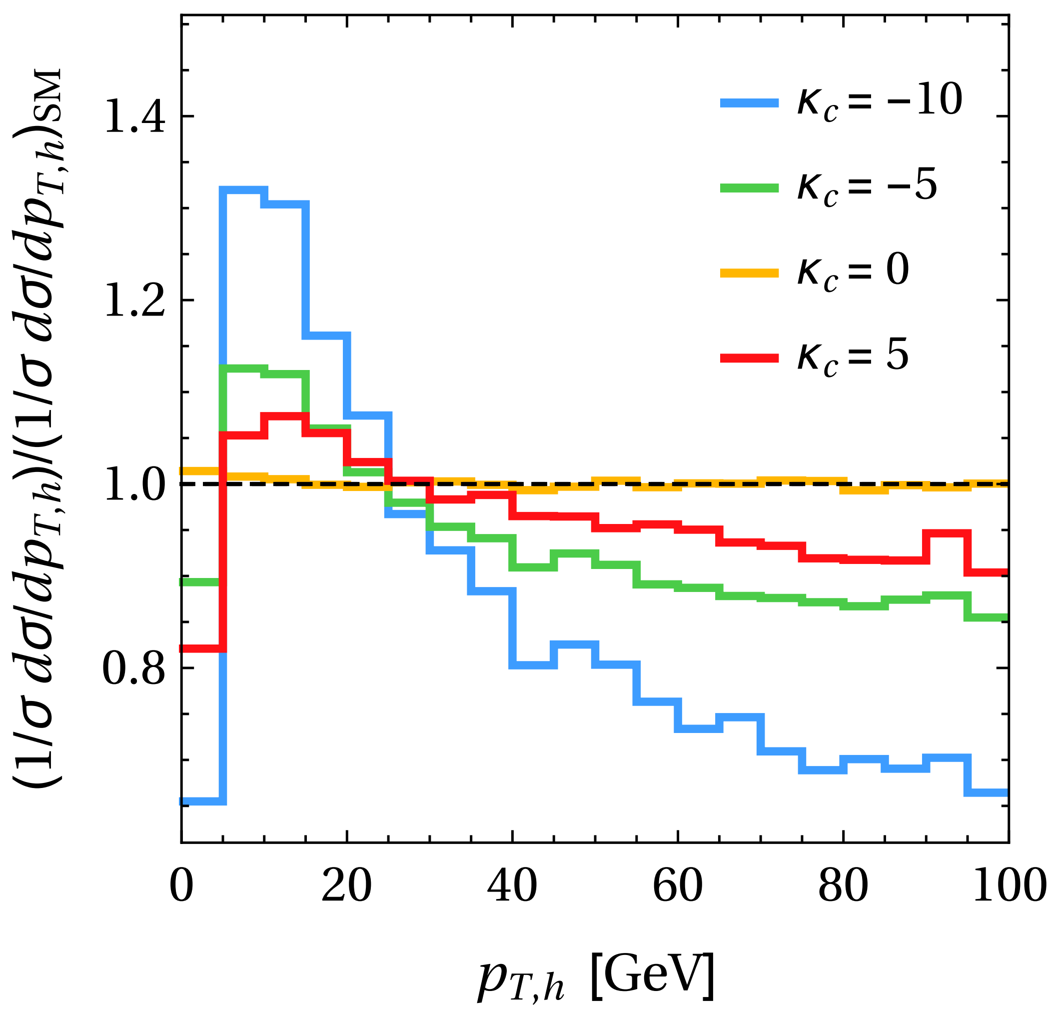
- Improvements can be done to make the analysis more advanced.
- Proper simulations for the background processes
- More robust methods to discriminate signal and backgrounds
- 2-dimension or multi-dimension fit
- Reconstruction & identification of merged electron signature
- ……

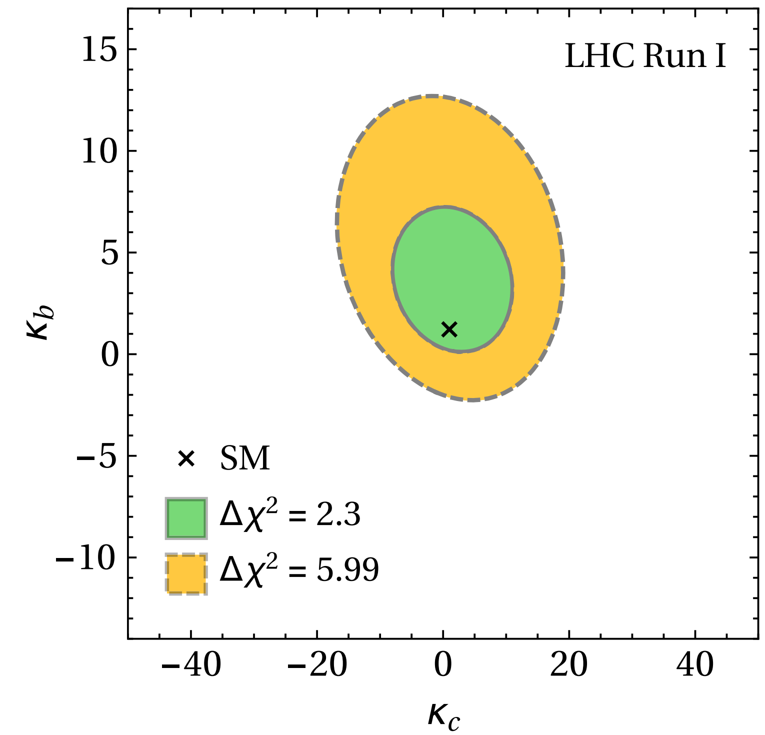
Backup

p_T^H v.s κ_c

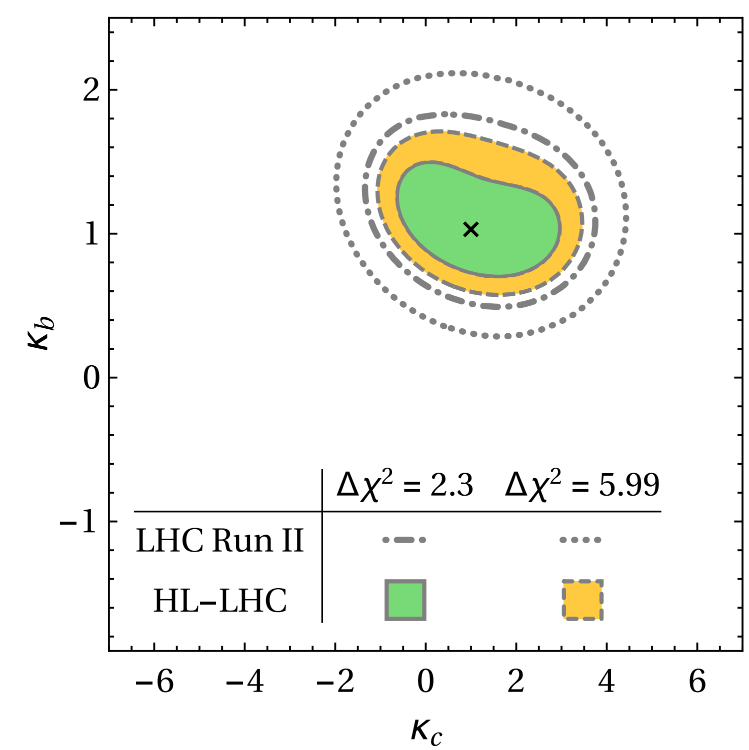
Phys. Rev. Lett. 118, 121801

Normalized (to the SM prediction) spectrum of the H p_T





- Using ATLAS HZZ & Hγγ Run1 results → $\kappa_c \in [-16,18]$

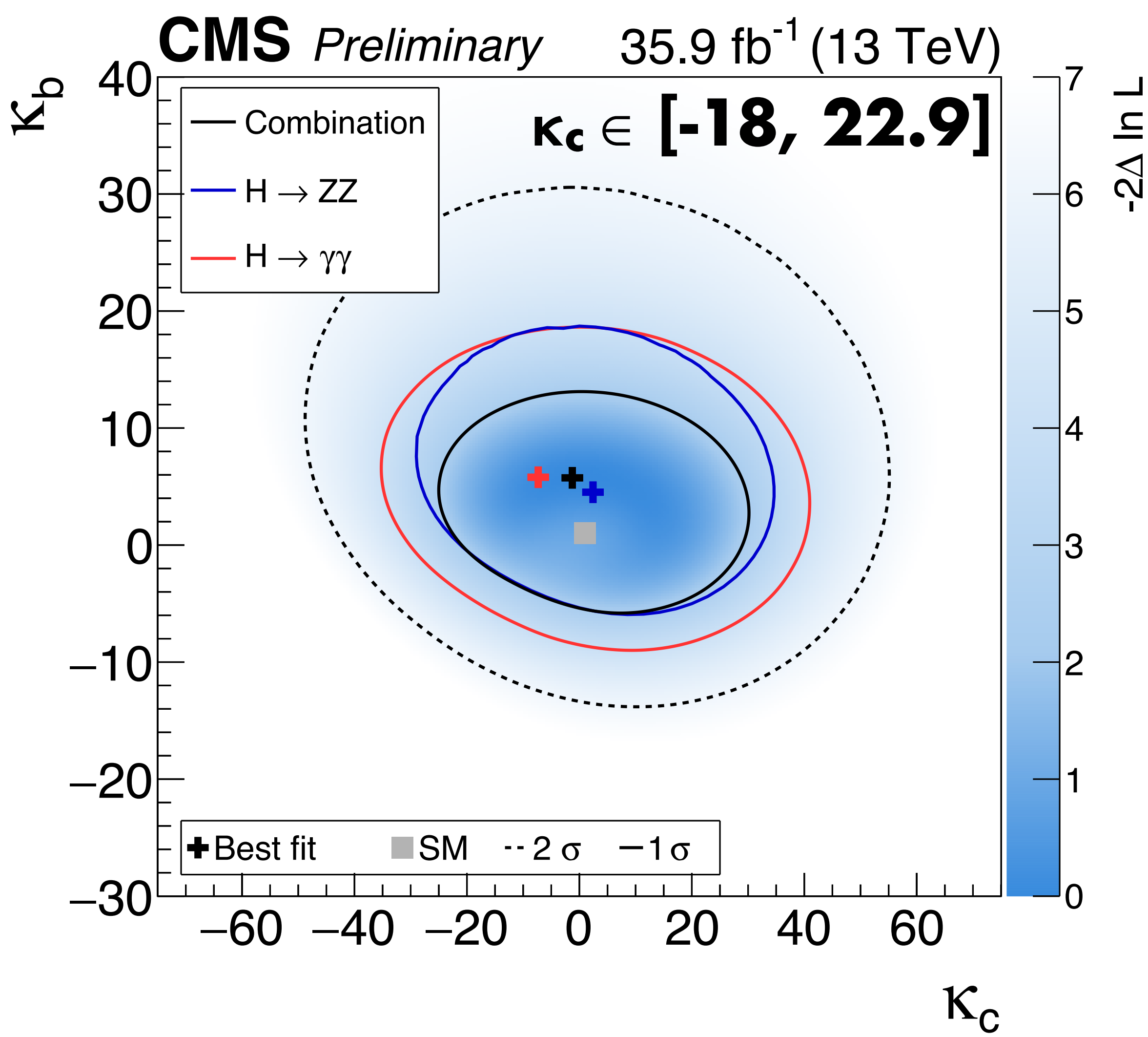


- Projection
  Full Run2: $\kappa_c \in [-1.4,3.8]$
  HL-LHC: $\kappa_c \in [-0.6,3.0]$

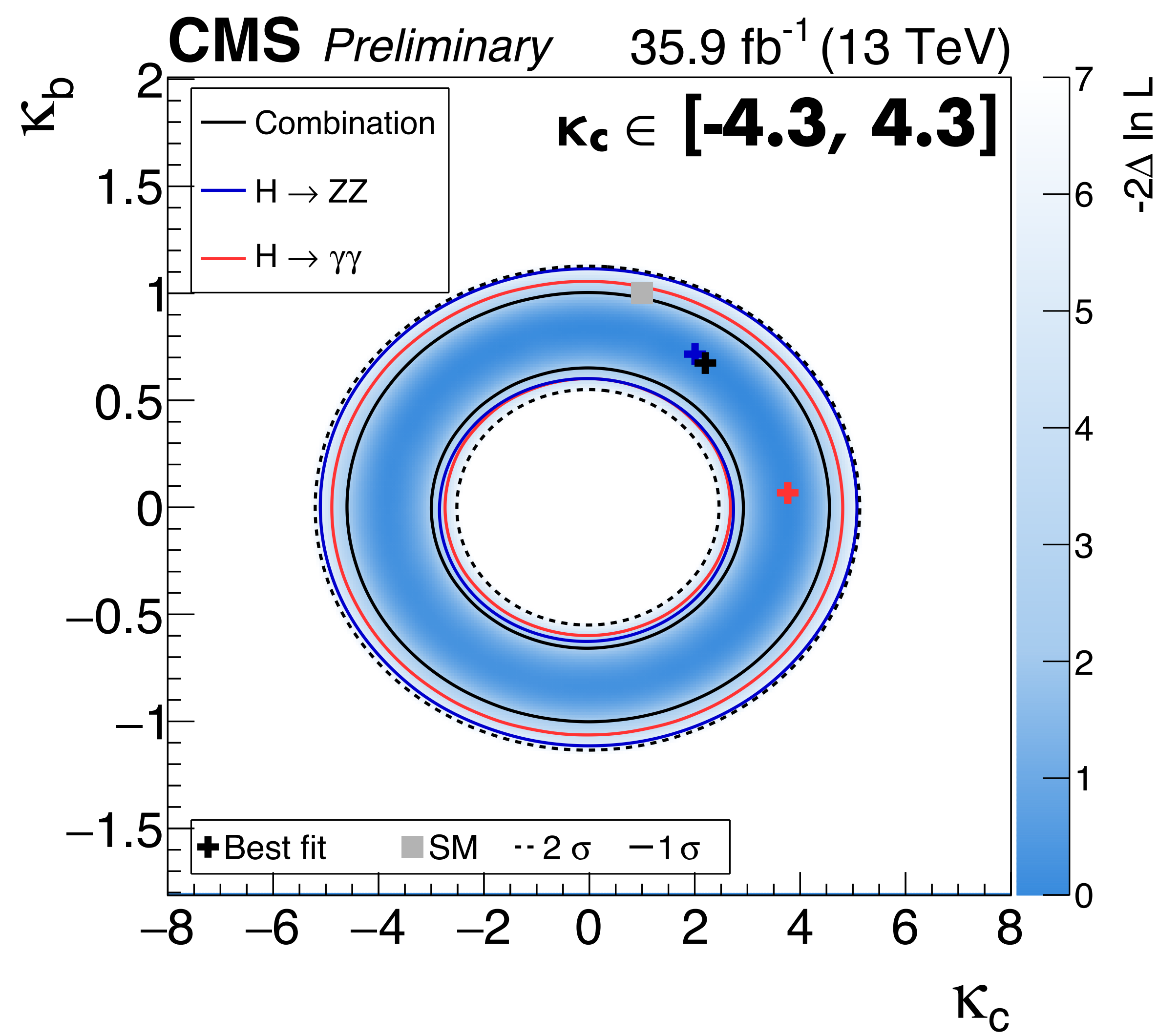
p_T^H v.s κ_c

PAS-HIG-17-028

Higgs boson production cross sections in CMS with 2016 dataset

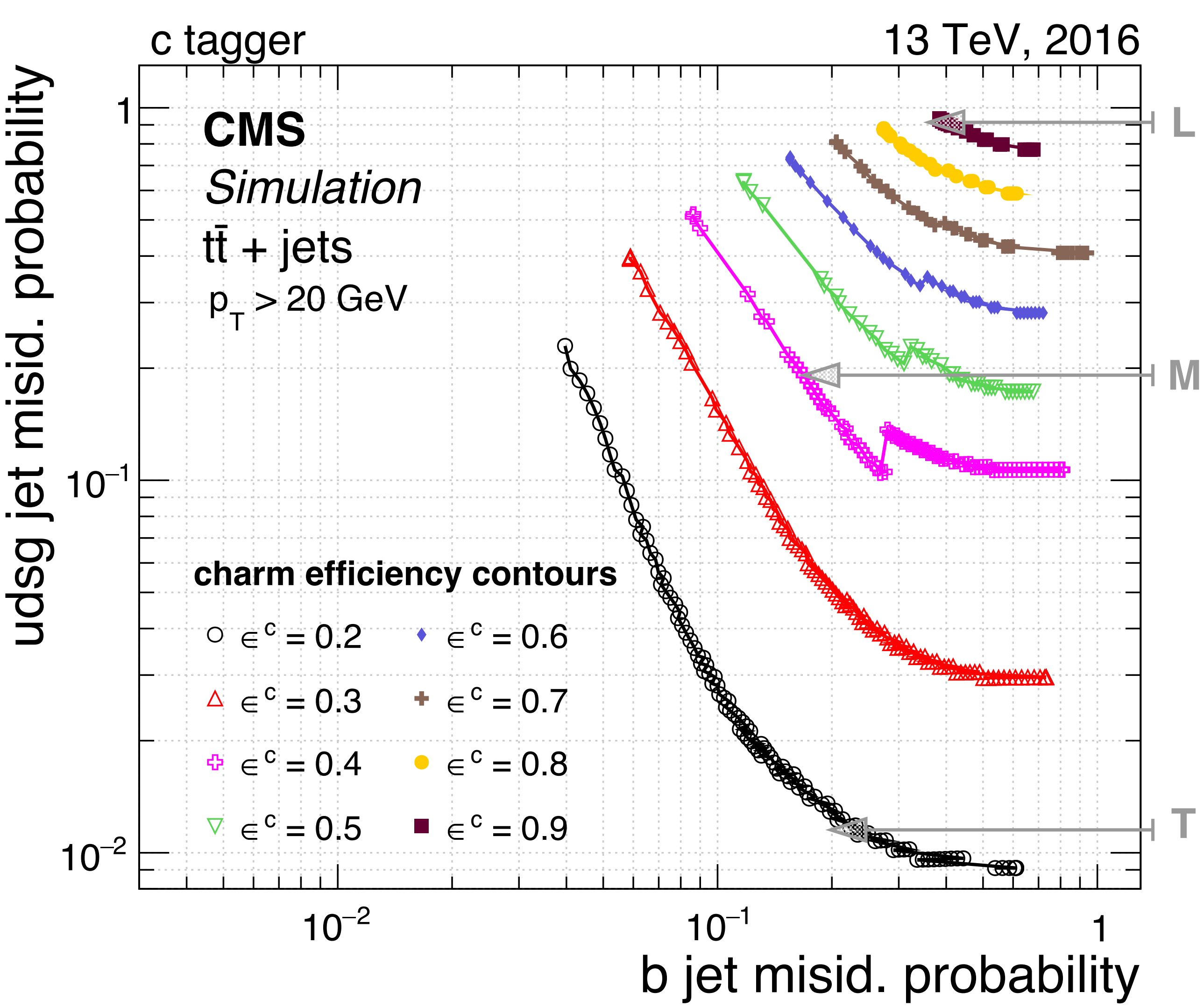


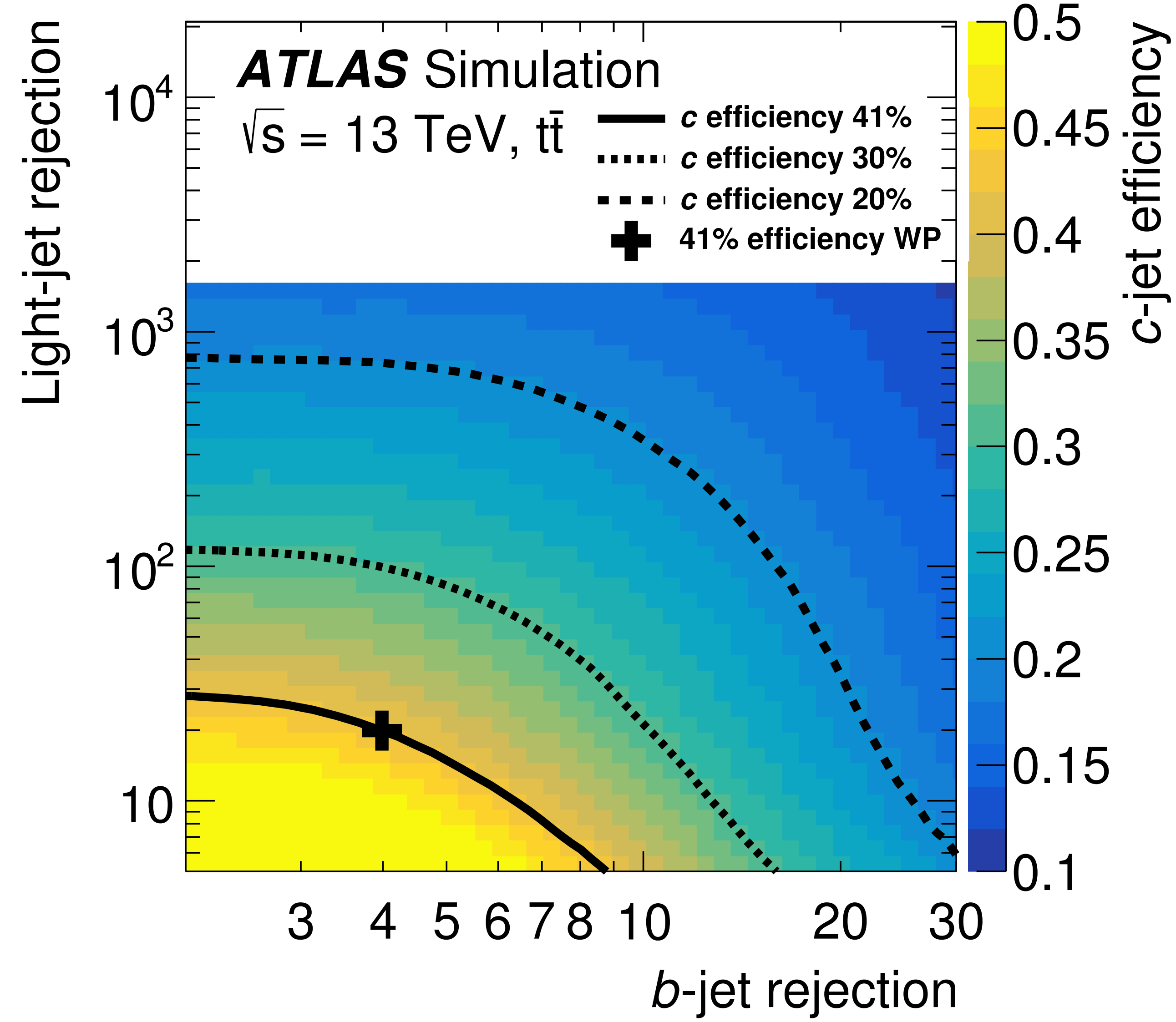
Purely shape information (without other constraint in the fit)



Constraints on BRs (coupling dependent) are imposed in the fit

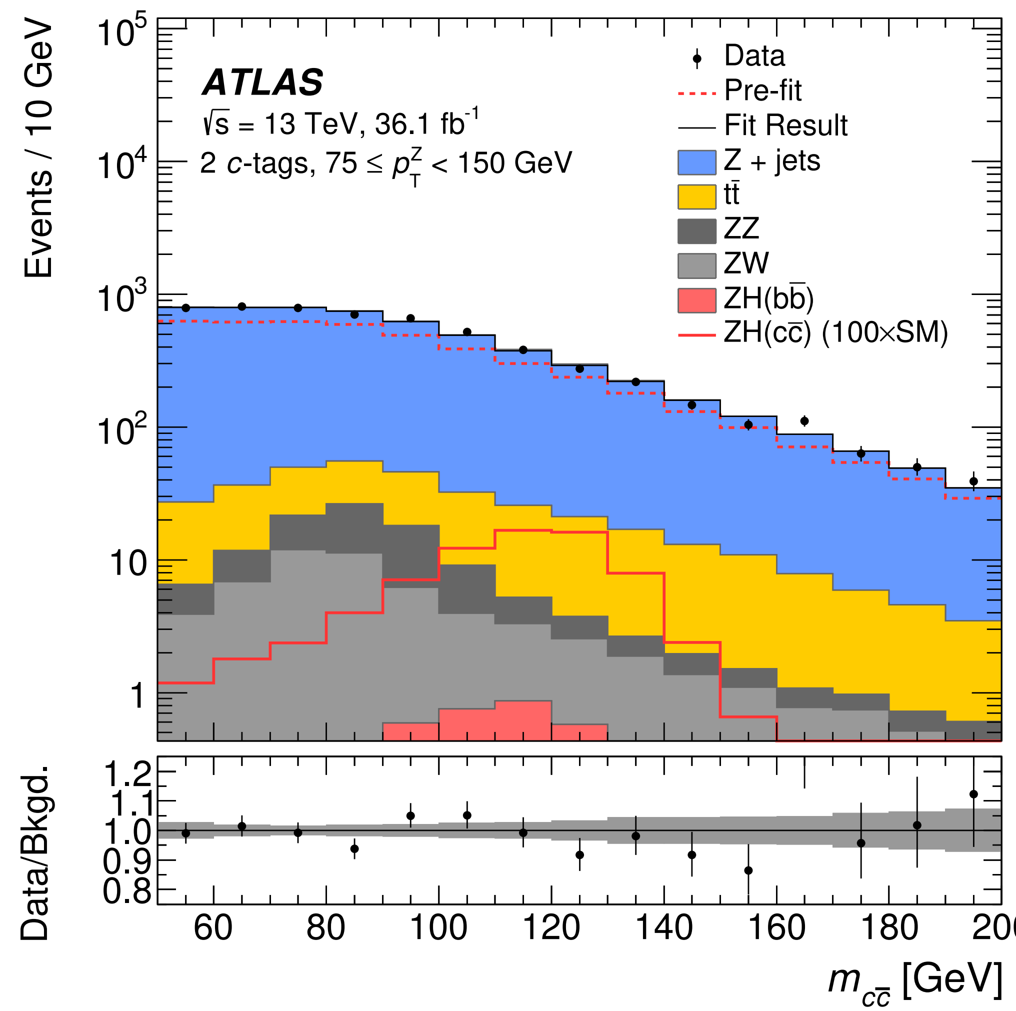
c-tagging performance





The Higgs-charm coupling

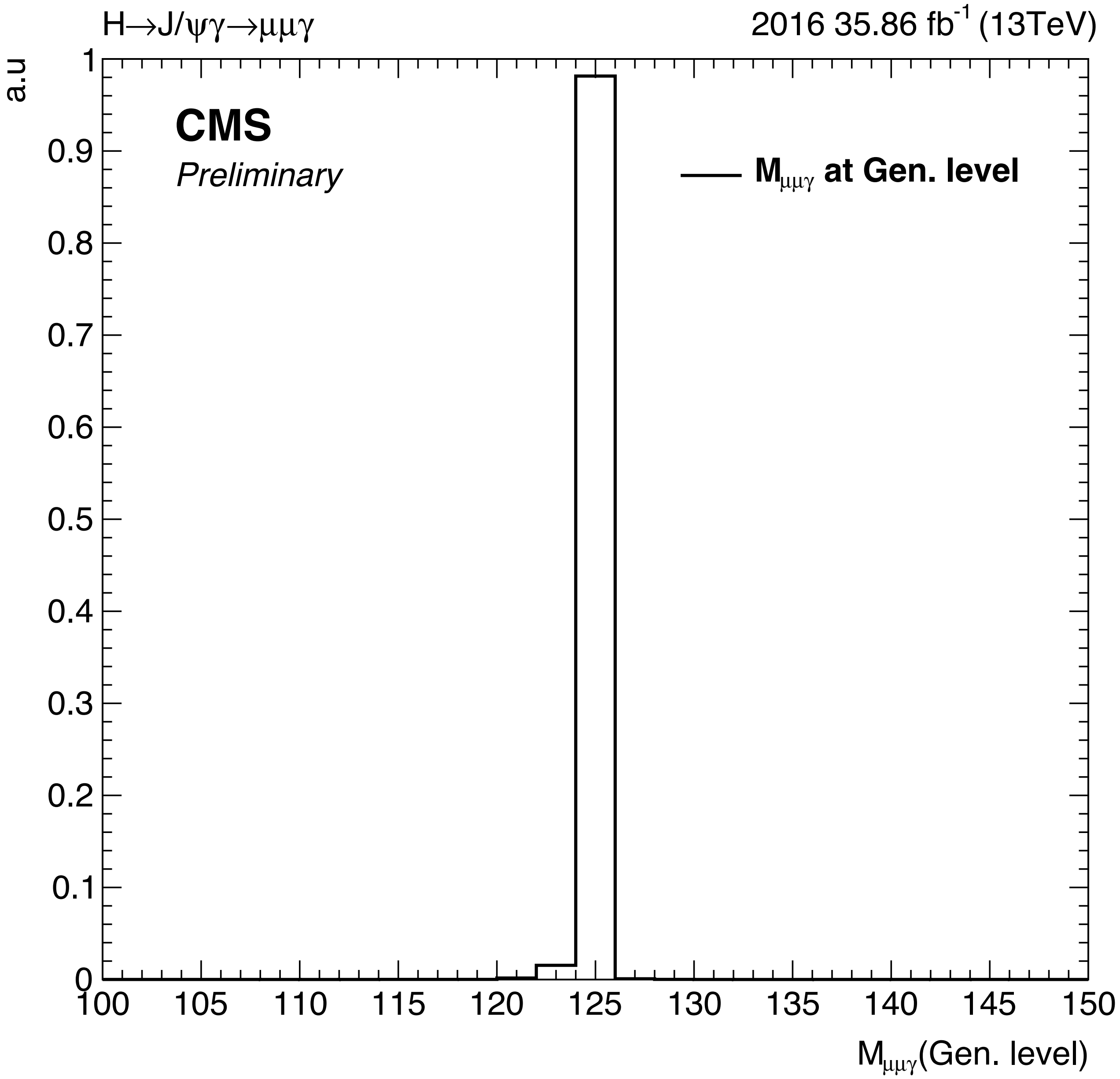
- A direct search for the decay $H \to c\bar{c}$ was recently performed by the ATLAS Collaboration
- Utilize the ZH production with the subsequent decay of the Z boson to dilepton
- The observed (expected) limit on the production cross-section is found to be 110 (150) times the SM prediction



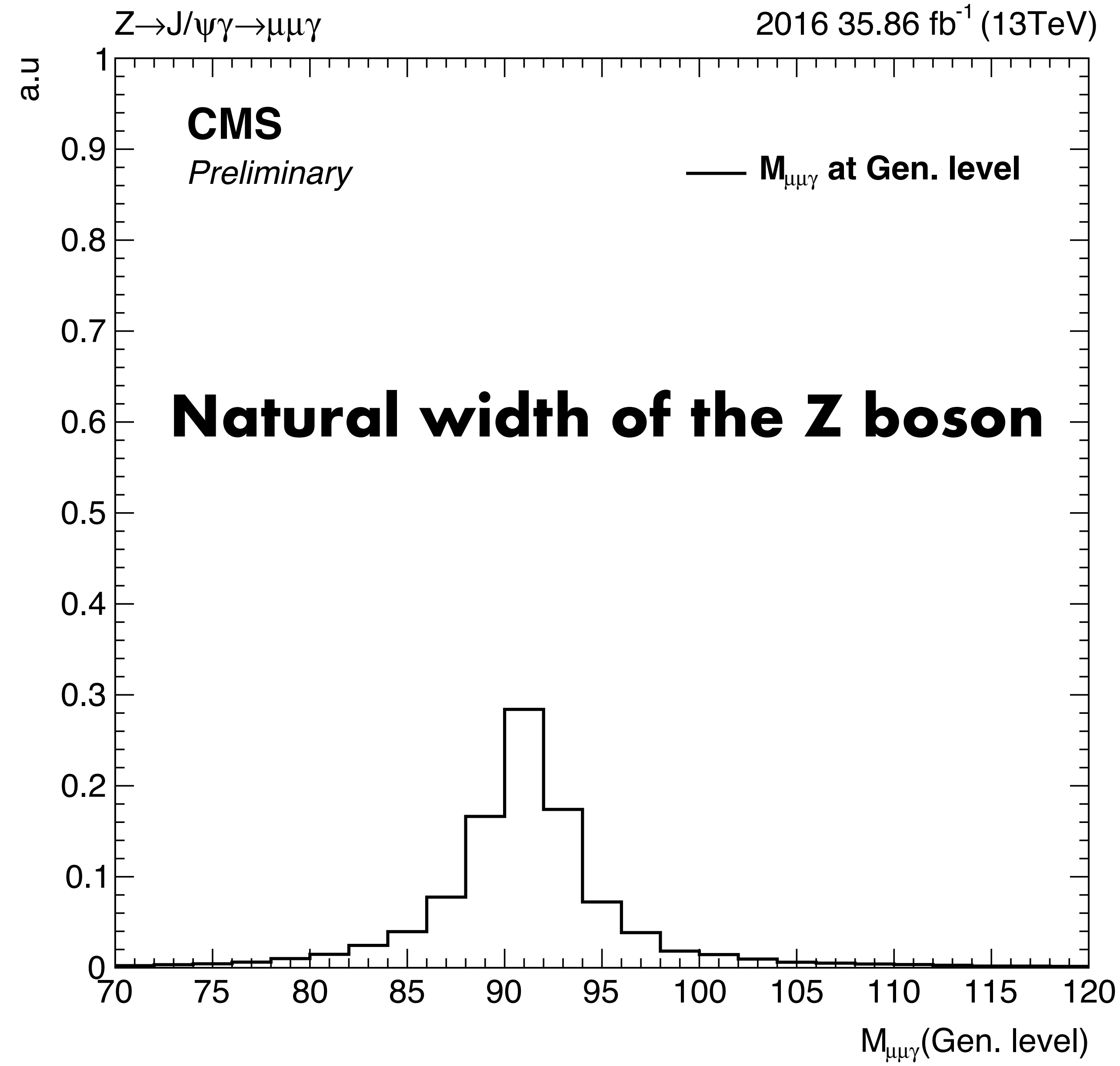
Ref: PRL. 120, 211802

$m_{\mu\mu\gamma}$ at Gen. level

$H \to J/\psi\ \gamma$

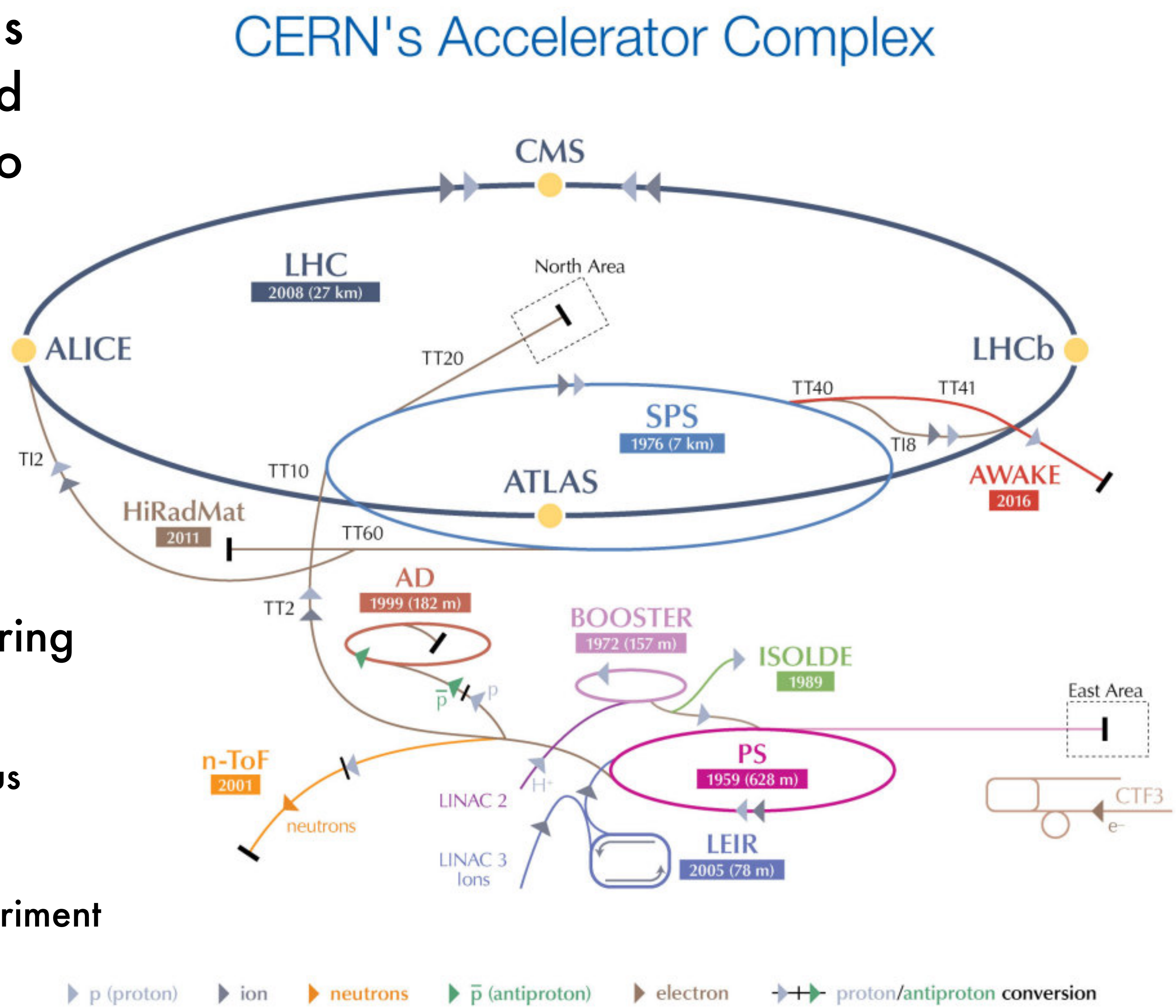


$Z \to J/\psi\ \gamma$



Large Hadron Collider

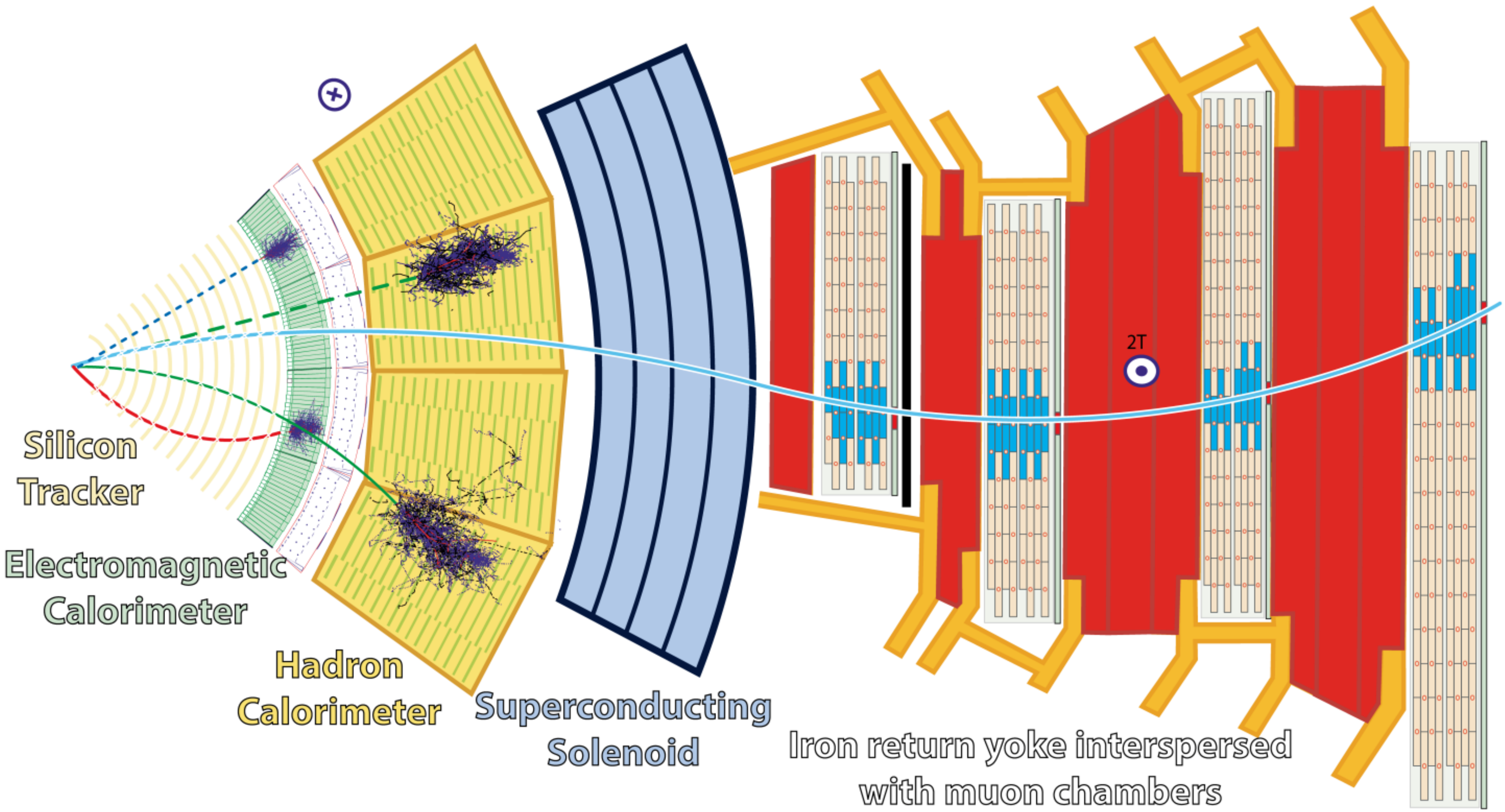
A series of machines successively accelerate and bring proton beams to higher energy



Four main detectors along the ring

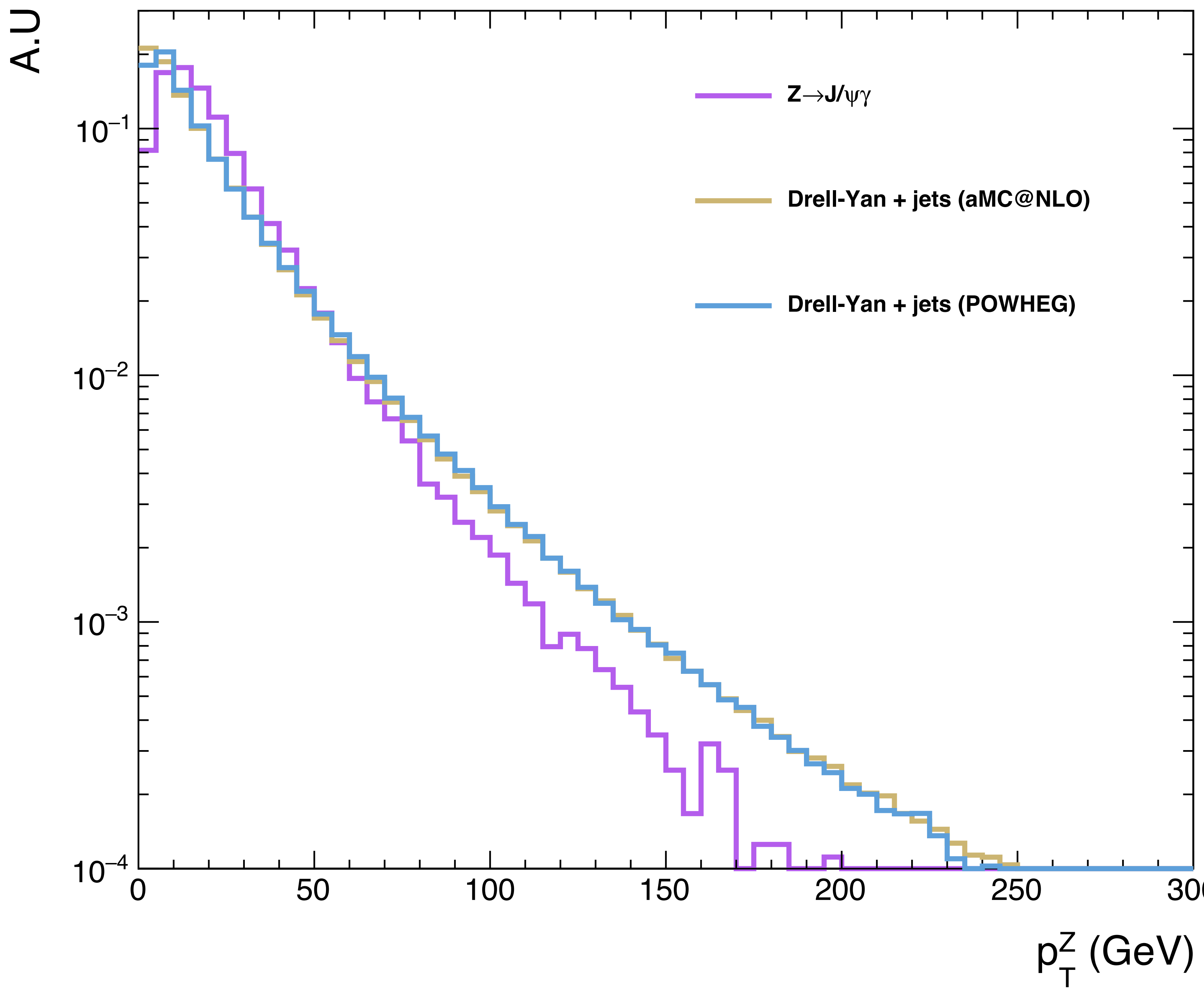
- **CMS**: Compact Muon Solenoid
- **ATLAS**: A Toroidal LHC Apparatus
- **LHCb**: LHC-beauty
- **ALICE**: A Large Ion Collider Experiment

CMS detector



Muon
Electron
Charged hadron (e.g. pion)
Neutral hadron (e.g. neutron)
Photon

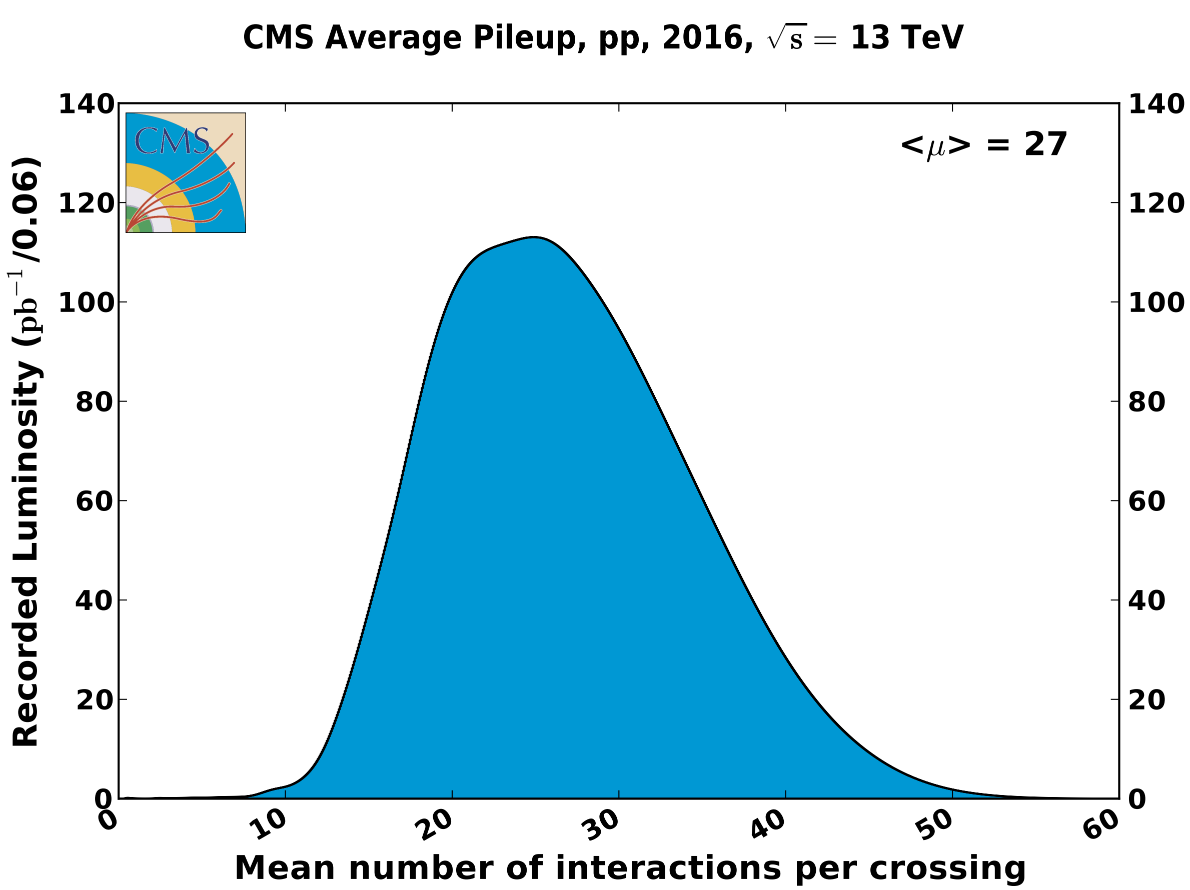
Z p_T reweighting



Simulated samples

- The generated events are processed through a detailed simulation of the CMS detector based on GEANT4

- Simultaneous pp interactions that overlap the event of interest (pileup) are included in the simulated samples.



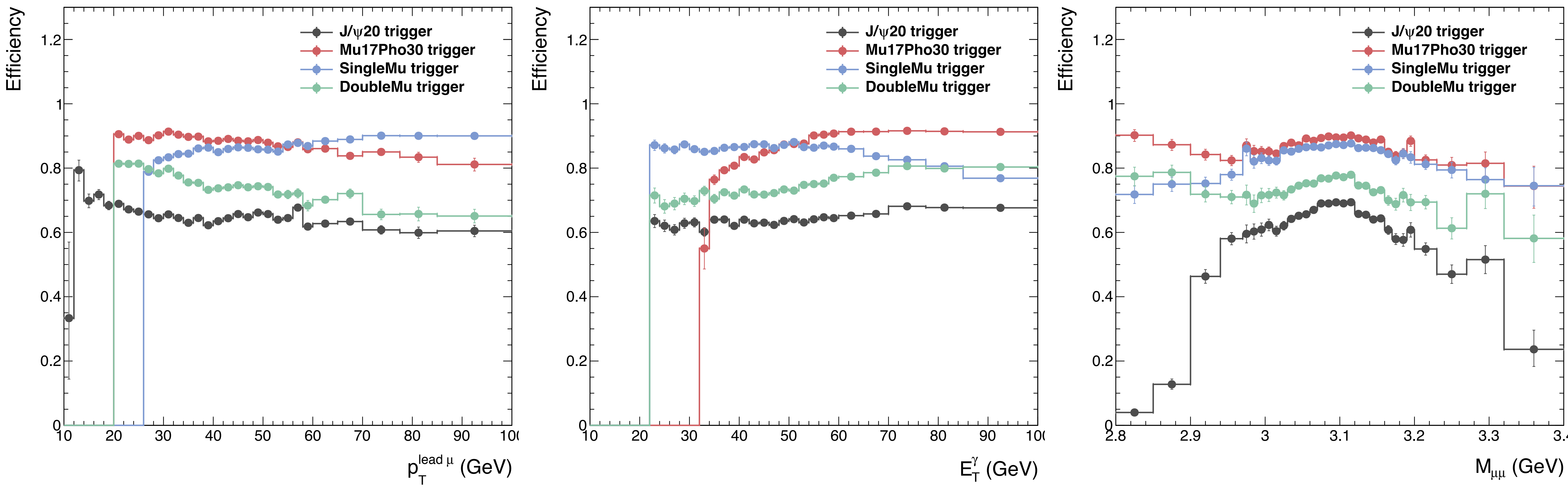
The distribution of the number of additional interactions per event in the simulation corresponds to that observed in the 13 TeV data collected in 2016.

Ref: CMS luminosity

Choice of the trigger

- Look at the efficiencies in signal events (Higgs channel) with different triggers

- The Muon-photon trigger seems to the best choice

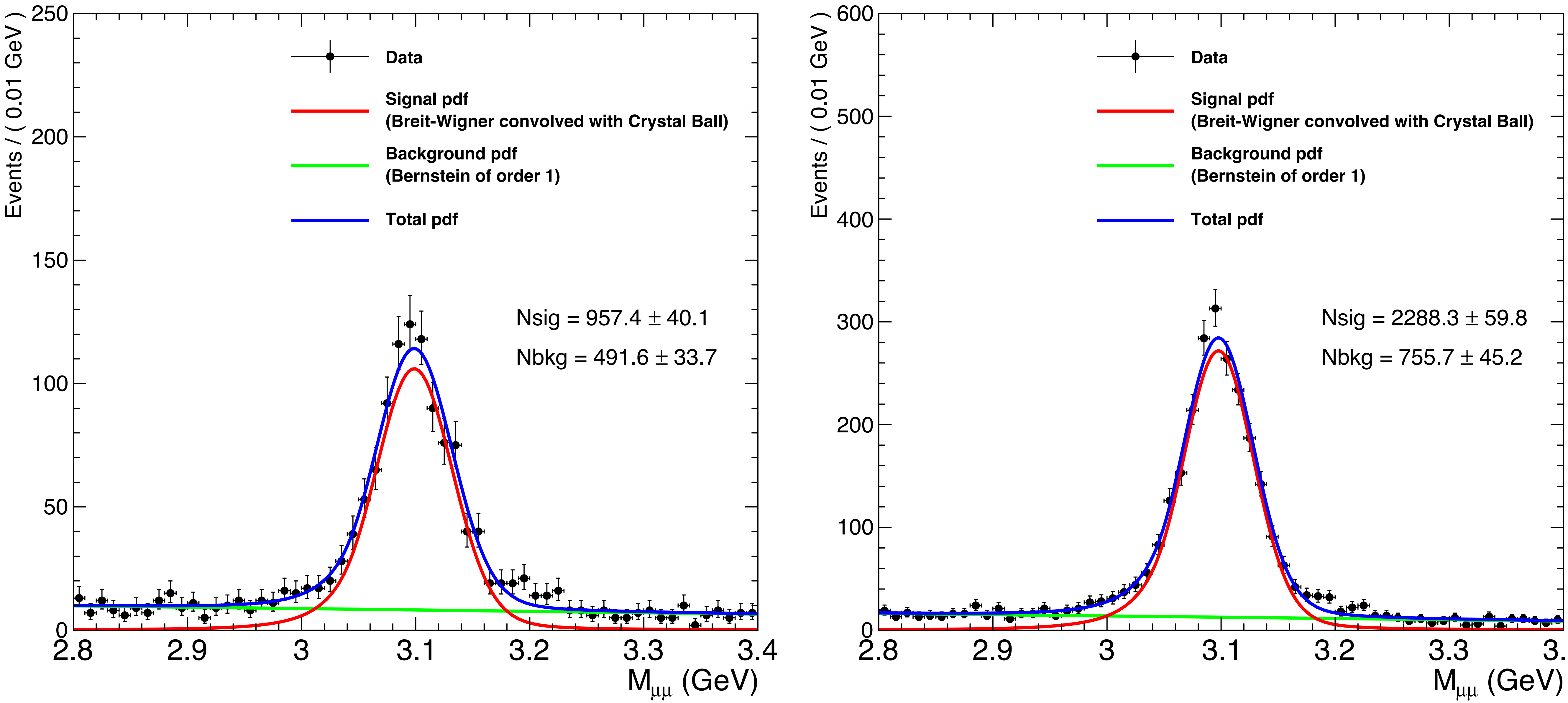


Muon ID

- Is Global muon or Tracker muon
- Impact parameter : $|d_{xy}| < 0.5$ cm, $|d_z| < 1$ cm, muSIP < 4
- Muon matched to at least one muon station
- Muon only reconstructed as Standalone muon are rejected
- For muons with $p_T > 200$ GeV
    - Is Tracker muon & matched to at least two muon station
    - $|d_{xy}| < 0.2$ cm, $|d_z| < 0.5$ cm
    - Number of valid pixel hits > 0 & Tracker hits > 5
    - $p_T / \sigma_{p_T} < 3$ (good p_T measurement)
- <u>After the full selection, there is no event with leading muon p_T greater than 200 GeV in both Z and Higgs channels</u>

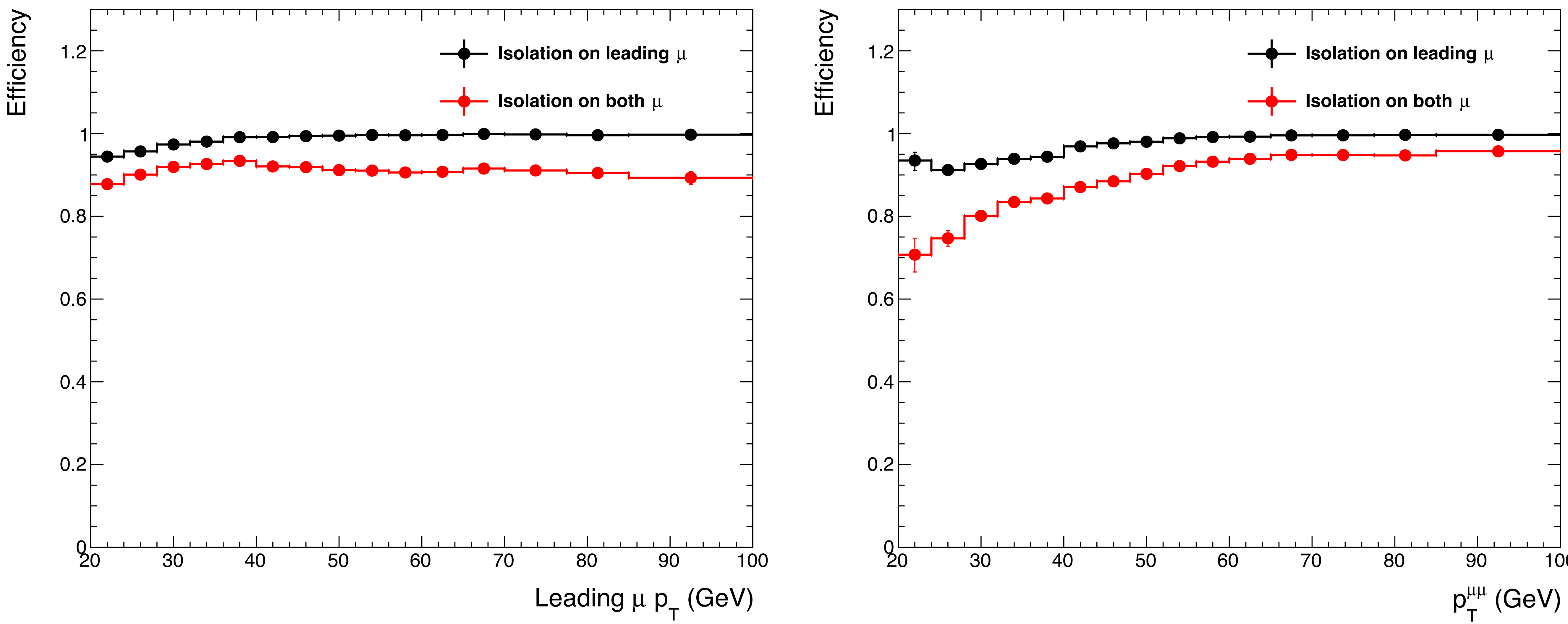
Muon isolation

- Lots of events from QCD background can be removed by applying the isolation. (the J/ψ in the distributions are from QCD events rather than from actual signal)
- Whether the isolation is applied has negligible impact on the expected signal yield



Muon isolation efficiency

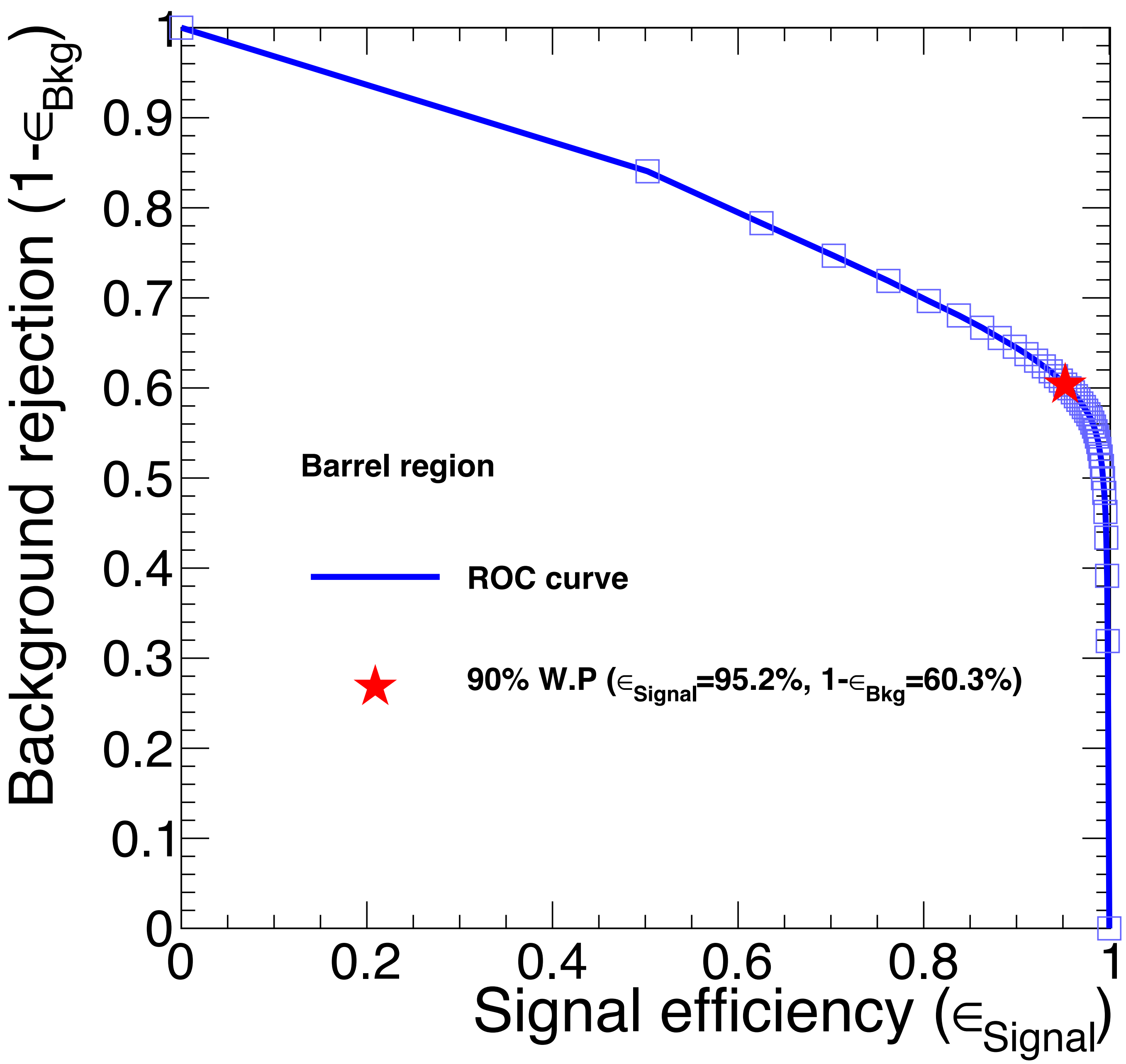
eff. = # of events passing all selections / # of events passing all selections without isolation

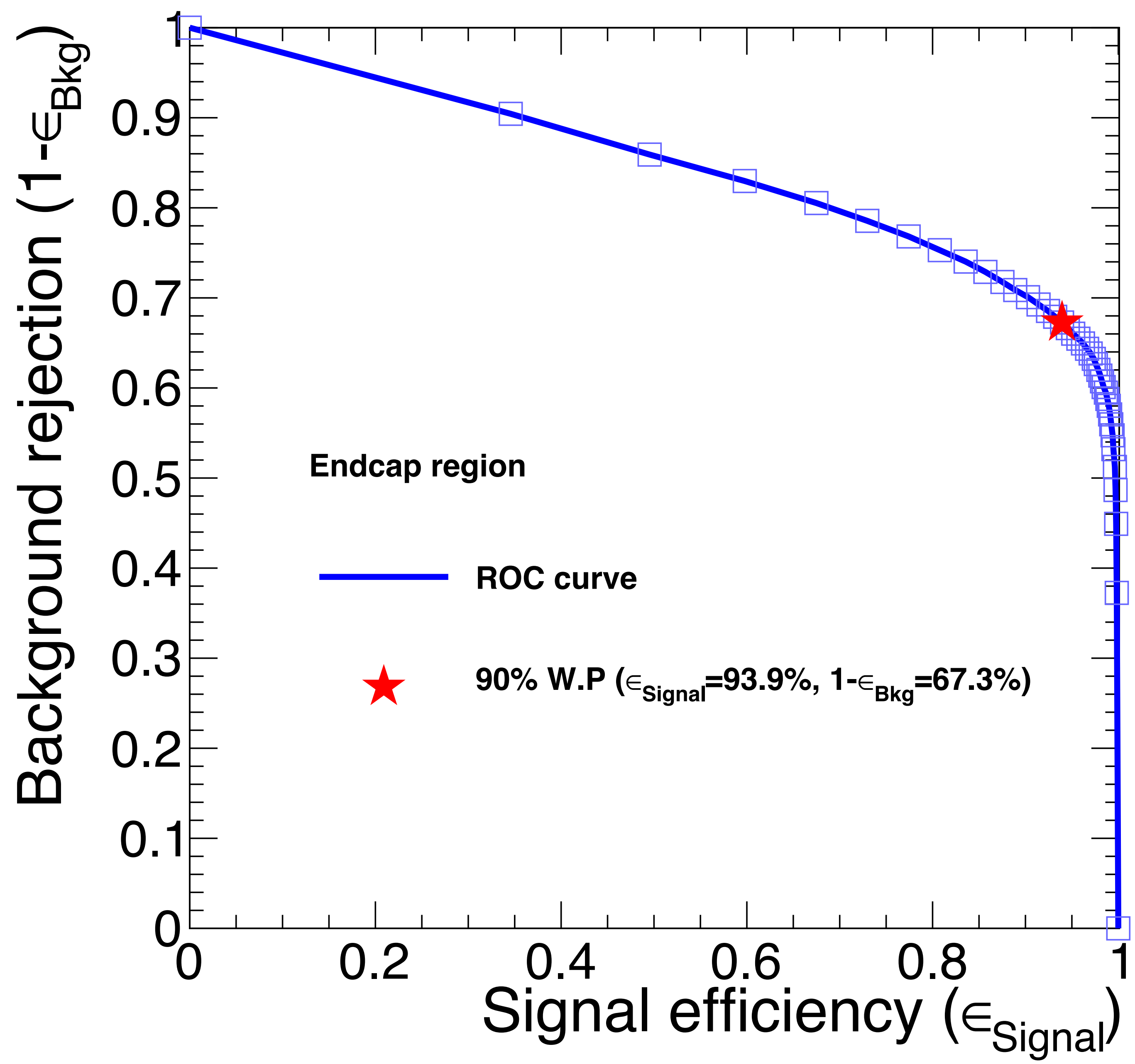


Applying isolation on trailing muon will reduce the signal efficiency

photon MVA ID

Treat photons in data as background



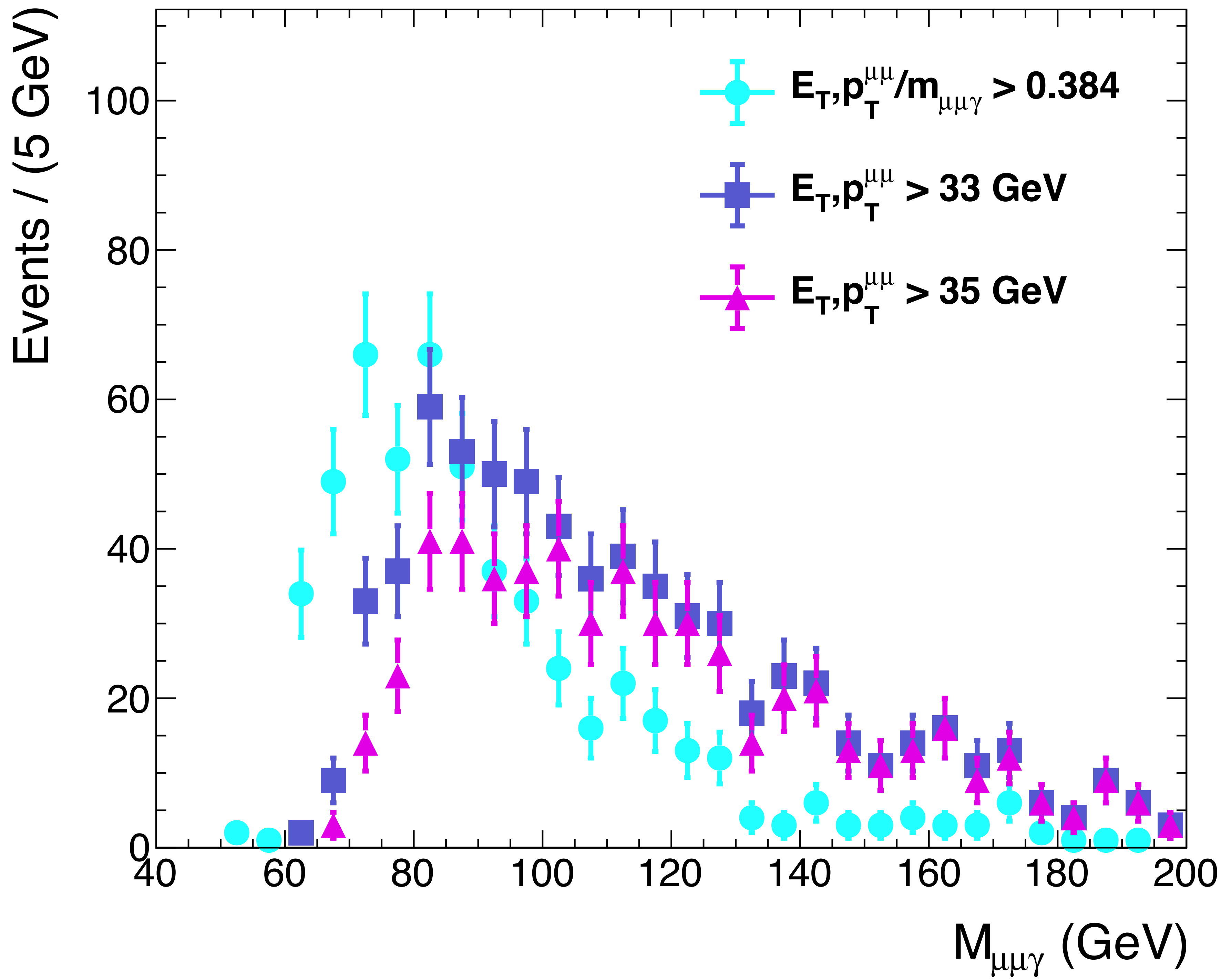


Fake photon estimation

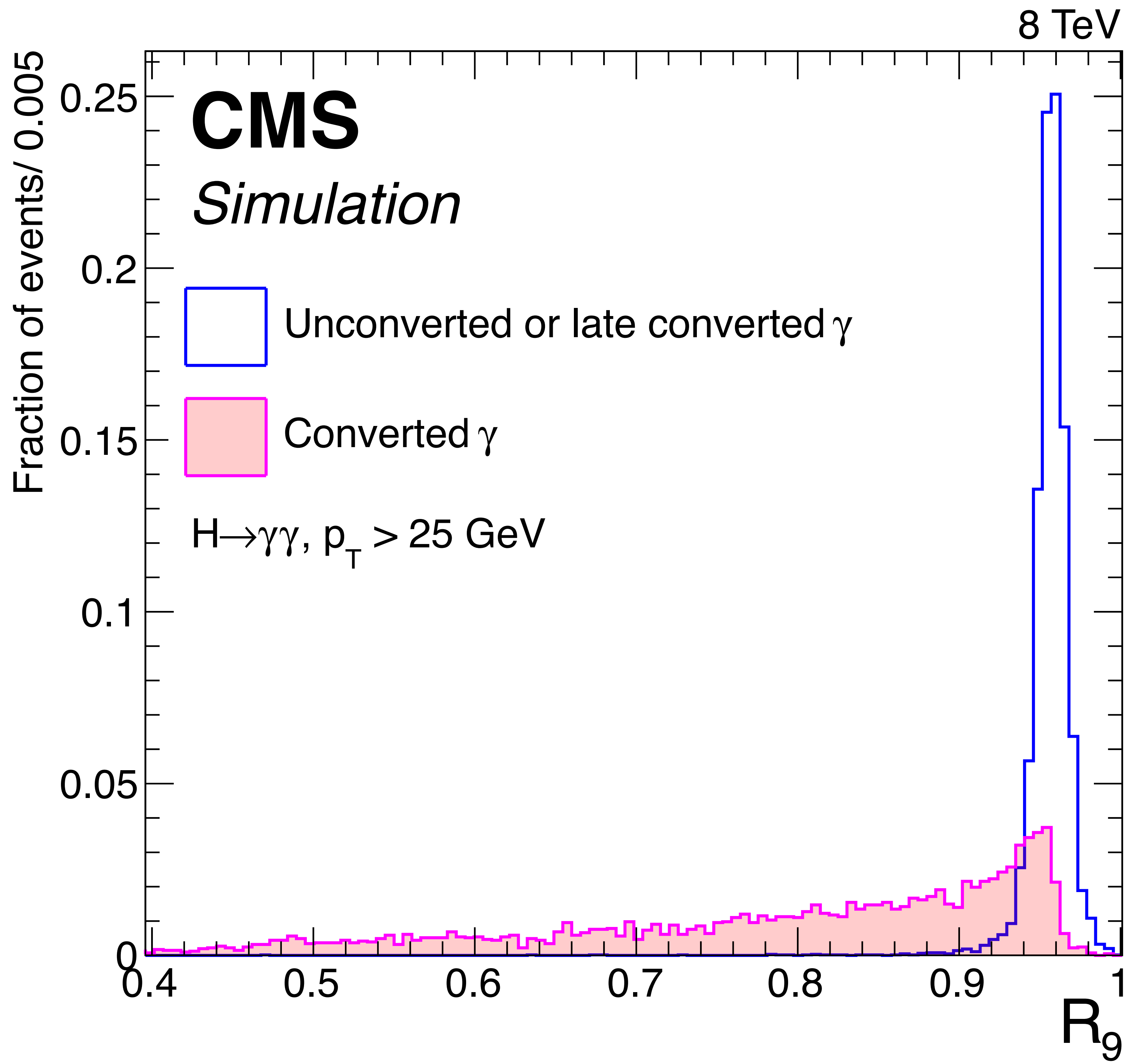
- We do not have proper background samples to estimate the contamination
- Alternatively, we use SM Zγ and Z+jets events to check the ratio Z+jets/Zγ
  - The yields are calculated by requiring ID selections used in this analysis and $\Delta R(\mu,\gamma) > 1.0$

photon E_T	Z+jets/Zγ (in %)
33~40	30
40~50	28
50~60	22
60~80	21

Ratio cuts v.s hard cuts



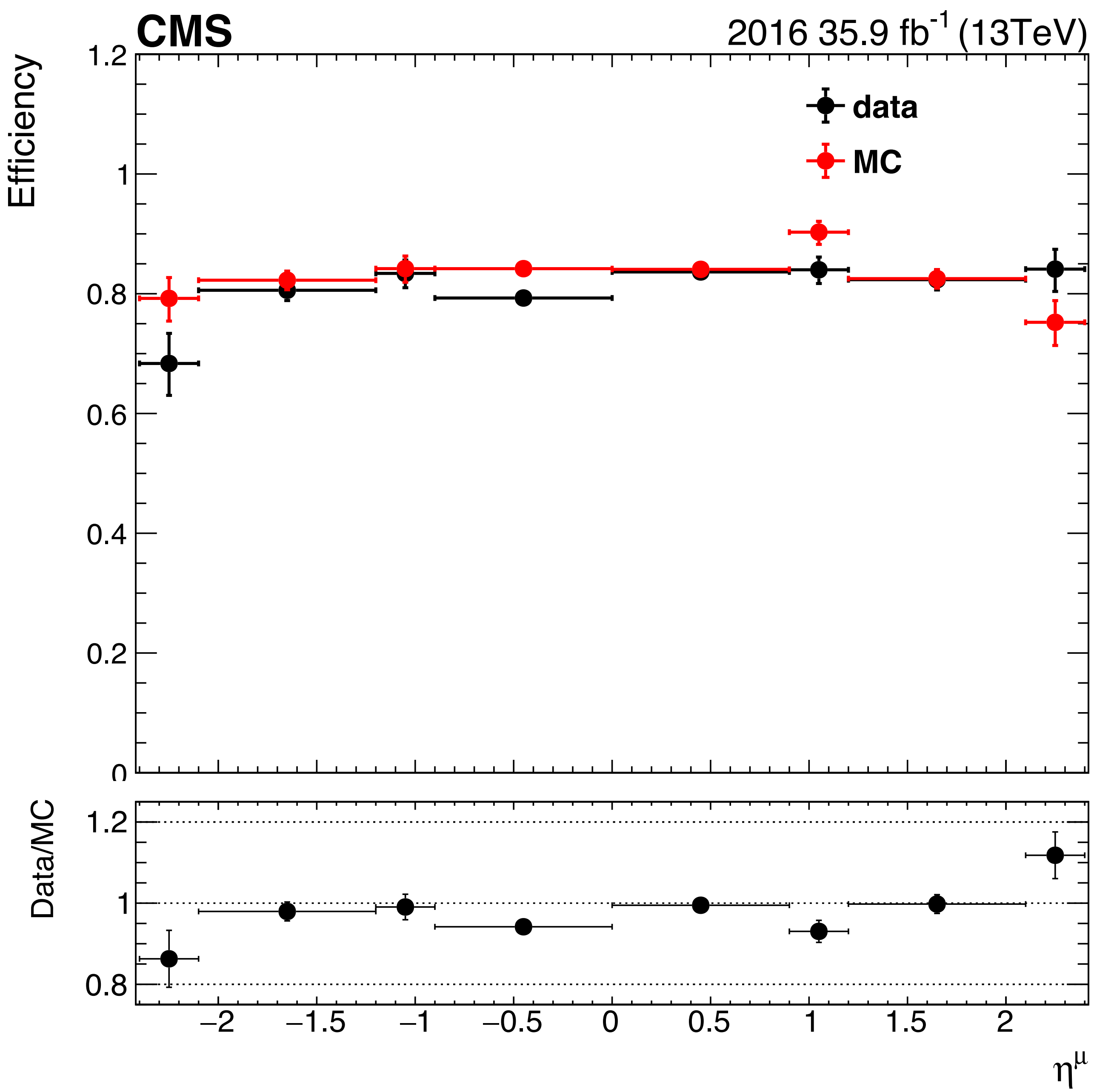
photon R_9 variable



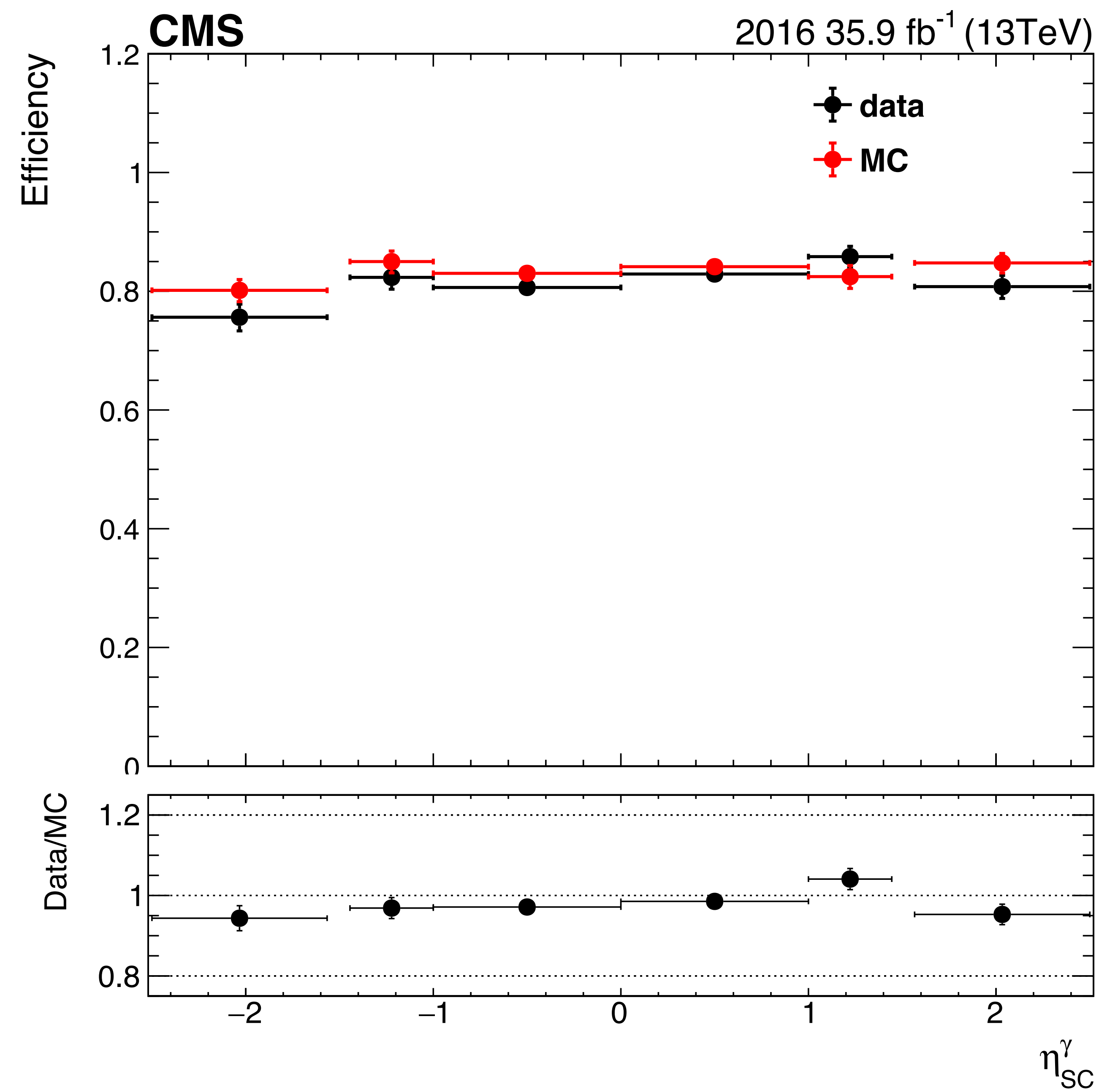
back

Trigger efficiency

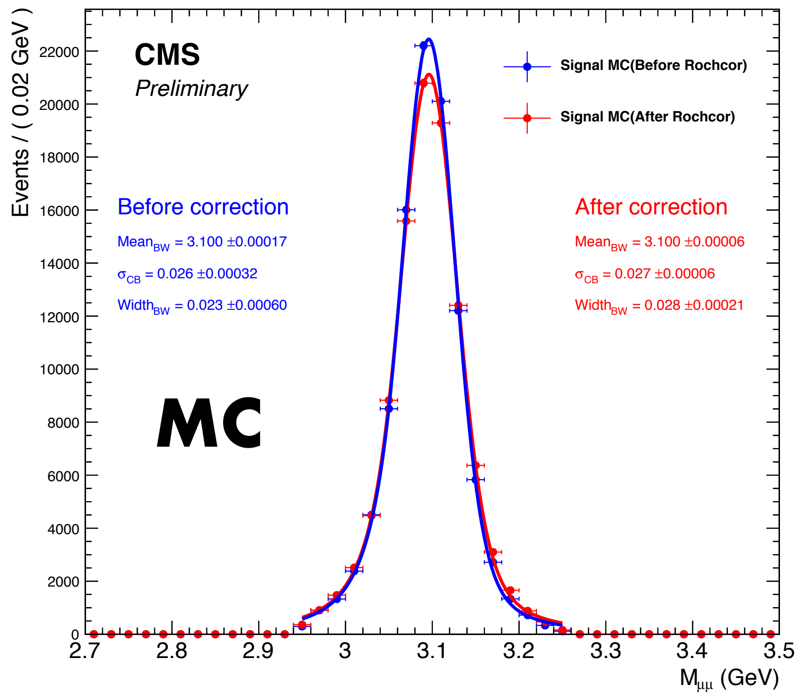
eff. vs η^{μ}

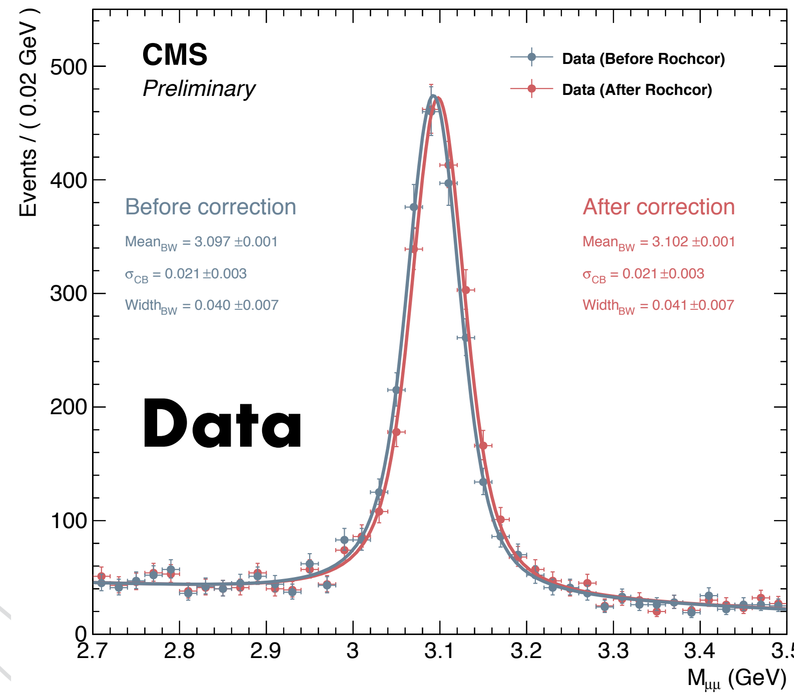


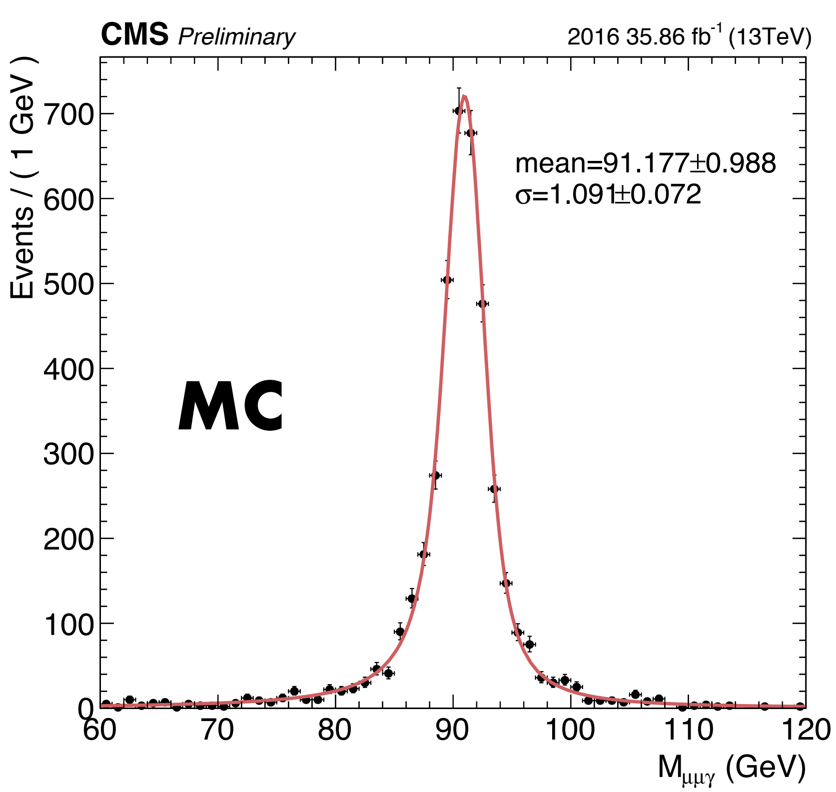
eff. vs η_{SC}^{γ}

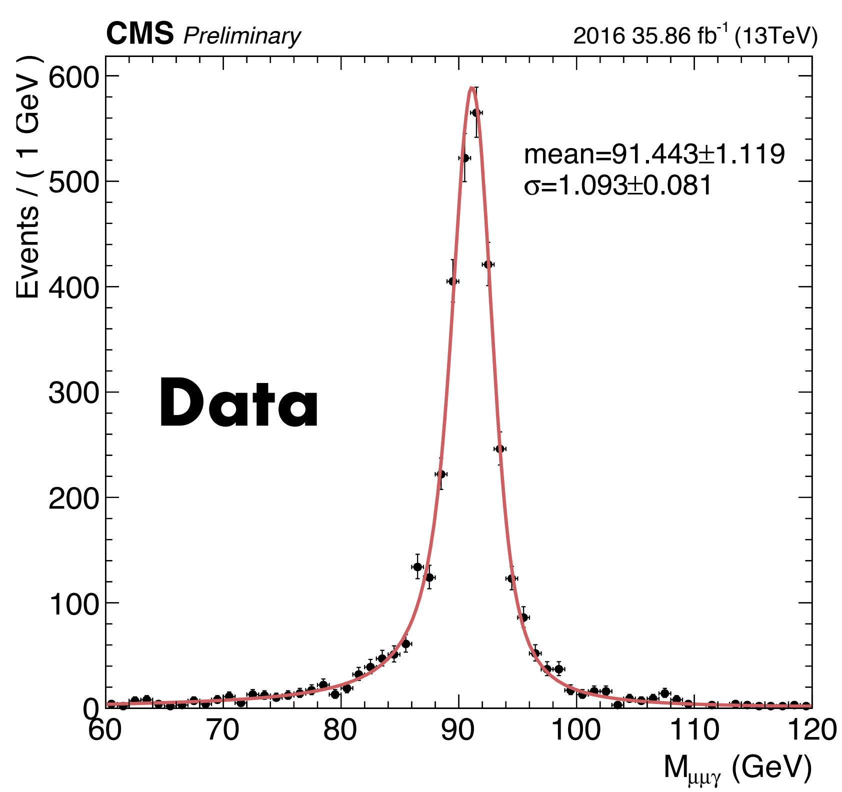


Validation on the object corrections









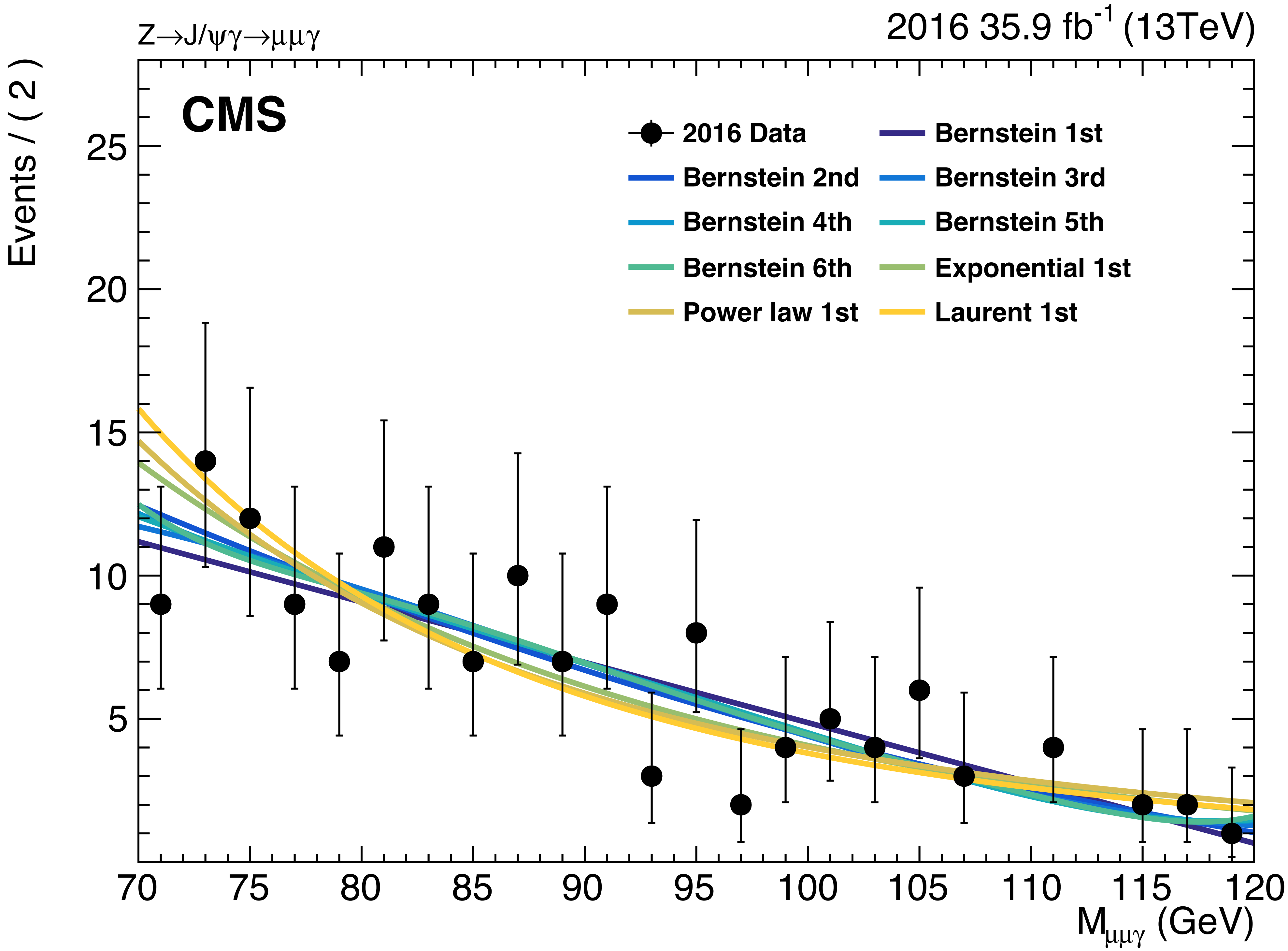
- Control samples are used to validate the object corrections.
- Good agreement in scale and resolution between data and MC.

Background model

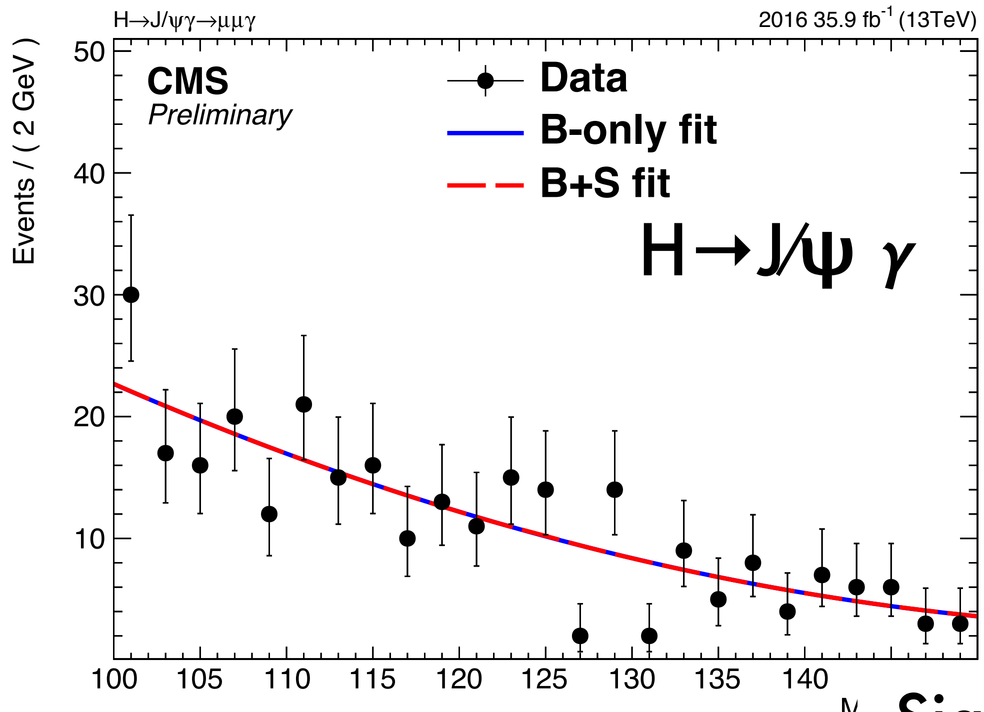
- 4 families of functions are considered :
  - **Bernstein polynomial**
  - **A sum of N exponential functions** : $\sum_{i=1}^{N} f_i e^{p_i m_{mmg}}$
  - **A sum of N power-law functions** : $\sum_{i=1}^{N} f_i m_{mmg}^{\ p_i}$
  - **Laurent polynomials**
    - 2 terms : $f_1(m_{mmg})^{-4} + f_2(m_{mmg})^{-5}$
    - 3 terms : $f_1(m_{mmg})^{-3} + f_2(m_{mmg})^{-4} + f_3(m_{mmg})^{-5}$
    - 4 terms : $f_1(m_{mmg})^{-3} + f_2(m_{mmg})^{-4} + f_3(m_{mmg})^{-5} + f_4(m_{mmg})^{-6}$

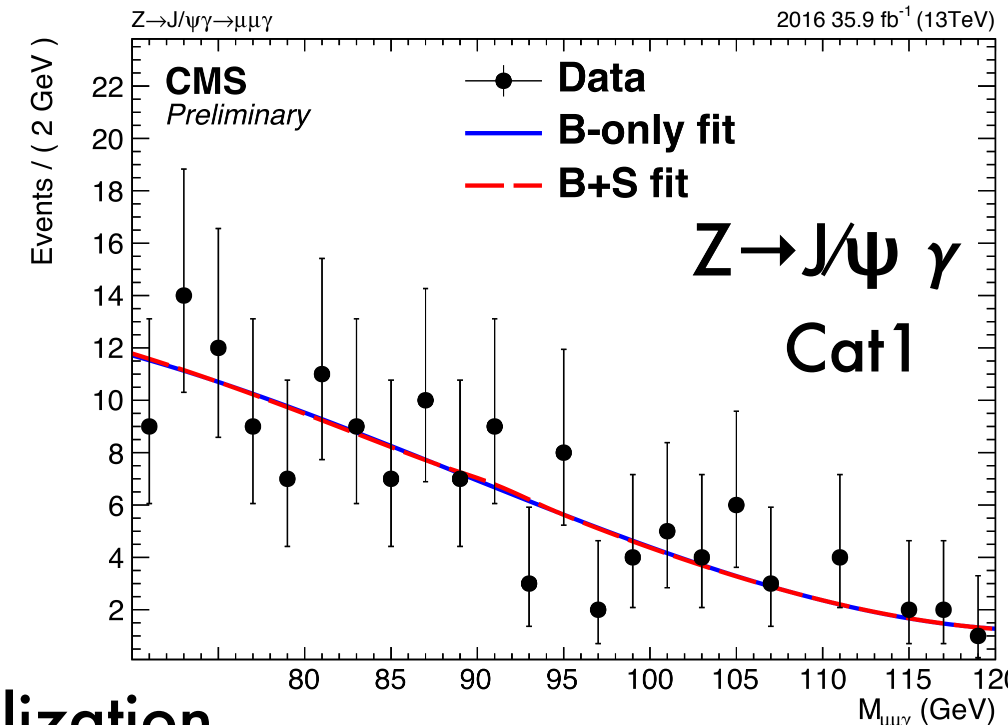
back

Background model

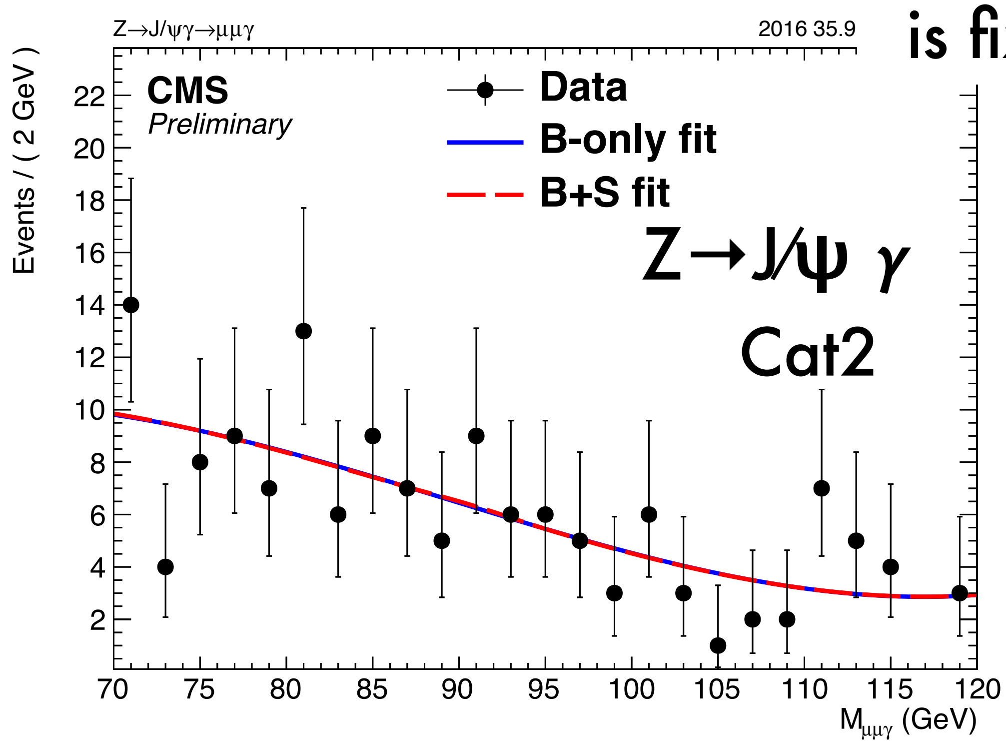


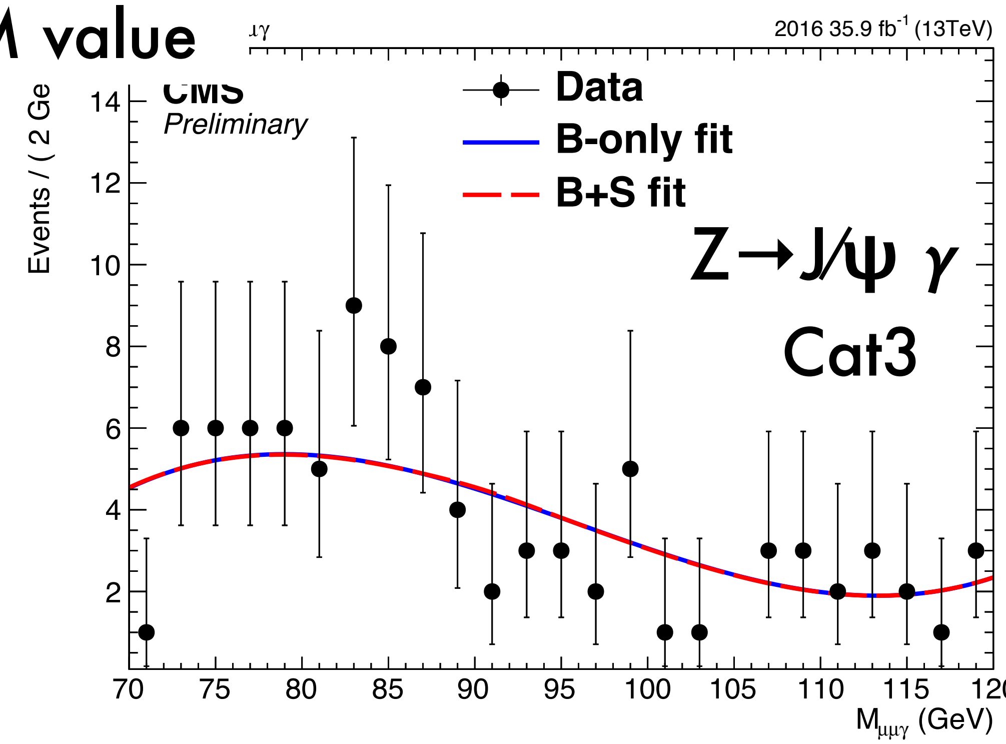
Signal+background fit



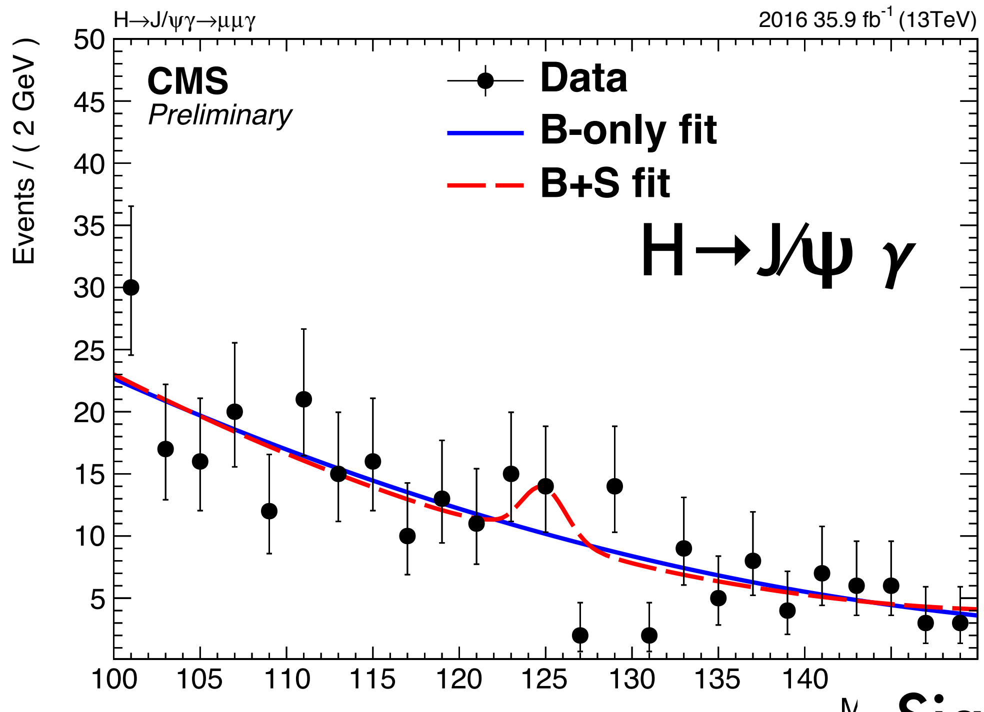


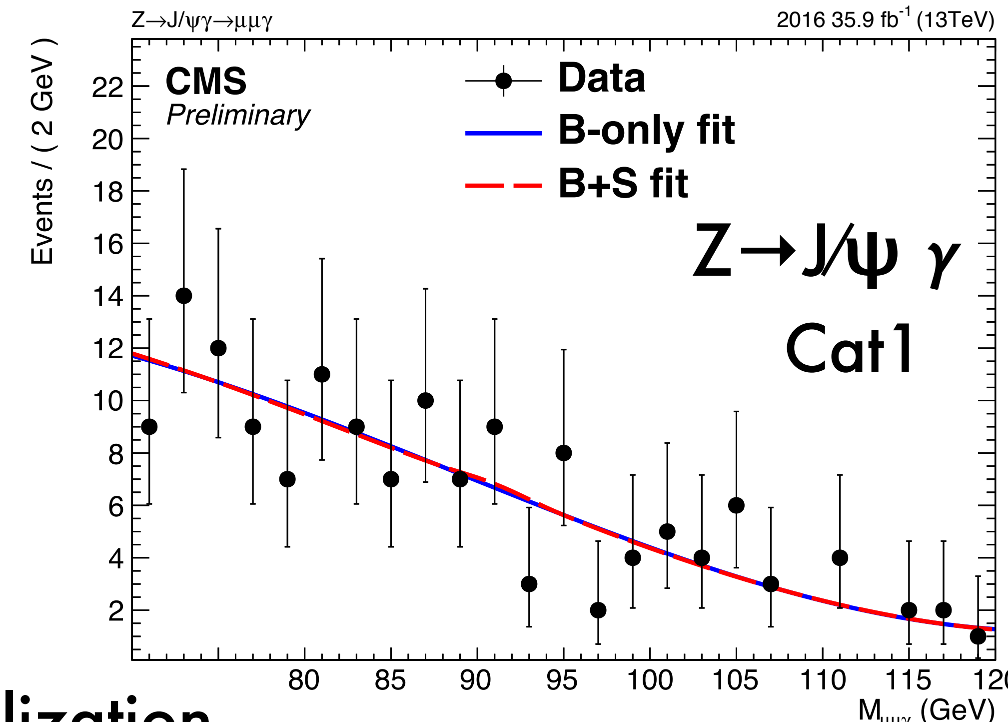
Signal normalization
is fixed to SM value



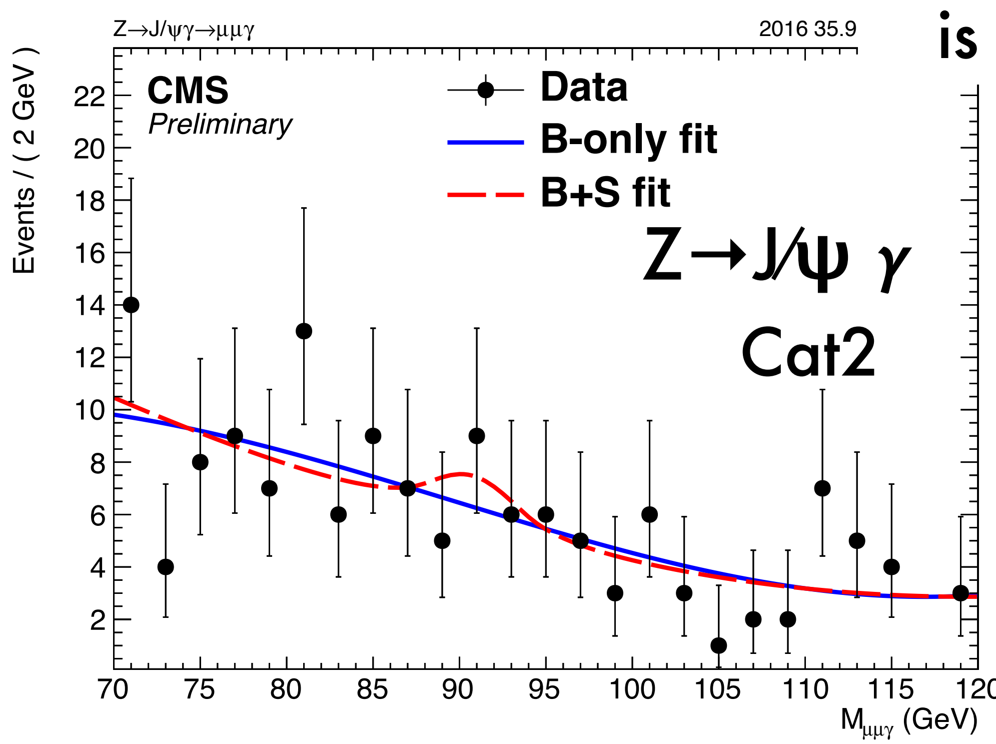


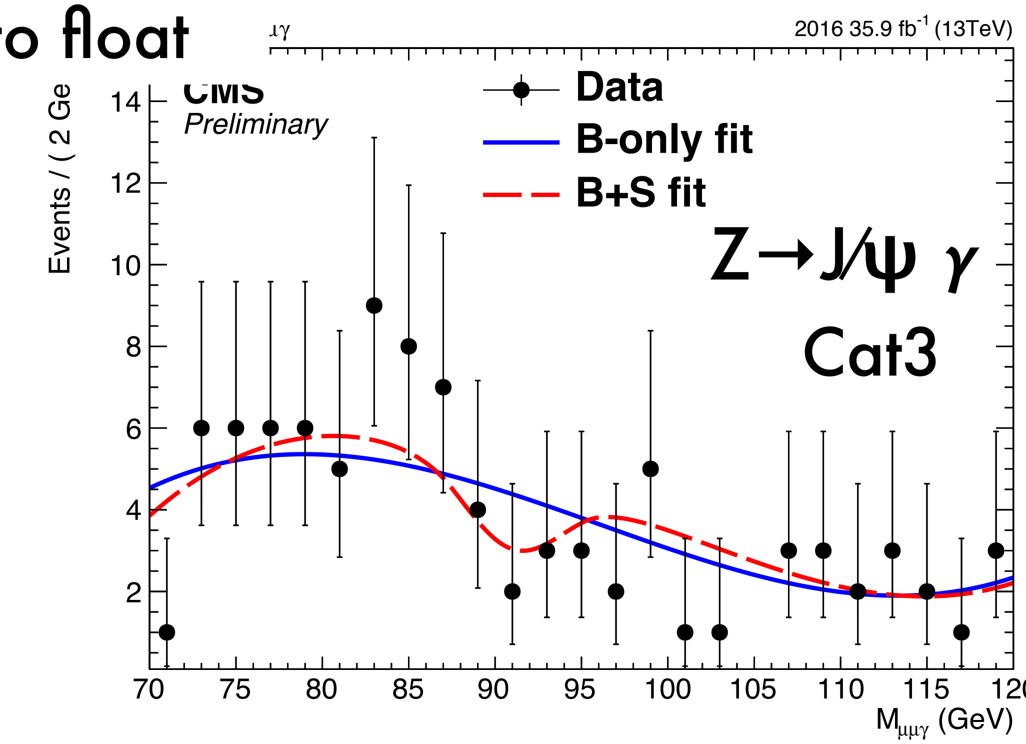
Signal+background fit



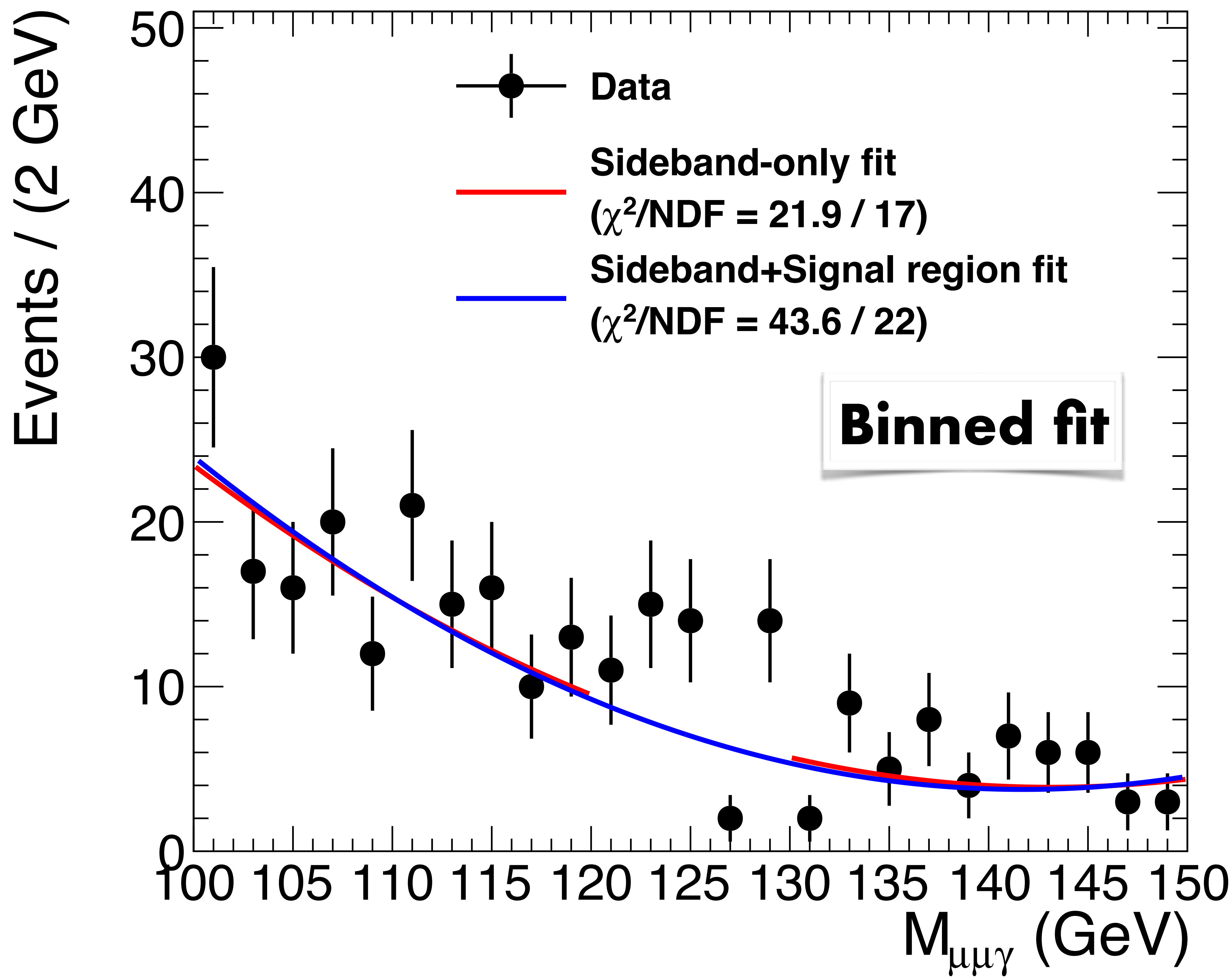


Signal normalization is allowed to float

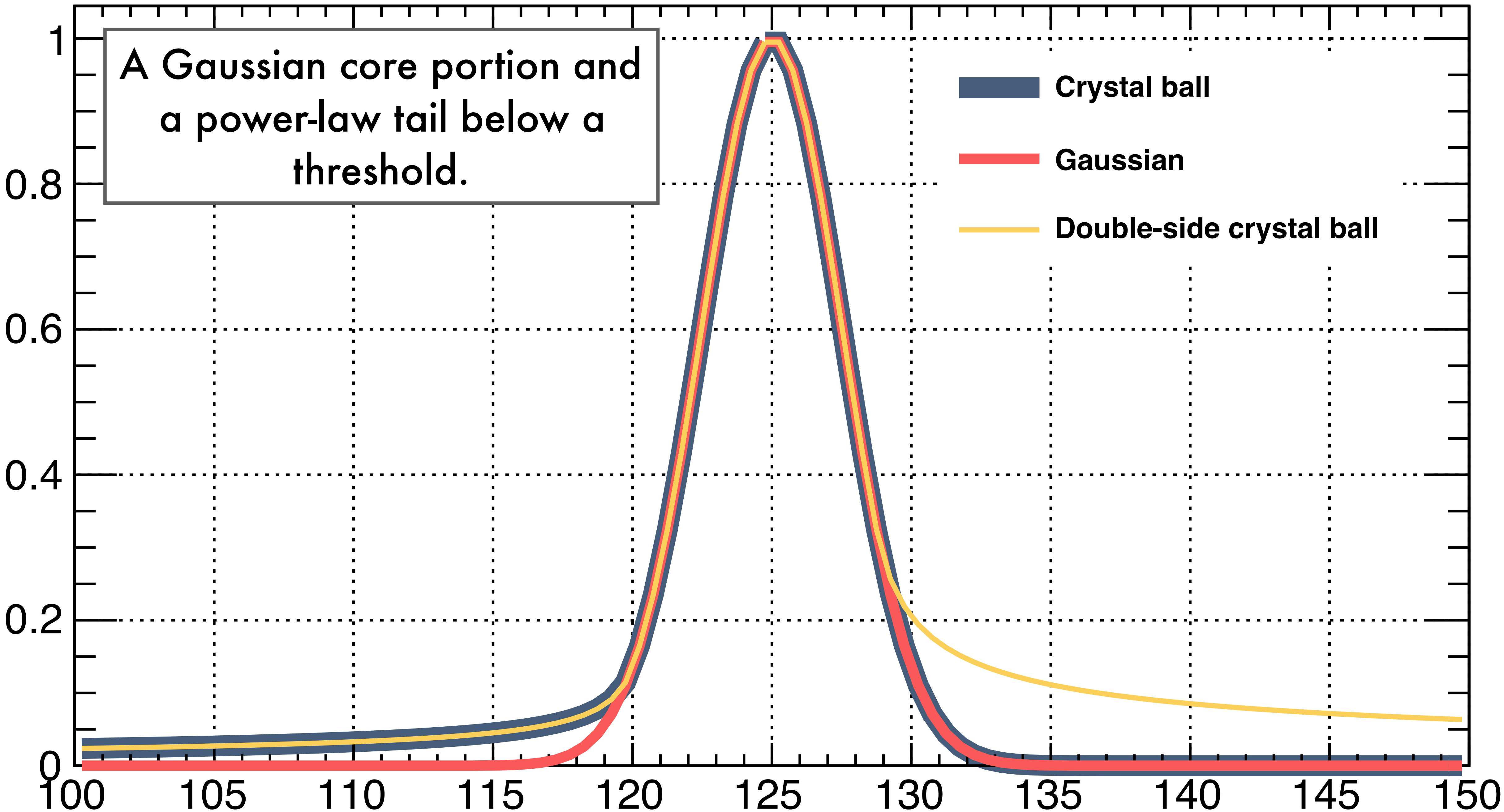




Sideband-only fit



Crystal Ball function



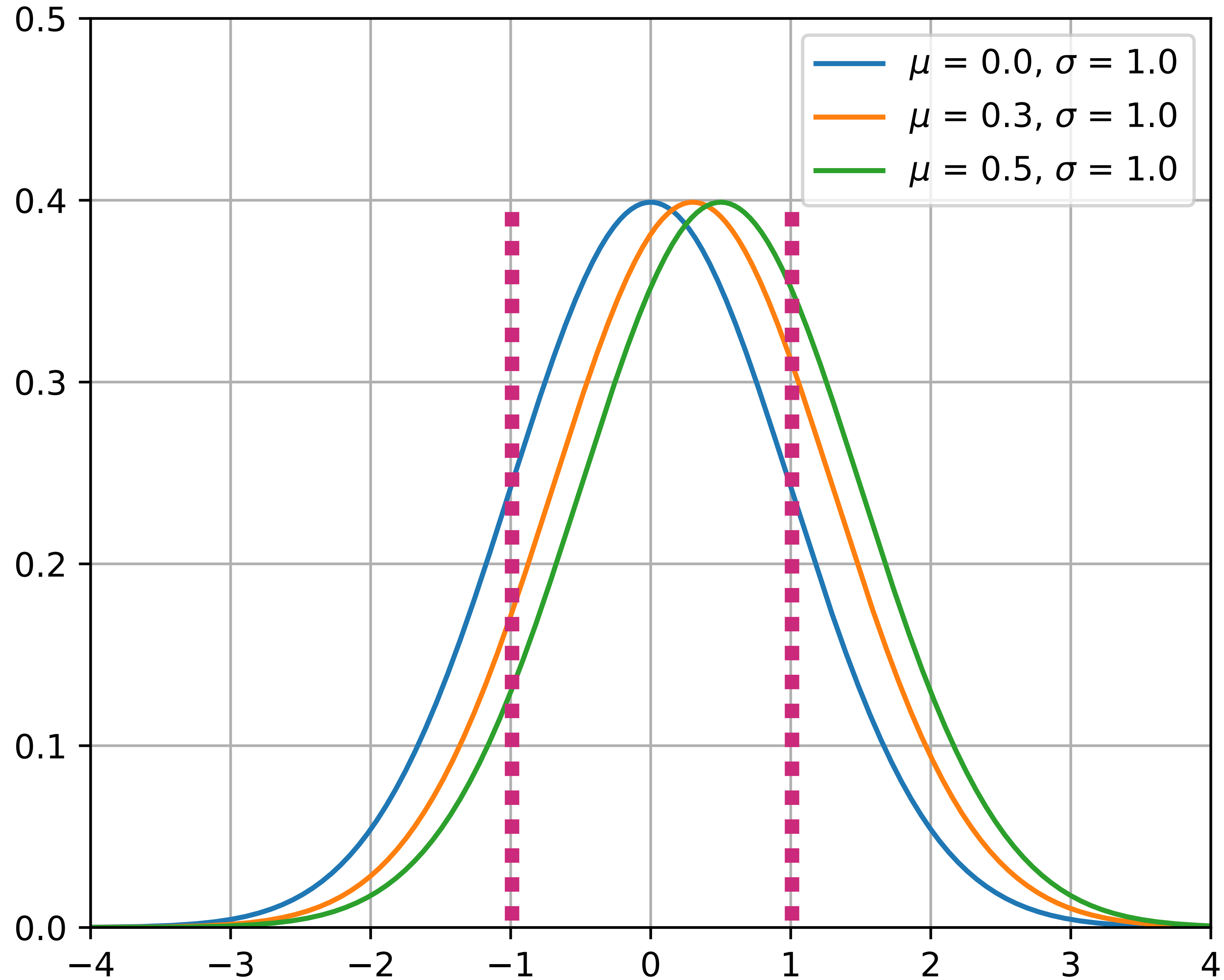
back

Bias requirement

The content of this slide is referenced from the study made by J.Bendavid

- A Gaussian with $\mu=0$ and $\sigma=1$
- Introduce a bias b, then the experiments are distributed as a Gaussian with $\mu=b$ and $\sigma = 1$ (orange & green)
- Frequentist coverage

  The fraction of experiments in which the true value is contained within the confidence interval (say, 68.3% for one sigma confidence intervals)

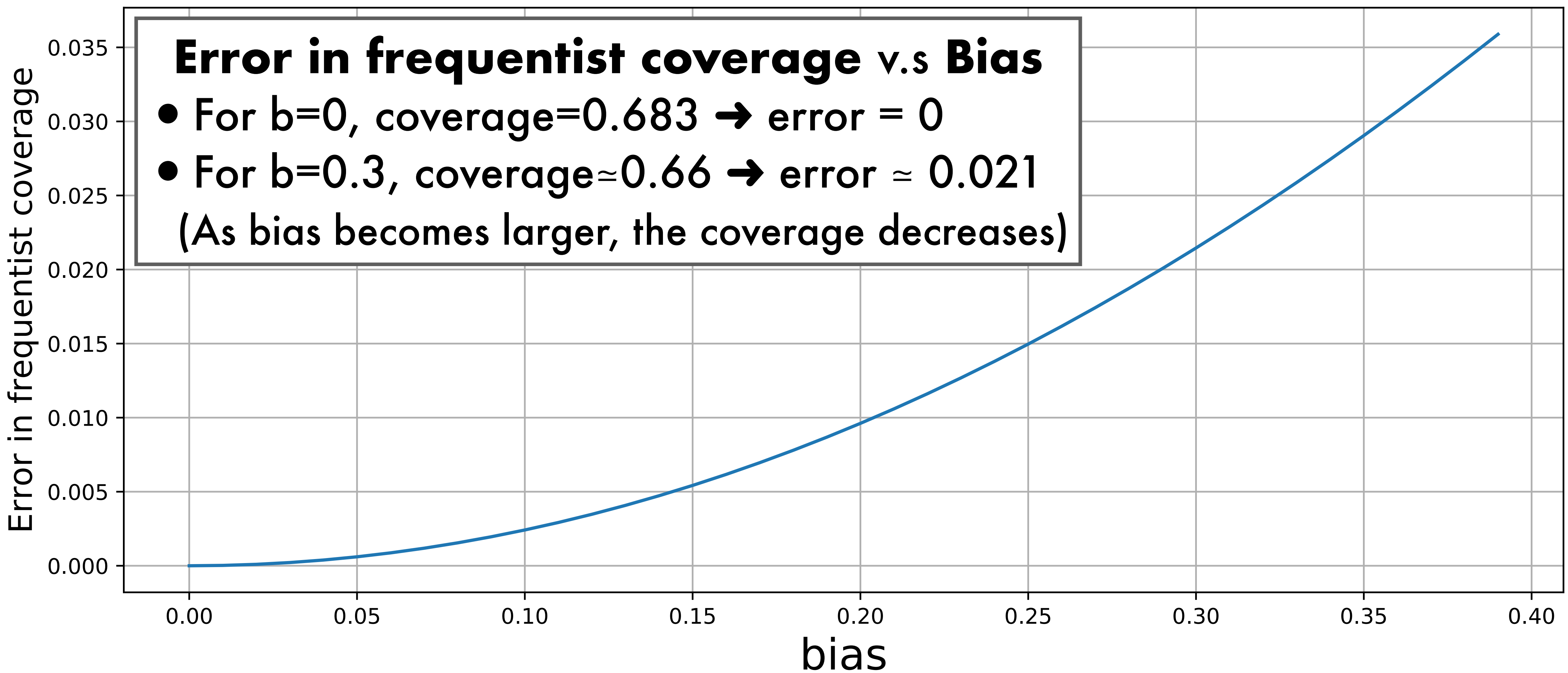


Bias requirement

The content of this slide is referenced from the study made by J.Bendavid

- The coverage is calculated as

$$\textbf{Coverage} = \frac{1}{2}\left[\textbf{erf}\left(\frac{1-b}{\sqrt{2}}\right) - \textbf{erf}\left(\frac{-1-b}{\sqrt{2}}\right)\right]$$

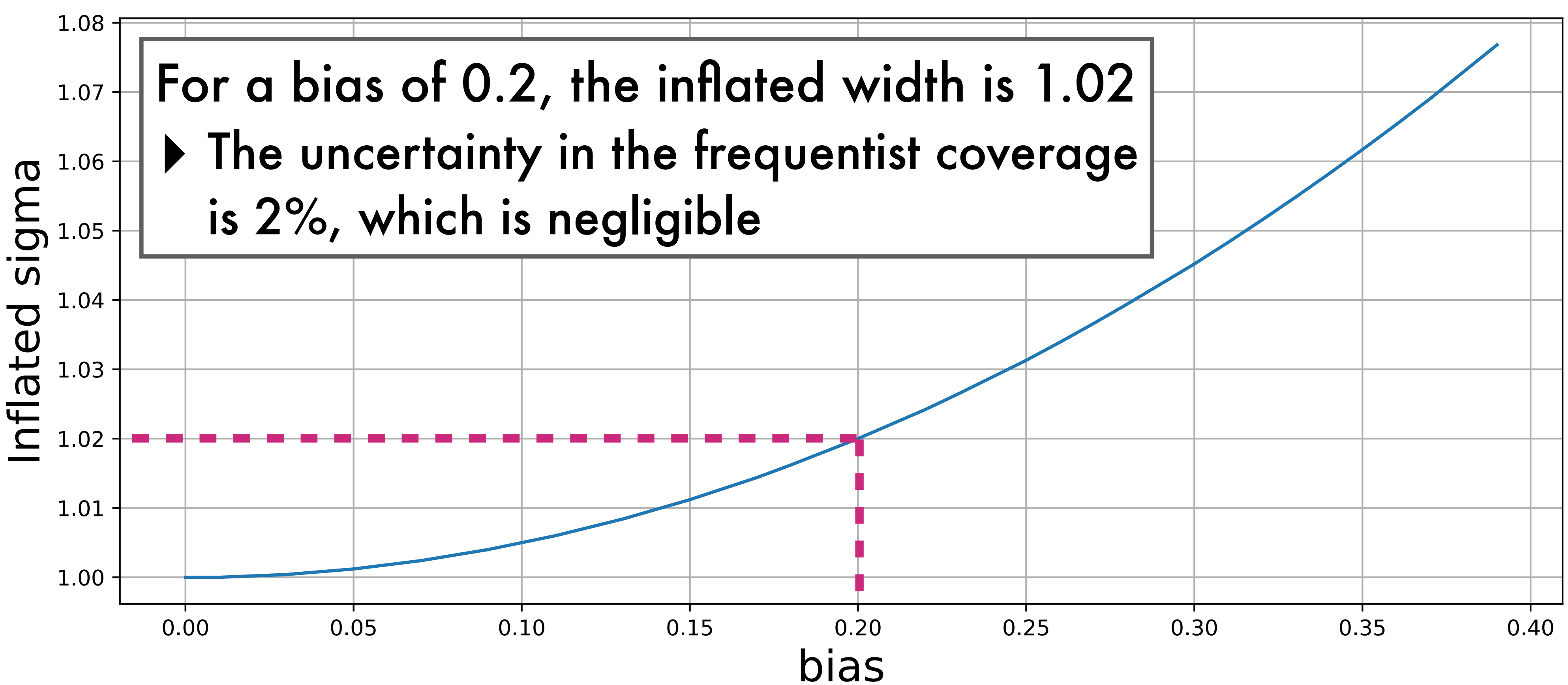


Bias requirement

The content of this slide is referenced from the study made by J.Bendavid

- Inflate the width of the original Gaussian (or, the quoted uncertainty) to maintain the coverage in the presence of bias
- The needed inflation can be derived by solving the equation

$$\mathbf{erf}\left(\frac{1}{\sqrt{2}}\right) - \frac{1}{2}\left[\mathbf{erf}\left(\frac{1-b}{\sqrt{2}}\right) - \mathbf{erf}\left(\frac{-1-b}{\sqrt{2}}\right)\right] = 0$$



Estimation on ψ(2S) feed down

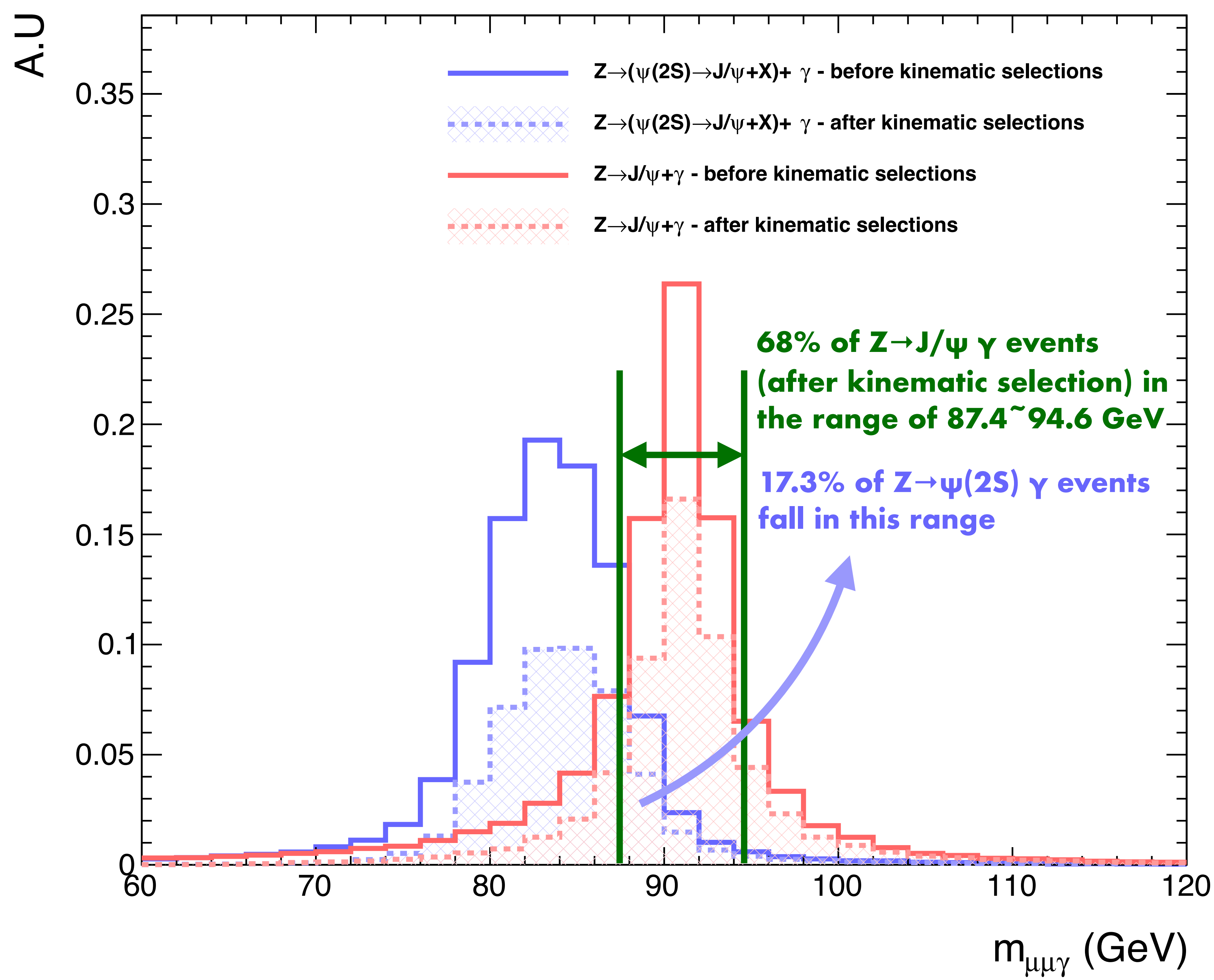
- The decay $\psi(2S) \to J/\psi(\to \mu\mu) + X$ contributes as a background source
- Assume the $\dfrac{N(Z \to J/\psi + \gamma)}{N(Z \to \psi(2S) + \gamma)} \simeq \dfrac{N(Z \to J/\psi + \ell\ell)}{N(Z \to \psi(2S) + \ell\ell)} = 3.5$

(currently there is no theoretical reference for the decay $Z \to \psi(2S) + \gamma$)

$$\frac{N(Z \to J/\psi + \gamma)}{N(Z \to \psi(2S) + \gamma[\to J/\psi(\to \mu\mu) + X])} \simeq \frac{N(Z \to J/\psi + \ell\ell)}{N(Z \to \psi(2S) + \ell\ell[\to J/\psi(\to \mu\mu) + X])} = \mathbf{5.7}$$

- We then expect to have 1.27/5.7 ≃ 0.22 from the ψ(2S) (where the 1.27 is the expected yield of $Z \to J/\psi + \gamma$), which is to be compared with the total background, 384.
  - We consider the ψ(2S) contribution negligible. Furthermore, this source of background will be taken into account in the continuum background fit. No additional uncertainty is quoted.

Estimation on ψ(2S) feed down



Evaluation of the likelihood

- The unbinned likelihood function

$$L(\text{data}|\mu, \theta) = \text{Poisson}\big(\text{data}|\mu\cdot s(\theta)+b(\theta)\big) \cdot p(\tilde{\theta}|\theta)$$

$$= k^{-1}\Big[\ \prod_i (\mu S f_s(x_i)+B f_b(x_i)\ \Big] \cdot e^{-(\mu s_i+b_i)}$$

data	actual experimental observation or pseudo-data
k	number of events in the data sample
μ	signal strength modifier
θ	the full set of nuisance parameters
Poisson(data|$\mu\cdot s+b$)	unbinned likelihood over k events in the data sample
$f_s(x)$, $f_b(x)$	pdfs of signal and background of some observable(s) x
S, B	total event rates expected for signal and backgrounds

Profile likelihood ratio

- The test statistic used in LHC analyses is the profile likelihood ratio

$$\tilde{q}_\mu = -2\ln\Big(L(\text{data}\,|\,\mu, \hat{\theta}_\mu)/L(\text{data}\,|\,\hat{\mu}, \hat{\theta})\Big),\ 0 \le \hat{\mu} \le \mu$$

$\hat{\theta}_\mu$	conditional maximum likelihood, given the signal strength μ
$\hat{\mu}$, $\hat{\theta}$	the estimates corresponding to the global maximum of the likelihood
$0 \le \hat{\mu}$	signal rate is positive
$\hat{\mu} \le \mu$	upward fluctuation of the data such that $\hat{\mu} > \mu$ are not considered as evidence against the signal hypothesis with a signal strength μ

Ref: ATL-PHYS-PUB-2011-11