Study of Higgs and Z boson decaying into J/ψ + γ in pp collisions at √s=13TeV

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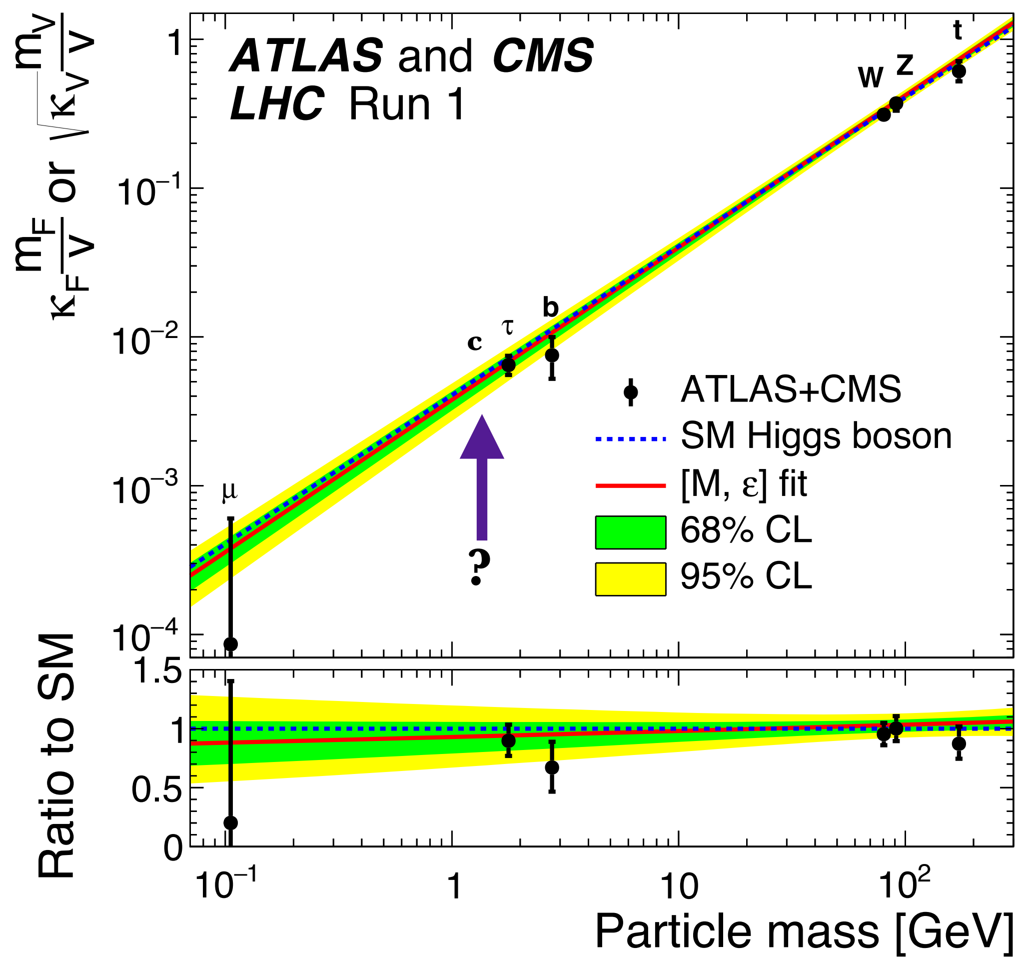
Content

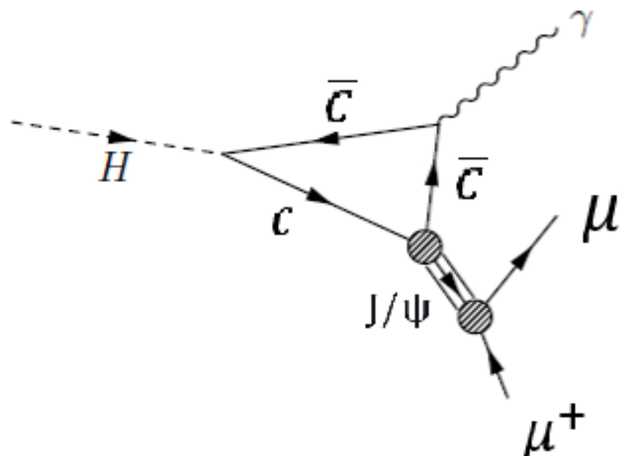
- Introduction
- Previous results from ATLAS and CMS
- Analysis strategy
  I. Data & simulation(Monte-Carlo) samples
  II. Trigger, object reconstruction & identification
  III. Signal & background modeling
  IV. Limits
- Summary
- Prospect & outlook

Introduction - H→(J/ψ)γ

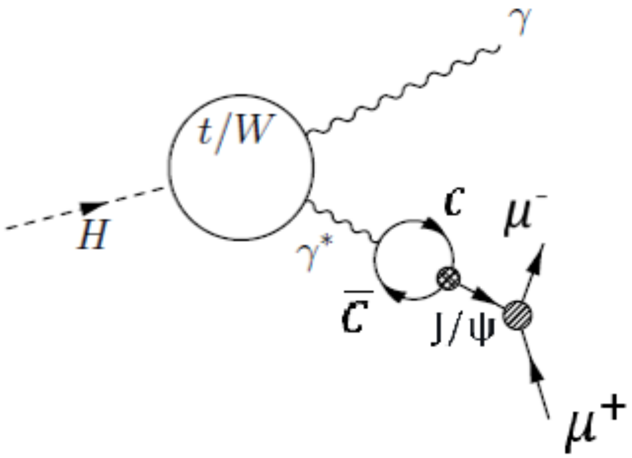
- Rare decay of Higgs (BR=2.8×10^{-6}) ⇒ Sensitive to BSM (Beyond the Standard Model)
- An alternative probe of the light-quark Yukawa couplings (H-c coupling) rather than direct search of H→c$\bar{c}$, which is more challenging in LHC



JHEP08(2016)045



Direct process - BR=5.48×10^{-8}



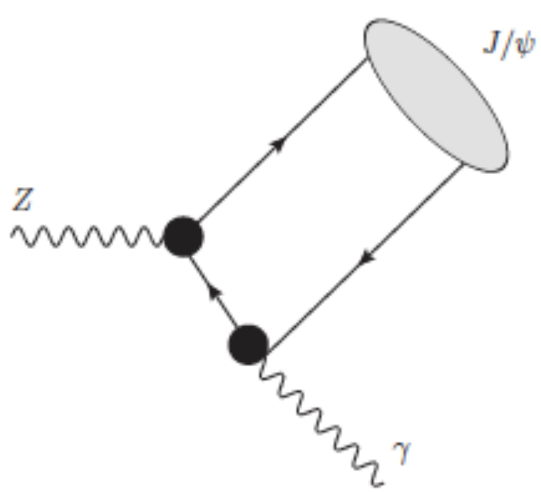
Indirect process - BR=3.25×10^{-6}

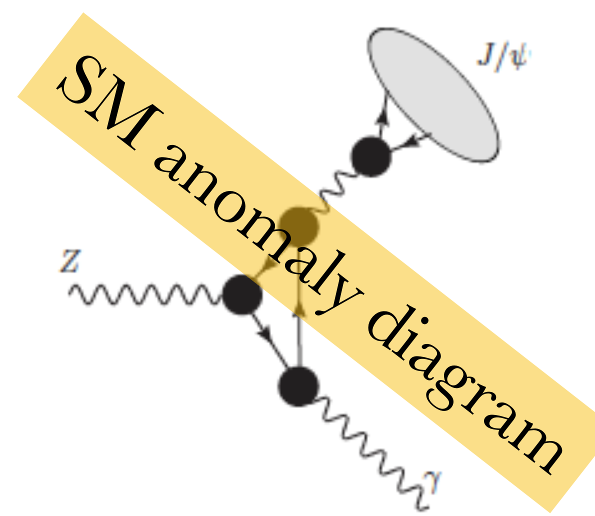
Interference

BR(H→(J/ψ)γ) = 2.79×10^{-6}

Introduction - $Z \to (J/\psi)\gamma$

- Standard model rare decay (BR=9.96×10^{-8}) ⇒ Also sensitive to BSM
  - Smaller BR than $H \to (J/\psi)\gamma$ but benefits from much larger cross-section
- Experimental benchmark for the Higgs decay
- Improve our understanding of the quarkonium production in hadronic collisions





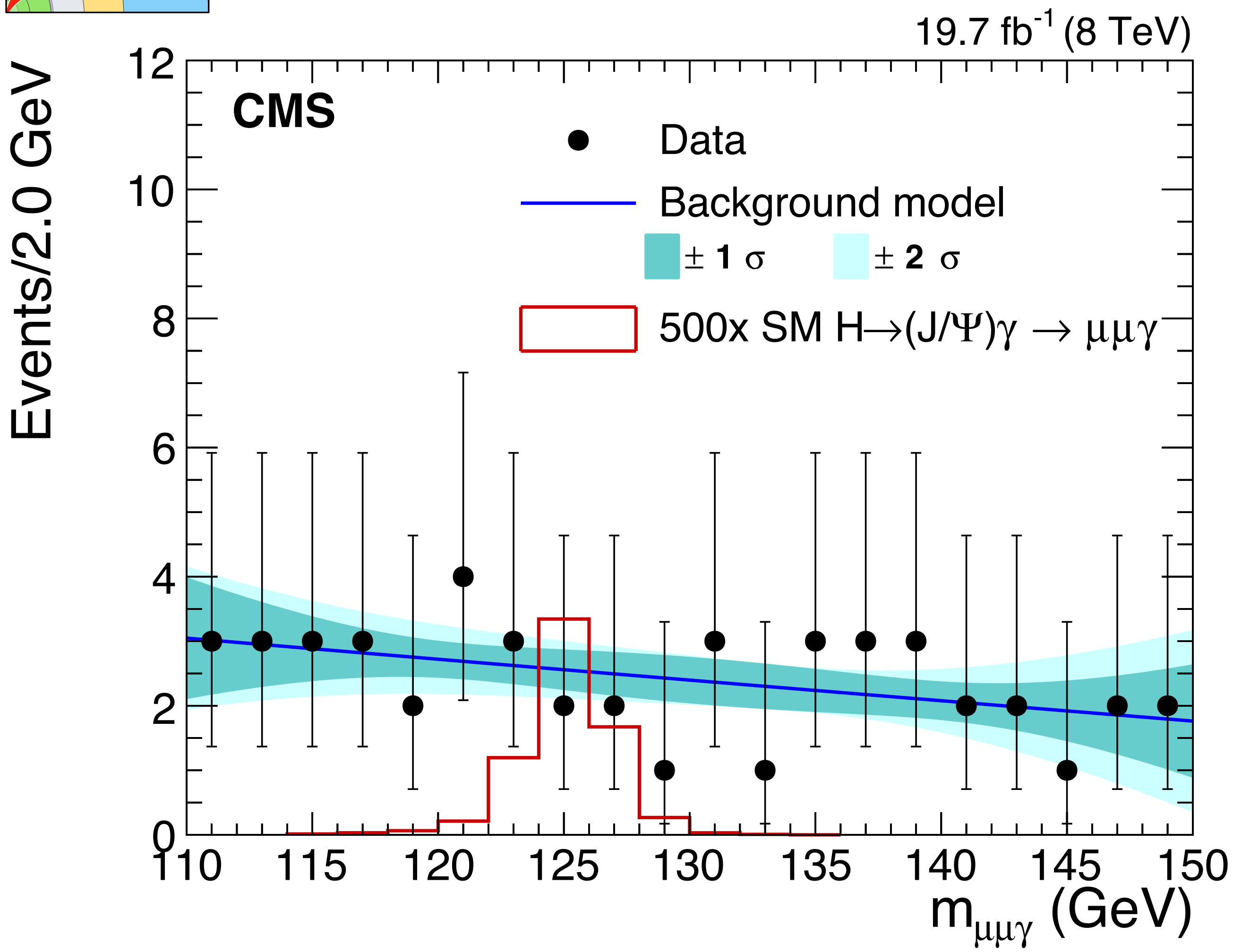
The suppression of indirect process & Destructive interference between 2 diagrams → The branching ratio is smaller than that of $H \to (J/\psi)\gamma$ by 1~2 order of magnitude

Introduction

Advantages	Disadvantages
‣ Distinguishable event signature ‣ High-E_T photon, which is back-to-back to di-muon system from a resonant state(J/ψ) ‣ The vertex where the muons and photon originate can be well defined. ‣ $Z \rightarrow J/\psi + \gamma$: Large production cross section of Z	‣ Muons from highly boosted J/ψ will be closed to each other in angle ‣ Dedicated strategies of reconstruction in both offline and trigger levels are needed ‣ Large QCD background in the hadron collider ‣ Backgrounds from b-hadron decays ‣ Rare decay

Previous results - CMS

Phys. Lett. B 753 (2016) 341-362



Special trigger : Mu-Pho trigger

- The efficiency of the single/double muon trigger might be low due to closed-by muons

Customized muon ID

- To increase the reconstruction efficiency. (Total signal efficiency = 22%)

Strategy of background estimation

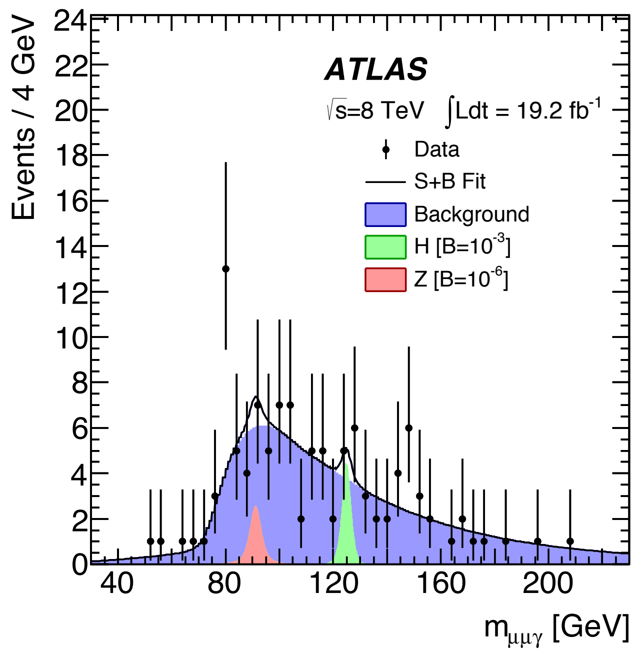
- Data-driven; Use the fit to the reconstructed $m_{\mu\mu\gamma}$ distribution in selected data events as background model

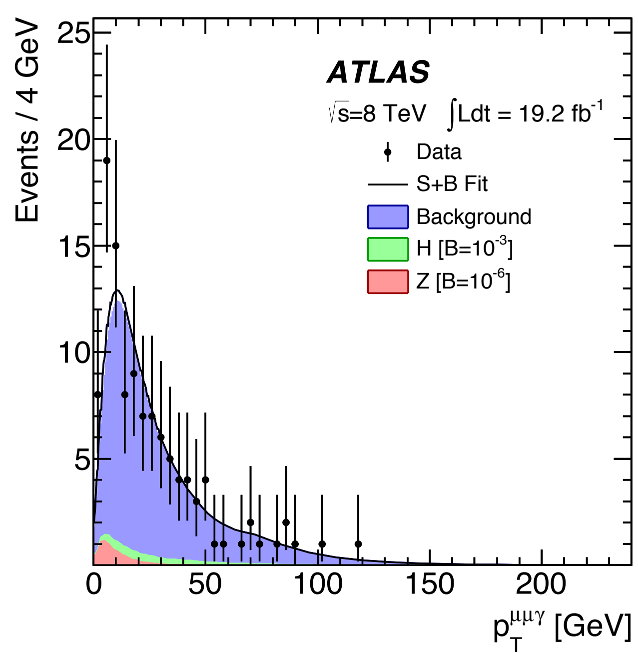
95% C.L upper limits

	BR($H \rightarrow J/\psi+\gamma$)
Expected	1.6×10^{-3}
Observed	**1.5×10^{-3}**
σ/σ_{SM}	538

$Z\rightarrow J/\psi+\gamma$ has not yet been studied in CMS!

Previous results - ATLAS





Phys. Rev. Lett. 114 (2015) 121801

Event categorization

- 4 categories based on the pseudorapidity of the muons and the photon reconstruction classification

Inclusive QCD background(Quarkonium + jets)

- Build up the templates of kinematic distributions using data events

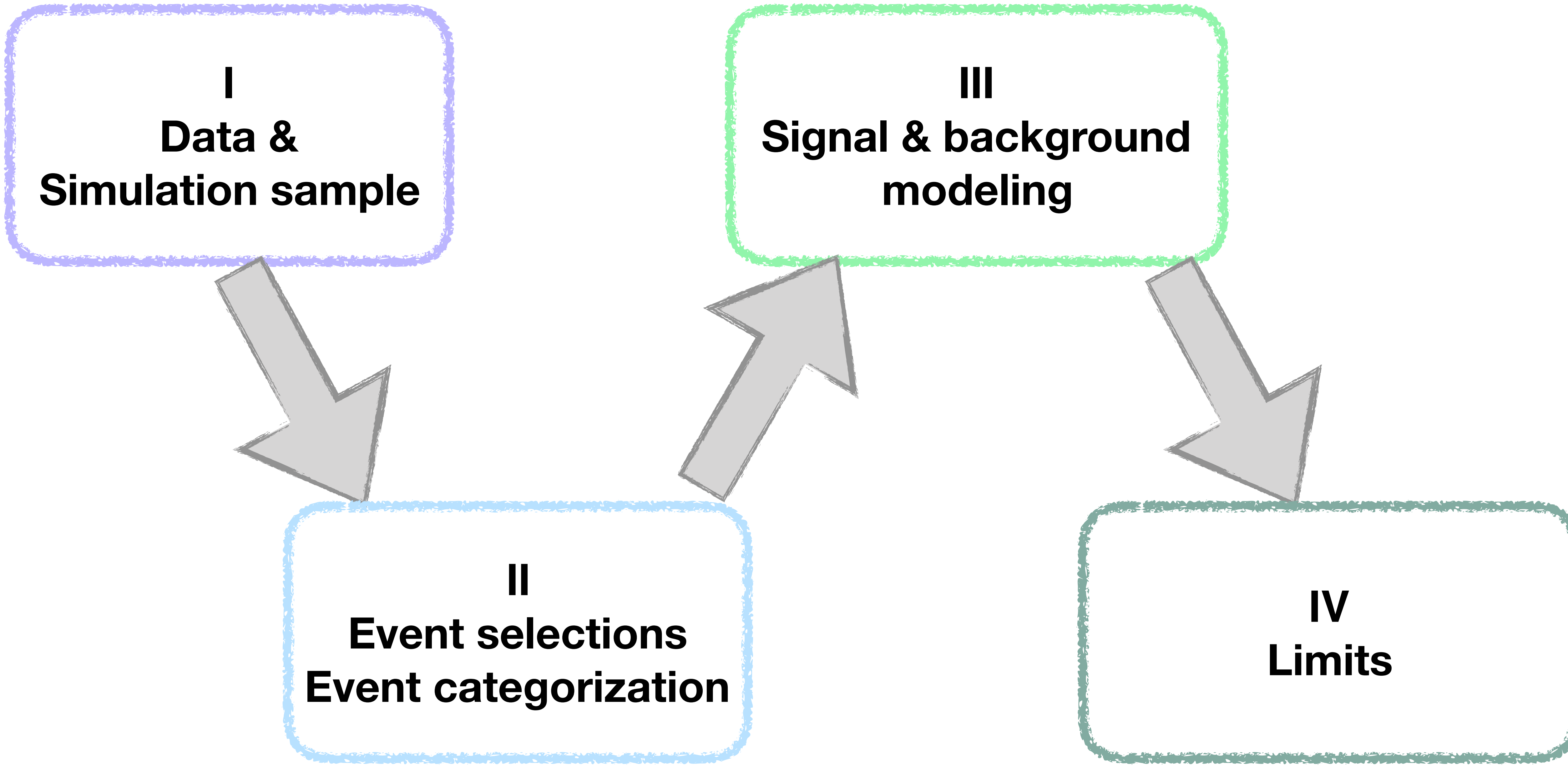
Simultaneous fit

- Simultaneous unbinned maximum likelihood fit on $m_{\mu\mu\gamma}$ and $p_{T\mu\mu\gamma}$

95% C.L upper limits

	BR(H→J/ψ+γ)	BR(Z→J/ψ+γ)
Expected	1.2×10^{-3}	2.0×10^{-6}
Observed	**1.5×10^{-3}**	**2.6×10^{-6}**
σ/σ_{SM}	538	26.1

Analysis strategy

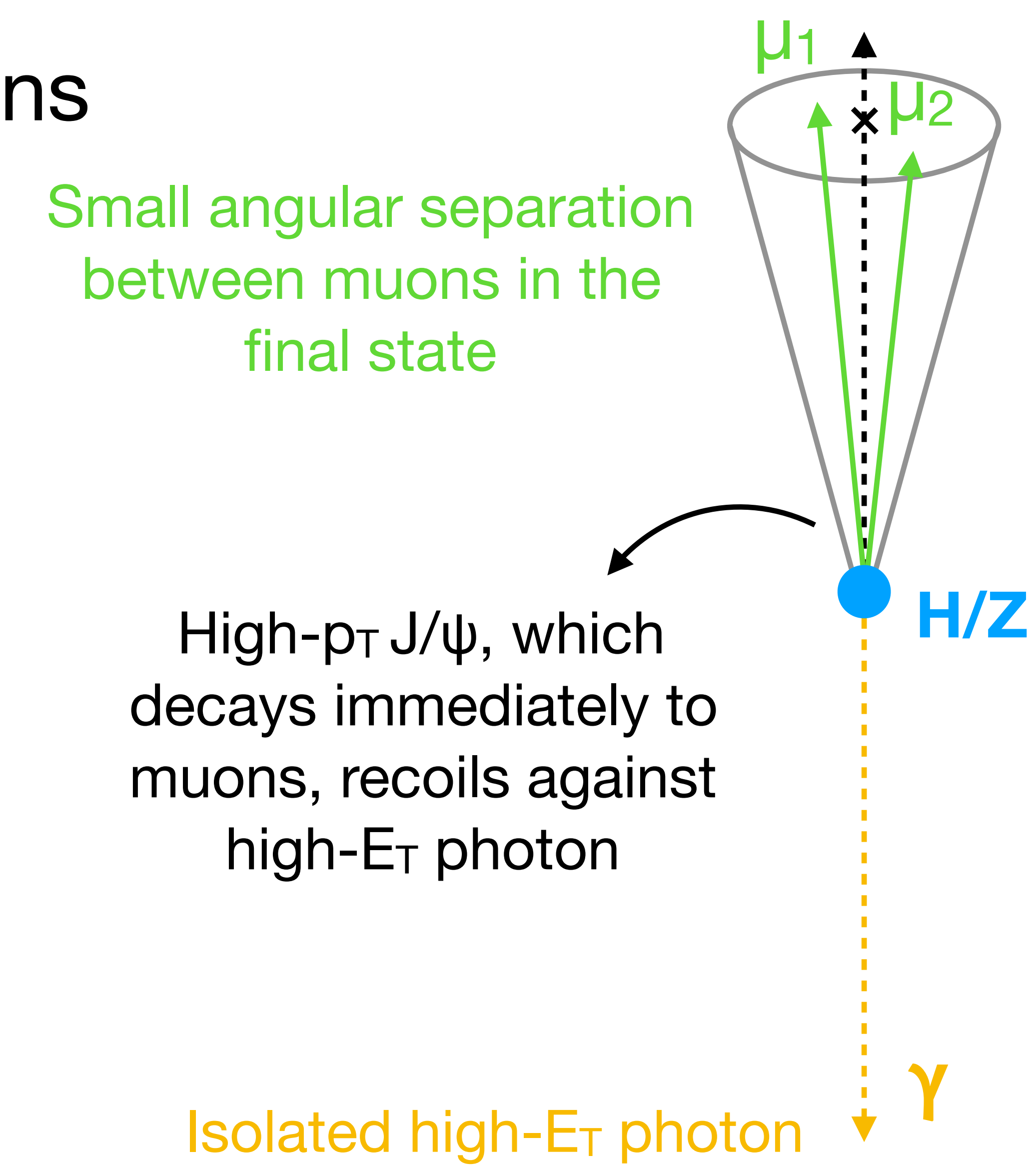


Analysis strategy - I

- **Data**
  - Full 2016 datasets with integrated luminosity of 35.86 fb^{-1}
- **Signal Monte-Carlo samples**
  - Generated by PYTHIA8, with m_Z = 91.18GeV for $Z \to J/\psi\gamma$ and m_H = 125.0 GeV for $H \to J/\psi\gamma$
- **Background Monte-Carlo samples**
  - Peaking background of $H \to J/\psi\gamma$
    - $H \to \gamma^*\gamma$(Higgs Dalitz decay) with $\gamma^* \to \mu\mu$ ($m_{\mu\mu} < 50$GeV) produced with MADGRAPH and showered with PYTHIA8

Analysis strategy - II

- **Trigger** : Mu-Pho trigger with thresholds on $p_T^{\mu}(E_T^{\gamma})$ > 17(30)GeV
    - No isolation requirement on muons
    - Isolated EM object at L1 level
    - High pT photon at HLT level
- Efficiency > 80% w.r.t offline selection
    - 81.5(83.3%) in Data(MC)

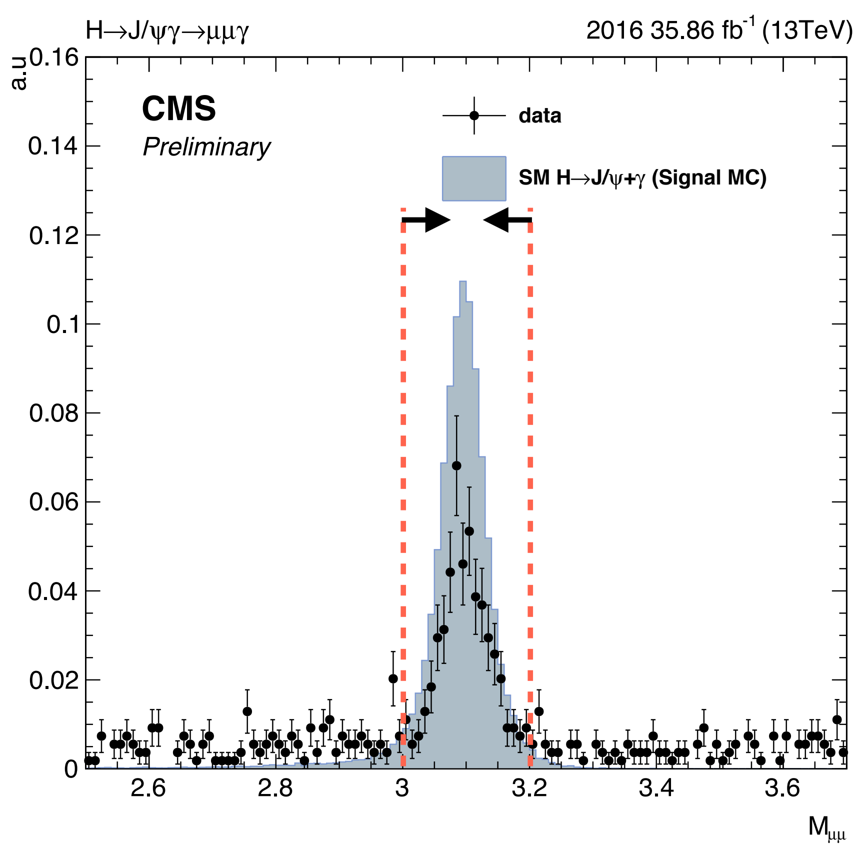


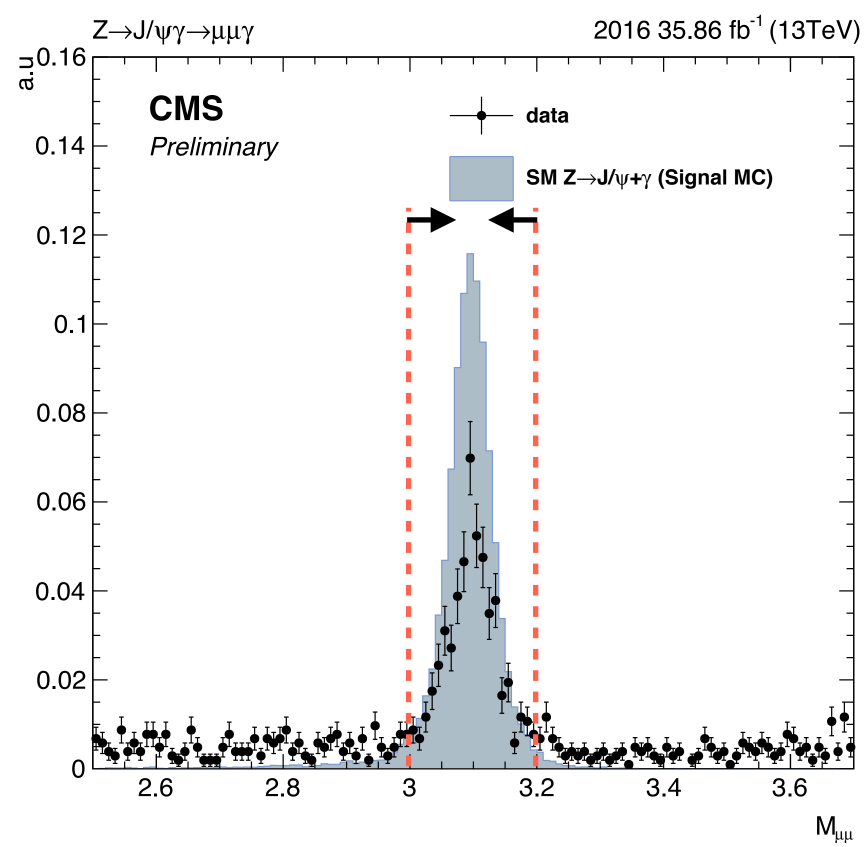
Analysis strategy - II

- **Reconstruction** & **Identification** :
  - **Muons** : $H \rightarrow ZZ^* \rightarrow 4\ell$ ID, without ambiguous tracks
    - $p_T^{lead\ \mu} > 20$GeV, $p_T^{trail\ \mu} > 4$GeV (Muons can reach muon station)
    - Muons must come from primary vertex(PV)
  - **Photon** : General purpose MVA, not electron-faking photon
    - $E_T^{\gamma} > 33$GeV (Driven by trigger threshold)
    - Isolated photon(isolation variables are included in the MVA training)
- **Particle flow isolation** calculated in $\Delta R=0.3$ for leading muon

Analysis strategy - II

- Di-muon system and photon should be separated
  - $\Delta R(\mu_{1\&2}, \gamma) > 1$, $\Delta R(\mu\mu, \gamma) > 2$, $|\Delta\phi(\mu\mu, \gamma)| > 1.5$
- J/ψ candidate selection: $3.0 < m_{\mu\mu} < 3.2$
- $p_T^{\mu\mu}, E_T^{\gamma}/m_{\mu\mu\gamma} > 35/91.18$ ($Z \to J/\psi\gamma$), $35/125$ ($H \to J/\psi\gamma$)





Total signal efficiency = 19.7(13.0%) in H(Z)→J/ψγ search

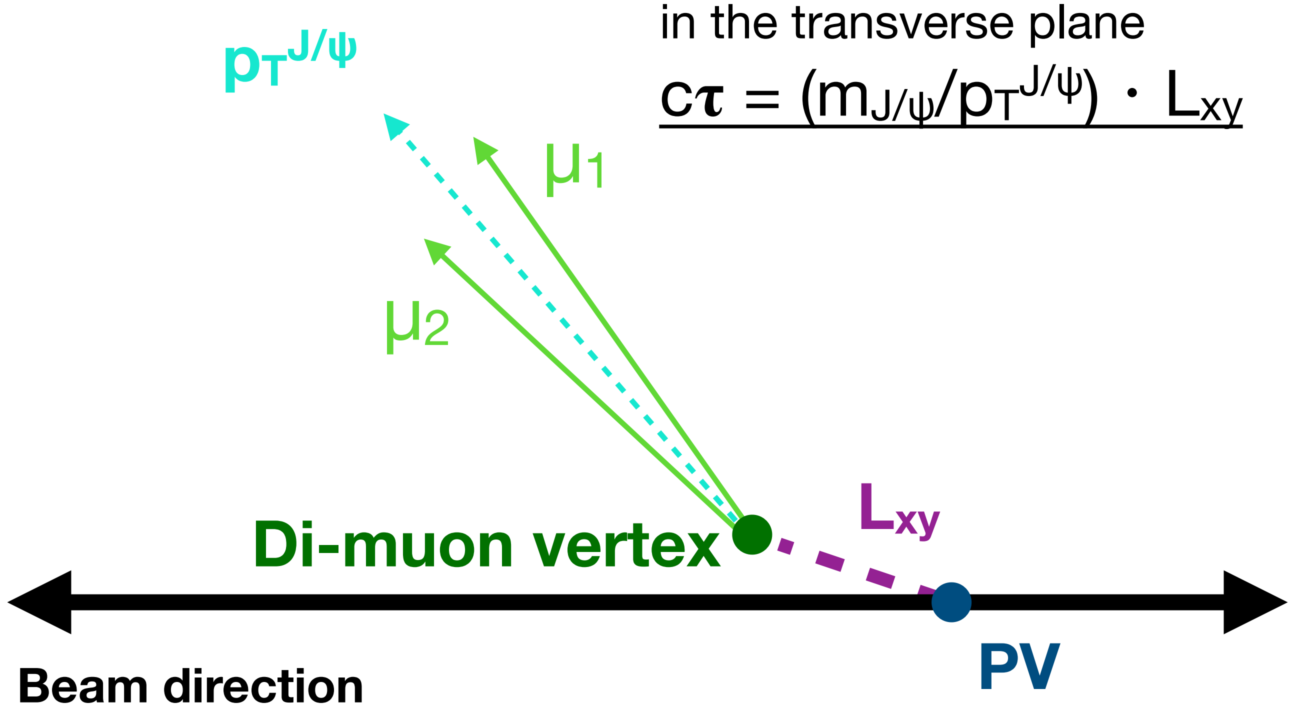
Analysis strategy - II

- J/ψ candidates in data events after full selections are compatible with promptly-produced J/ψ

Transverse lifetime, cτ

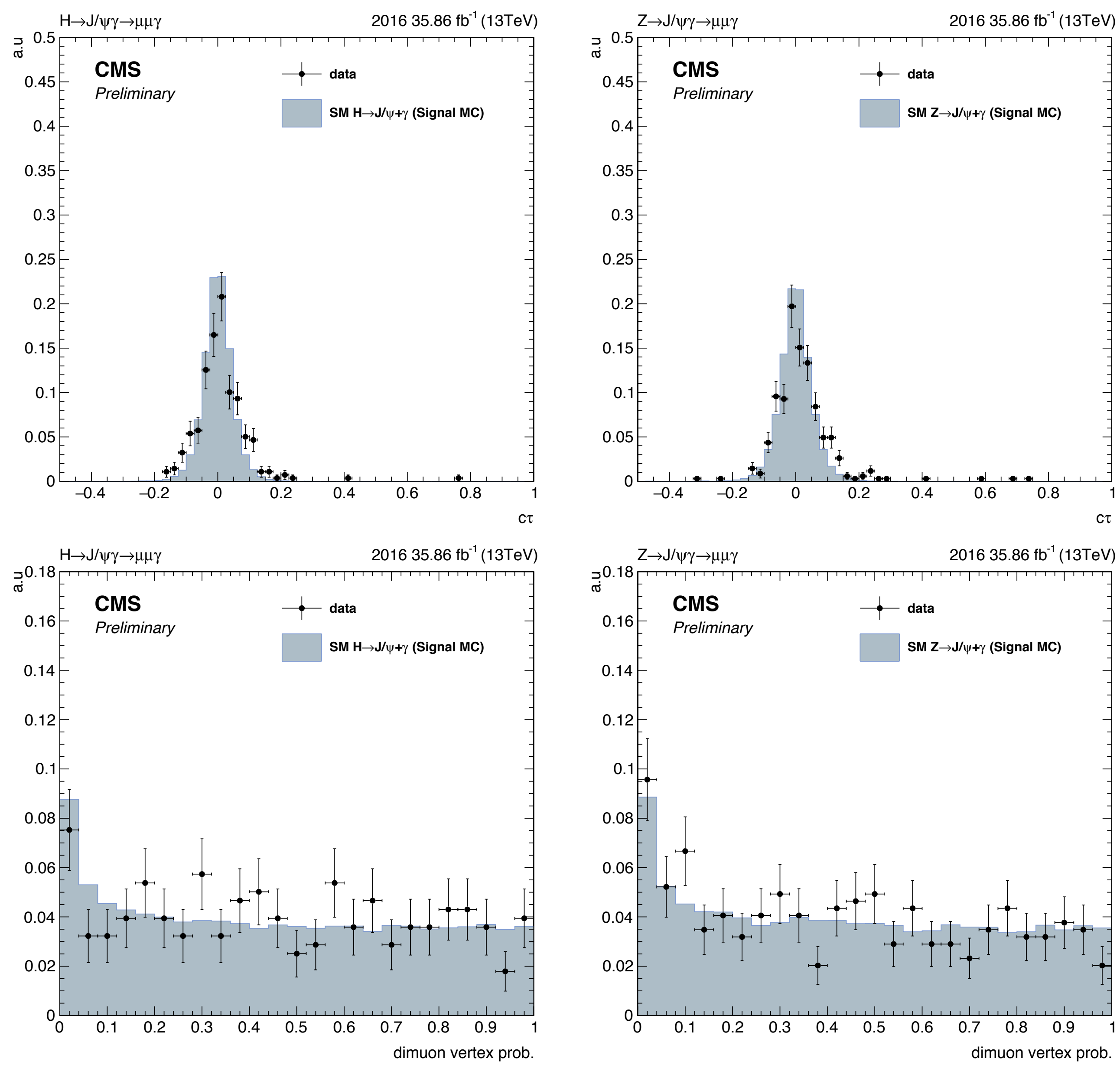
The lifetime of J/ψ candidates in the transverse plane

$c\tau = (m_{J/\psi}/p_T^{J/\psi}) \cdot L_{xy}$



Di-muon vertex probability

The probability that the two leptons come from the same vertex



Analysis strategy - II

- $H \to J/\psi\gamma$: No event categorization.
- $Z \to J/\psi\gamma$: Events are divided into 3 categories

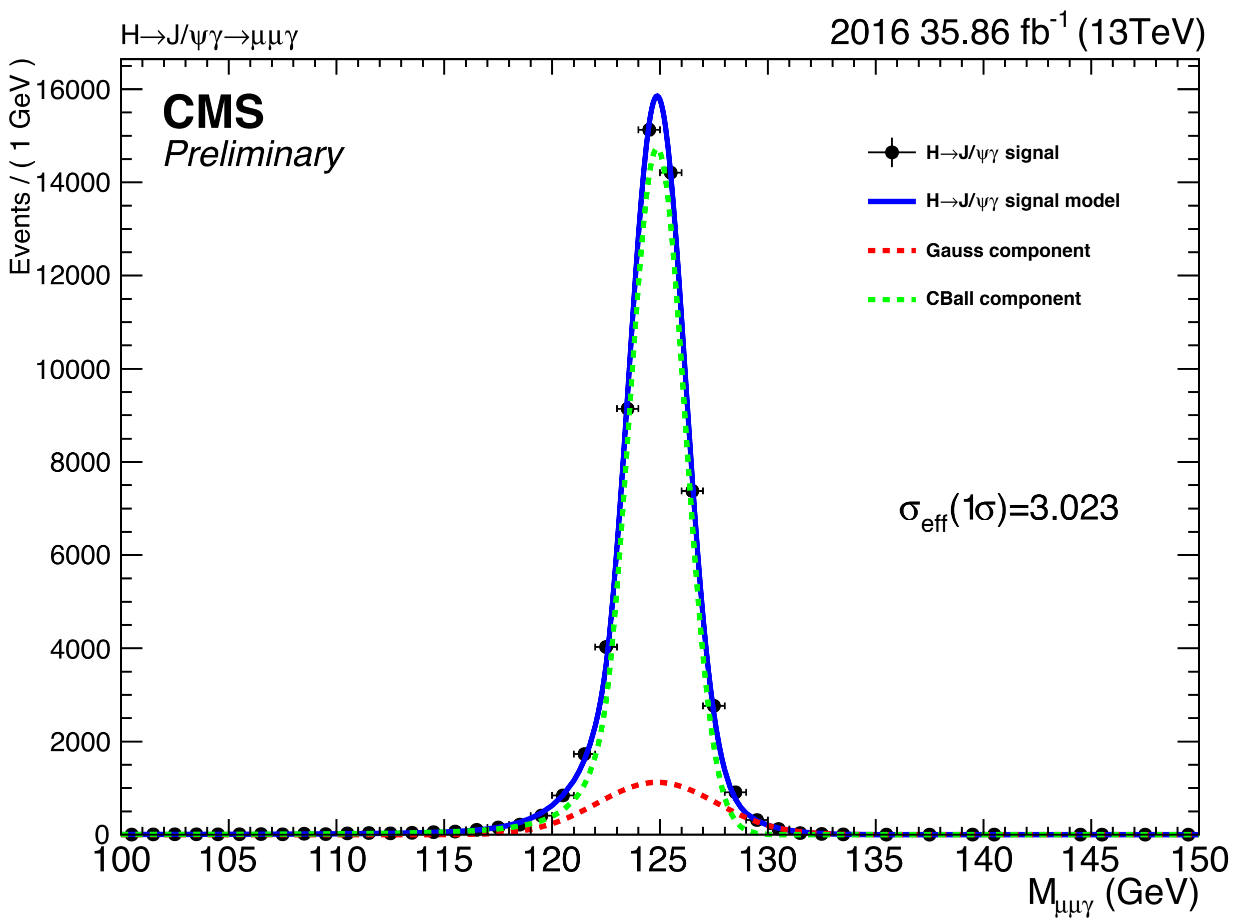
	Category 1	Category 2	Category 3
Definition	Photon in Ecal Barrel ($0 < \lvert\eta_{SC}\rvert < 1.4442$) Unconverted photon	Photon in Ecal Barrel ($0 < \lvert\eta_{SC}\rvert < 1.4442$) Converted photon	Photon in Ecal Endcap $1.566 < \lvert\eta_{SC}\rvert < 2.5$
Fraction of events (Data)	40.3%	36.2%	23.5%
Fraction of events (Signal)	49.0%	30.6%	20.3%
S/B ($\times 10^3$)	5.54	3.84	3.70

Analysis strategy - III

- An un-binned maximum likelihood fit to reconstructed $m_{\mu\mu\gamma}$ in signal events as signal model

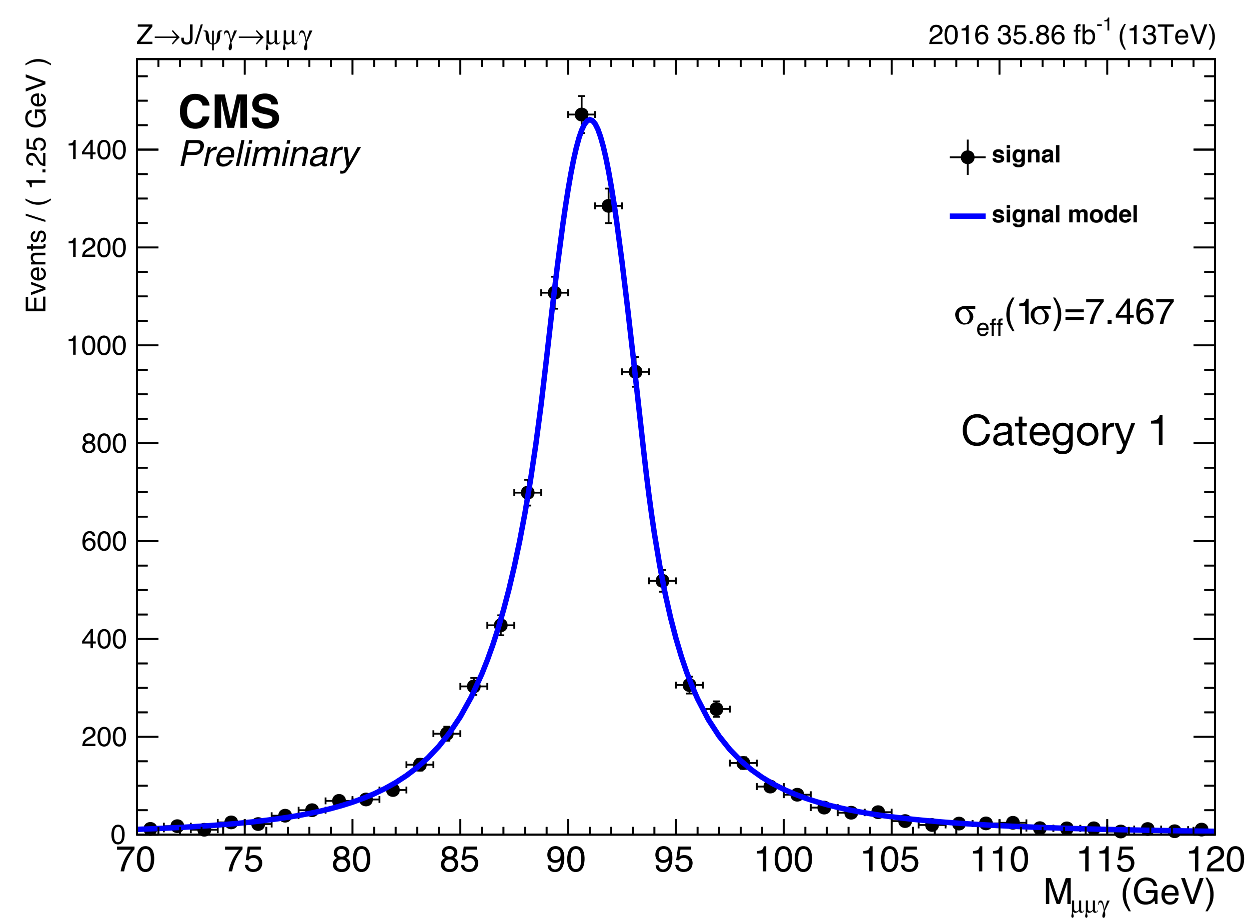
H→J/ψγ

Gaussian + Crystal Ball with the same mean



Z→J/ψγ

Double-sided Crystal Ball

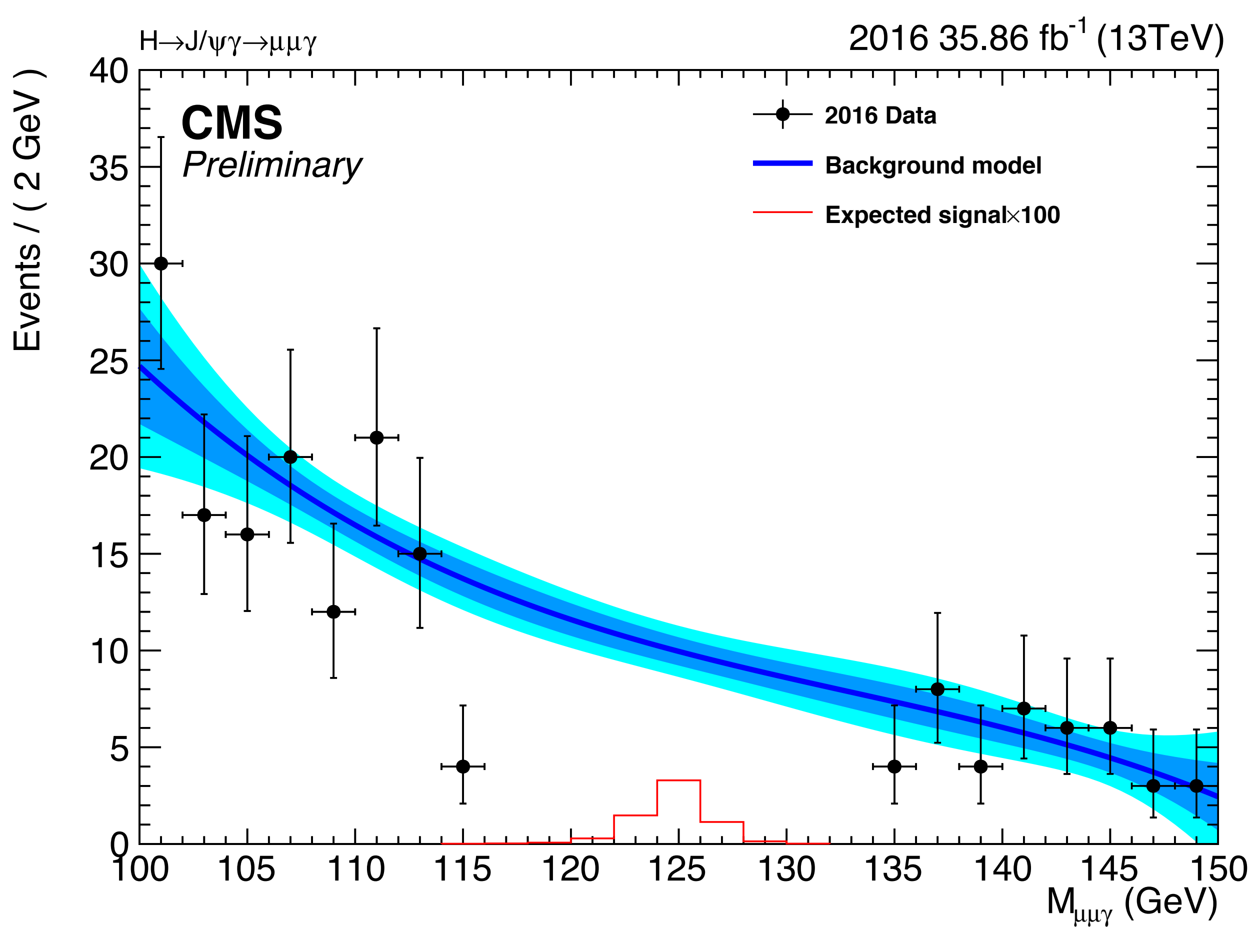


Analysis strategy - III

- An un-binned maximum likelihood fit to reconstructed $m_{\mu\mu\gamma}$ in data events as background model

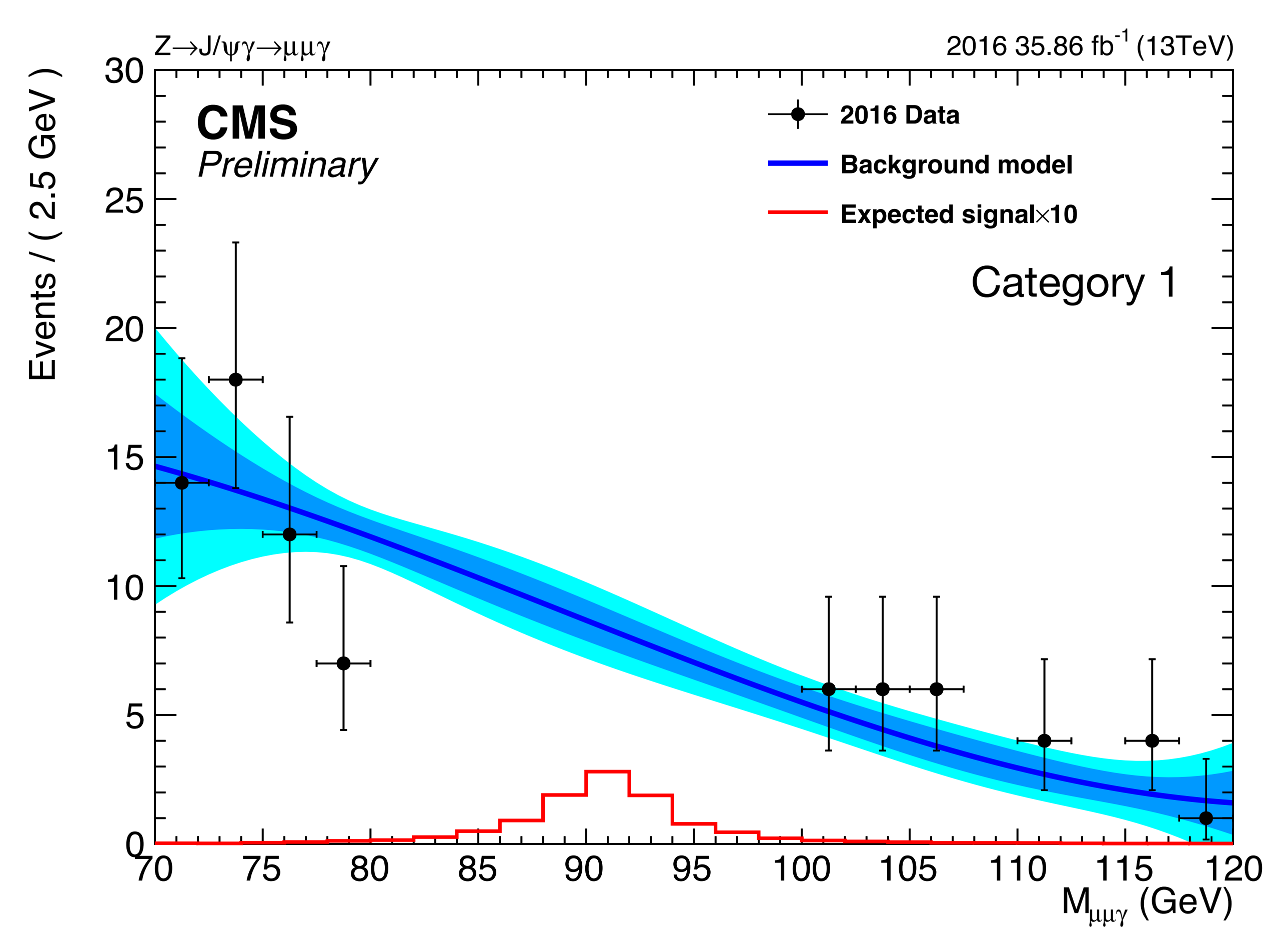
H→J/ψγ

Bernstein 3rd-order polynomial



Z→J/ψγ

Bernstein 3rd-order polynomial

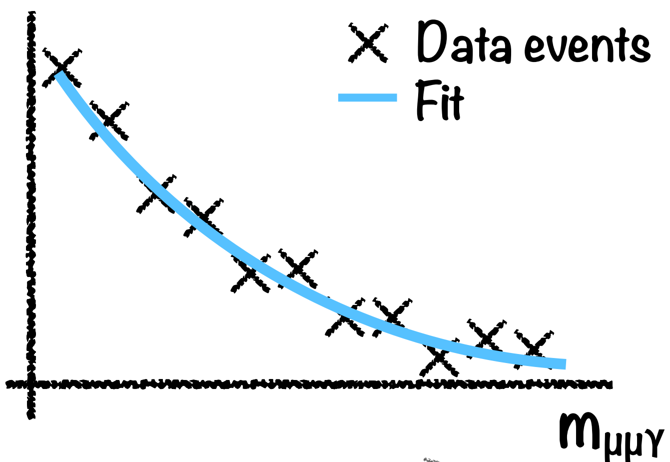


Analysis strategy - III

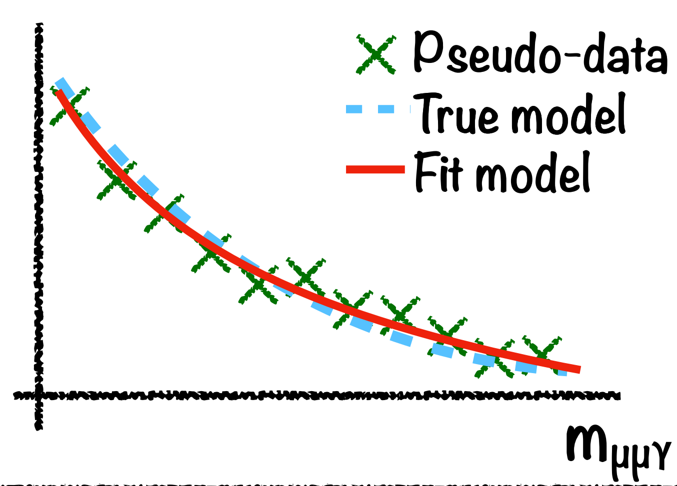
	$H \to J/\psi\gamma$	$Z \to J/\psi\gamma$
Integrated luminosity	2.5%	
Theoretical uncertainty		
SM cross section - scale	+4.6% -6.7%	3.5%
SM cross section - PDF+α_s	3.2%	1.73%
SM Higgs Dalitz decay BR	6.0%	-
Detector simulation, reconstruction, efficiency		
Pile-up weight	0.79~1.4%	
Trigger	3.0~7.0% (Statistical uncertainty dominates)	
Muon ID/Iso	2.3~3.0%	
Photon MVA ID	1.1~1.3%	
Electron veto	0.45~1.2%	
Signal model		
Mean (scale)	< 0.1% (Uncertainty from photon dominates)	
Sigma (resolution)	0.8~5.0% (Uncertainty from photon dominates)	

Analysis strategy - III

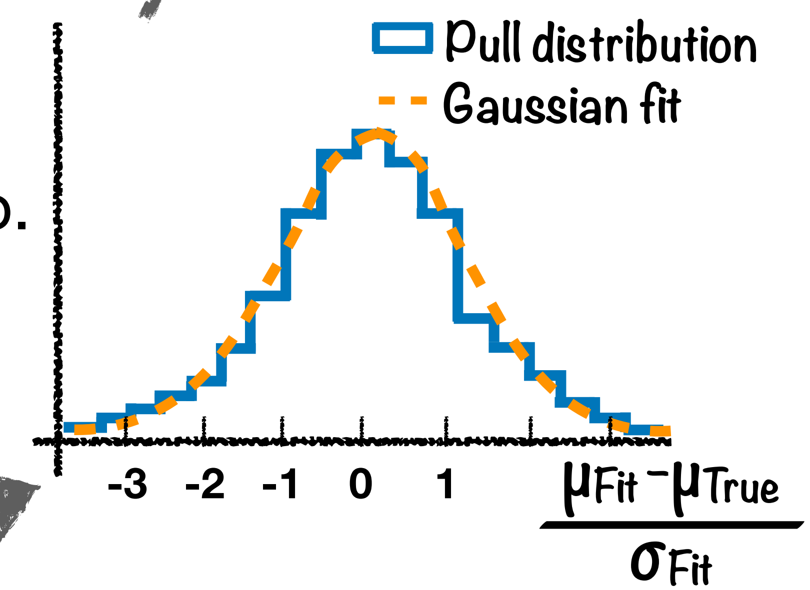
- No uncertainty on background modeling is assigned. Instead, a study of the potential bias on the estimated background is performed.



Use the resulting fit as the **true model** to generate pseudo-data



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



Find a function that gives a mean value for the fitted strength consistent with zero.

Bernstein 3rd order polynomial is chosen

Analysis strategy - IV

The 95% C.L exclusion upper limit		
Channel	**$\sigma(pp\rightarrow H/Z)\times BR(H/Z\rightarrow (J/\psi)\gamma\rightarrow\mu\mu\gamma)$**	**$BR(H/Z\rightarrow (J/\psi)\gamma)$**
$H\rightarrow J/\psi\gamma$	< 2.37 fb (with 1σ band: $1.66 < \sigma\times B < 3.43$ fb)	$<$ **7.21×10^{-4}** (~**258.4** times the SM prediction) **SM prediction = 2.79×10^{-6}**
$Z\rightarrow J/\psi\gamma$	< 5.70 fb (with 1σ band: $4.04 < \sigma\times B < 8.18$ fb)	$<$ **1.69×10^{-6}** (~**17.0** times the SM prediction) **SM prediction = 9.96×10^{-8}**

$\sigma(pp\rightarrow H) = 55.6$ pb
$\sigma(pp\rightarrow Z, m_{ll} > 50\text{GeV}) = 57094.5$ pb, $BR(J/\psi\rightarrow\mu\mu)=0.059$

Run1 results			Expected	Observed
$H\rightarrow J/\psi\gamma$	CMS	95% C.L (upper limit)	**1.6×10^{-3}**	1.5×10^{-3}
	ATLAS		**1.2×10^{-3}**	1.5×10^{-3}
$Z\rightarrow J/\psi\gamma$	ATLAS		**2.0×10^{-6}**	2.6×10^{-6}

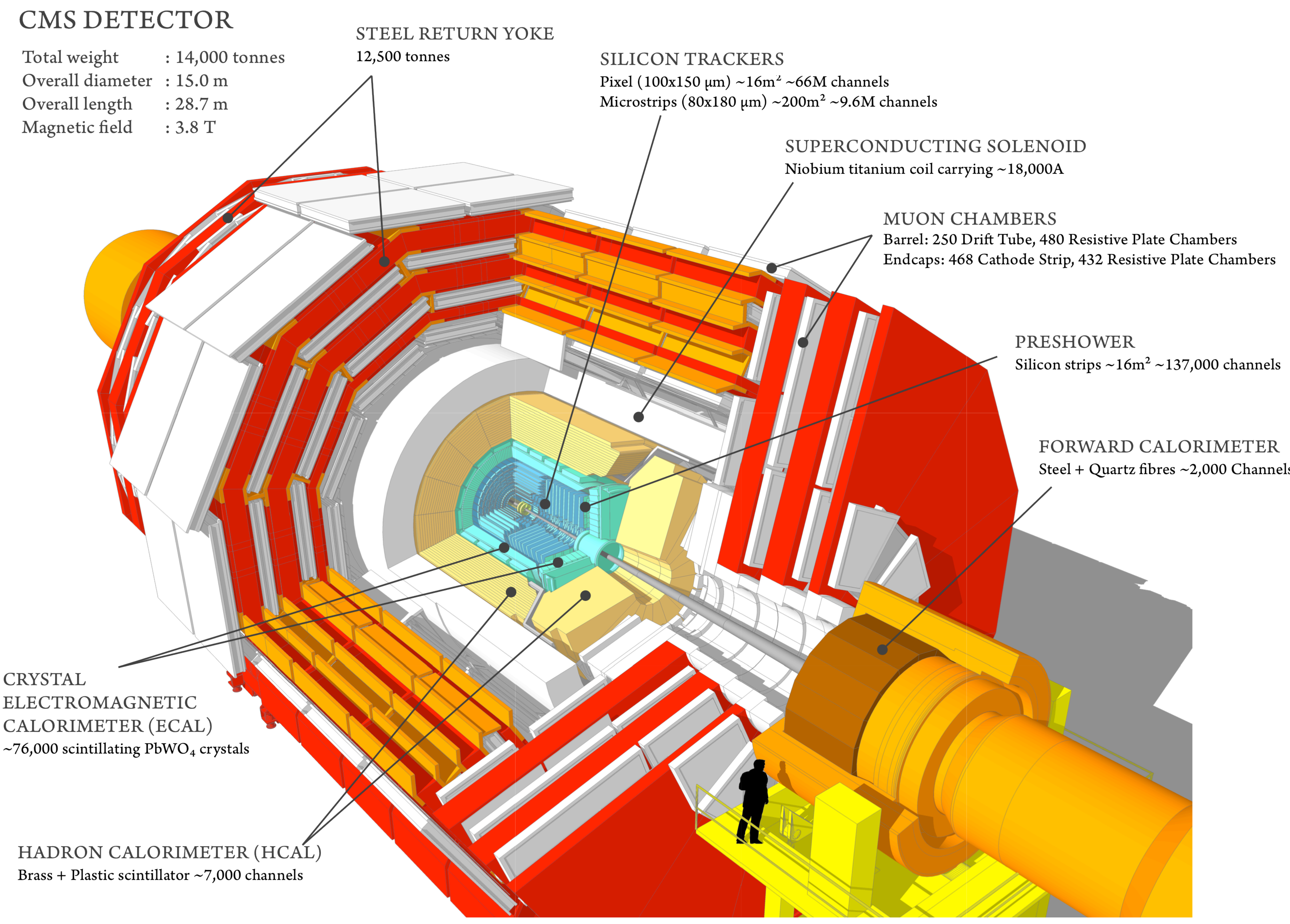
Summary

- The search of $H/Z \to J/\psi\gamma$ using full 2016 datasets with integrated luminosity of 35.86 fb^{-1} collected CMS detector is performed.
  - First result on $Z \to J/\psi\gamma$ in CMS!
- The latest upper limit(95% C.L) on branching fraction
  - H(Z)→$J/\psi\gamma$: 7.21×10^{-4}(1.69×10^{-6}), which is 258(17)×SM

Prospect & Outlook

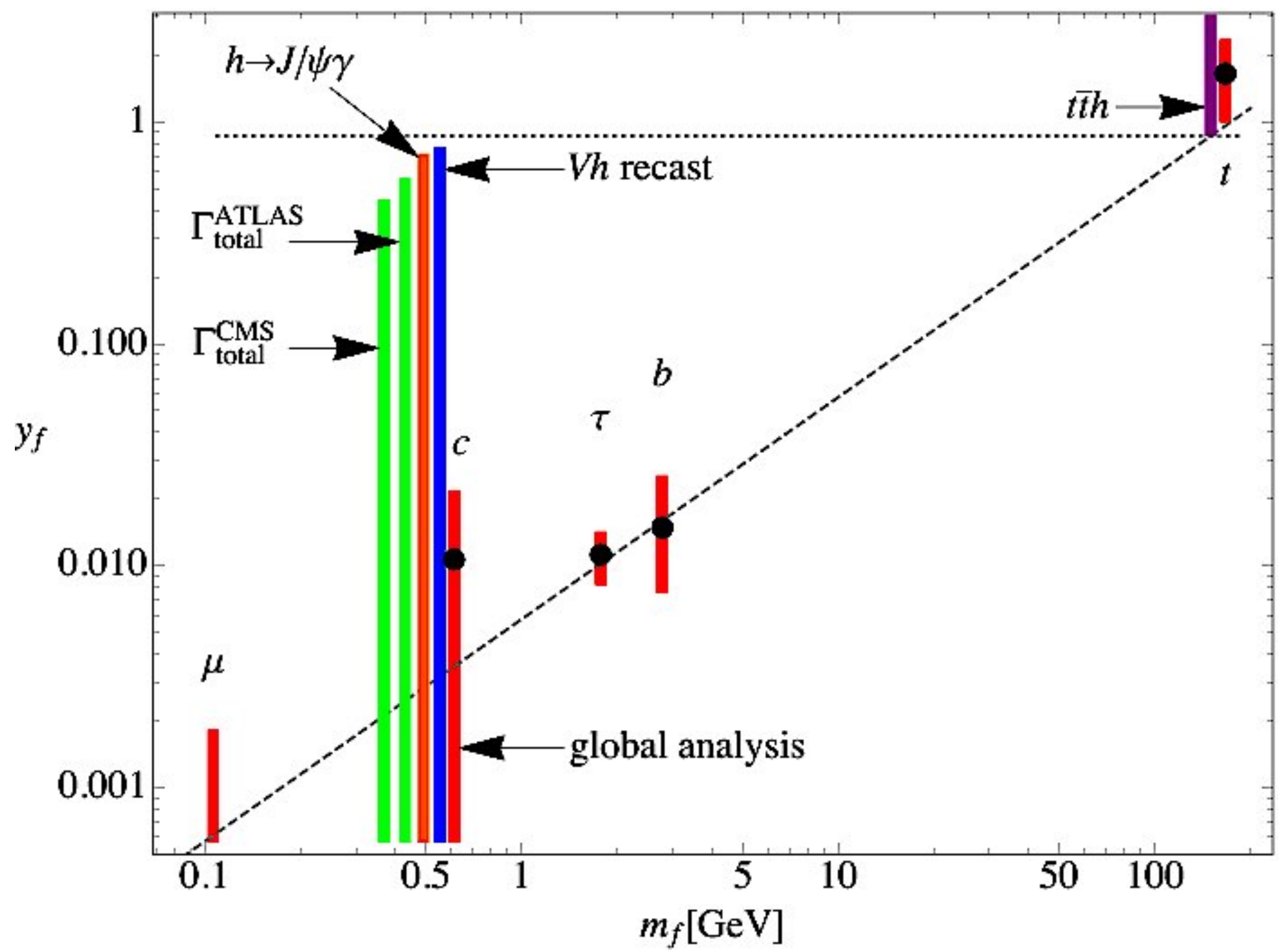
- Dedicated simulation of background processes is needed, as priority in 2017 analysis
  - Better understanding of background composition & optimization of event selections
- Several techniques can be applied to improve the sensitivity
  - Event categorization
  - MVA or MELA(Matrix Element Likelihood Analysis)
  - Electron channel. Dedicated trigger is needed
- $H/Z \rightarrow \Upsilon \gamma$

Backup


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

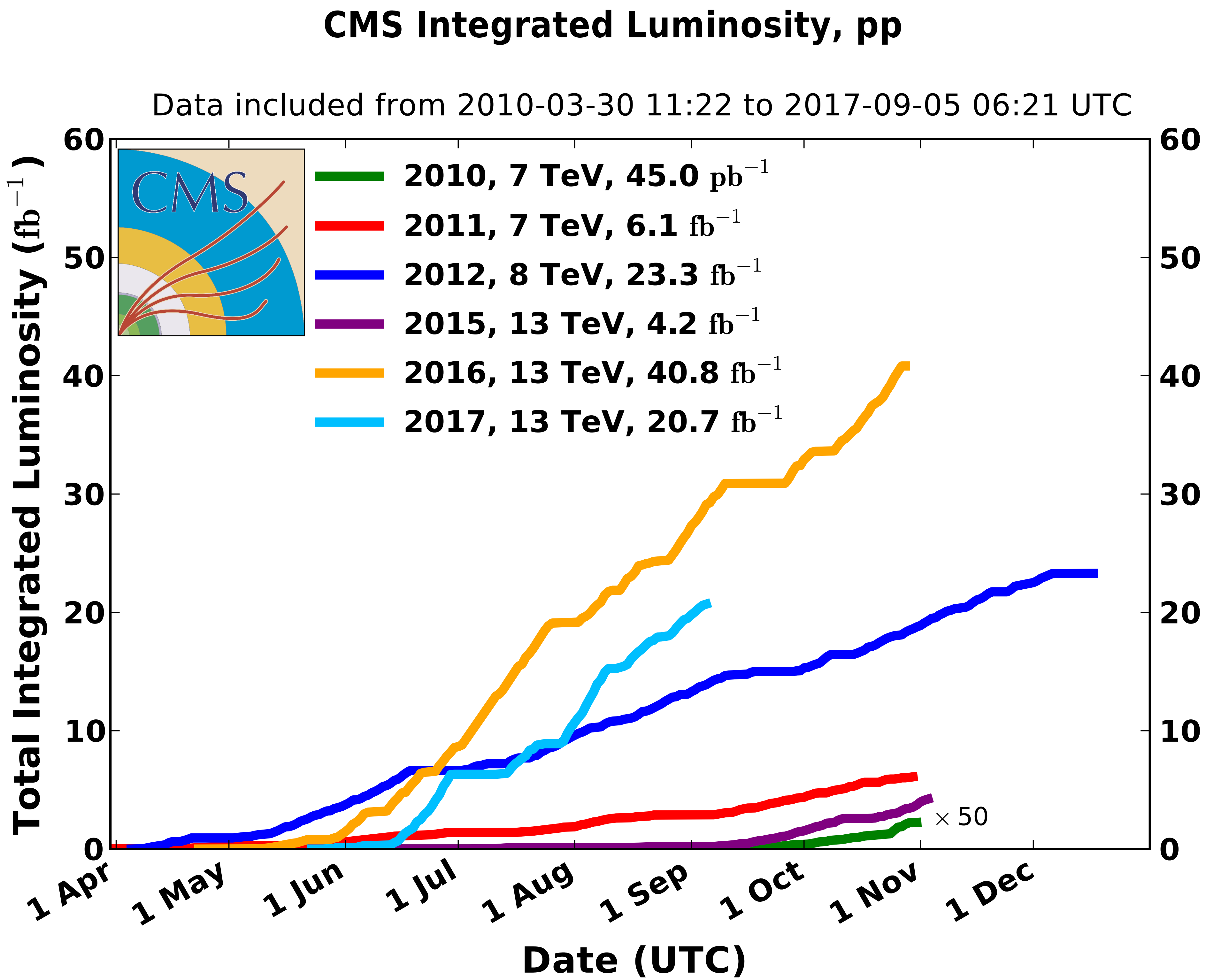
Higgs couplings

Latest constraints on the Higgs couplings to fermions including the new bounds on the charm.

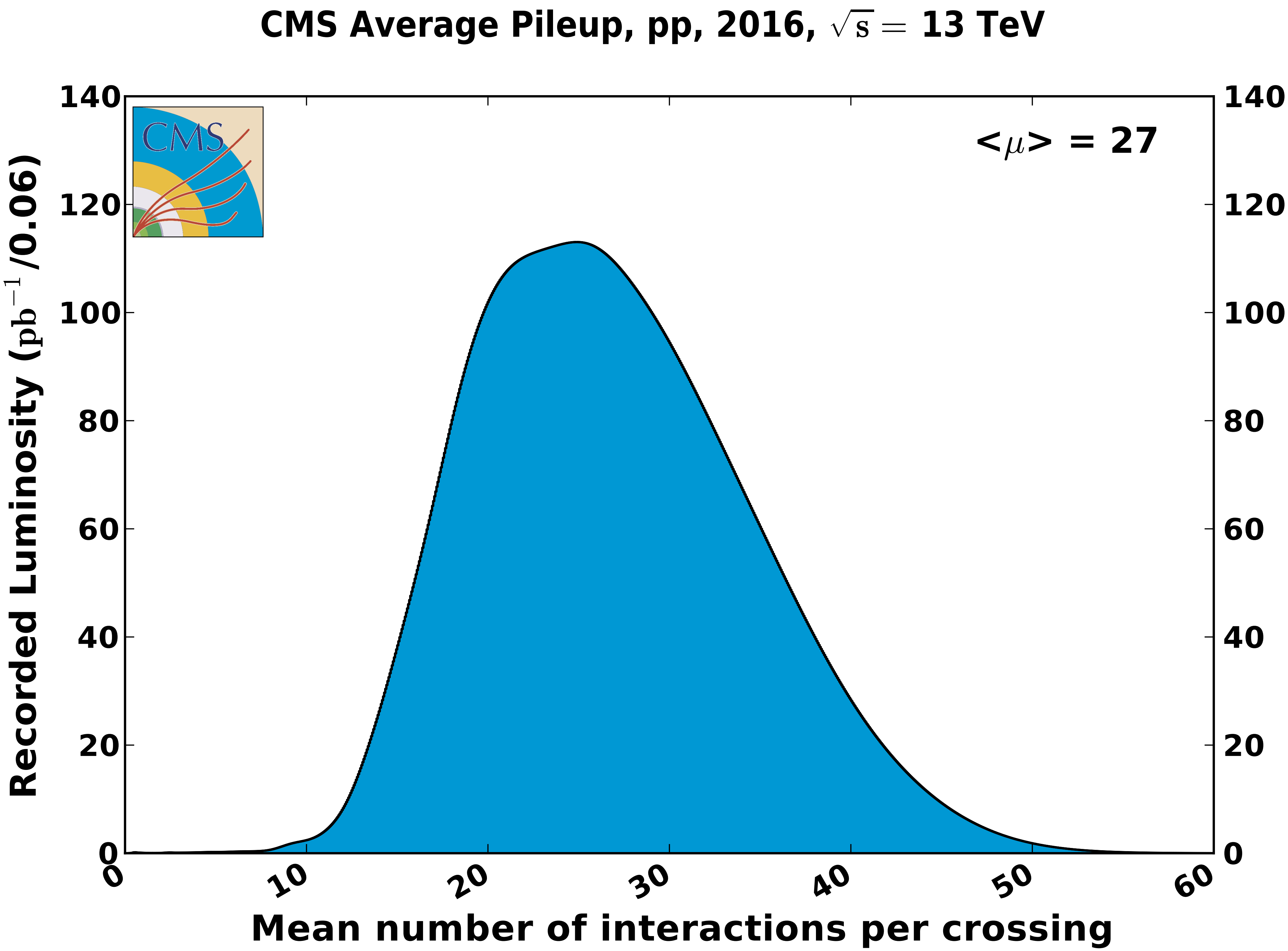


Gilad Perez et al., "Constraining the charm Yukawa and Higgs-quark coupling universality", Phys.Rev. D92 (2015) no.3, 033016

Integrated Luminosity



Average Pileup in 2016



Backgrounds

- **Background Monte-Carlo samples**
  - Peaking background for Z is not available.
  - Non-peaking background samples for both searches are not available currently.

➡ **PRIORITY IN 2017 !!!**

Background composition

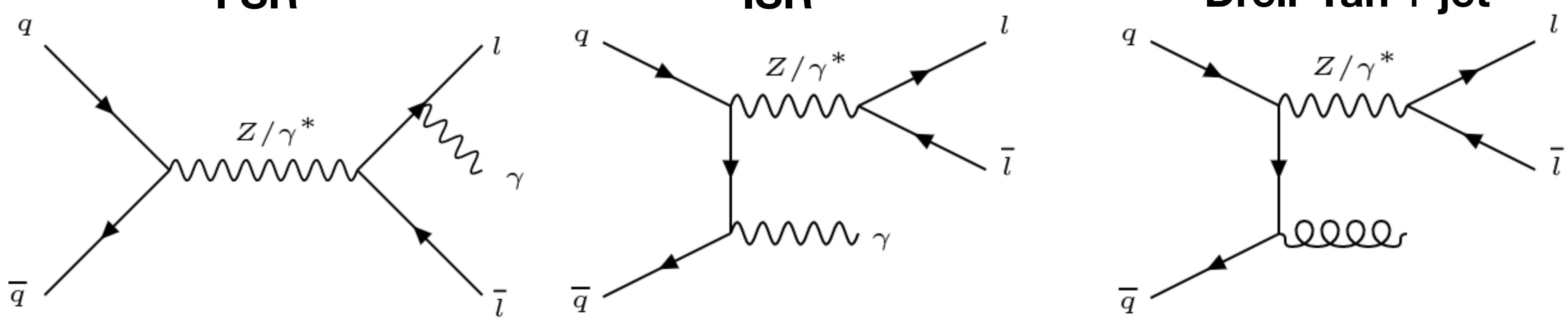
Process	Description	
Drell-Yan + FSR	$m_{\mu\mu\gamma}$ in the H/Z mass window	Irreducible
Drell-Yan + ISR	$m_{\mu\mu}$ in the J/ψ mass window $m_{\mu\mu\gamma}$ in the H/Z mass window	
pp→Z/γ*(→μμ)+jets	A jet is misidentified as an energetic photon in the event	
pp→γ + jets	The muons can come from the jets.	Reducible
Inclusive Quarkonium + jets/γ	Muons come from the J/ψ, jets is misidentified as a photon	

Background composition

- In Run1, an attempt to describe the backgrounds with MC simulation was made.
  - 2 main backgrounds: Drell-Yan+**γ**(FSR&ISR) & Drell-Yan+jet

Irreducible | **Reducible**

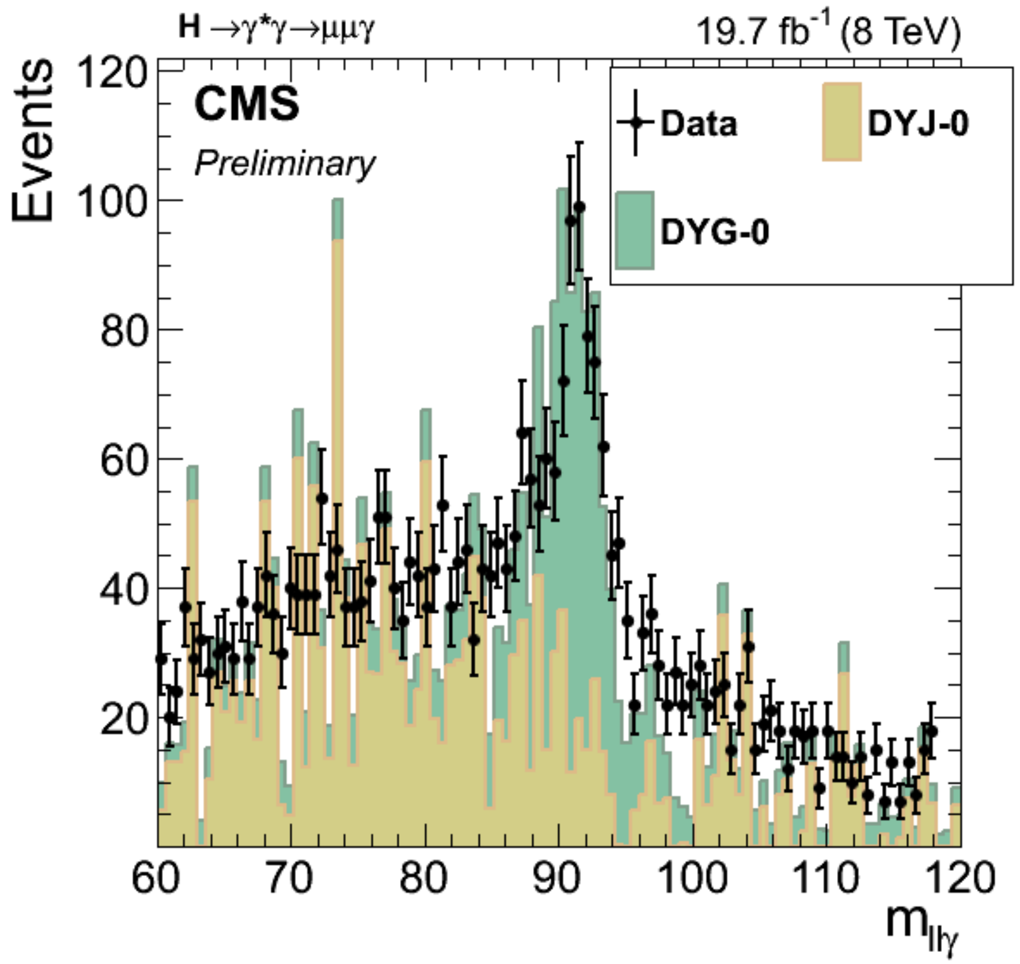
FSR | **ISR** | **Drell-Yan + jet**

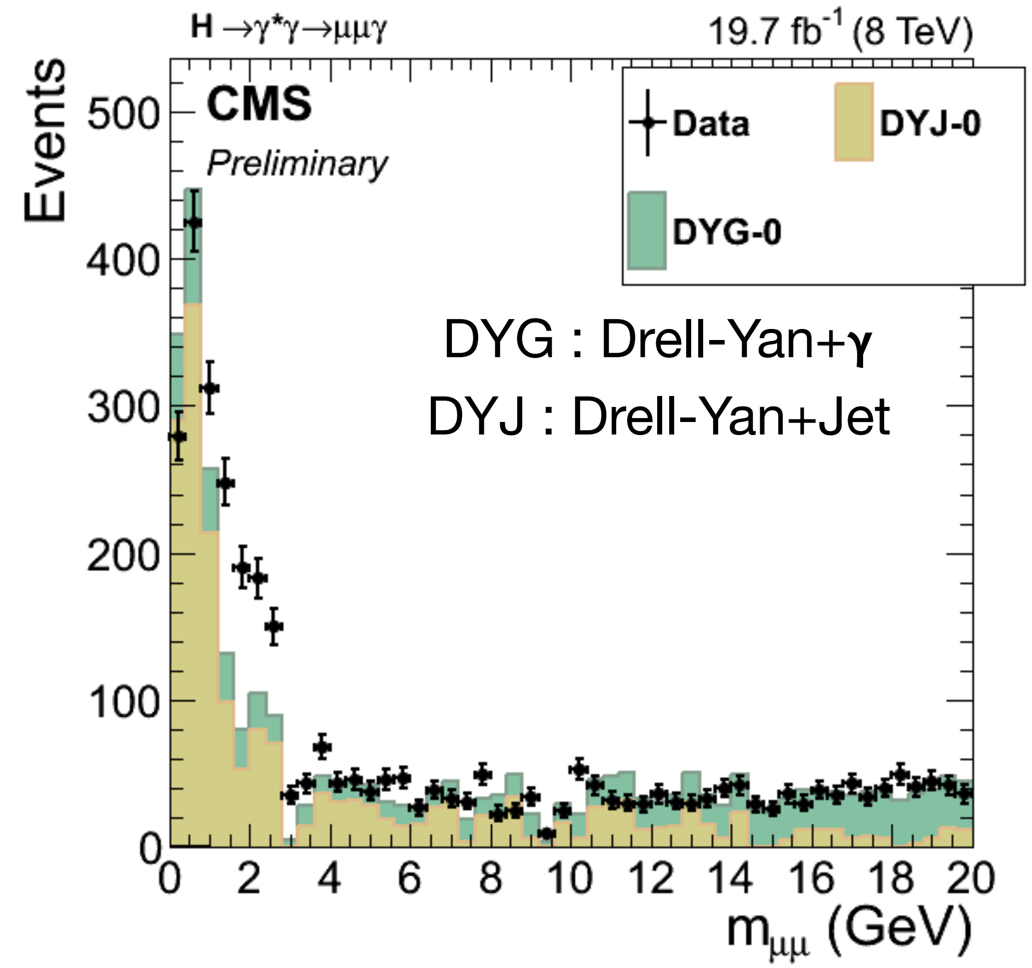


arXiv:1601.00790

Background composition

- Normalization of the MC samples were determined from the fit to the data in the control region (CR), defined as $60 < m_{\mu\mu\gamma} < 120\text{GeV}$





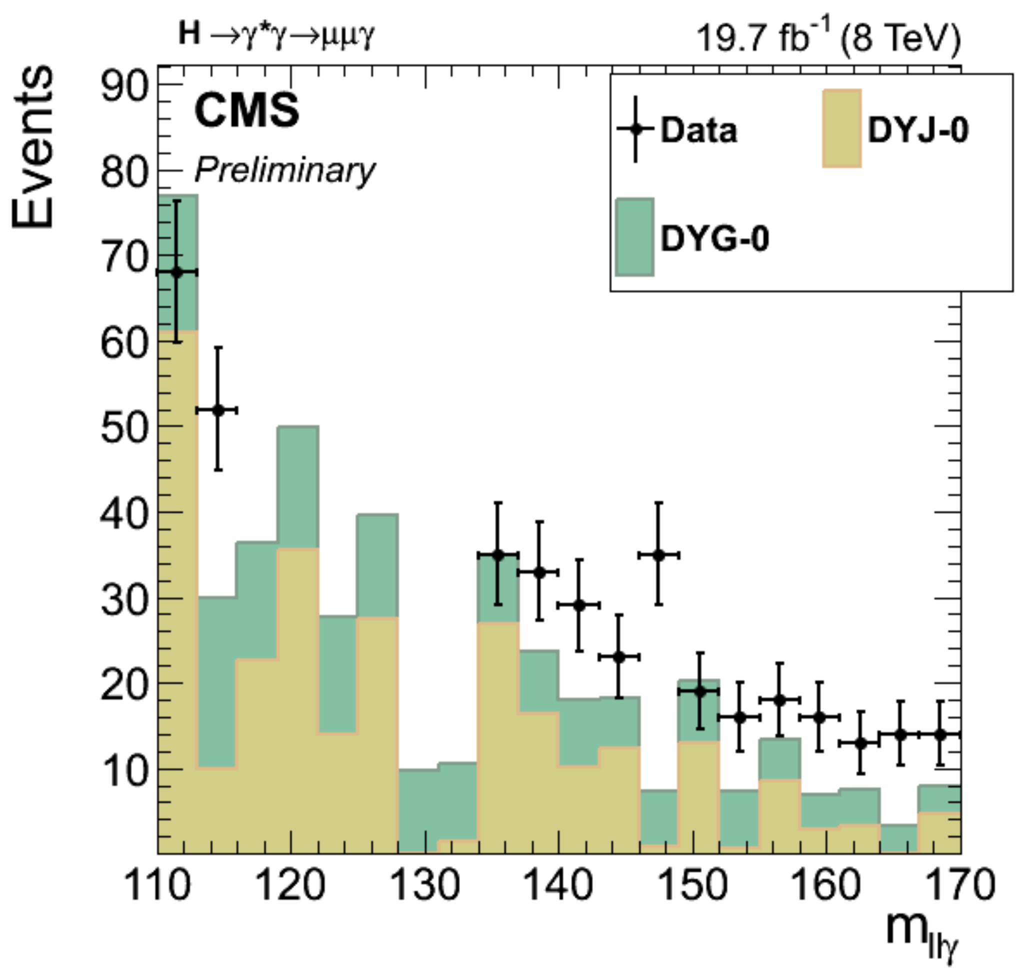
~10% events were missing…

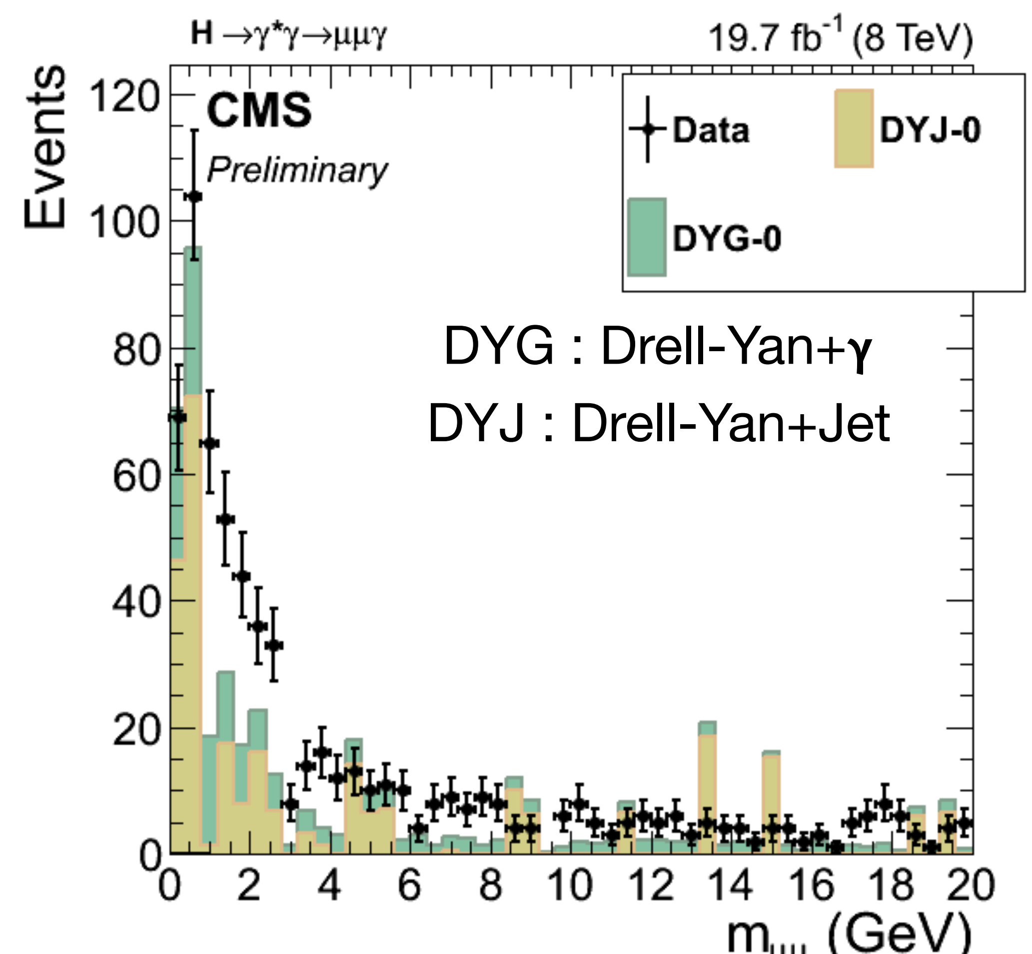
- Probably due to the mis-modeling of jets in the DYJ sample

arXiv:1601.00790

Background composition

- The predictions of the background in the signal region(SR), defined as $110 < m_{\mu\mu\gamma} < 170 GeV$



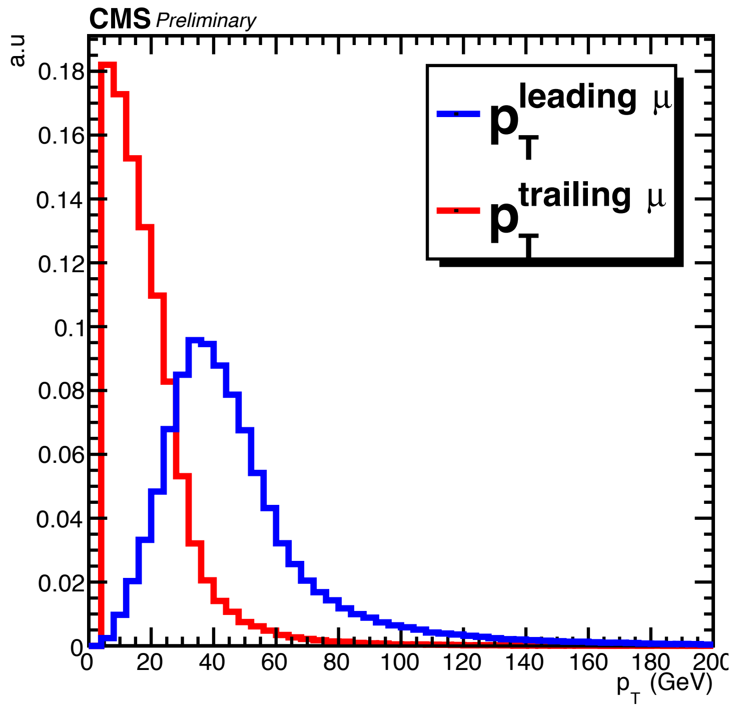


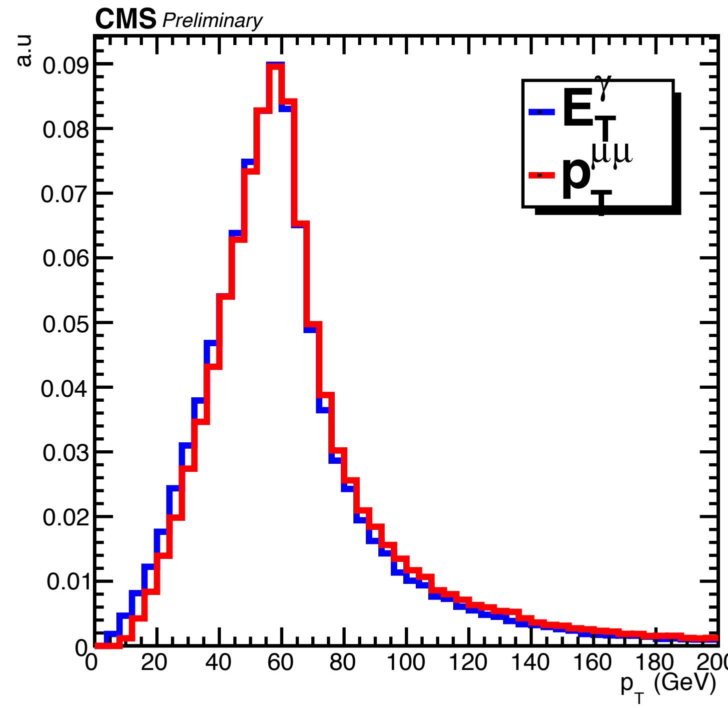
~35% events were not properly described…

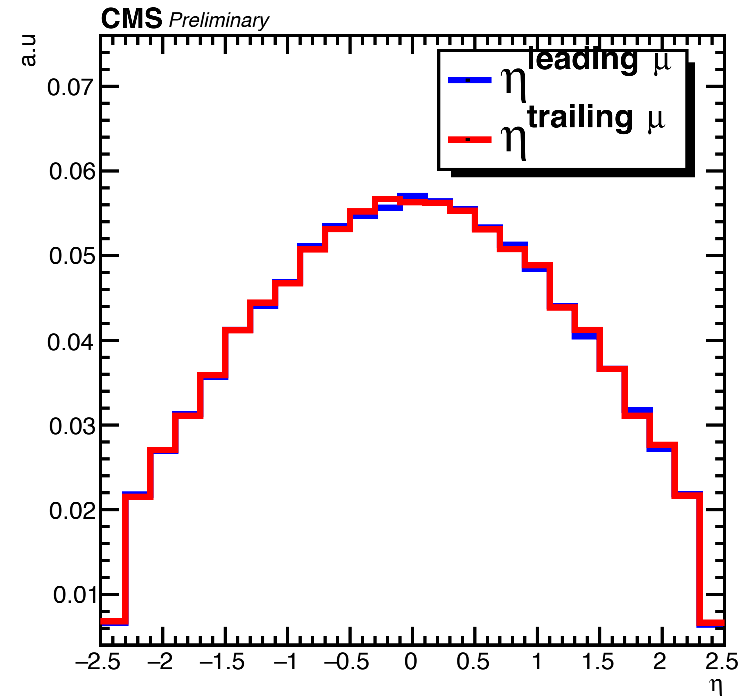
- The discrepancy came from the DYJ sample

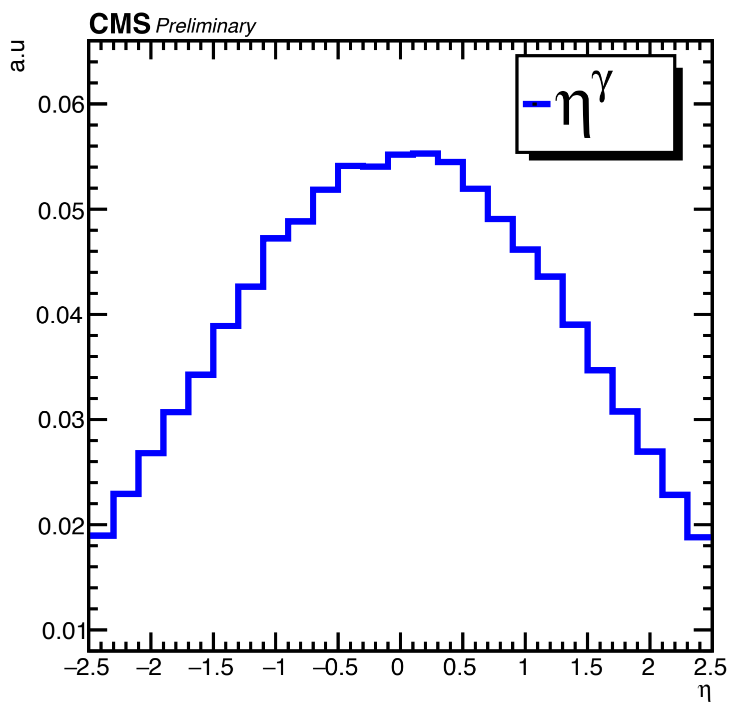
arXiv:1601.00790

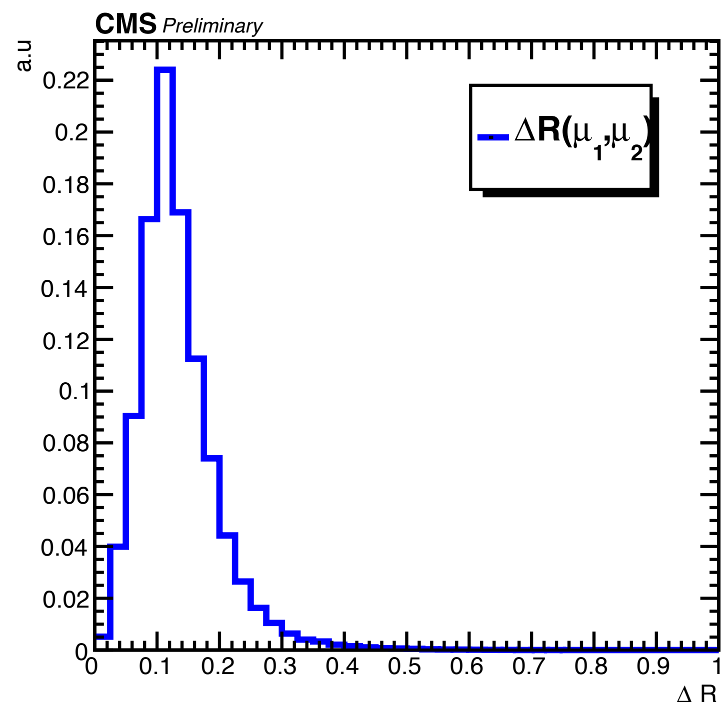
Kinematics at Gen. level - H→(J/ψ)γ

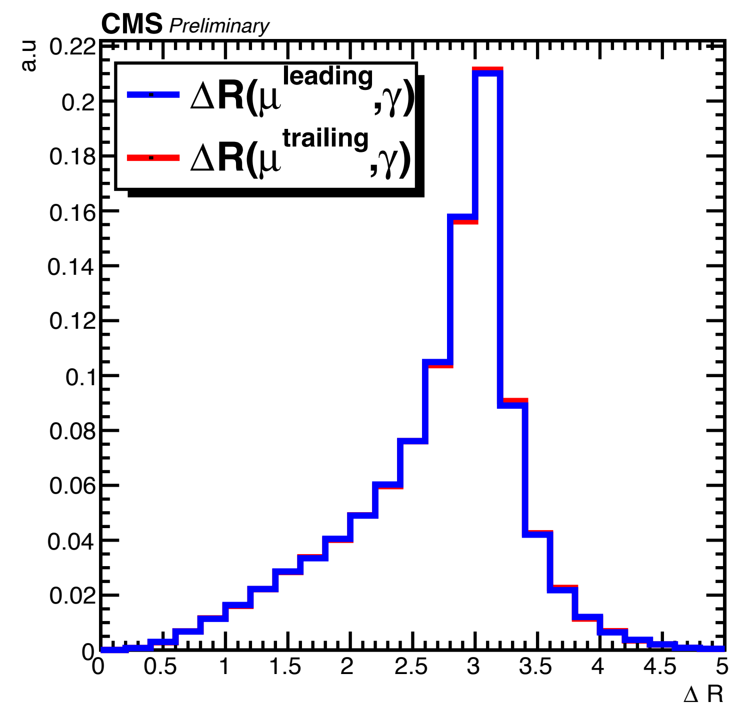




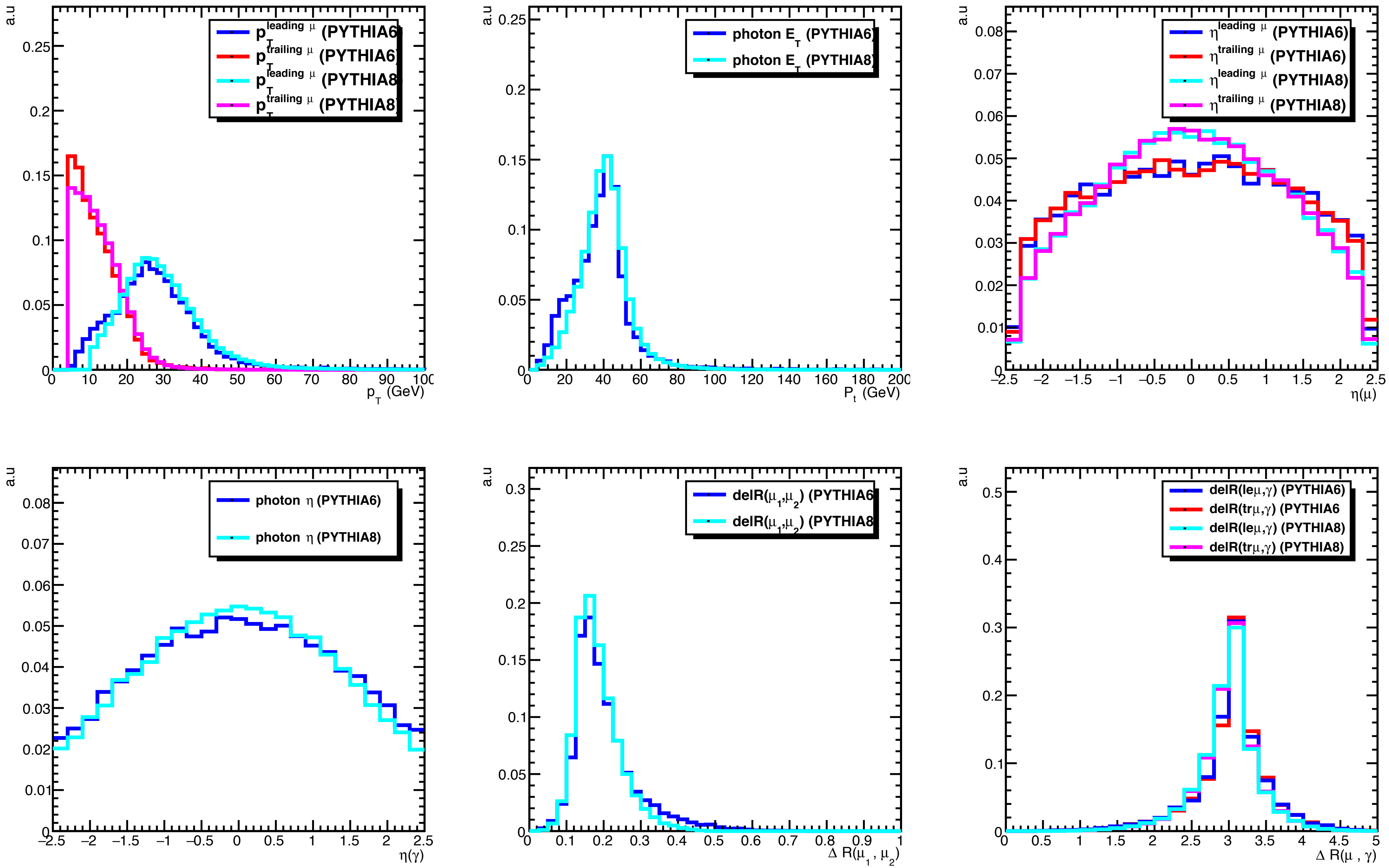




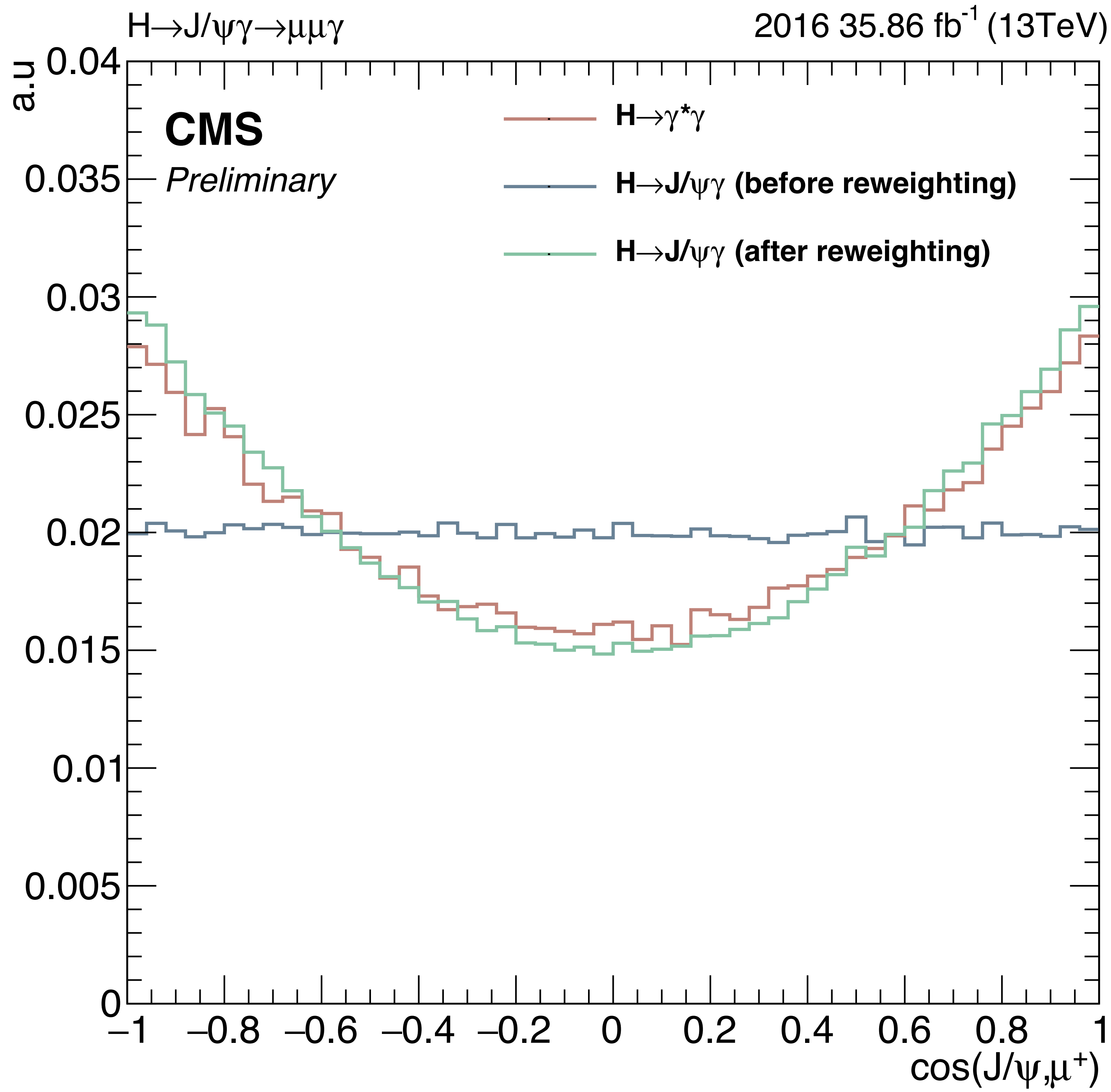




Kinematics at Gen. level - Z→(J/ψ)γ

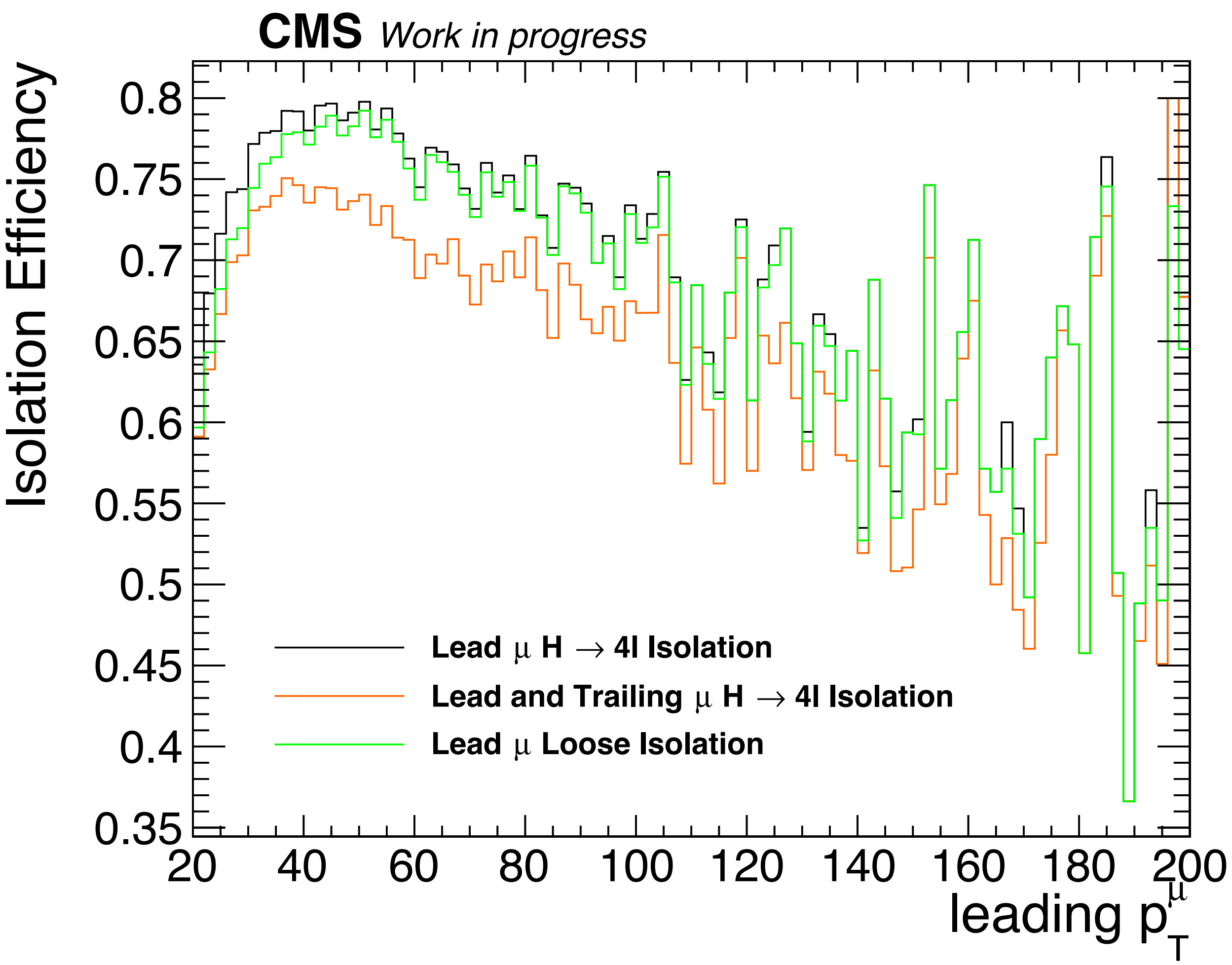


Polarization of J/ψ

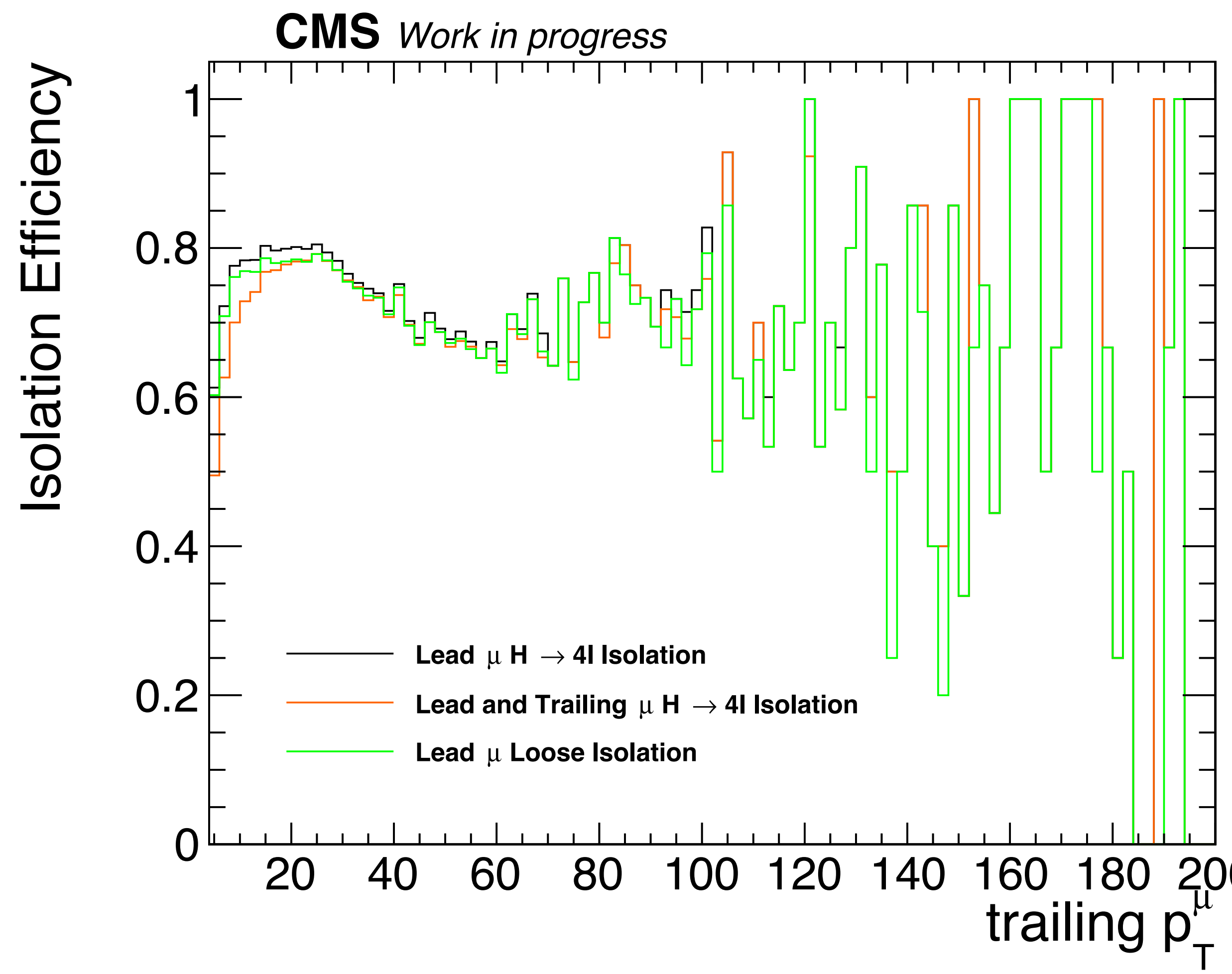


Efficiency of isolation

Eff. v.s $p_T^{\text{lead}\ \mu}$



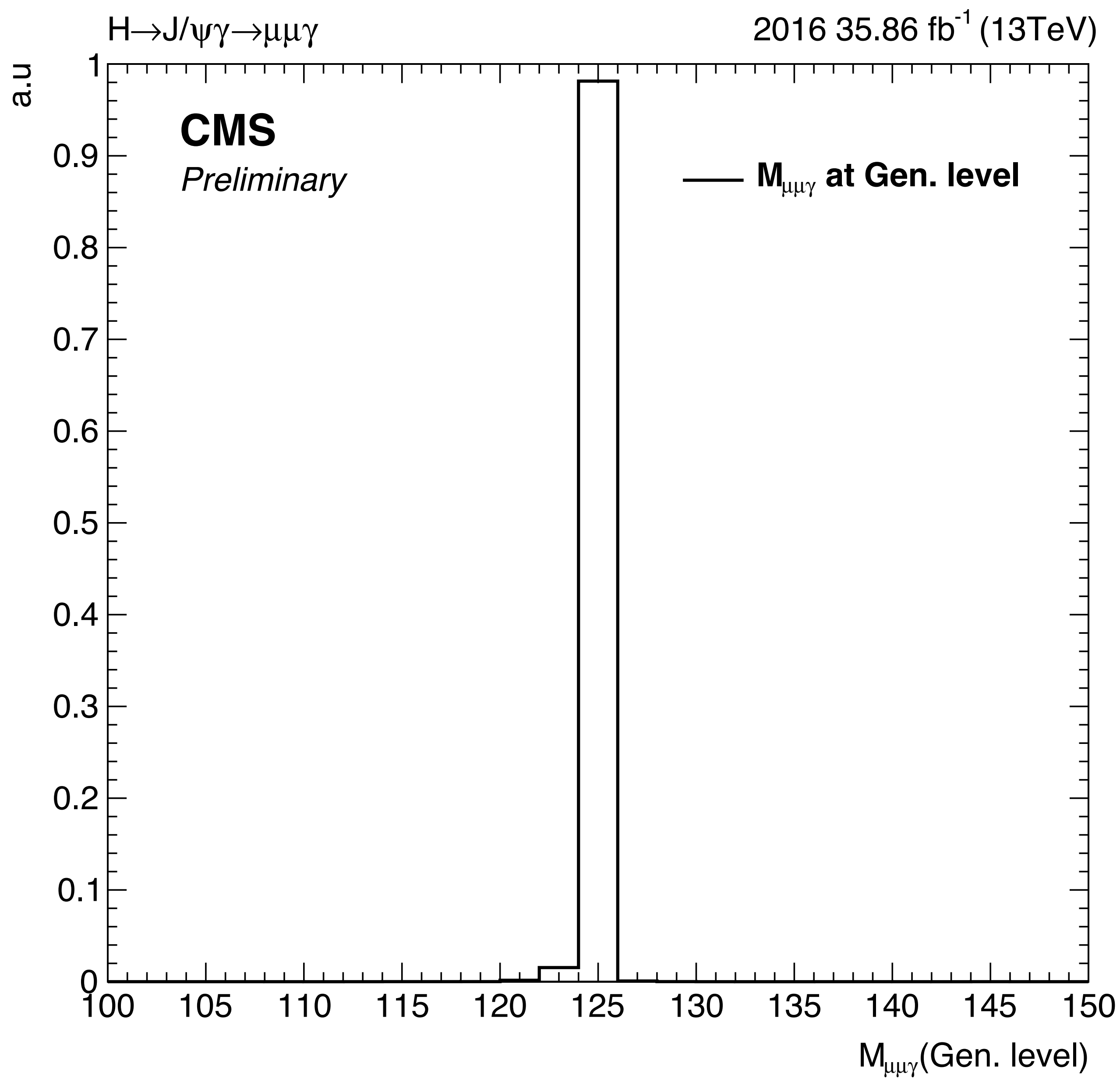
Eff. v.s $p_T^{\text{trail}\ \mu}$



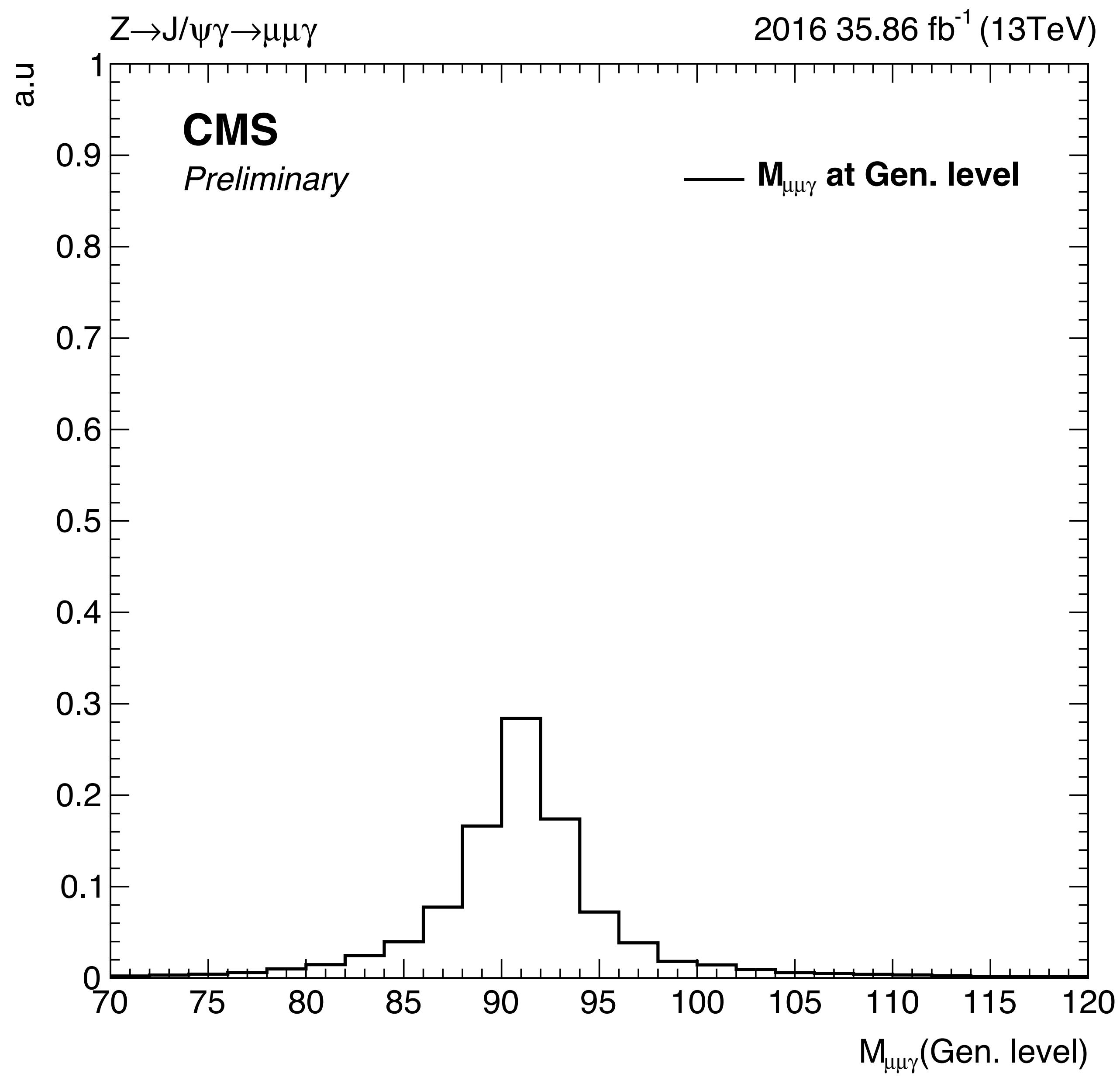
$H \rightarrow \gamma^*\gamma(\rightarrow \mu\mu\gamma)$ analysis

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

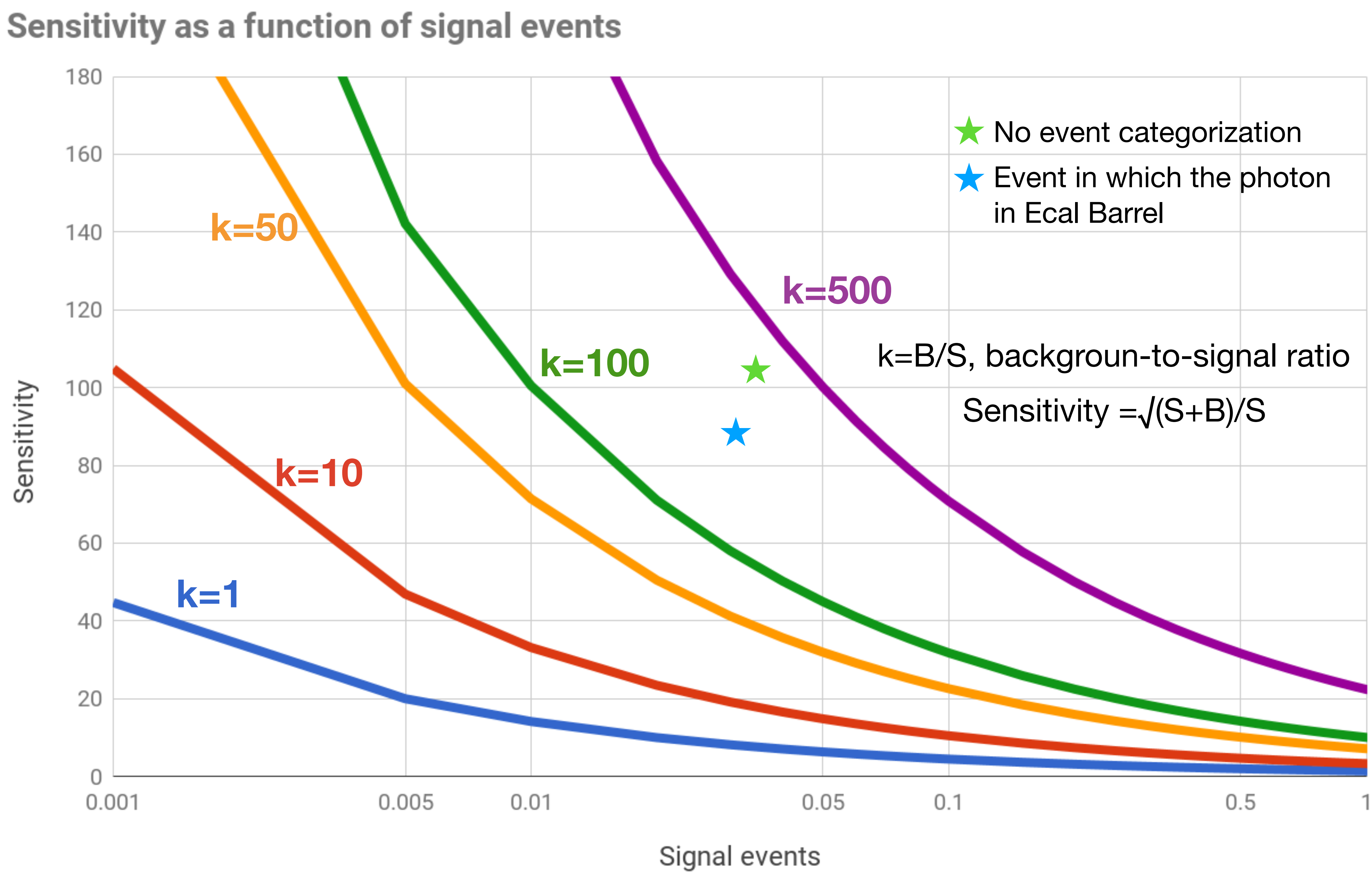
H→J/ψγ



Z→J/ψγ



Sensitivity



Projection

	Luminosity(fb^{-1})	Limit on BR	σ/σ_{SM}
$H\rightarrow J/\psi\gamma$ (Without categorization)	35.86 (2016 full datasets)	7.21×10^{-4}	258
	300 (Run-2)	2.34×10^{-4}	83.9
	3000 (HL-LHC)	6.93×10^{-5}	24.8
	Theoretical BR : 2.79×10^{-6}		
$Z\rightarrow J/\psi\gamma$ (Combination of 3 categories)	35.86 (2016 full datasets)	1.69×10^{-6}	17.0
	300 (Run-2)	5.73×10^{-7}	5.75
	3000 (HL-LHC)	1.79×10^{-7}	1.80
	Theoretical BR : 9.96×10^{-8}		