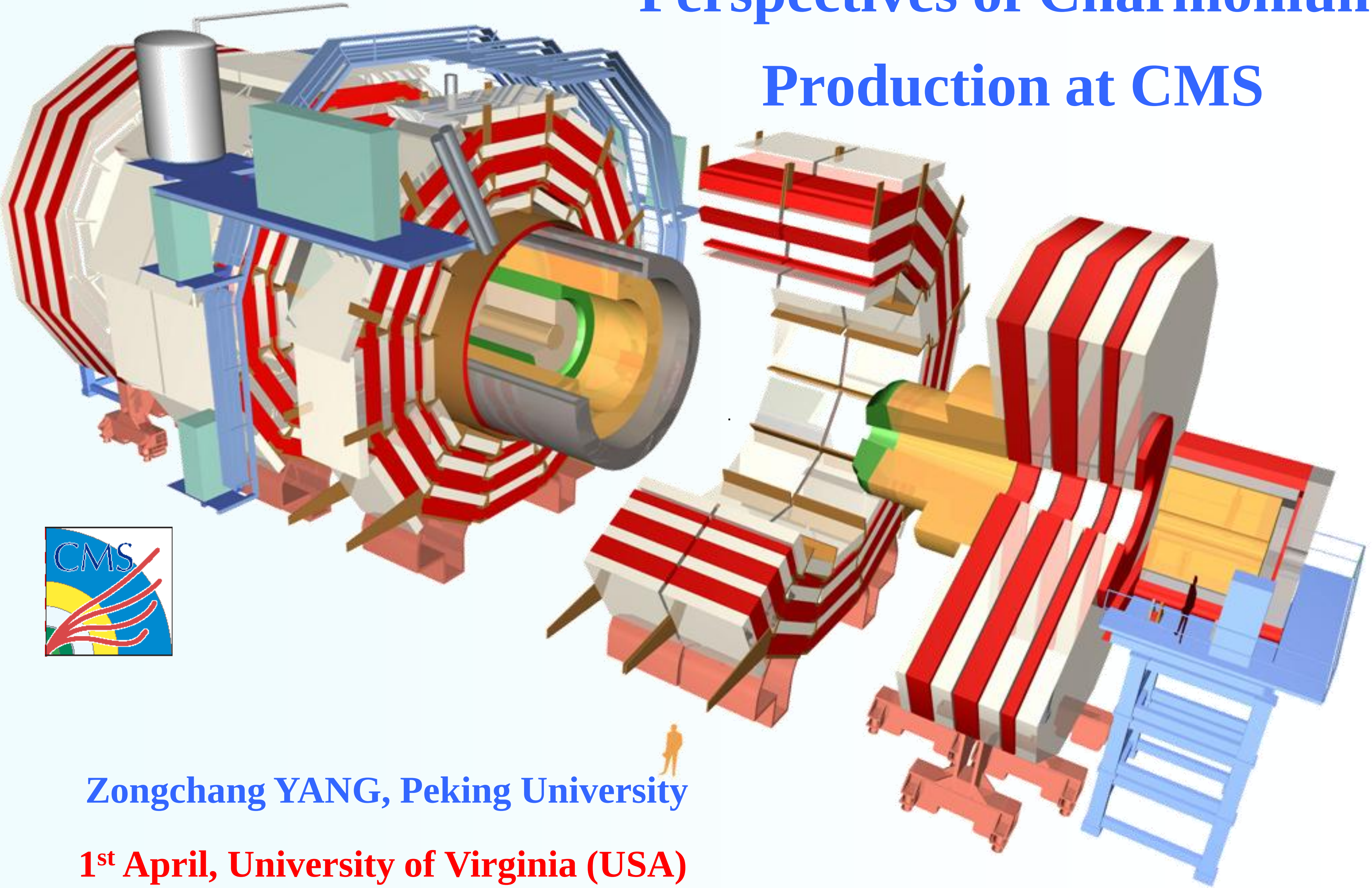
Perspectives of Charmonium Production at CMS



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1st April, University of Virginia (USA)

Outline

- Introduction to LHC, CMS and motivations
- Muon and di-muon trigger
- Muon and di-muon reconstruction
- Inclusive J/ψ cross-section measurement
- B fraction fit
- Misalignment effect in early data
- Systematic uncertainties
- Expected results at $3pb^{-1}$
- Muon performance with cosmic muons (real data)
- Summary

The Large Hadron Collider (LHC)

- **LHC: the world's largest particle accelerator at CERN, Geneva**

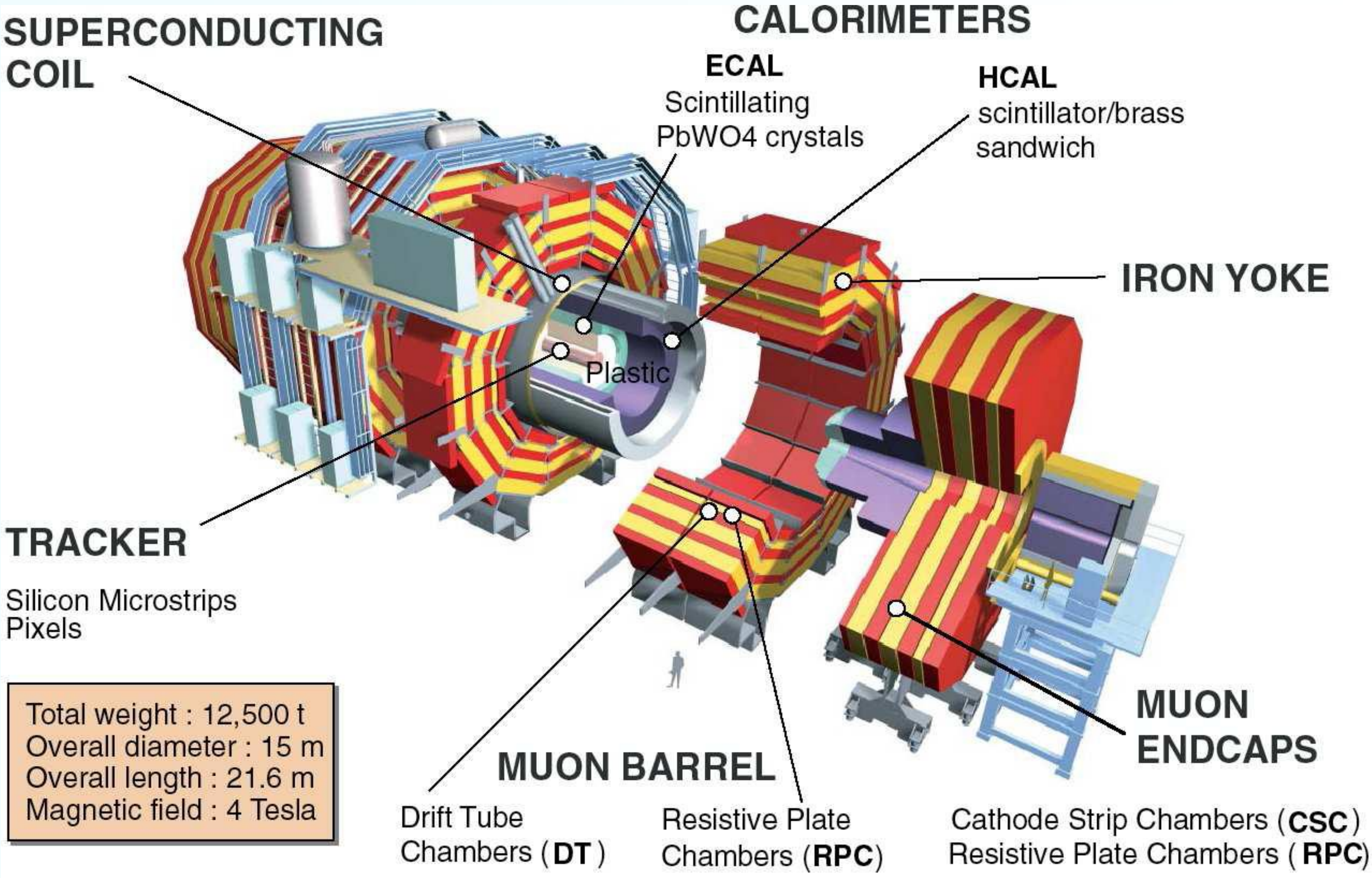
Circumference	**26658 m**
Momentum at collision	**7 TeV**
Design luminosity	**10^{34} cm^{2}s^{-1}**
Protons per bunch	**1.15×10^{11}**
Number of bunches	**2808**
Collision rate	**40 MHz**
Operating temperature	**1.9 K**

Some of the LHC parameters for *pp* operation.

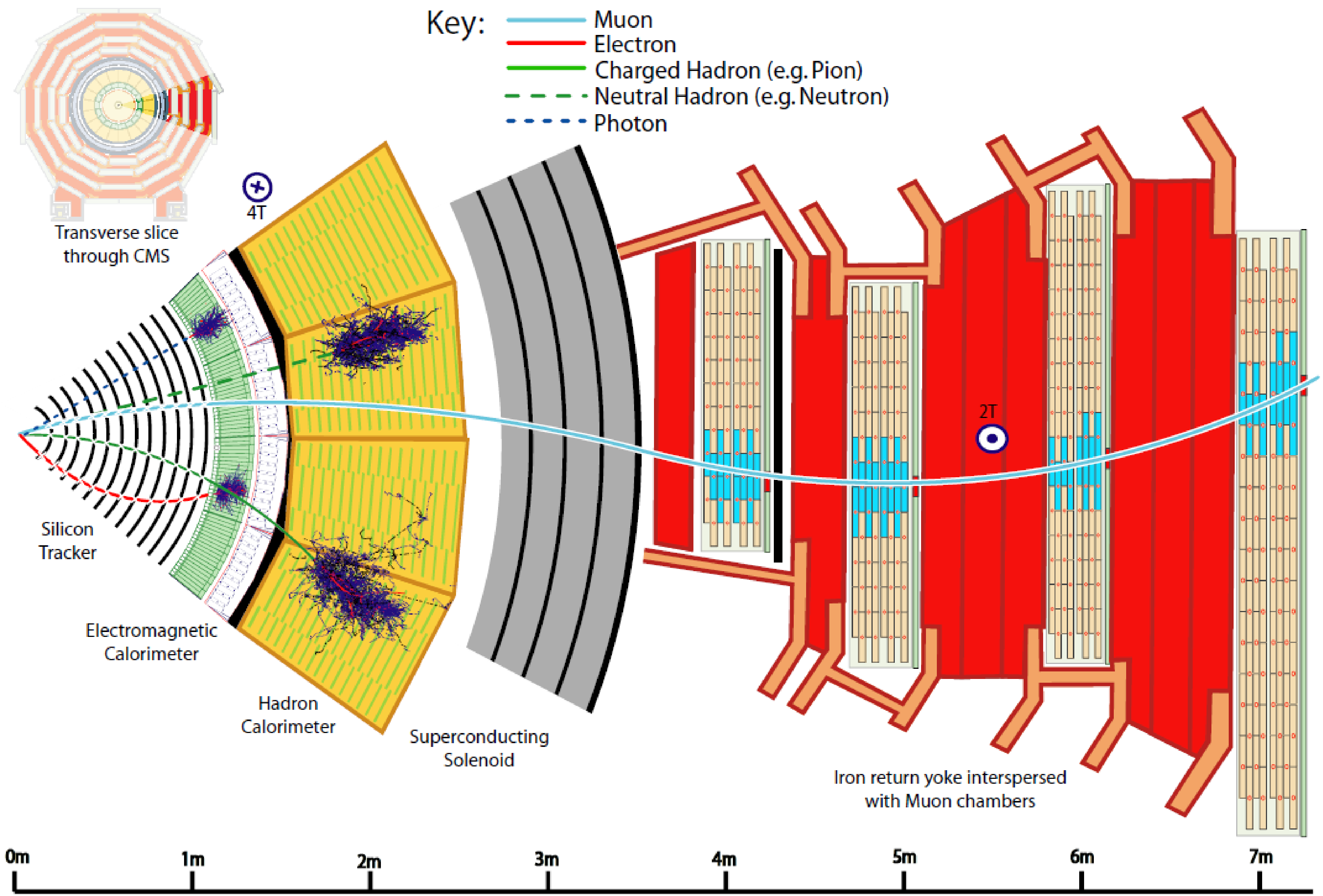
•LHC experiments: ALICE, ATLAS, CMS, LHCb, LHCf and TOTEM

The Compact Muon Solenoid (CMS)

More than 2000 scientists, from 155 institutes in 37 countries

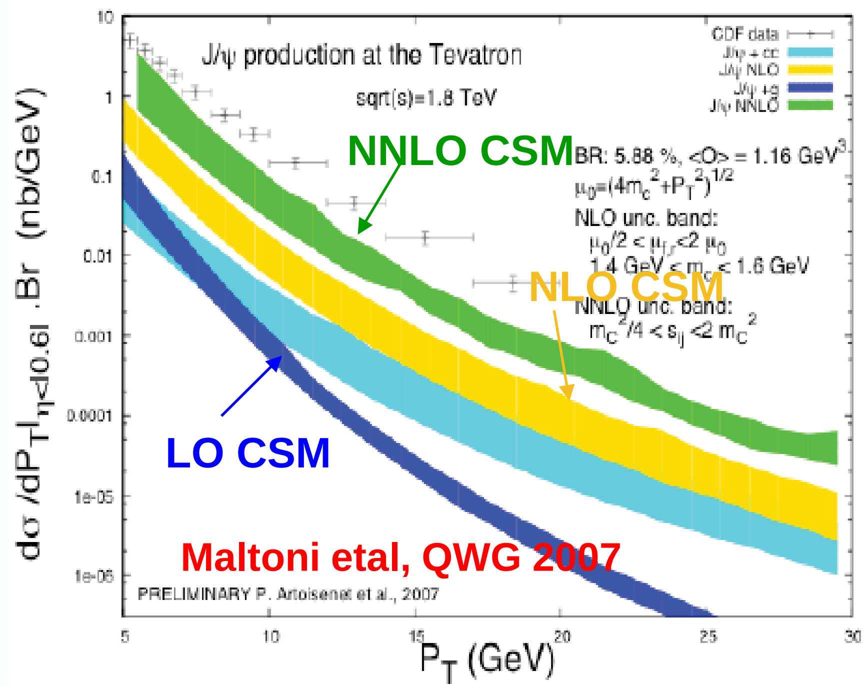


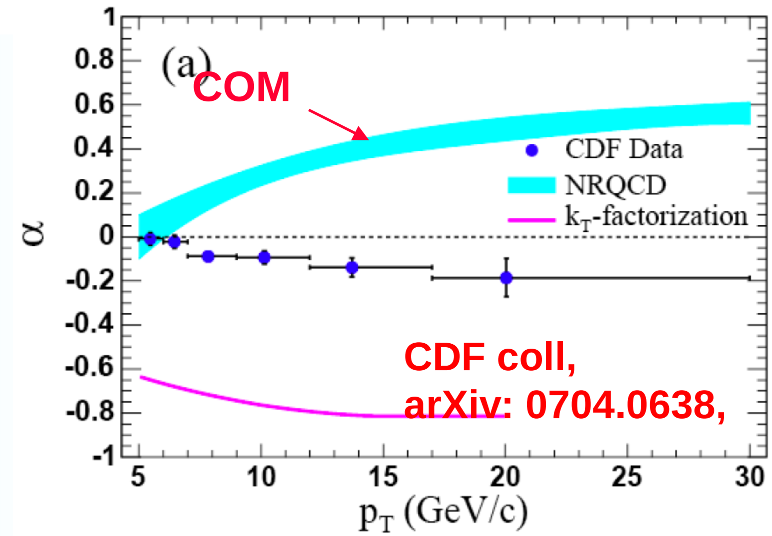
Interactions in the CMS detector



Motivations

- The J/ψ production is dominated by:
  - prompt J/ψ:
    - direct J/ψ production
    - indirect from prompt χ_{c0}, χ_{c1}, χ_{c2}..
  - non-prompt J/ψ: from B hadrons decay
- Prompt puzzle: no satisfactory models fit x-section and polarization simultaneously, for example :
  - CSM (Color Singlet Model) : LO, NLO, NNLO
    - can not explain the cross section
  - COM (Color Octet Mechanism): NRQCD
    - COM means polarization
- Motivations:
  - Quarkonia production and polarization for theoretical interest
  - J/ψ and Y are crucial to understand the detector performance:
    - alignment and calibration
    - muon efficiency
  - Can be done with first data, <=10pb^{-1}





CMS Detector for Quarkonia

Muon system:

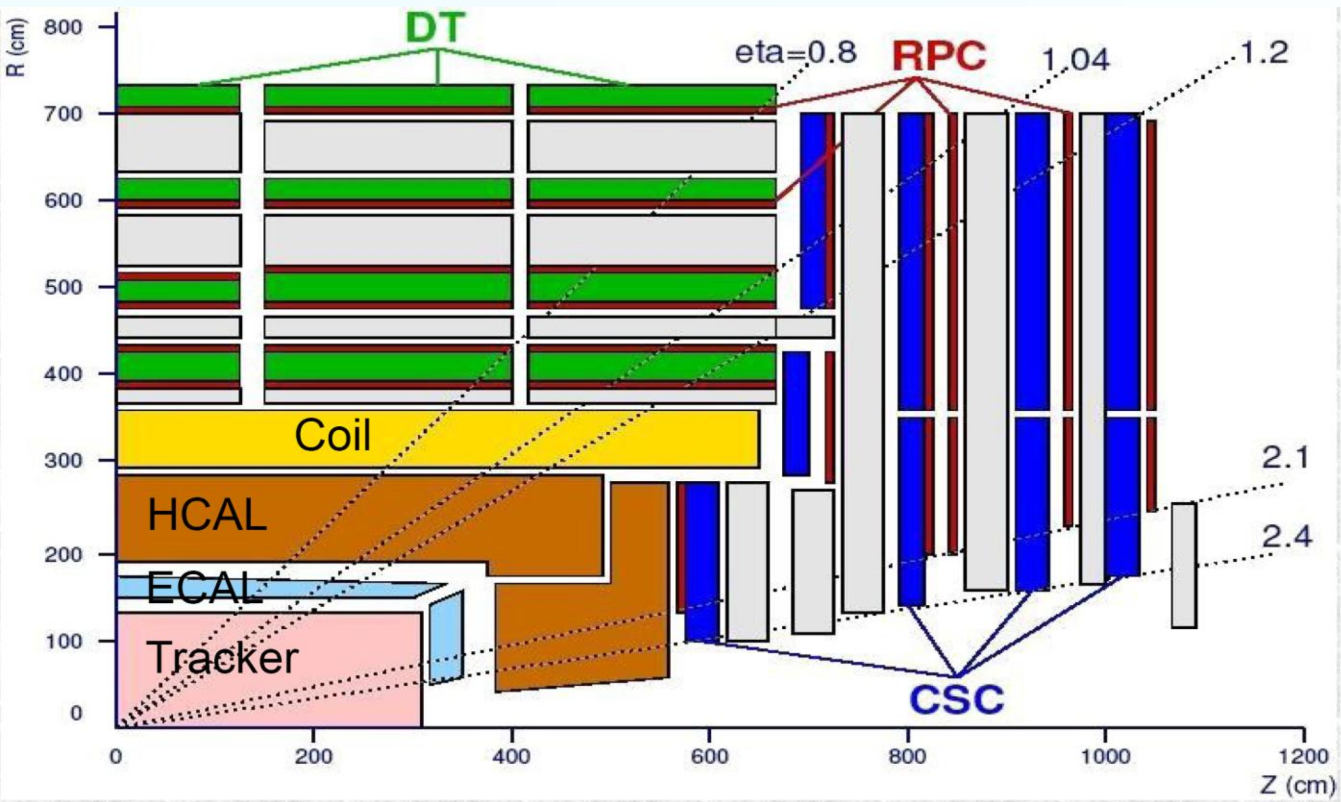
- **Drift Tubes (DT) in central barrel region**
- **Cathode Strip Chambers (CSC) in endcap region**
- **Resistive Plate Chambers (RPC) in barrel and endcap**

} ➡ **precise measurement of position (momentum)** (DT, CSC)

➡ **fast info for LVL-1 trigger** (RPC)

Tracker system:

- **Silicon pixel layers (3 in barrel, 2 in endcap)**
- **Silicon strips layers (10 in barrel, 12 in endcap)**



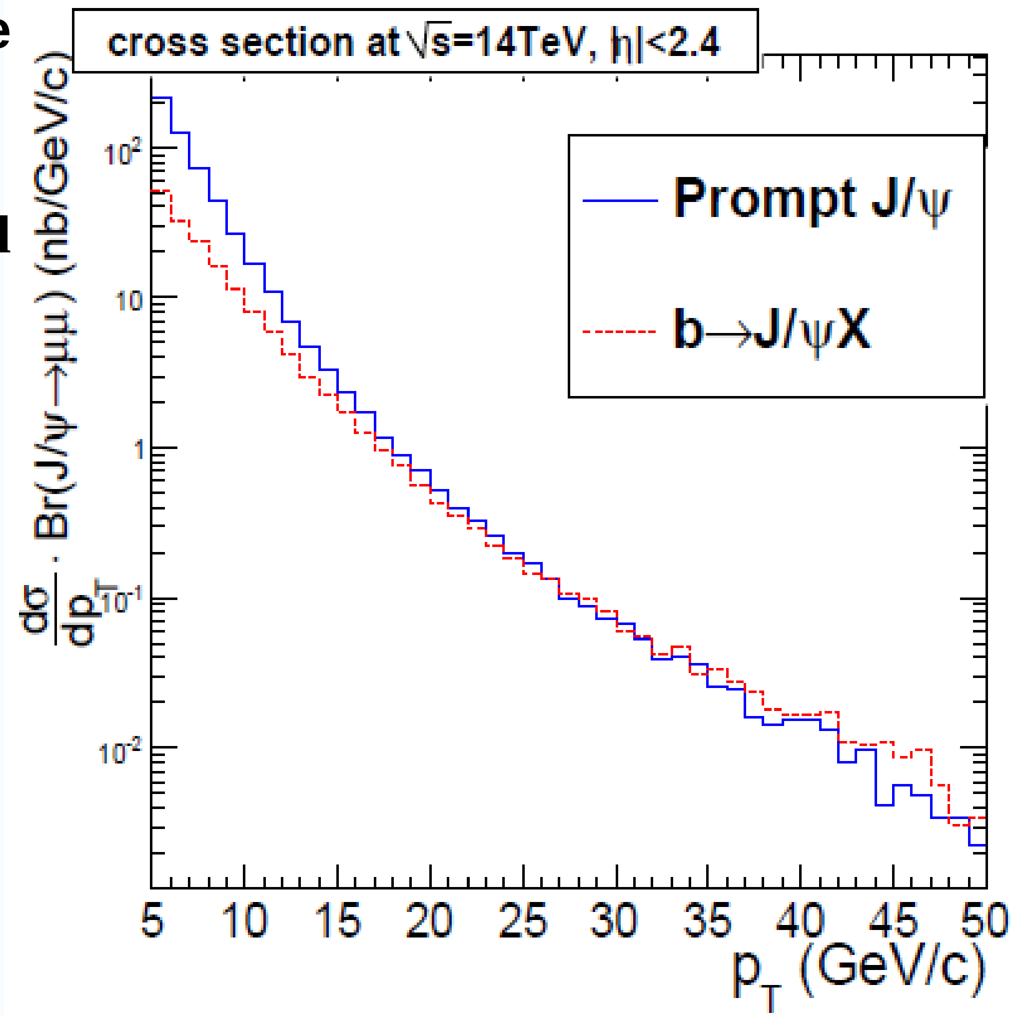
- **Excellent coverage:**
  ~5 units of rapidity and 2π of ϕ
- **Strongest magnetic field:**
  4 T, 2 T (return yoke)
- **Tag from muon stations, momentum resolution from Silicon tracker:**
  ~2% of momentum resolution for tracks with p_T <100 GeV
- **Ecal+Hcal+Coil – absorbs hadrons**

Charmonium generation

- **Prompt J/ψ production: NRQCD COM+CSM processes in Pythia (see backup slides) with NRQCD matrix elements from: hep-ph/0003142**
  - **CSM values extracted from potential models (hep-ph/9503356)**
  - **COM values from CDF data**
  - **Total 0.3846 mb at 14 TeV**

- **B hadrons production: MSEL=1 in Pythia and decay with EvtGen**
  - **gluon fusion (50μb)**
  - **gluon splitting (190μb)**
  - **flavor excitation (220μb)**

- **Prediction of the differential cross-section of prompt J/ψ and B-decay J/ψ at LHC, 14TeV (right).**

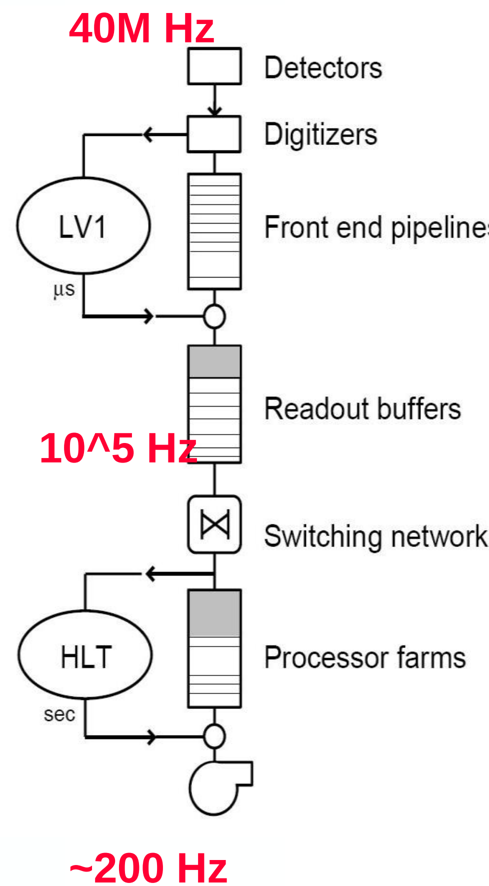


The L1 and HLT muon trigger

CMS muon trigger

HLT path	L1 seeds	Description
HLT_Mu3	L1_SingleMu3	one L3 muon pT>3 GeV/c, |η|<2.1
HLT_Mu5	L1_SingleMu3	one L3 muon pT>5 GeV/c, |η|<2.1
HLT_Mu9	L1_SingleMu7	one L3 muon pT>9 GeV/c, |η|<2.1
HLT_DoubleMu3	L1_DoubleMu3	two L3 muon pT>0 GeV/c, |η|<2.4
HLT_JPsiMuMu	L1_DoubleMu3	two L3 muon pT>0 GeV/c, |η|<2.4 , mass window cut [2.8, 3.4]
HLT_UpsilonMuMu	L1_DoubleMu3	two L3 muon pT>0 GeV/c, |η|<2.4 , mass window cut [8, 12]

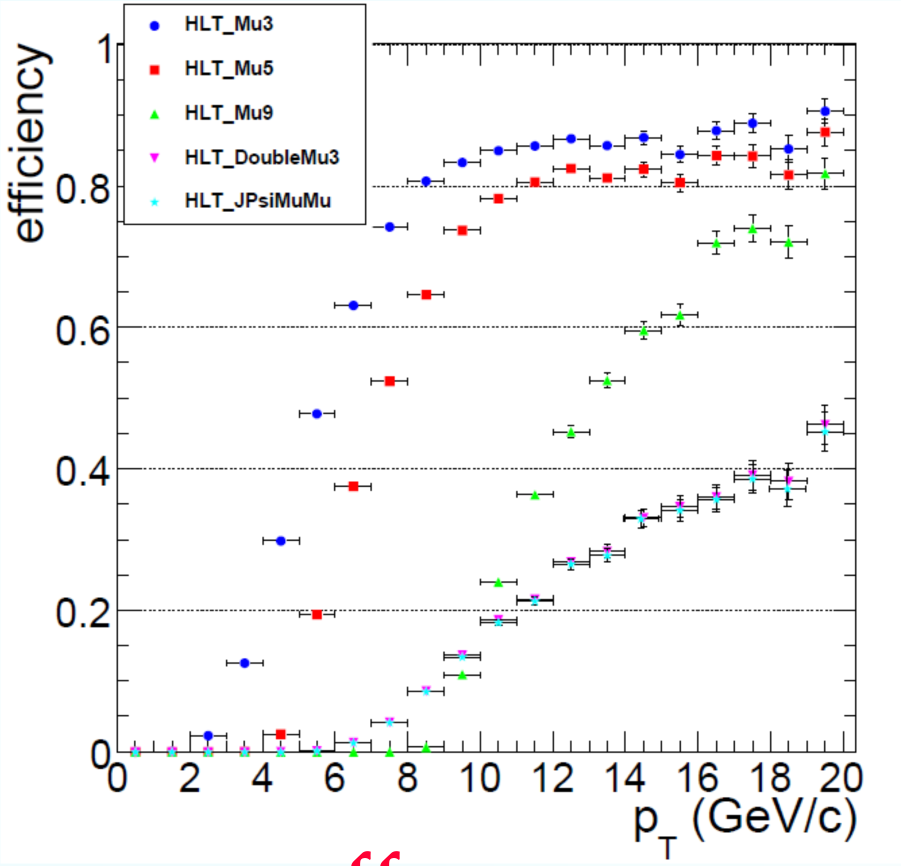
CMS trigger system



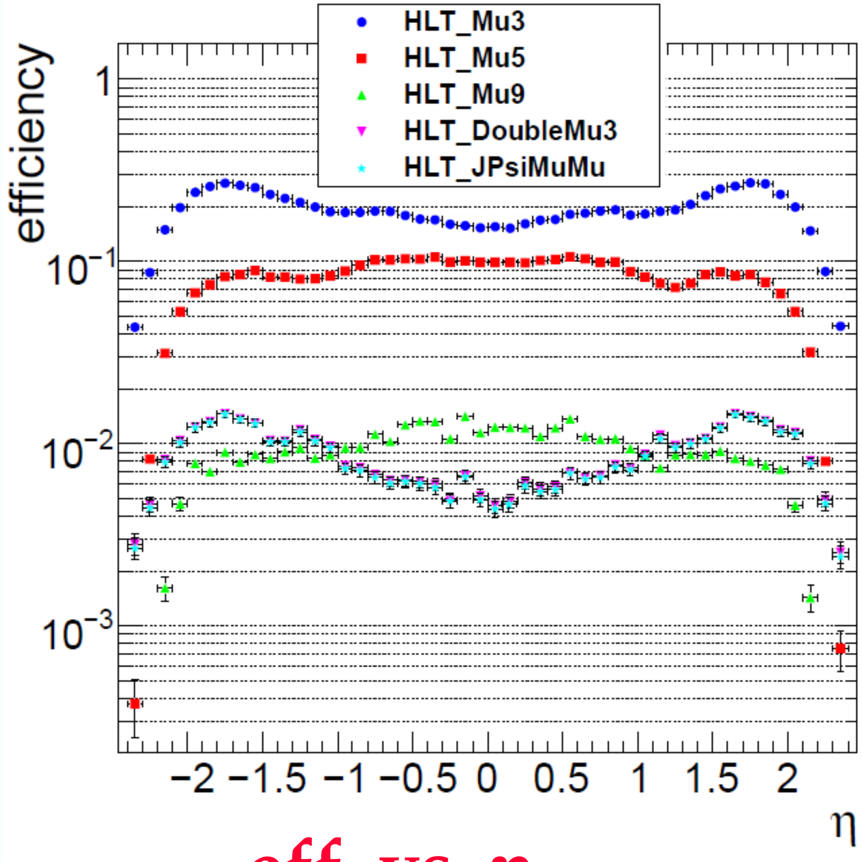
For example, the CMS dimuon trigger :

- **L1 filter: hardware-based**
  - **DT's range |η|<1.2; CSC 0.9<|η|<2.4; RPC |η|<2.1**
  - **Two L1 muons p_T>3GeV/c, |η|<2.5**
- **HLT L2 filter: on-line reconstructed L2 muons from the muon system (DT, CSC)**
  - **Two L2 muons p_T>3GeV/c, |η|<2.5**
- **HLT L3 filter: using L2 muons as input and constrain to the interaction region in the silicon tracker.**
  - **Two L3-μ p_T>3GeV/c, |η|<2.5**

J/ψ HLT trigger efficiency



eff. vs. p_T



eff. vs. η

The pre-scale factors and trigger rates

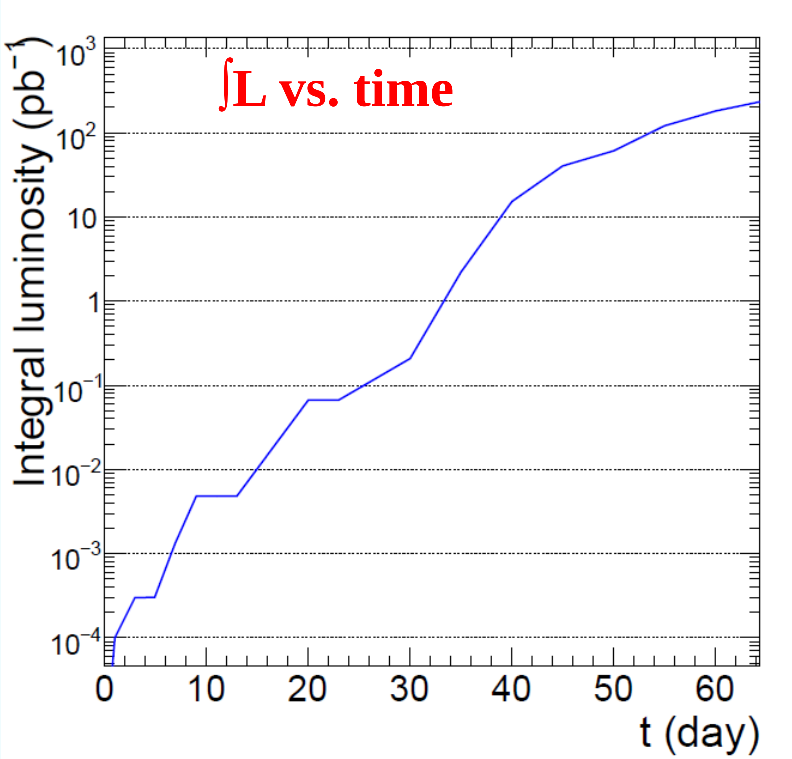
• The prescale factors and unprescaled trigger rates at luminosity = 8E29 $cm^{-2}s^{-1}$.

HLT path	Prescale	Prompt J/ψ	B-decay J/ψ	background	Total
HLT_Mu3	1	0.256 Hz	0.0838 Hz	15.6 Hz	15.9 Hz
HLT_Mu5	1	0.107	0.0472	6.23	6.38
HLT_Mu9	1	0.0116	0.00886	0.814	0.834
HLT_DoubleMu3	1	0.0120	0.00793	0.122	0.142
HLT_JPsiMuMu	1	0.0117	0.00630	0.00294	0.0209

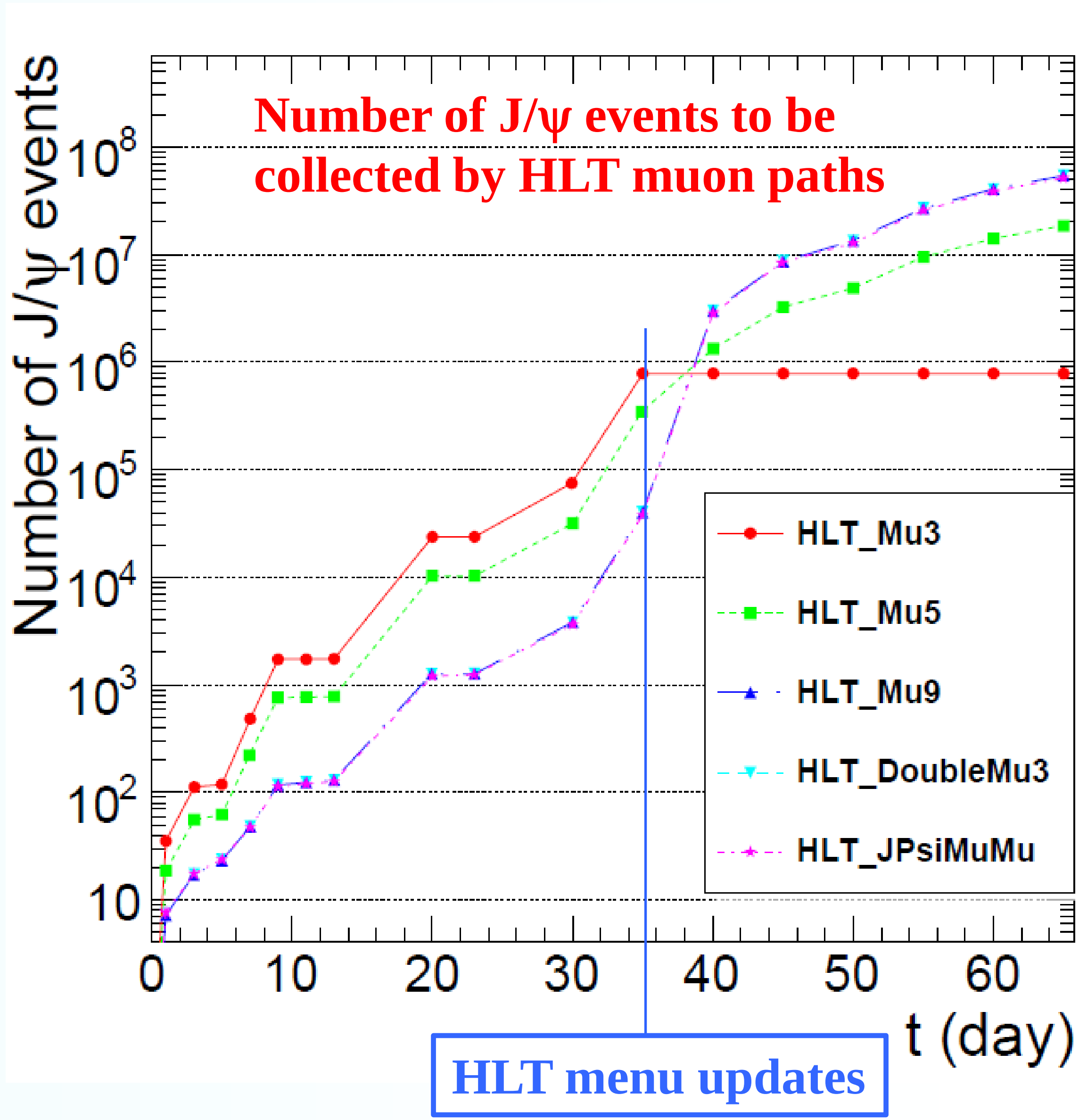
• The prescale factors and unprescaled trigger rates at luminosity = 1E31 $cm^{-2}s^{-1}$.

HLT path	Prescale	Prompt J/ψ	B-decay J/ψ	background	Total
HLT_Mu3	**infinity**	3.20 Hz	1.05 Hz	195 Hz	None
HLT_Mu5	25	1.34	0.590	77.4	79.8 Hz
HLT_Mu9	1	0.145	0.111	10.2	10.5
HLT_DoubleMu3	1	0.150	0.099	1.53	1.78
HLT_JPsiMuMu	1	0.146	0.079	0.037	0.261

Expected number of J/ψ events



- In the first run of 2009-2010, the total integral luminosity is about 200 pb^{-1} .
- The new plan is to measure the cross section at 3pb^{-1} by using HLT_Mu3 path.



Muon and J/ψ reconstruction

Reconstructed muons and J/ψs

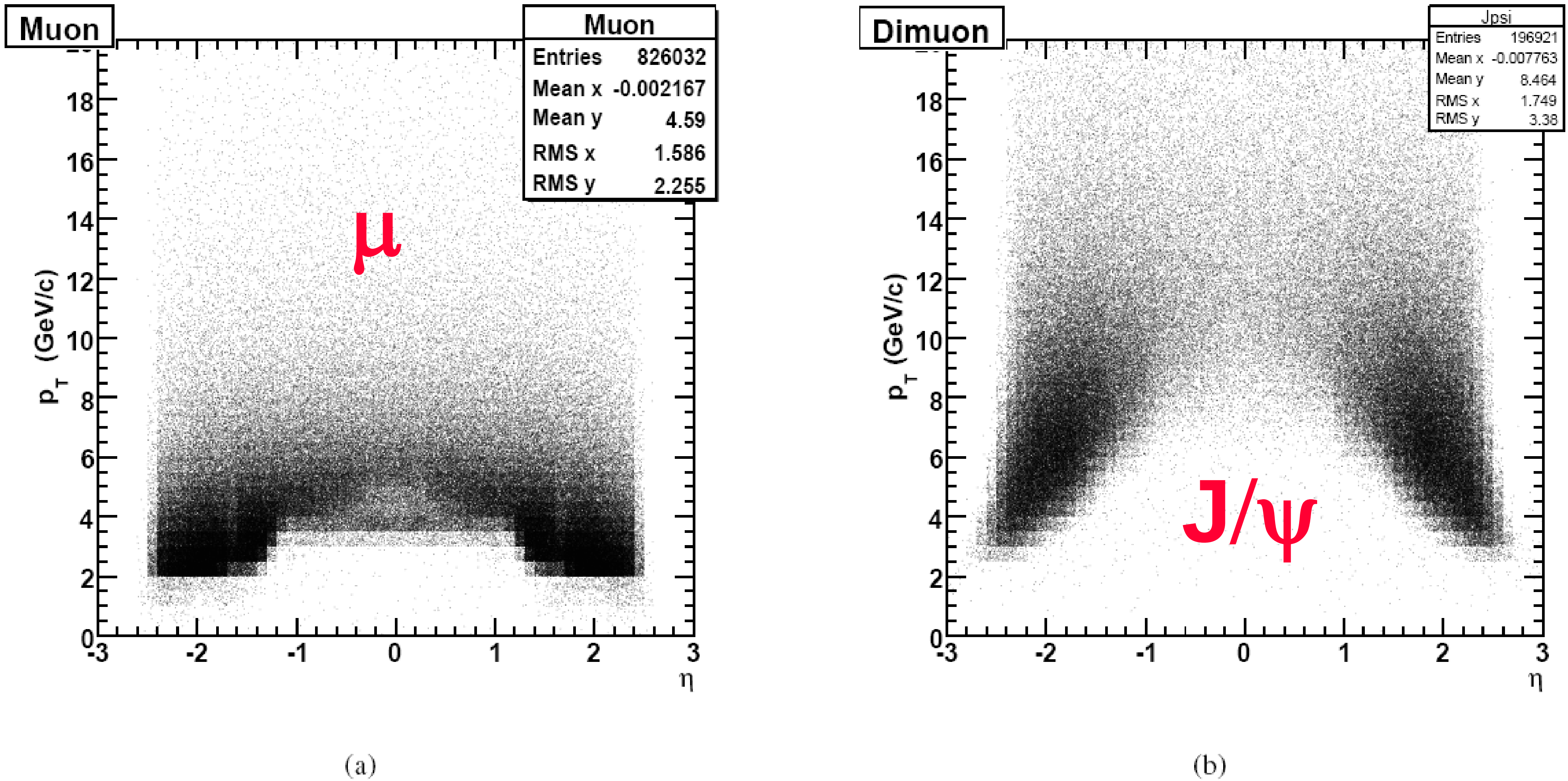
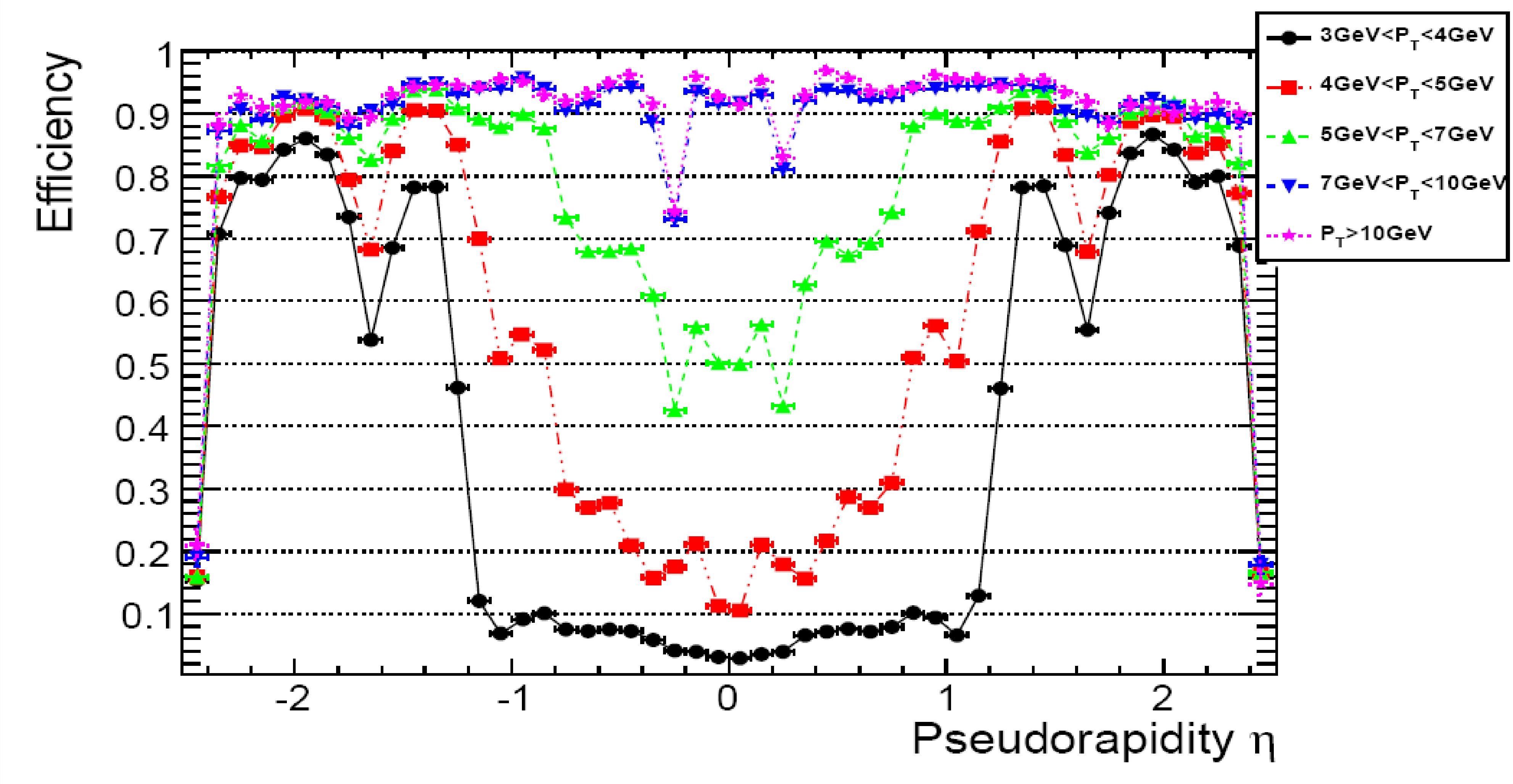


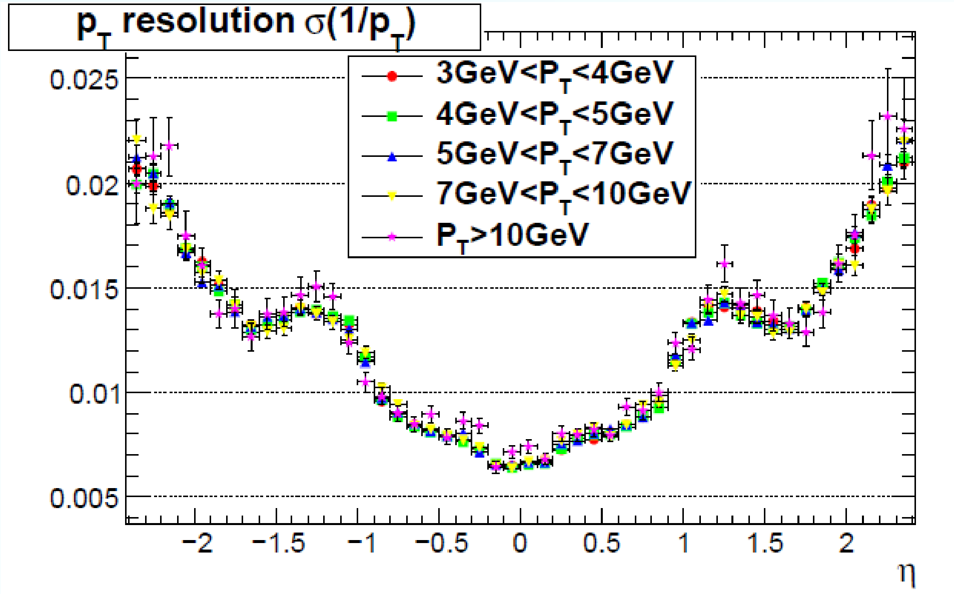
Figure 7: The η and p_T 2D distributions of muon and prompt J/ψ for reconstructed J/ψ-events.

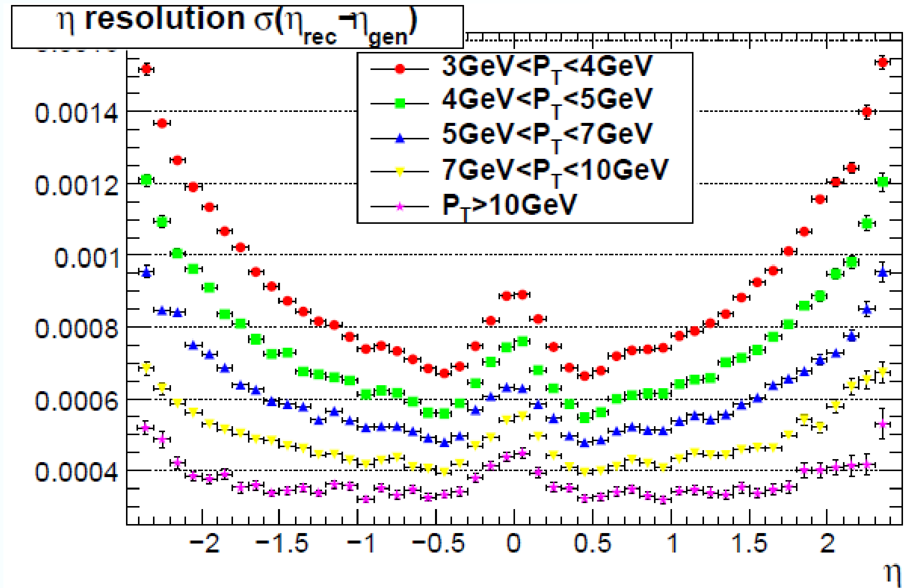
Muon Acceptance



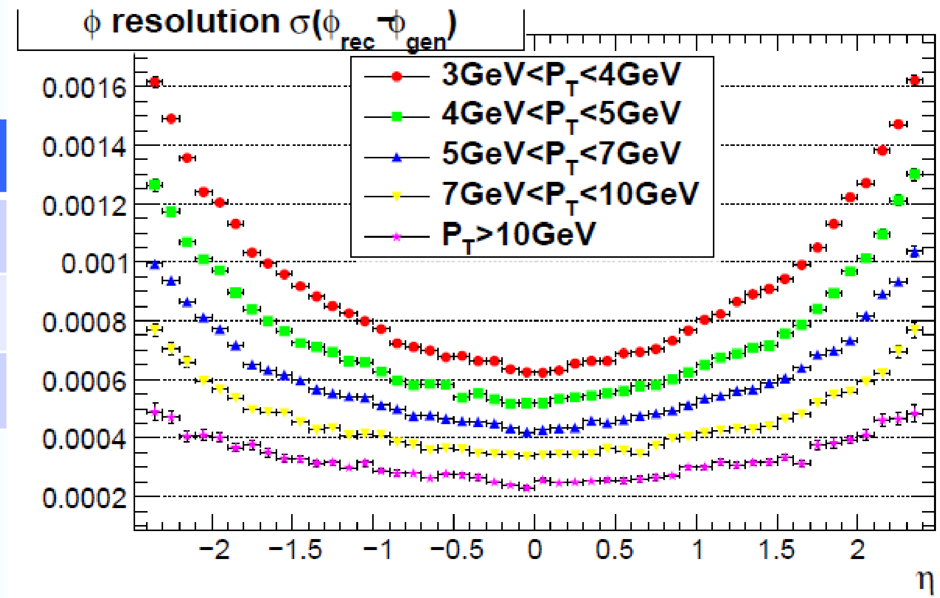
•We calculated the efficiency by matching the global reconstructed muon with MC truth: (1) same charge, (2) $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, (3) $\Delta p_T / p_T < 0.2$

Muon reconstruction performance





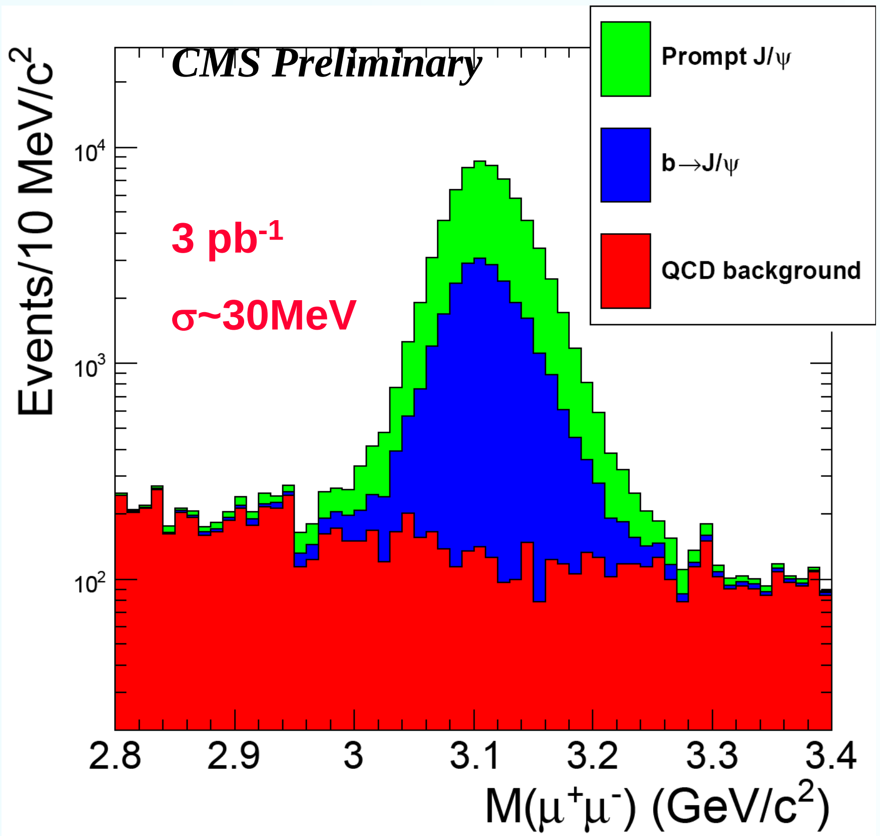
	barrel	transition	end-cap
$\sigma(1/p_T)$	0.6~1.0%	1.1~1.5%	1.5~2.3%
$\sigma(\eta)$	0.0003~0.0016		
$\sigma(\phi)$	0.0002~0.0016		

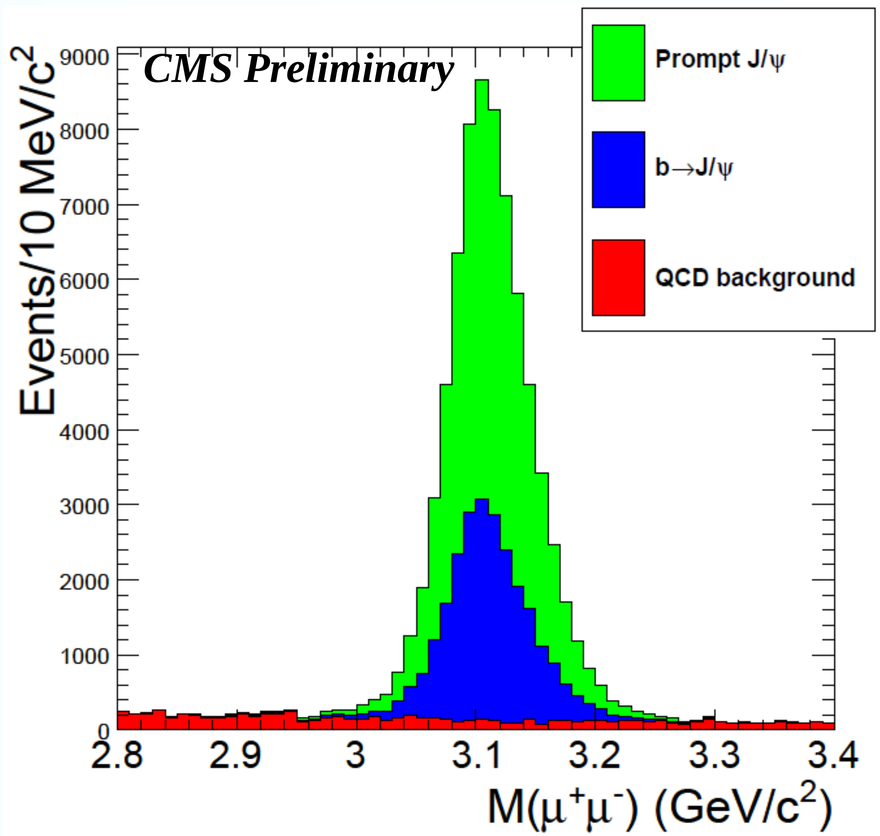


J/ψ selection

- We selected reconstructed global muon pairs by requiring:
  1. HLT_DoubleMu3 trigger
  2. Opposite charge.
  3. Each muon p_T>3GeV/c, $|\eta|$<2.4.
  4. Dimuon invariant mass between 2.8 to 3.4GeV/c^2.
  5. Two muons come from a common vertex.

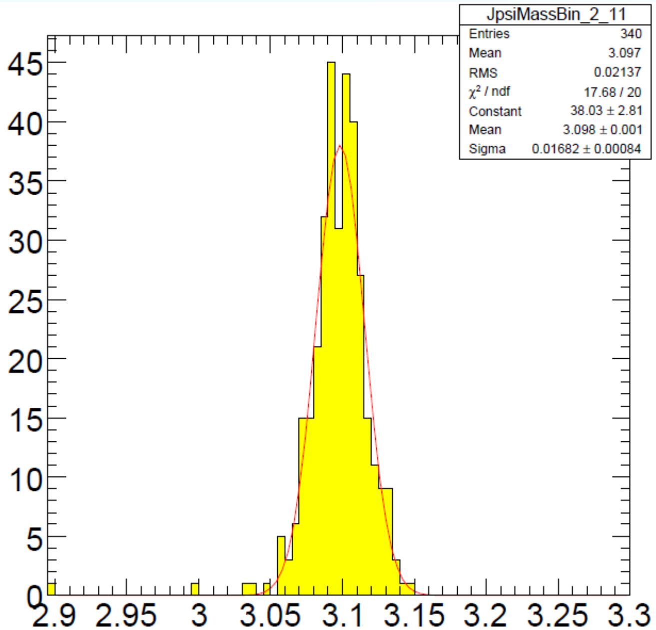
Offline selection criteria will depend on the trigger selection.





J/ψ mass distribution

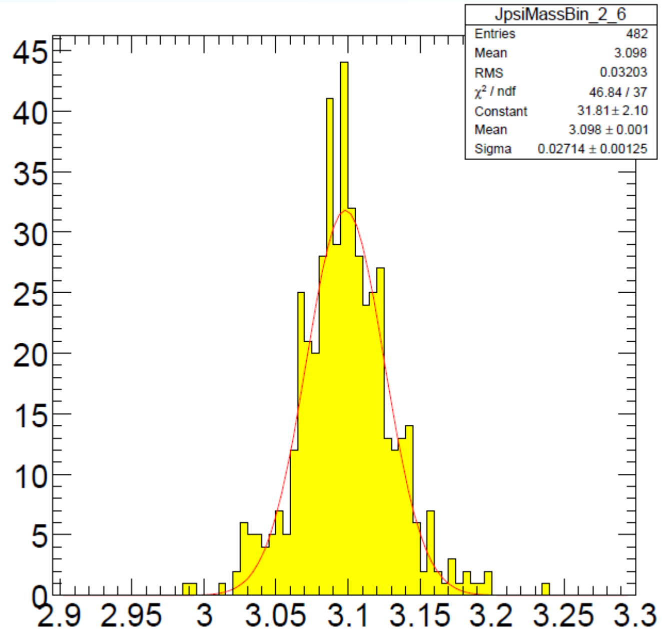
- We divided J/ψ into p_T and η bins and fit the mass distribution in each bin with a single Gaussian:



0.0<|η|<0.2

Mean=3.098 GeV/c^2

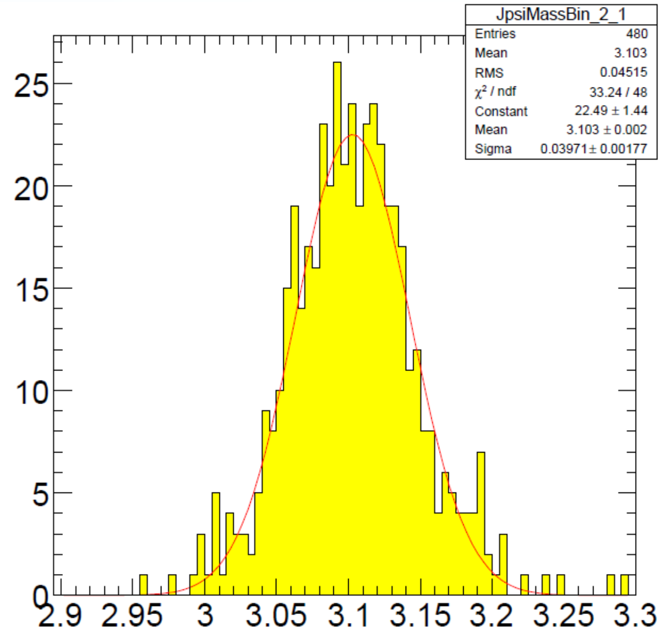
σ=16.8 MeV/c^2



1.0<|η|<1.2

Mean=3.098 GeV/c^2

σ=27.1 MeV/c^2

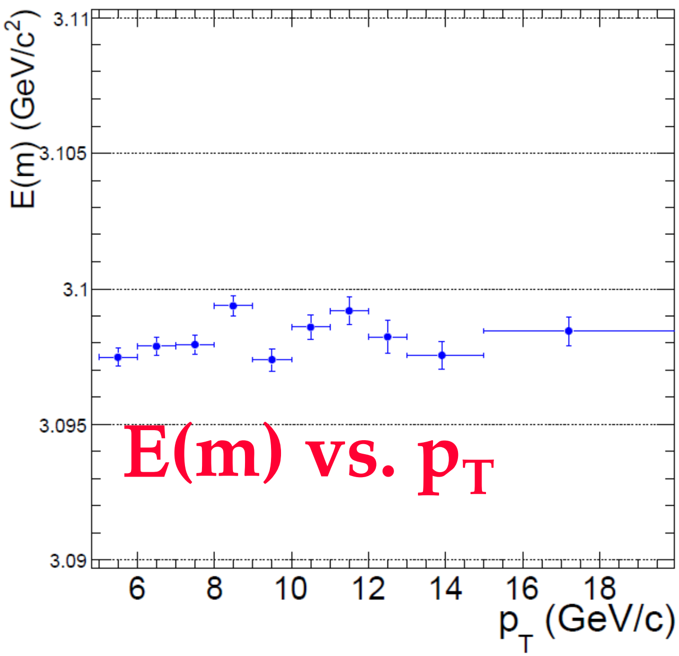


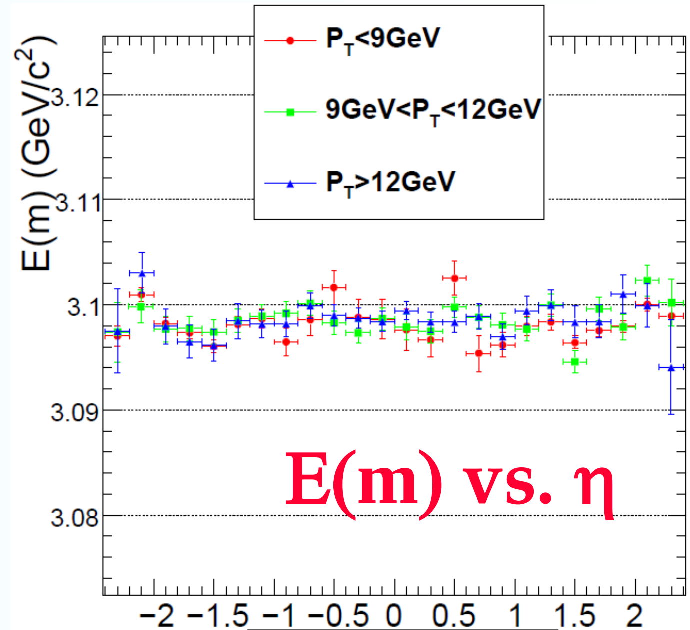
2.0<|η|<2.2

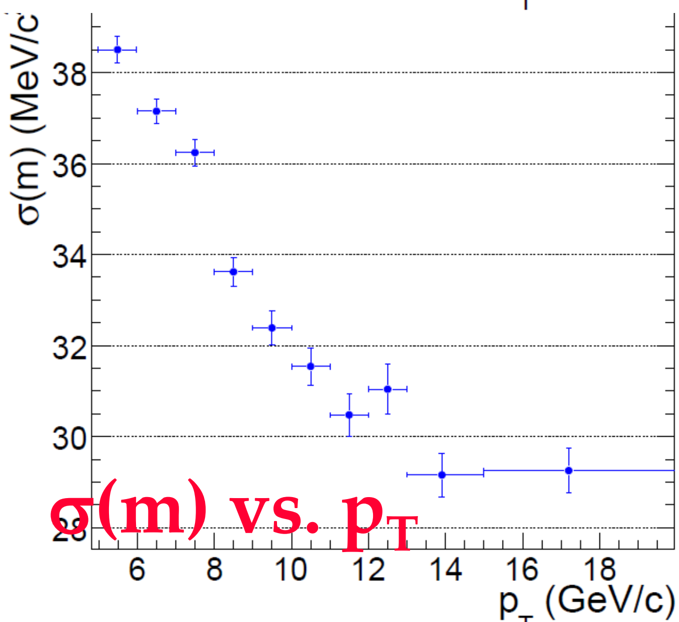
Mean=3.103 GeV/c^2

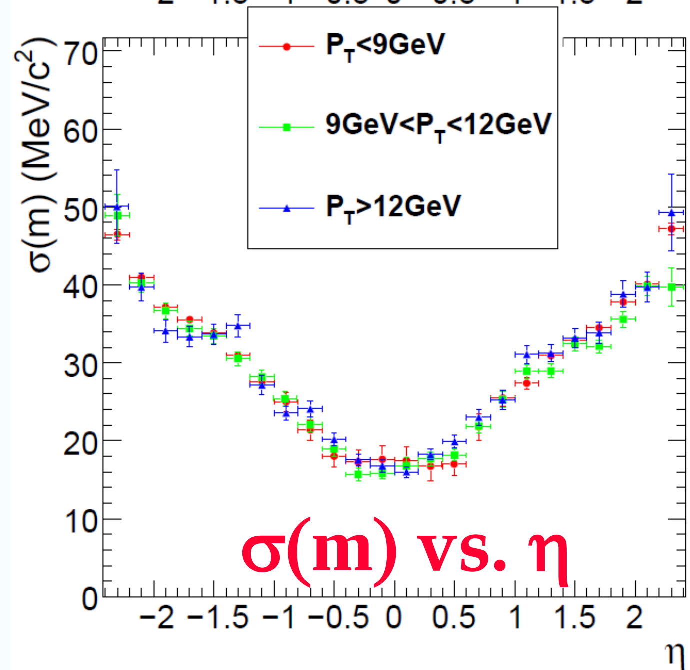
σ=39.7 MeV/c^2

J/ψ mass resolution









Inclusive J/ψ cross-section

Measurement of Cross-section

- Following the CDF measurement, the inclusive J/ψ cross-section is determined by

$$\frac{d\sigma}{dp_T}(J/\psi)\cdot Br(J/\psi\rightarrow\mu^+\mu^-) = \frac{N^{sig}_{J/\psi}}{\int Ldt\cdot A\cdot\lambda^{corr}_{trigger}\cdot\lambda^{corr}_{reco}\cdot\Delta p_T}$$

1. $\int Ldt$: the integral luminosity
2. ΔP_T : the size of the pT bin. We divided into 15 bins from 5 to 40 GeV/c
3. N_{sig} : the number of reconstructed J/ys from fitting
4. A : the total efficiency determined from MC simulation
5. $\lambda^{corr}_{trigger}$ and λ^{corr}_{reco}: correction factors to the trigger and offline efficiencies, as measured in data compared to the MC.

J/ψ mass fitting

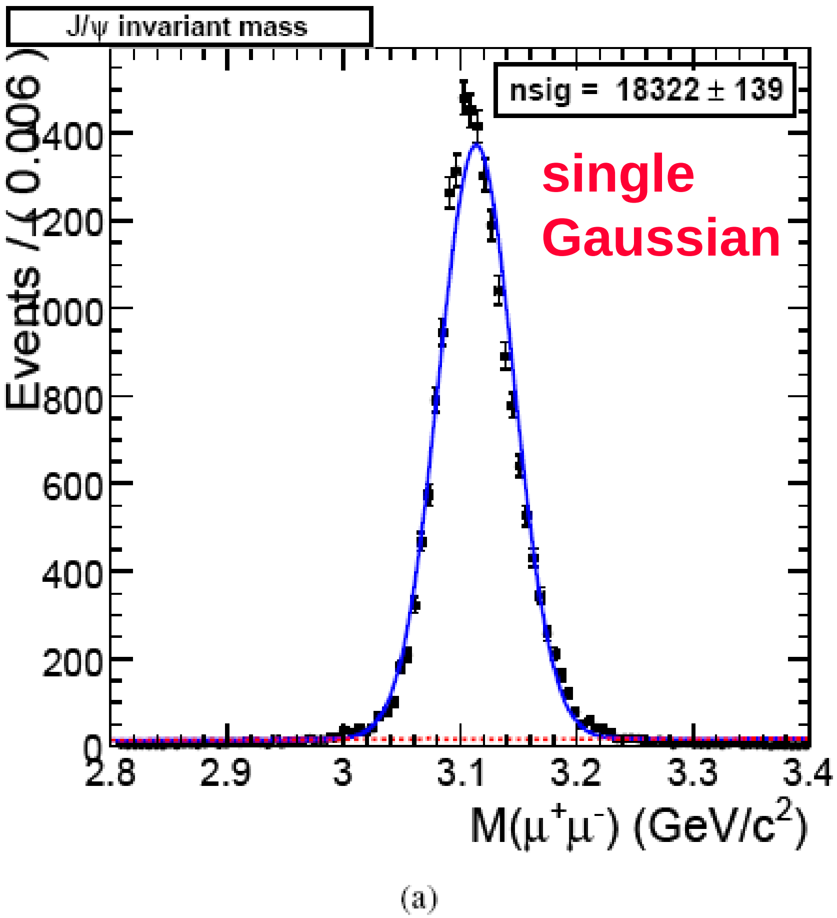
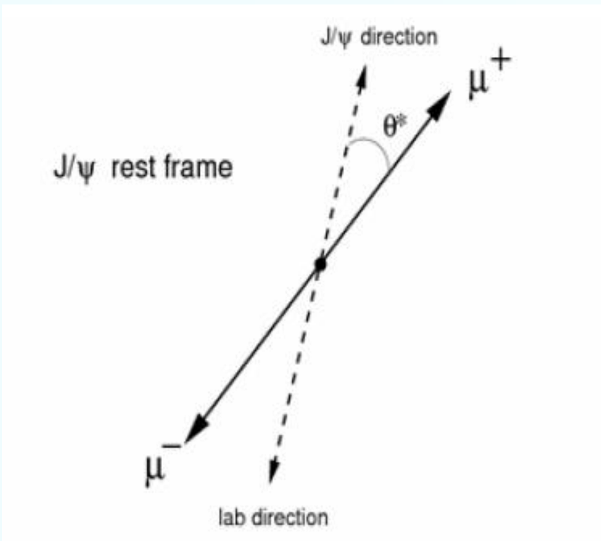


Figure 18: Mass distribution fit with linear background and signal peak of a simple Gaussian (a) or double Gaussian (b) in pT range 9GeV/c< p_T <10GeV/c.

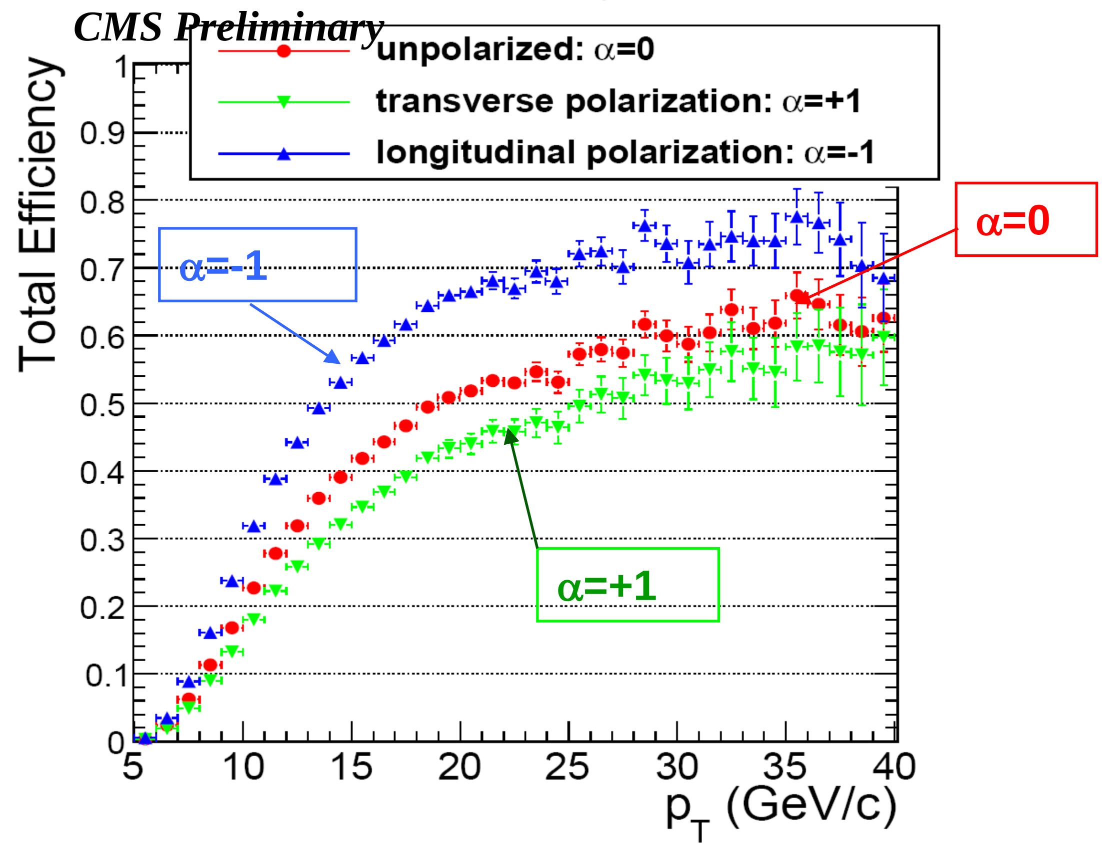
Total selection efficiency

$$A(p_T^{J/\psi},\eta^{J/\psi}) = \frac{N_{J/\psi}^{rec}(p_T^{J/\psi},\eta^{J/\psi})}{N_{J/\psi}^{gen}(p_T^{J/\psi},\eta^{J/\psi})}$$

Total efficiency includes:
- **detector acceptance**
- **trigger efficiency**
- **offline efficiency**



$$I(\cos\theta) = \frac{3}{2(\alpha+3)}(1+\alpha\cos^2\theta)$$



- **Here we take existing measurements as default (CDF for prompt, BaBar for non-prompt), uncertainty in systematic error analysis.**
- **Polarization measurement at CMS will be done too.**

Correction factors

•The J/ψ reconstruction efficiency can be expressed by:

$$\epsilon^{J/\psi}_{offline}(p_T^{J/\psi}, \eta_{J/\psi}, \theta_{J/\psi}) = \epsilon_{\mu_1}(p_T^{\mu 1}, \eta_{\mu_1}) \times \epsilon_{\mu_2}(p_T^{\mu 2}, \eta_{\mu_2}),$$

- •Muon reconstruction efficiency can be measured from data by Tag&probe method.
- •Tag&probe can be used both on MC events or real data. Thus the correction factor is:

$$\lambda^{corr}_{reco}(p_T^{\mu}, \eta^{\mu}) = \frac{\epsilon^{\mu}_{data}(p_T^{\mu}, \eta^{\mu})}{\epsilon^{\mu}_{MC}(p_T^{\mu}, \eta^{\mu})}$$

- $\lambda^{corr}_{reco}(p_T^{\mu}, \eta^{\mu})$ is ideal to be 1 if the MC simulation is perfect.
- Absolute muon efficiency is difficult to obtain at low p_T.

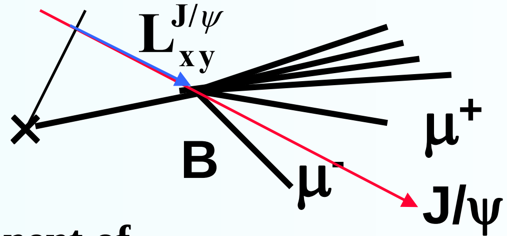
•Correction factors to the J/ψ trigger efficiency can be determined in a similar way.

B fraction fit

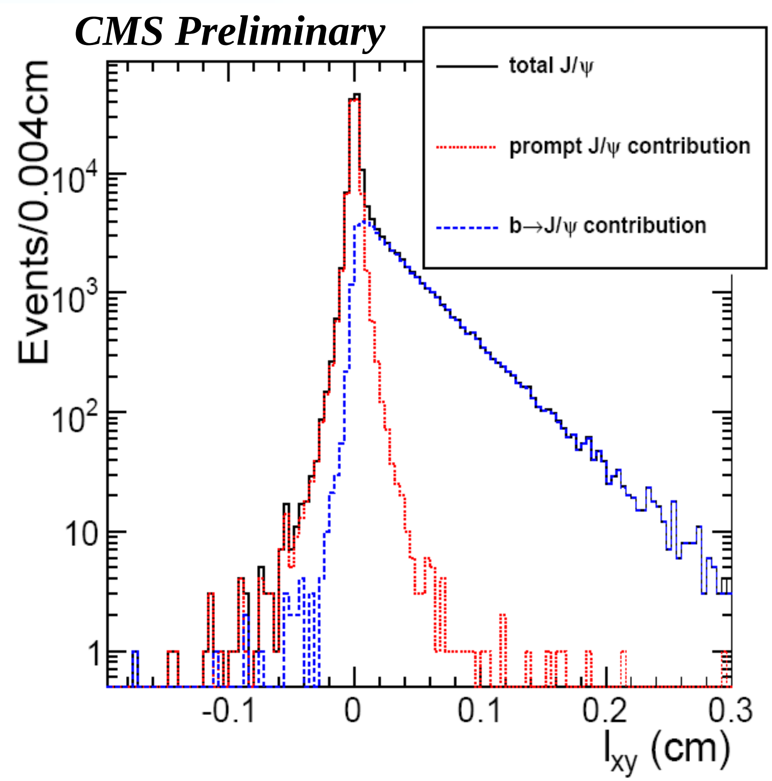
B fraction fit (1)

- To distinguish b→J/ψ from prompt J/ψ, we use the pseudo-proper decay length:

$$\ell_{xy} = \frac{L_{xy}^{J/\psi} \cdot M^{J/\psi}}{P_T^{J/\psi}}$$



$L_{xy}^{J/\psi}$ is the transverse component of decay length in lab system



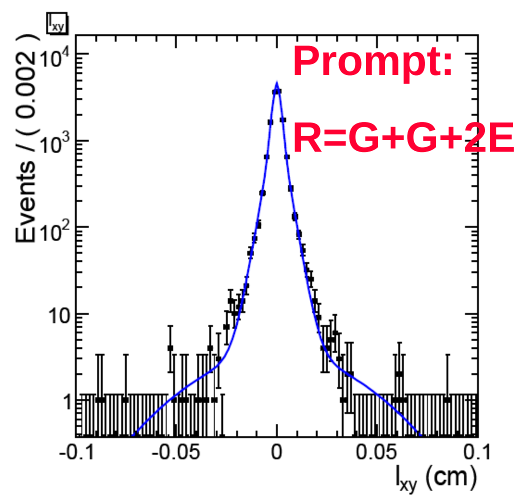
1 **Prompt J/ψ:** decays at the primary vertex (**red**), described with resolution function: double Gaussian + double-sided exponential,

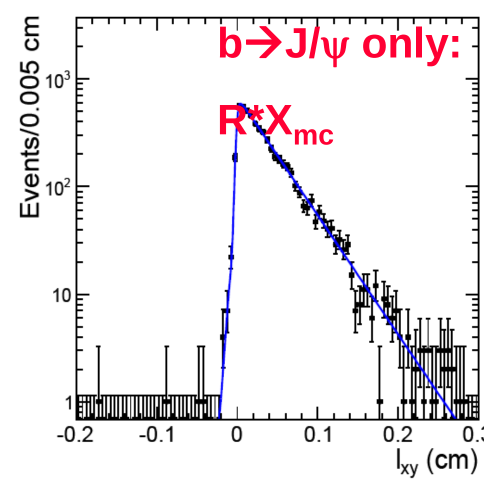
$$F_p(\ell_{xy}) = R(\ell_{xy}, \sigma)$$

2 **Non-prompt J/ψ**: B-hadrons have long lifetimes:

$$F_B(\ell_{xy}) = R(\ell_{xy} - \ell'_{xy}, \sigma) \otimes X_{mc}(\ell'_{xy})$$

$X_{mc}(\ell'_{xy})$ is the b→J/ψ lifetime distribution, an exponential function convoluted with a Gaussian.





B fraction fit (2)

- **Unbinned Maximum Likelihood fit is used.**
  - **Both pseudo-proper decay length and invariant mass distributions are used.**
  - **Likelihood of mass signal and side-band events are minimized simultaneously.**

- **The likelihood function is:**

$$\ln L = \sum_{i=1}^{N} \ln F(\ell_{xy}, m_{\mu\mu})$$

$$F(\ell_{xy}, m_{\mu\mu}) = f_{sig} F_{sig}(\ell_{xy}) M_{sig}(m_{\mu\mu}) + (1 - f_{sig}) F_{bkg}(\ell_{xy}) M_{bkg}(m_{\mu\mu})$$

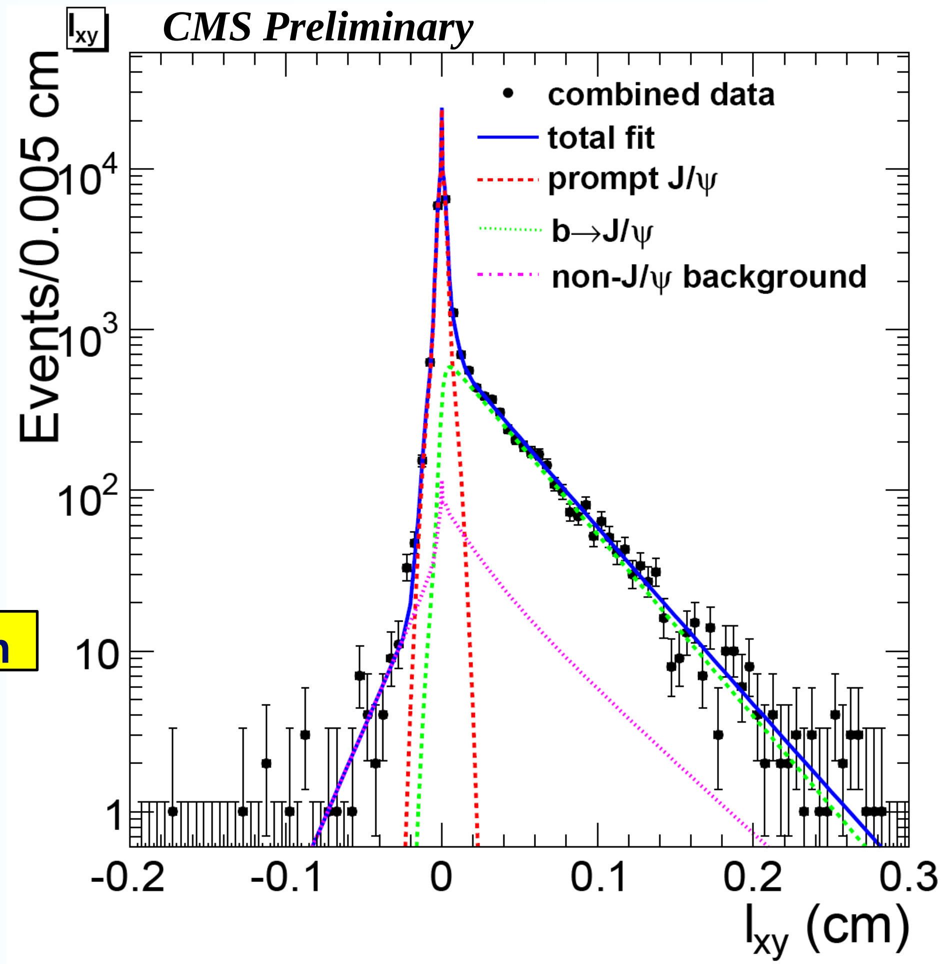
Double Gaussian

linear

$$F_{sig}(\ell_{xy}) = (1 - f_B) F_p(\ell_{xy}) + f_B F_B(\ell_{xy})$$

B fraction: what we want

$$R(\ell_{xy}, \sigma) \quad R(\ell_{xy} - \ell'_{xy}, \sigma) \otimes X_{mc}(\ell'_{xy})$$



Example of B fraction fit in J/ψ p_T bin 9-10 GeV/c

B fraction fit result

- **The fit result is very well compared to the MC truth.**

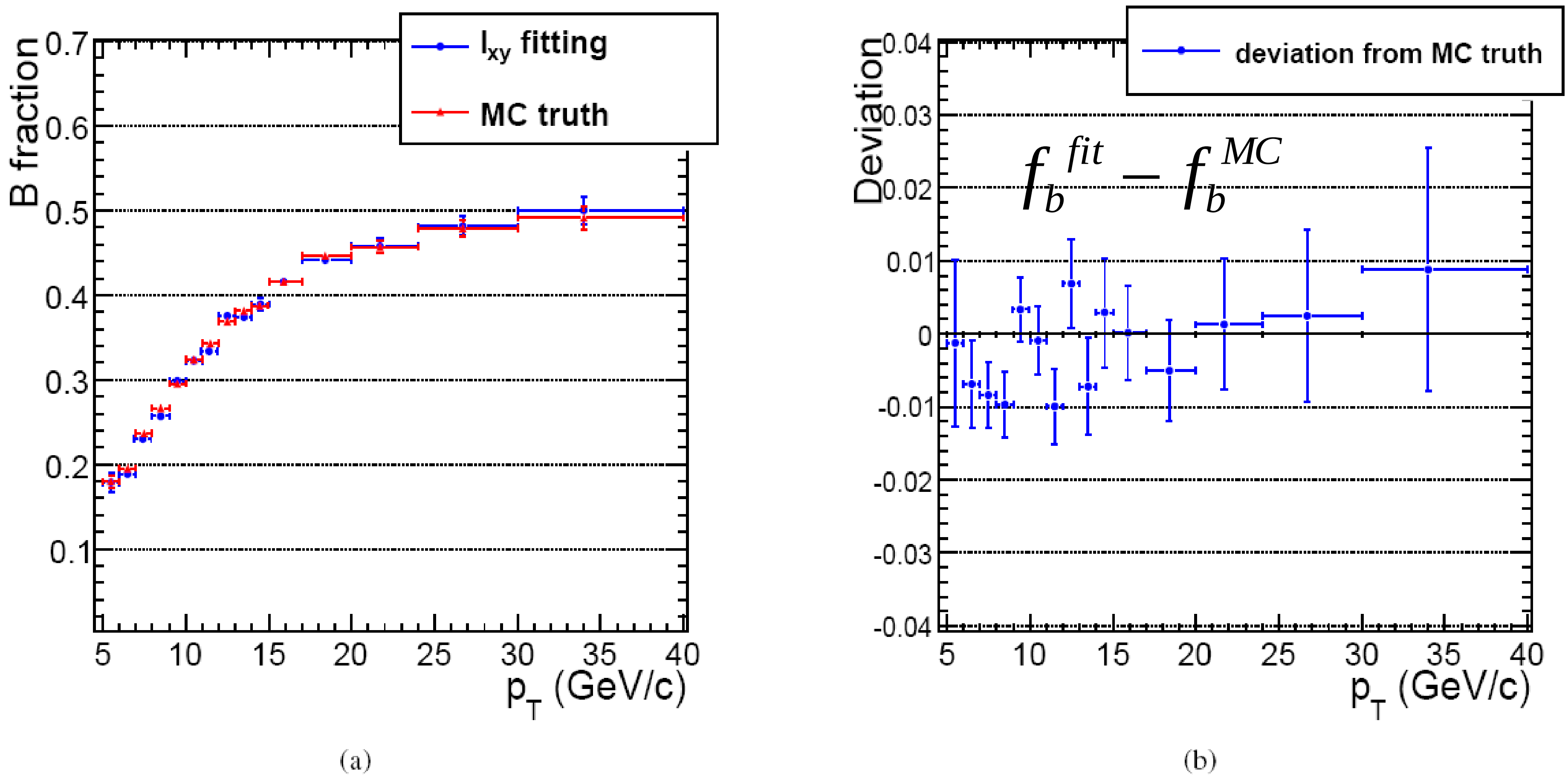
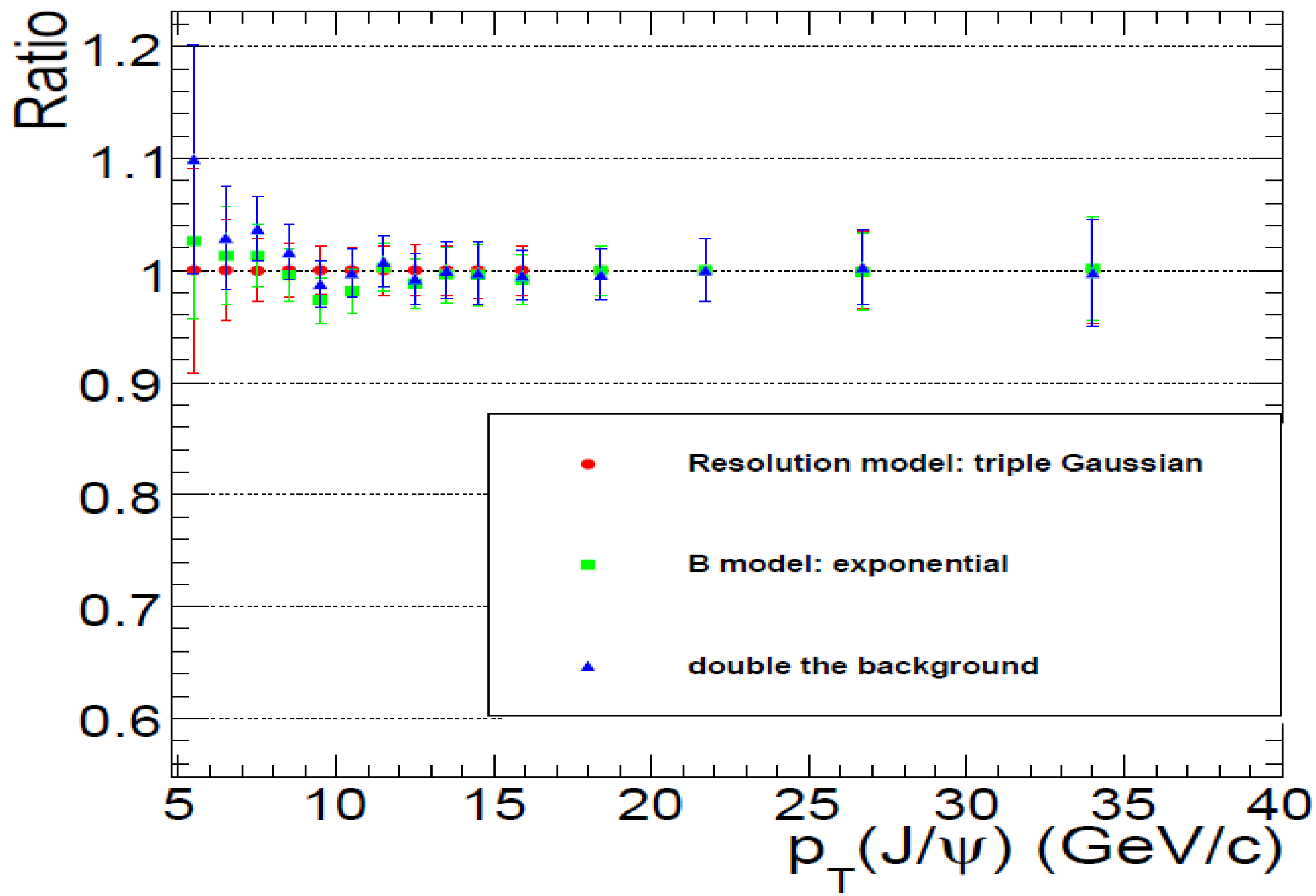


Figure 25: (a) B fraction from fitting (dot) and the MC truth (triangle) (b) the deviation of B fraction from MC truth. The unbinned maximize likelihood fitting provides the correct results, within the range of three σ.

Validation of B fraction fit

$$\frac{f'}{f_{\text{standard}}}$$



- The figure shows the results of other fits divided by the standard fitting, and the differences are considered as systematic uncertainties (see slide 35).
- Systematic uncertainties in B fraction fit seem small.

Misalignment

Mass resolution

•**Plots of J/ψ invariant mass distribution in $10pb^{-1}$, $100pb^{-1}$ and ideal conditions. And table 5 gives the numbers of the mass resolutions.**

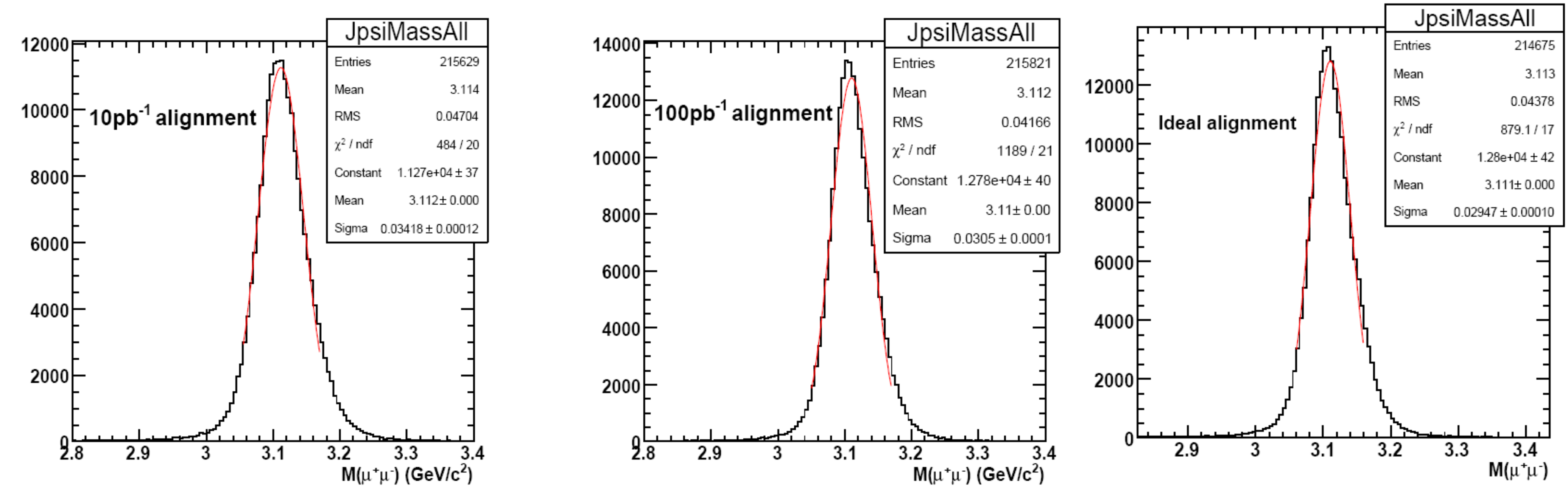
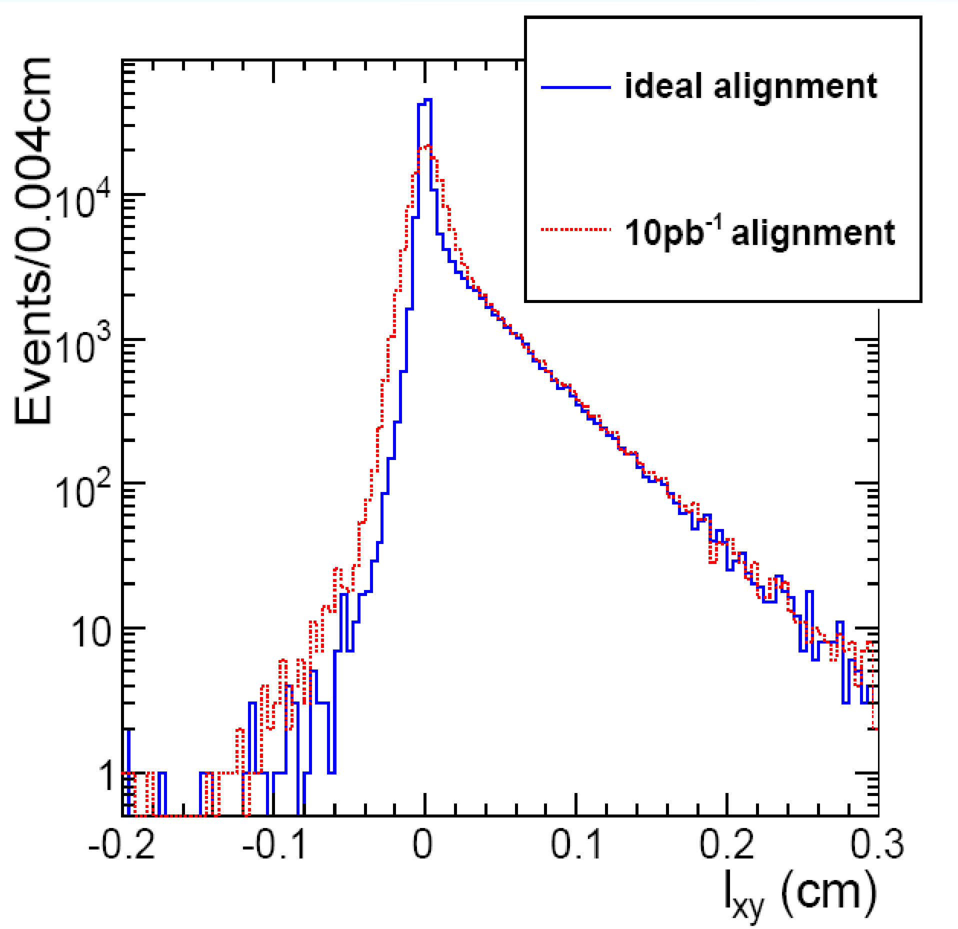


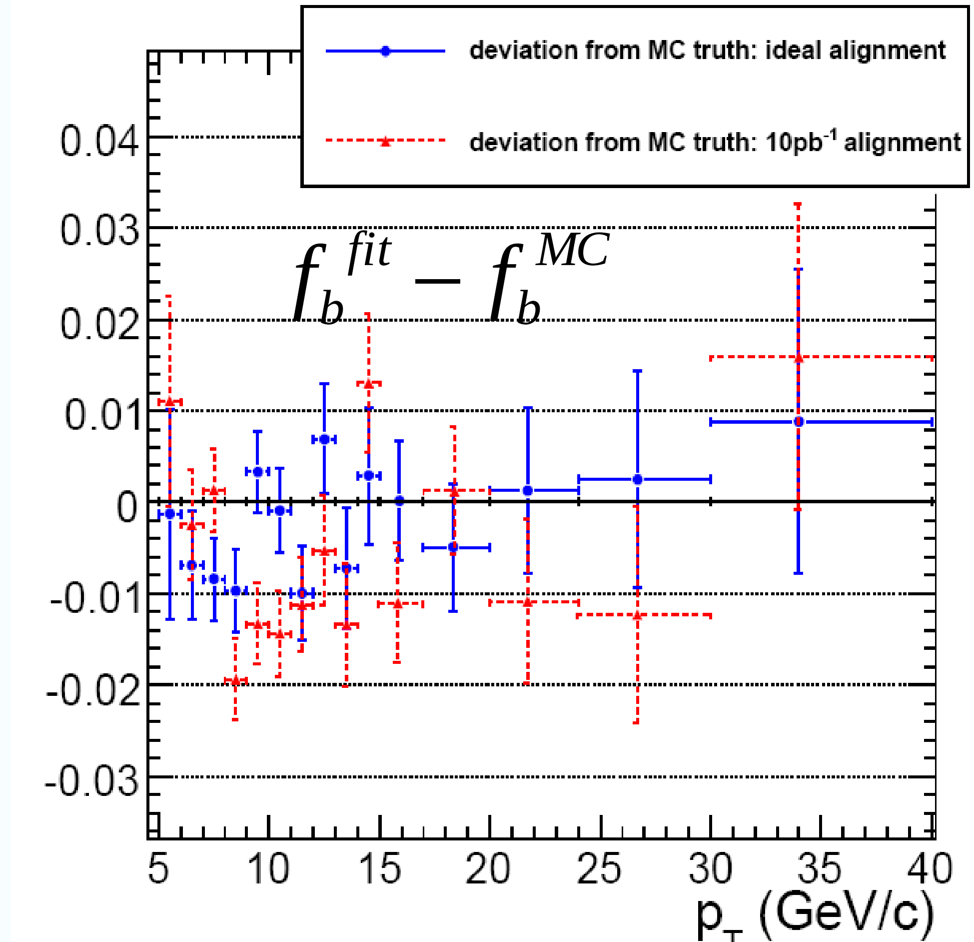
Table 5: J/ψ mass resolution in different misalignment scenarios

	$10pb^{-1}$	$100pb^{-1}$	ideal
J/ψ mass resolution	34.2MeV	30.5MeV	29.5MeV

B fraction

- **Left: Misalignment effects on the pseudo-proper decay length distribution.**
- **Right: We fitted the B fraction in $10pb^{-1}$ sample and compared with MC and result in ideal.**





•We conclude that there is no bias in neither of the two scenarios and take 50% of the difference as a systematic error.

Systematic uncertainties

Summary of systematic errors

Table 6: Summary of possible systematic uncertainties in the J/ψ cross-section measurement in CMS early data. All the uncertainties are p_T-depended, except the uncertainty from luminosity. The total uncertainty is about 10% in the region p_T >20GeV/c and 16% at the first p_T bin 5-6GeV/c.

Parameter	Source	Size
Luminosity	Luminosity	$\sim 5\%$
Number of J/ψ	Mass PDF	1.6 - 9.5%
Number of J/ψ	Momentum scale	$\sim 1\%$
Acceptance	J/ψ polarization	1.8 - 7.0%
Acceptance	p_T spectrum	0.1 - 10%
Acceptance	MC statistics	0.53 - 1.7%
$\epsilon_{reconstruction}$	Determine in tag-and-probe	$\sim 5\%$
$\epsilon_{trigger}$	Determine in tag-and-probe	$\sim 5\%$
B fraction	Resolution model	0. - 2.6%
B fraction	B-decay J/psi model	0.01 - 0.05%
B fraction	Background	$\sim 1.5\%$
B fraction	Misalignment	0.7 - 3.5%
total 10% - 16%		

Only for the prompt and non-prompt cross section

- **The total uncertainties is about 10% in pT above 20GeV, and 16% at the first p_T bin**
- **The most important uncertainties will be shown, and others are in backup slides.**

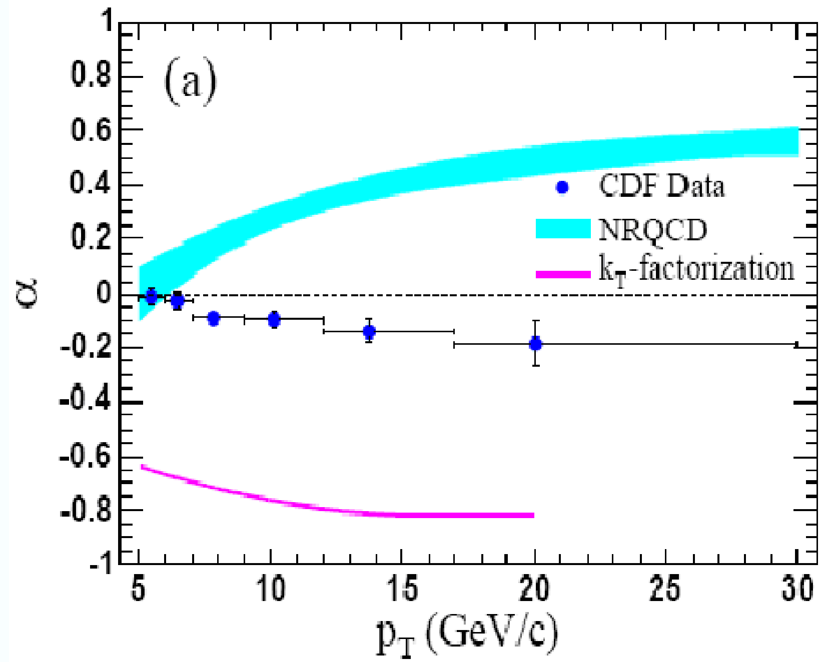
Uncertainties: J/ψ polarization

- **What we used:**
  - **Prompt J/ψ:**
    - **CDF, arXiv:0704.0638v1 (2007)**
  - **B-decay J/ψ: α_B=-0.13±0.01**
    - **BaBar, PRD 67, 032002 (2003).**

- **We used the mean value and varied it by ±σ:**
  - **$\alpha=x$, $\alpha_+=x+3\sigma$, $\alpha_-=x-3\sigma$**
  - **With α, α_+, α_-, we have acceptances: A, A_+, A_-**
    - **$A_+ < A < A_-$**

$$\frac{\Delta\sigma}{\sigma} = \frac{A_{*} - A}{A}$$

- **$\Delta\sigma/\sigma_{sys}$ = 1.8 ~ 7.0 %**



p_T (GeV/c)	$<p_T>$ (GeV/c)	f_{bkd} (%)	α
5−6	5.5	2.8 ± 0.2	−0.009 ± 0.029 ± 0.007
6−7	6.5	3.4 ± 0.2	−0.022 ± 0.028 ± 0.007
7−9	7.8	4.1 ± 0.2	−0.088 ± 0.023 ± 0.007
9−12	10.1	5.7 ± 0.3	−0.094 ± 0.028 ± 0.007
12−17	13.7	6.7 ± 0.6	−0.139 ± 0.043 ± 0.007
17−30	20.0	13.6 ± 1.4	−0.187 ± 0.090 ± 0.007

•arXiv:0704.0638v1 (2007)

Uncertainties: p_T spectrum

- The J/ψ p_T spectrum is the subject of this analysis.
- The Acceptance from MC in each p_T bin depends on the generated spectrum.
- In order to estimate this systematic, we take the difference between the flat spectrum and the generated one:
  - For each p_T bin, we divided into 4 smaller bins of equal p_T size:
  - Calculate each small bin's acceptance:

$$\Delta A = \sum_{i=1}^{4} A_i - \frac{\sum_{i=1}^{4} A_i N_i}{\sum_{i=1}^{4} N_i}$$

- ΔA/A gives a uncertainty from 0.1 to 10%.

Uncertainties: others

- Mass fit: we split each p_T bin into three separate $|\eta|$ regions (0. – 0.8 – 1.6 – 2.4) and fit each region with a single Gaussian. The difference with respect to a single η bin and double Gaussian is taken as systematics.
  - 1.6 – 9.5%

- Residual misalignment effect: the B fraction fitting result in $10pb^{-1}$ and ideal alignment is shown in slide 29. We conclude that there is no bias in neither of the two scenarios and take 50% of the difference as a systematic error.
  - 0.7 – 3.5%

- The luminosity uncertainty is supposed to be 5%, and the errors from Tag&Probe are also considered as 5%.

- More details in the backup slides.

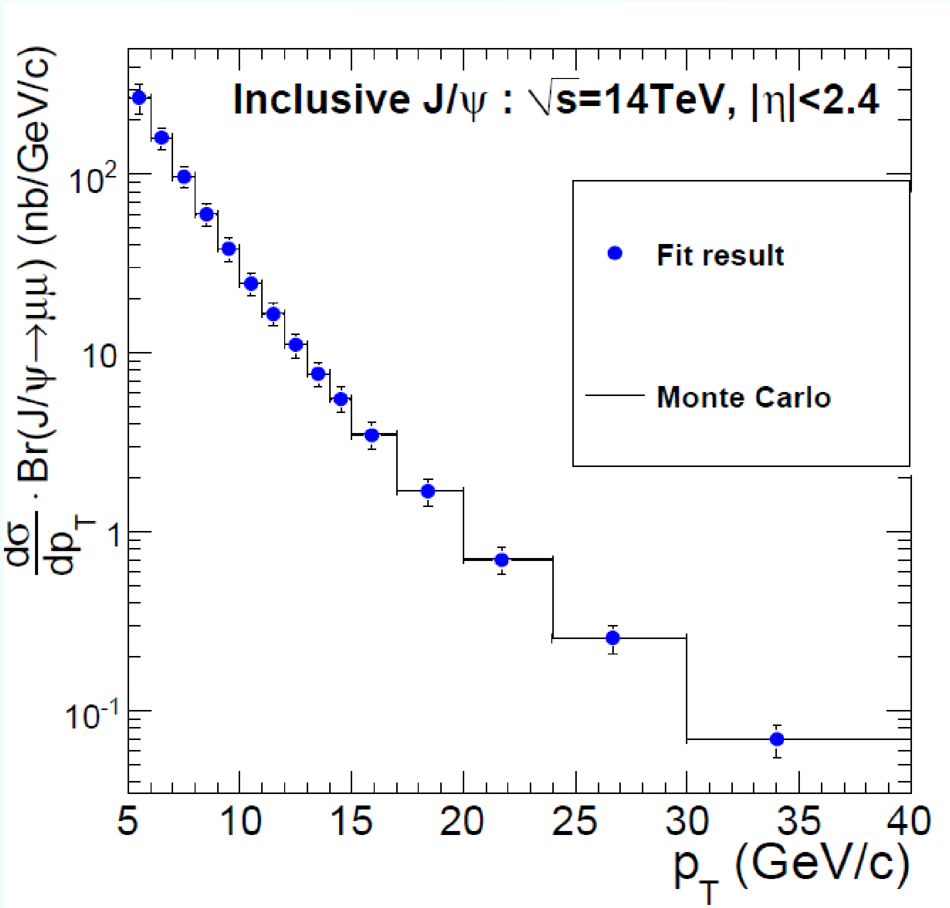
Results

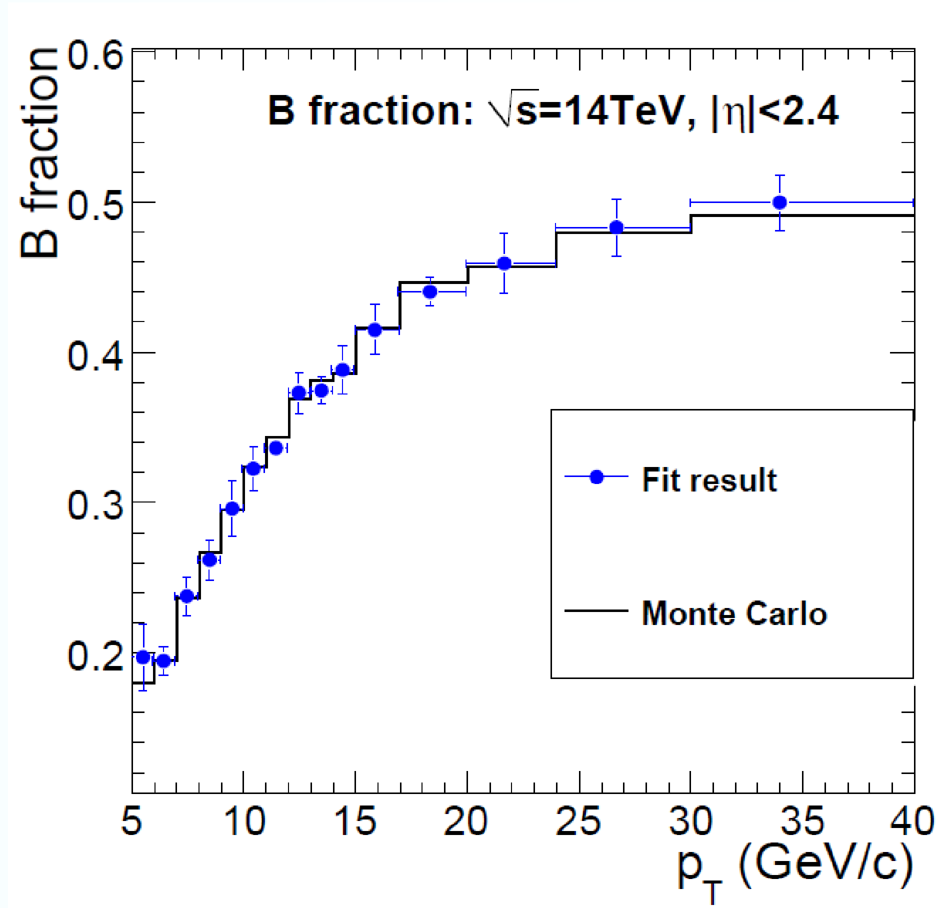
Summary table

Table 8: The prompt and B-decay J/ψ differential cross sections as a function of p_T with statistical and systematic uncertainties. The cross section in each p_T bin is integrated over the η range $|\eta| < 2.4$. The Monte Carlo input values are listed in the last 2 columns.

p_T	$d\sigma/dp_T \cdot Br(nb/(GeV/c))$		MC input values (nb/(GeV/c))	
GeV/c	prompt J/ψ	B-decay J/ψ	prompt J/ψ	B-decay J/ψ
5-6	$220\pm5(stat)\pm41(syst)$	$47.8\pm3.2(stat)\pm8.9(syst)$	217	50.6
6-7	$130\pm2\pm18$	$30.2\pm1.0\pm4.1$	127	32.9
7-8	$74.9\pm0.7\pm10.2$	$22.2\pm0.5\pm3.0$	73.6	23.8
8-9	$44.5\pm0.4\pm6.3$	$15.4\pm0.3\pm2.2$	43.8	16.4
9-10	$26.9\pm0.3\pm4.0$	$11.4\pm0.2\pm1.7$	27.1	11.5
10-11	$16.6\pm0.2\pm2.4$	$7.91\pm0.13\pm1.14$	16.7	8.09
11-12	$11.1\pm0.2\pm1.6$	$5.53\pm0.10\pm0.81$	10.9	5.88
12-13	$6.97\pm0.10\pm1.06$	$4.19\pm0.08\pm0.64$	7.03	4.23
13-14	$4.80\pm0.07\pm0.72$	$2.87\pm0.06\pm0.43$	4.76	2.98
14-15	$3.39\pm0.06\pm0.54$	$2.16\pm0.05\pm0.35$	3.35	2.23
15-17	$2.03\pm0.03\pm0.35$	$1.45\pm0.03\pm0.25$	2.03	1.48
17-20	$0.942\pm0.016\pm0.158$	$0.745\pm0.015\pm0.12$	0.934	0.765
20-24	$0.379\pm0.009\pm0.067$	$0.320\pm0.008\pm0.057$	0.377	0.325
24-30	$0.131\pm0.004\pm0.024$	$0.122\pm0.004\pm0.022$	0.128	0.125
30-40	$0.0347\pm0.0015\pm0.0071$	$0.0347\pm0.0015\pm0.0071$	0.0333	0.0356

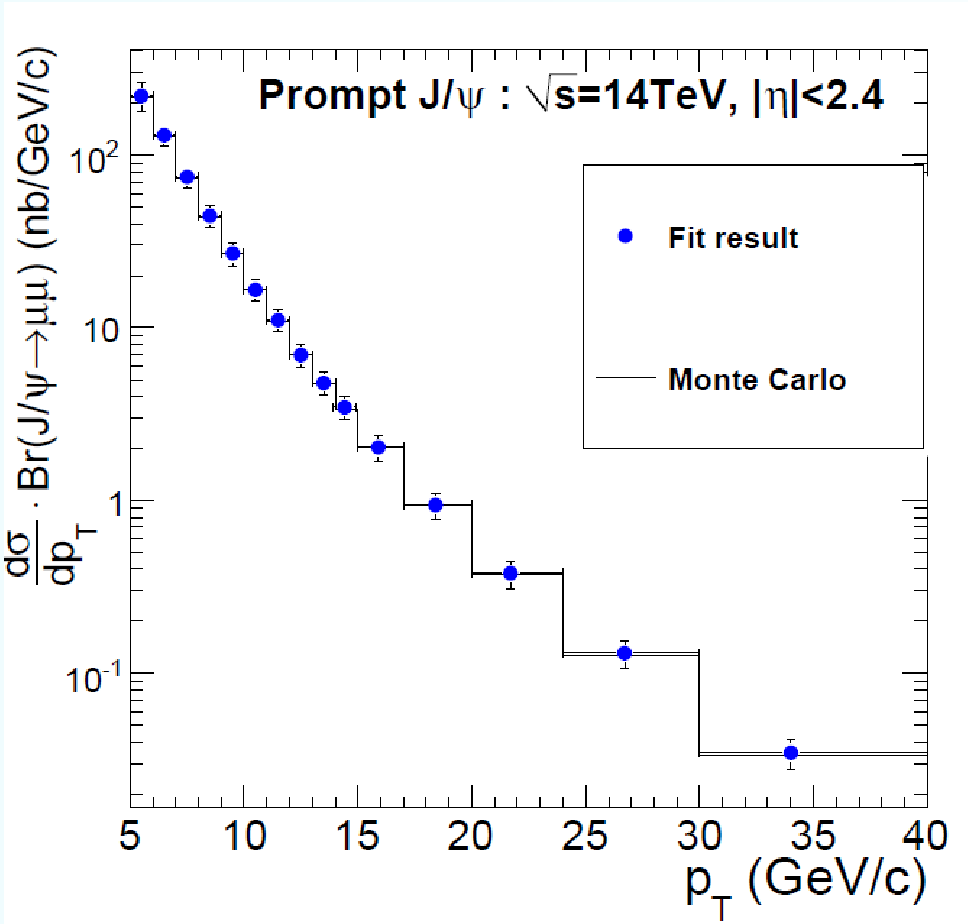
Inclusive J/ψ cross section and B fraction

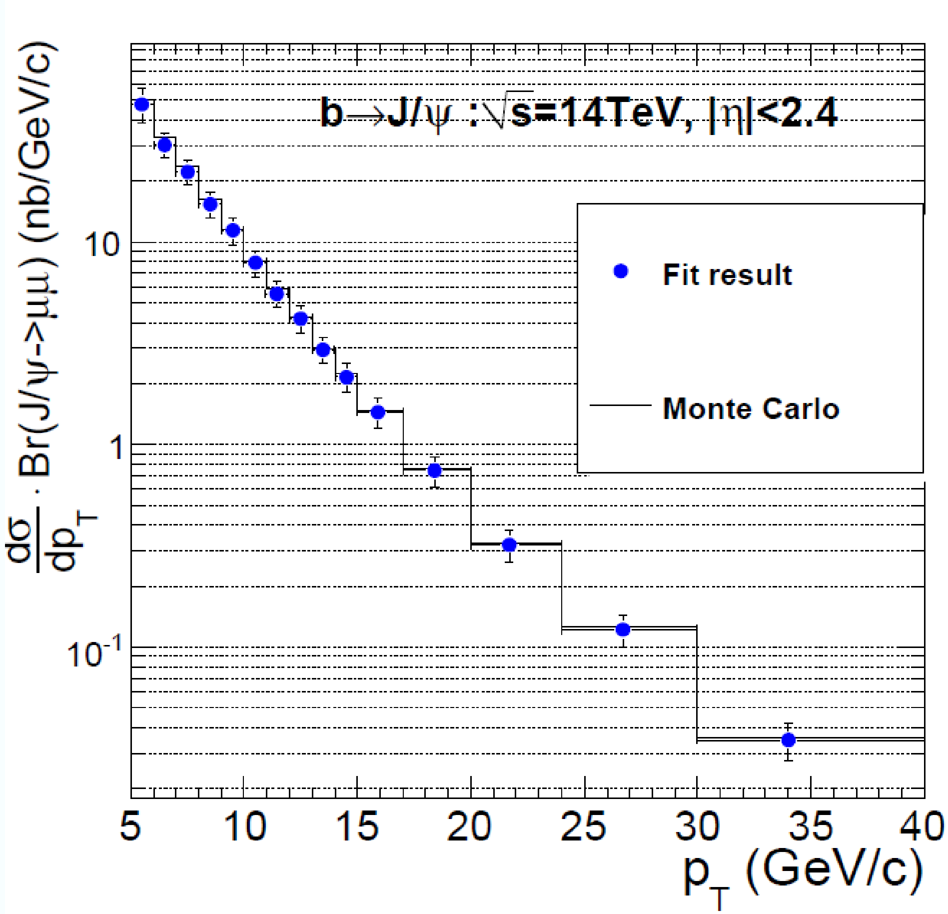




- The inclusive J/ψ differential cross-section as a function of p_T, integrated over the pseudorapidity range $|\eta|<2.4$, corresponding to a integral luminosity of $3pb^{-1}$.
- Results of B fraction fit.

Prompt and non-prompt J/ψ cross section



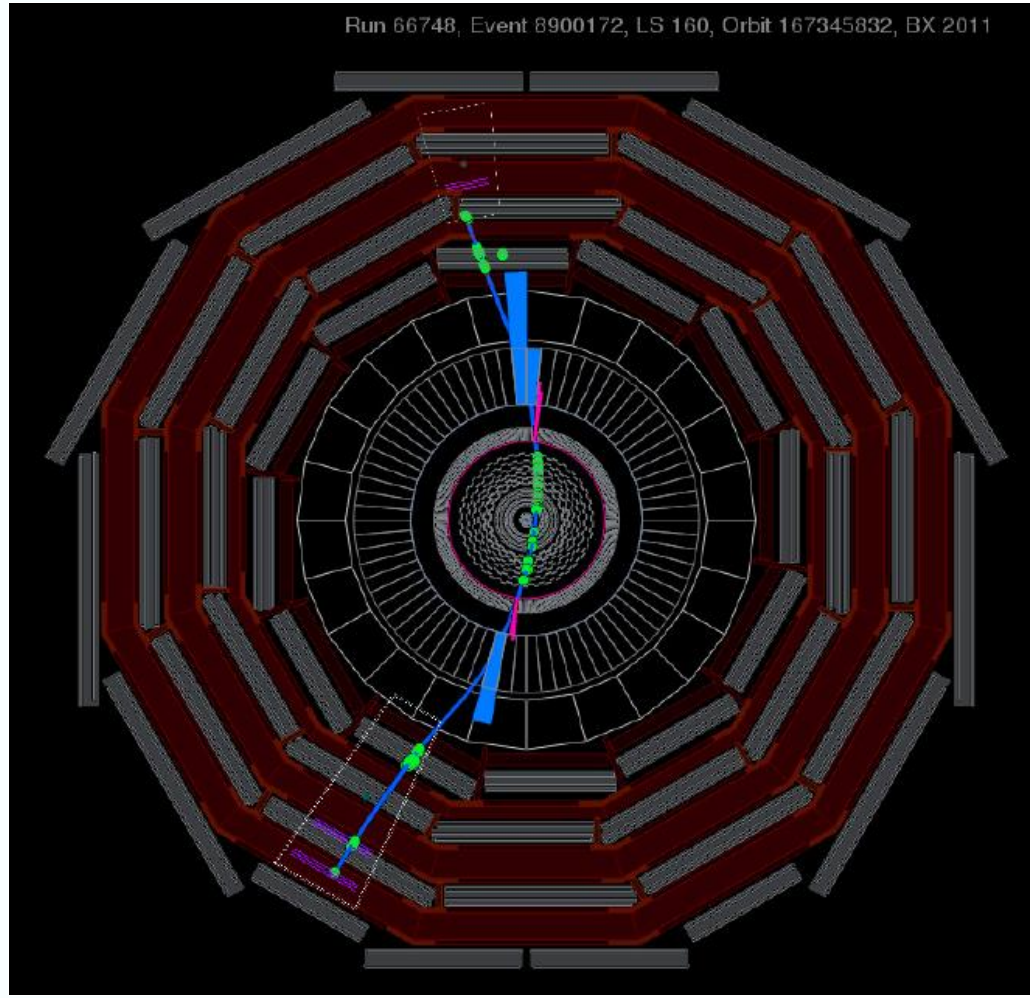


- The prompt and non-prompt J/ψ differential cross-section as a function of p_T, integrated over the pseudorapidity range $|\eta|<2.4$, corresponding to a integral luminosity of $3pb^{-1}$.
- This study is expected to be the first physics paper with real collision data in CMS.

Cosmic Muon Study

Cosmic muon reconstruction

- The normal cosmic muon reconstruction contains one-leg track and two standalone muons.
- It can also be reconstructed as two splitted global muons:
  - two tracks and two standalone muons
  - up muon's outer position y>0
  - down muon's outer position y<0

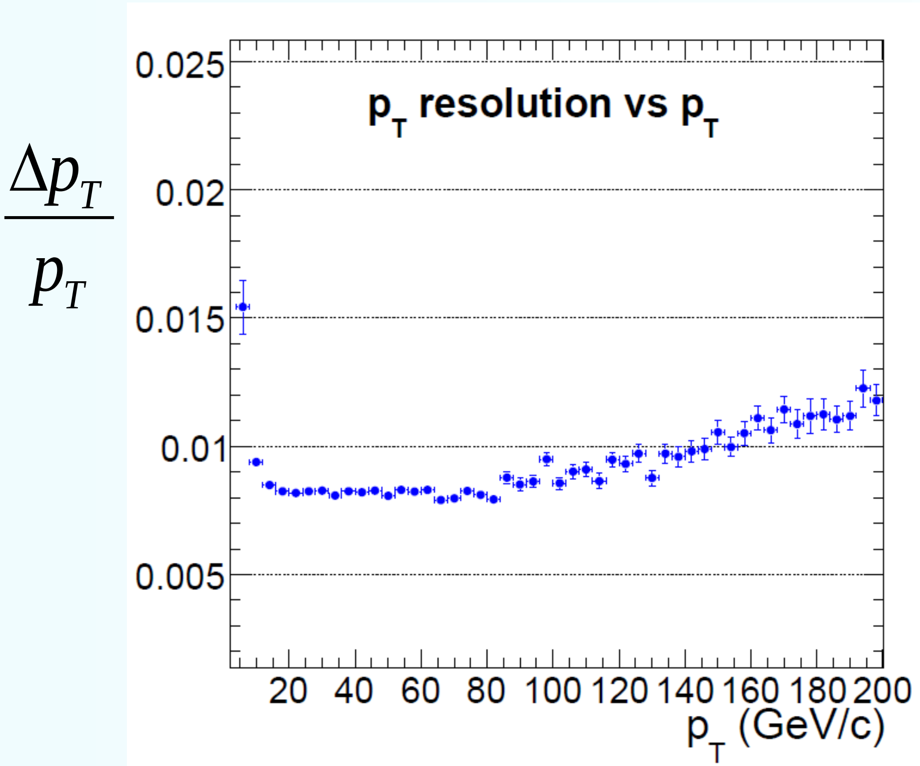


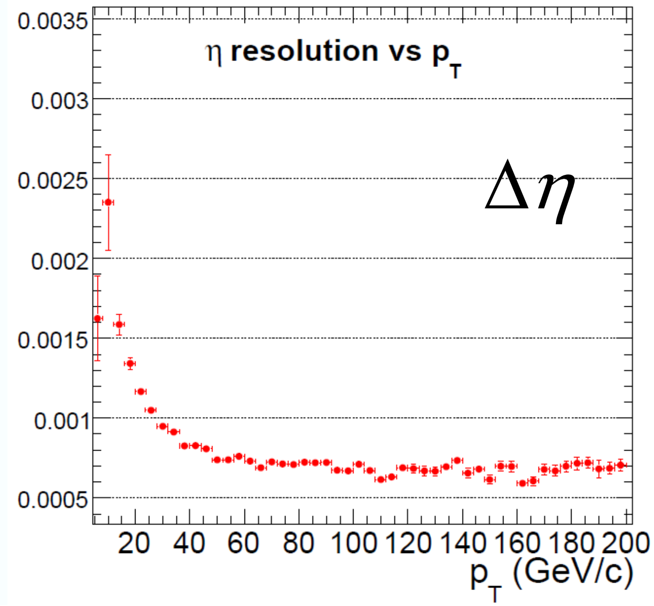
- Cosmic muon selection:
  1. Good runs with B field on (3.8 T)
  2. Events with 2 tracks in opposite hemispheres
  3. Each track: |d0|<10 and |dz|<40

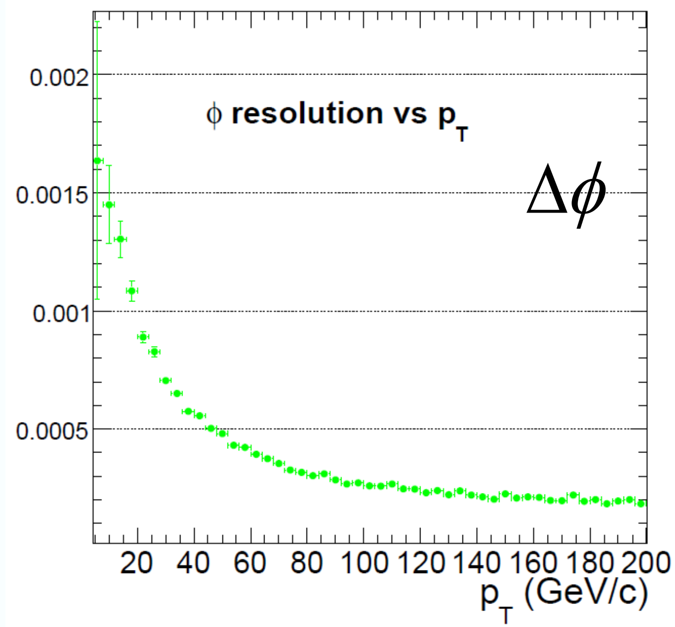
- Total 85 K events after selection

- Plot $\Delta p_T/p_T$, $\Delta\eta$, and $\Delta\phi$ of the two splitted tracks in bins of the one-leg muon's p_T, η, ϕ and number of valid hits.

Muon resolution vs. p_T





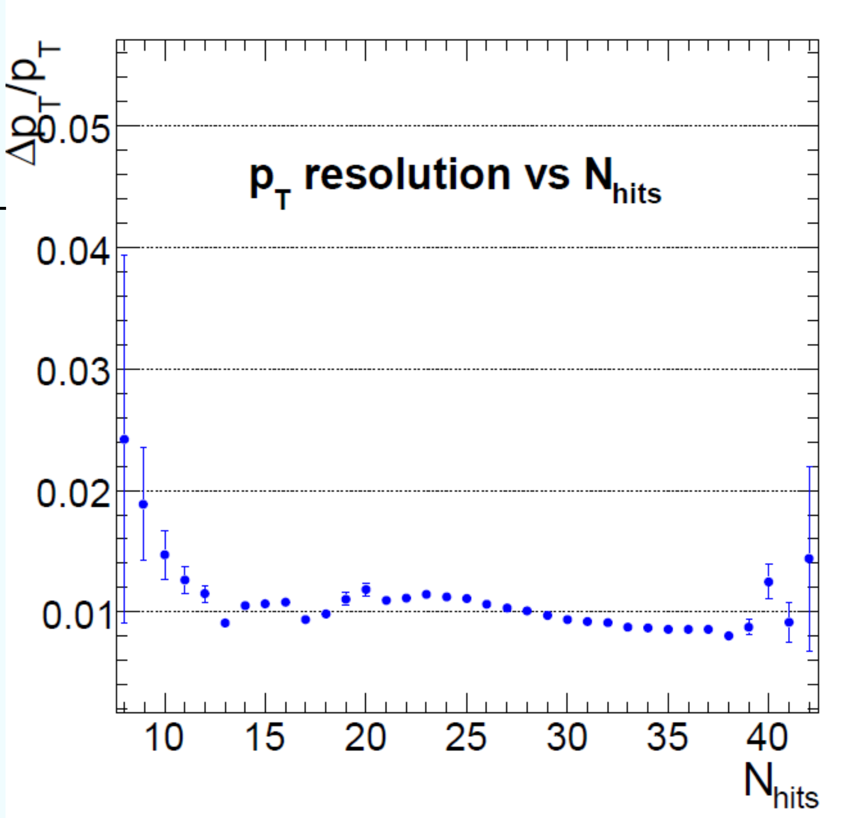


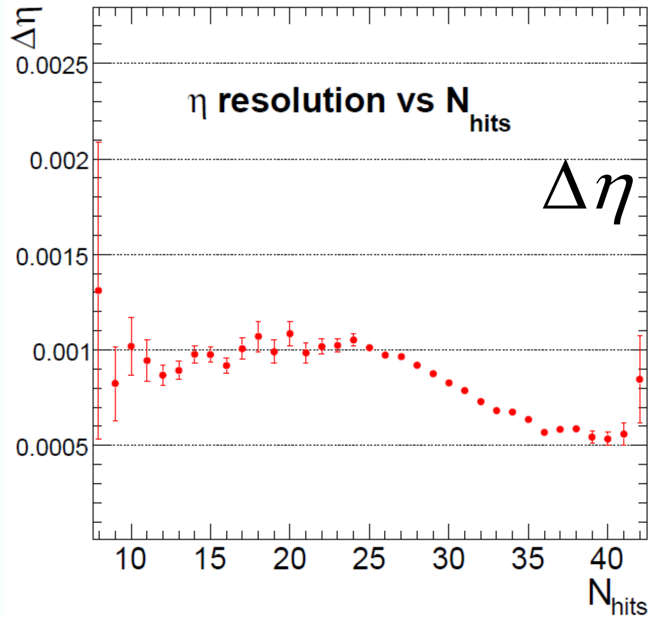
- Gaussian width of $p_T(\mu_{up})$-$p_T(\mu_{down})$ divided by the center value and rescaled by 1/sqrt(2) for single prong resolution.
  - the same to $\Delta\eta$ and $\Delta\phi$.

- The p_T resolution is consistent with CMS PTDR (Physics Technical Design Report)!

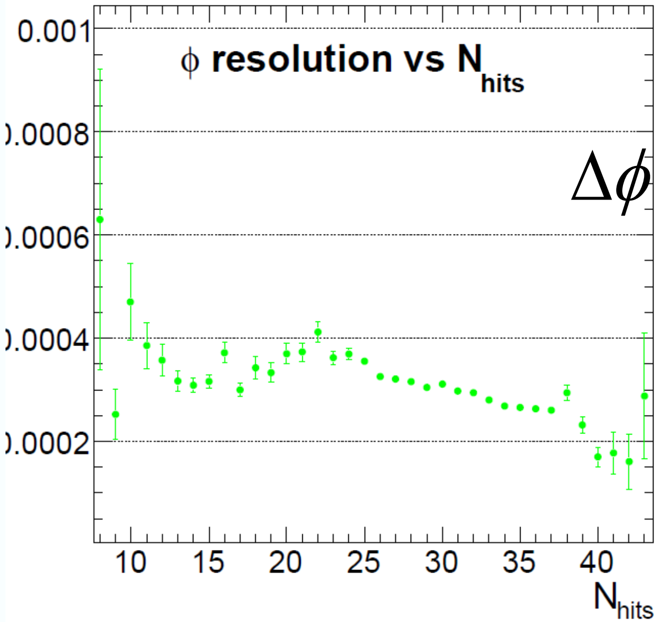
Muon resolution vs. N_{hits}

$$\frac{\Delta p_T}{p_T}$$





$$\Delta\eta$$



$$\Delta\phi$$

$$N_{hits}(\mu_{up}) + N_{hits}(\mu_{down}) \leq N_{hits}(\mu_{one-leg})$$

The resolution as a function of η and ϕ is in the back-up slides

Summary

- We present a feasibility study of the J/ψ cross section measurement with first data:
  1. Inclusive J/ψ cross section measurement
  2. B fraction fitting
  3. Misalignment effects are considers
  4. Systematic uncertainties are estimated.

- J/ψ in CMS:
  1. Mass resolution: $\sigma_{J/\Psi}$=30 MeV/c^2 (|η|<2.4)
  2. Signal/Background: ~7 for J/ψ by requiring two muons p_T>3 GeV/c
  3. Expected rates in |η|<2.4: two muons p_T>3GeV/c, ~25K J/ψ per 1 pb^{-1} (1.2 days @$10^{31}cm^{-2}s^{-1}$)

- Splitted cosmic muons can be used to inspect the detector performance.
  – The tracker seems to behave very well.

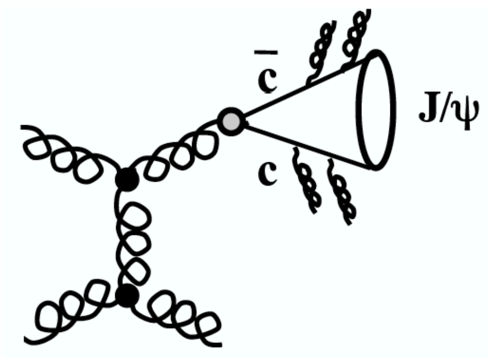
The LHC will start at September 2009!

Thank you !
&Backup slides

Event Generation (1)

- COM J/ψ generation were originally implemented by S. Wolf (2002, never in official release)
  - Based on NRQCD- approach
  - Singlet and octet QQ produced perturbatively, followed by shower
  - Parton showers for radiation off octet QQ

- In Pythia:
  - Code integrated (Sjöstrand): PYTHIA ≥6.324
  - Possibility to dampen cross section at small PT like for gg→gg in underlying event (PYEVWT)
  - NRQCD matrix elements tuned (See Bargiotti, CERN-LHCb-2007-042)



NRQCD matrix elements

- Rates for all quarkonium processes given by NRQCD matrix elements

See also talk by M.Bargiotti at HERA-LHC workshop 2006

- Motivation of tuning: agreement MC⇔data
- NRQCD matrix elements from: hep-ph/0003142
  - CSM values extracted from potential models (hep-ph/9503356)
  - COM values from CDF data
- Quark masses: m_c= 1.5 GeV, m_b = 4.88 GeV

PARP(141)	$\langle O^{J/\psi}[^3S_1^{(1)}]\rangle$	1.16
PARP(142)	$\langle O^{J/\psi}[^3S_1^{(8)}]\rangle$	0.0119
PARP(143)	$\langle O^{J/\psi}[^1S_0^{(8)}]\rangle$	0.01
PARP(144)	$\langle O^{J/\psi}[^3P_0^{(8)}]\rangle / m_c^2$	0.01
PARP(145)	$\langle O^{\chi_{c0}}[^3P_0^{(1)}]\rangle / m_c^2$	0.05
PARP(146)	$\langle O^{\Upsilon}[^3S_1^{(1)}]\rangle$	9.28
PARP(147)	$\langle O^{\Upsilon}[^3S_1^{(8)}]\rangle$	0.15
PARP(148)	$\langle O^{\Upsilon}[^1S_0^{(8)}]\rangle$	0.02
PARP(149)	$\langle O^{\Upsilon}[^3P_0^{(8)}]\rangle / m_b^2$	0.02
PARP(150)	$\langle O^{\chi_{b0}}[^3P_0^{(1)}]\rangle / m_b^2$	0.085

Event generation (2)

- **Prediction of the differential cross-section of prompt J/ψ and B decayed J/ψ at LHC, 14TeV**

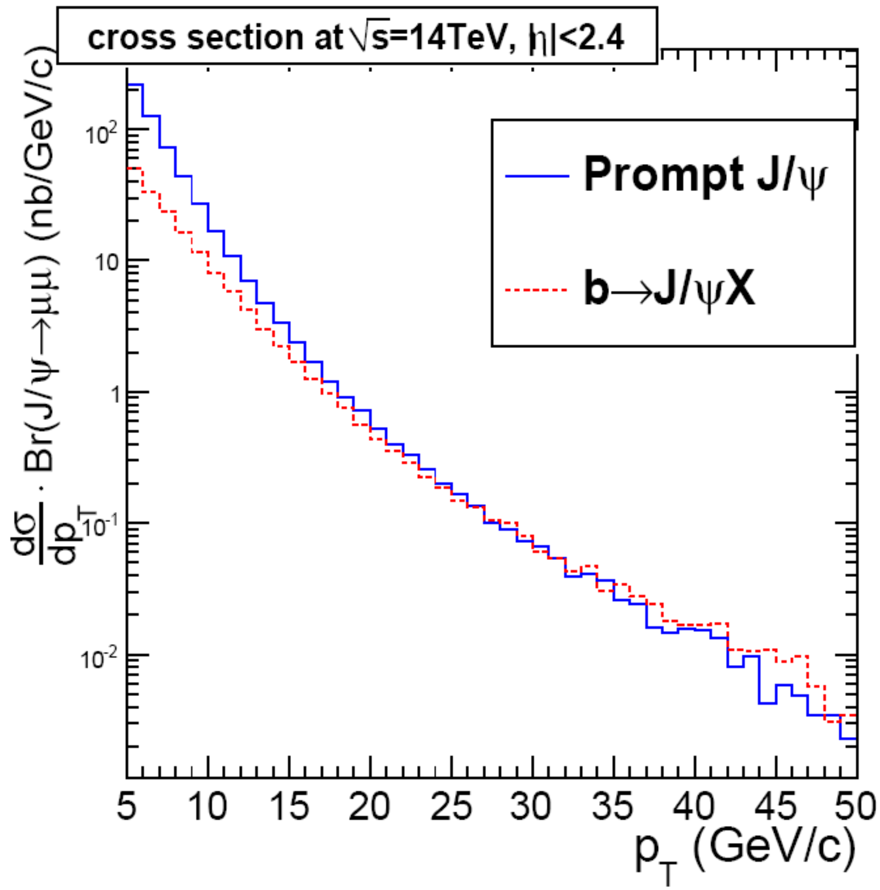
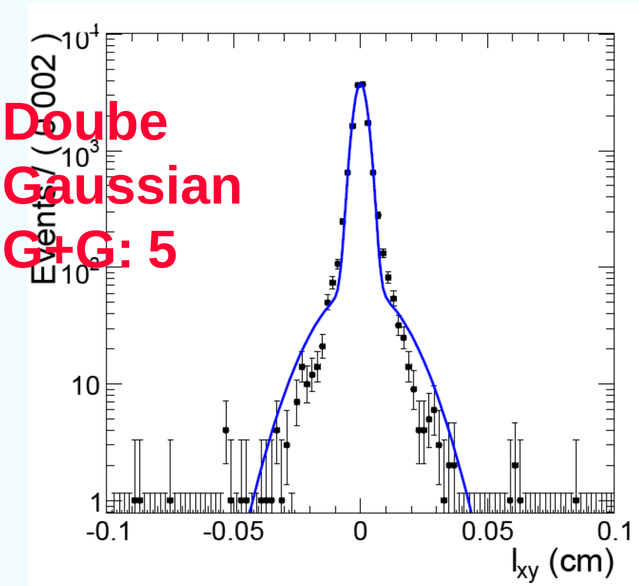


Figure 3: Prompt and non-prompt J/ψ differential cross sections in pp collision at 14TeV integrated over the range $|\eta| < 2.4$.

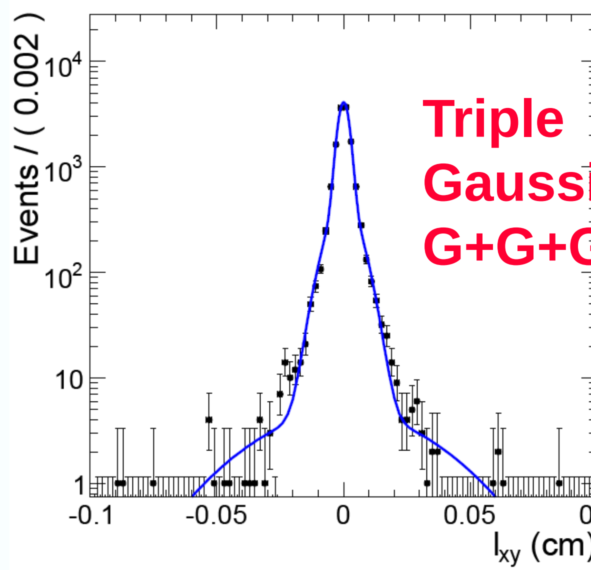
- **Prompt J/ψ: Use the tuned parameters and increase energy to 14TeV**
- **B decayed J/ψ: MSEL=1, QCD processes**

Update (1)

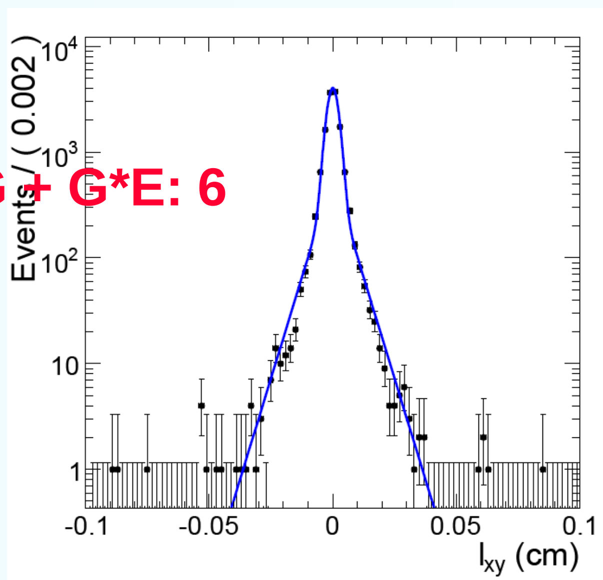
- **Resolution function: to parameterize the prompt J/psi pseudo-proper decay length.**



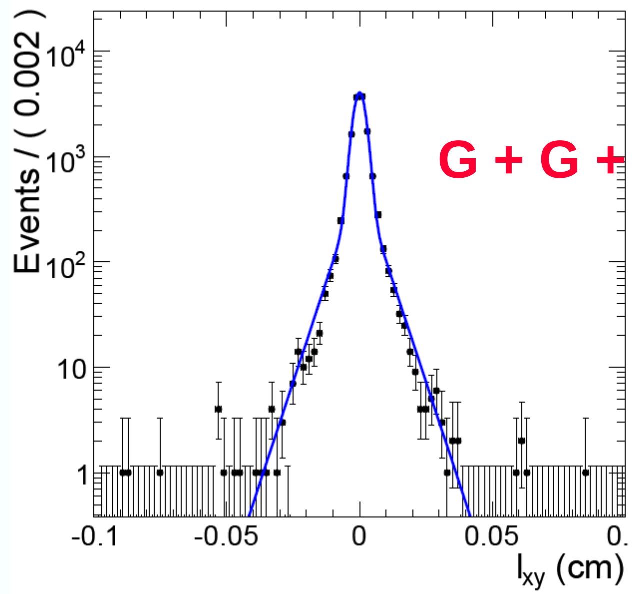
Doube Gaussian
G+G: 5



Triple Gaussian
G+G+G: 8



G + G*E: 6



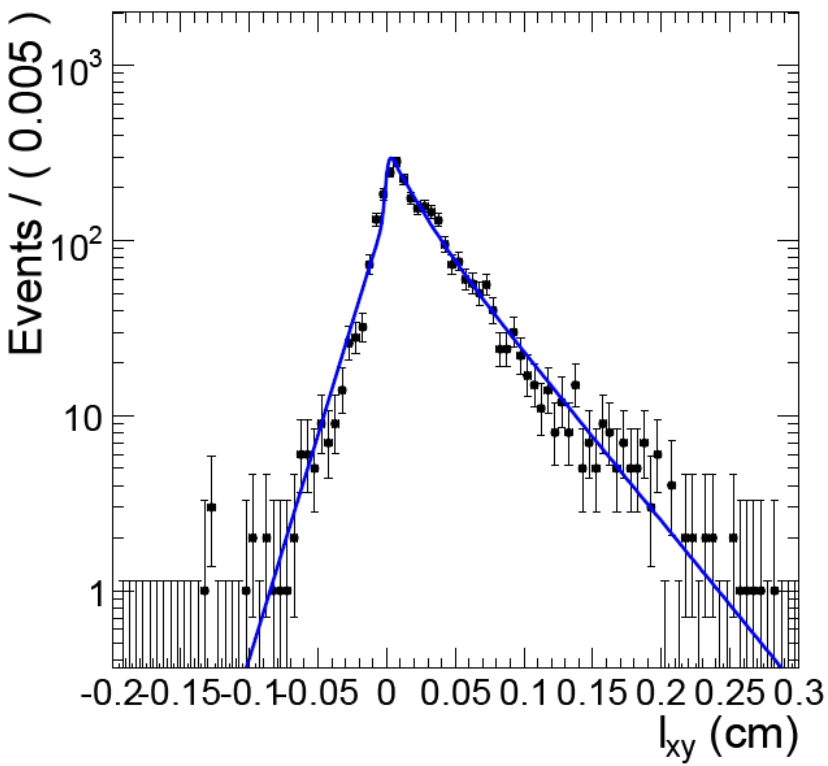
G + G + E + E : 7

Update (2)

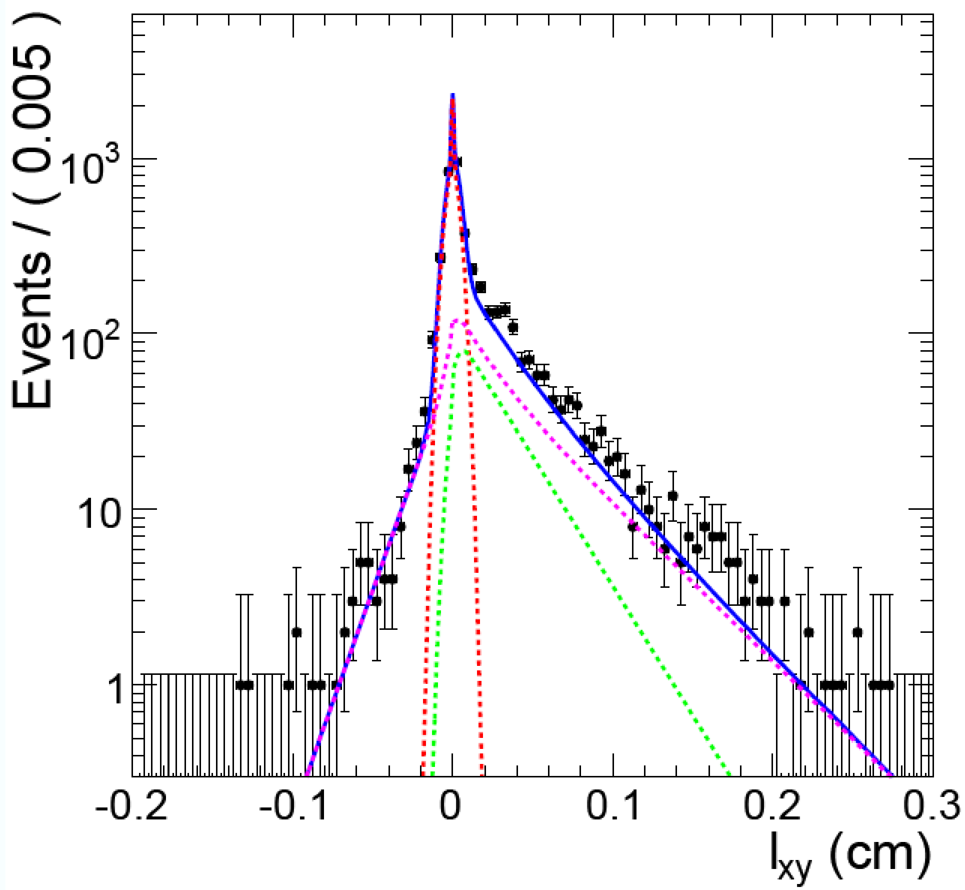
- **Non-J/psi QCD background life time fitting**

$$F_{Bkg}(\ell_{xy}) = \begin{cases} (1-f_+-f_--f_{sym})\cdot R(\ell_{xy},\sigma) + \frac{f_+}{\lambda_+}e^{-\frac{\ell'_{xy}}{\lambda_+}} \otimes R(\ell'_{xy}-\ell_{xy},\sigma) \\ \quad + \frac{f_{sym}}{2\lambda_{sym}}e^{-\frac{\ell'_{xy}}{\lambda_{sym}}} \otimes R(\ell'_{xy}-\ell_{xy},\sigma) & \text{when } \ell_{xy}>0, \\ (1-f_+-f_--f_{sym})\cdot R(\ell_{xy},\sigma) + \frac{f_-}{\lambda_-}e^{\frac{\ell'_{xy}}{\lambda_-}} \otimes R(\ell'_{xy}-\ell_{xy},\sigma) \\ \quad + \frac{f_{sym}}{2\lambda_{sym}}e^{\frac{\ell'_{xy}}{\lambda_{sym}}} \otimes R(\ell'_{xy}-\ell_{xy},\sigma) & \text{when } \ell_{xy}<0, \end{cases} \quad (26)$$

Background only



- Because of the small background statistics, I didn't split them into pT bins but put them all into one bin:
  - Each pT bin will have different background level
  - Likelihood functions of the events in mass signal and mass side-band window are minimized simultaneously.

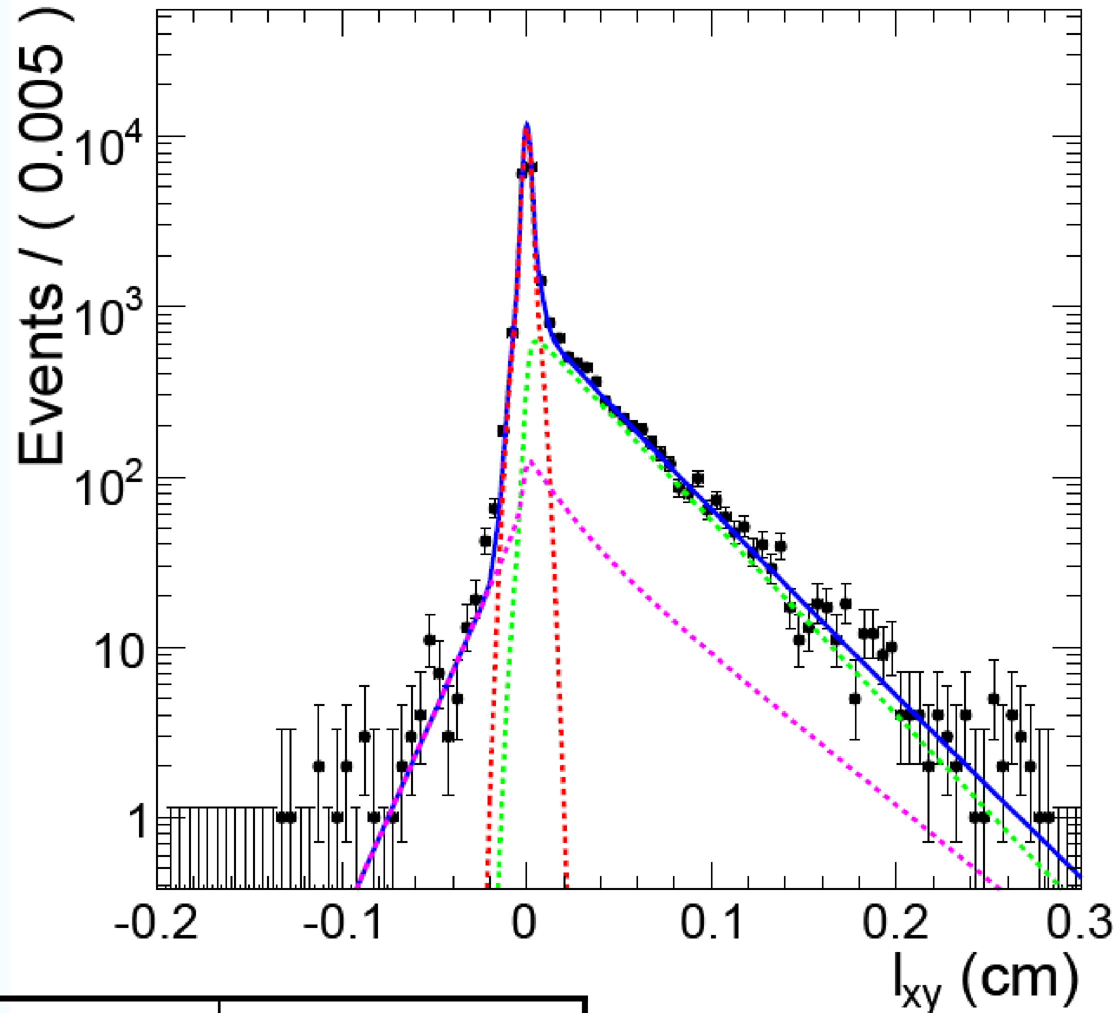


In pT bin 5-6 GeV/c, the background level S/B = 2.35

	fit (w bkg)	fit (w/o bkg)	MC input
f_b	0.212±0.019	0.178±0.012	0.180

Update (4)

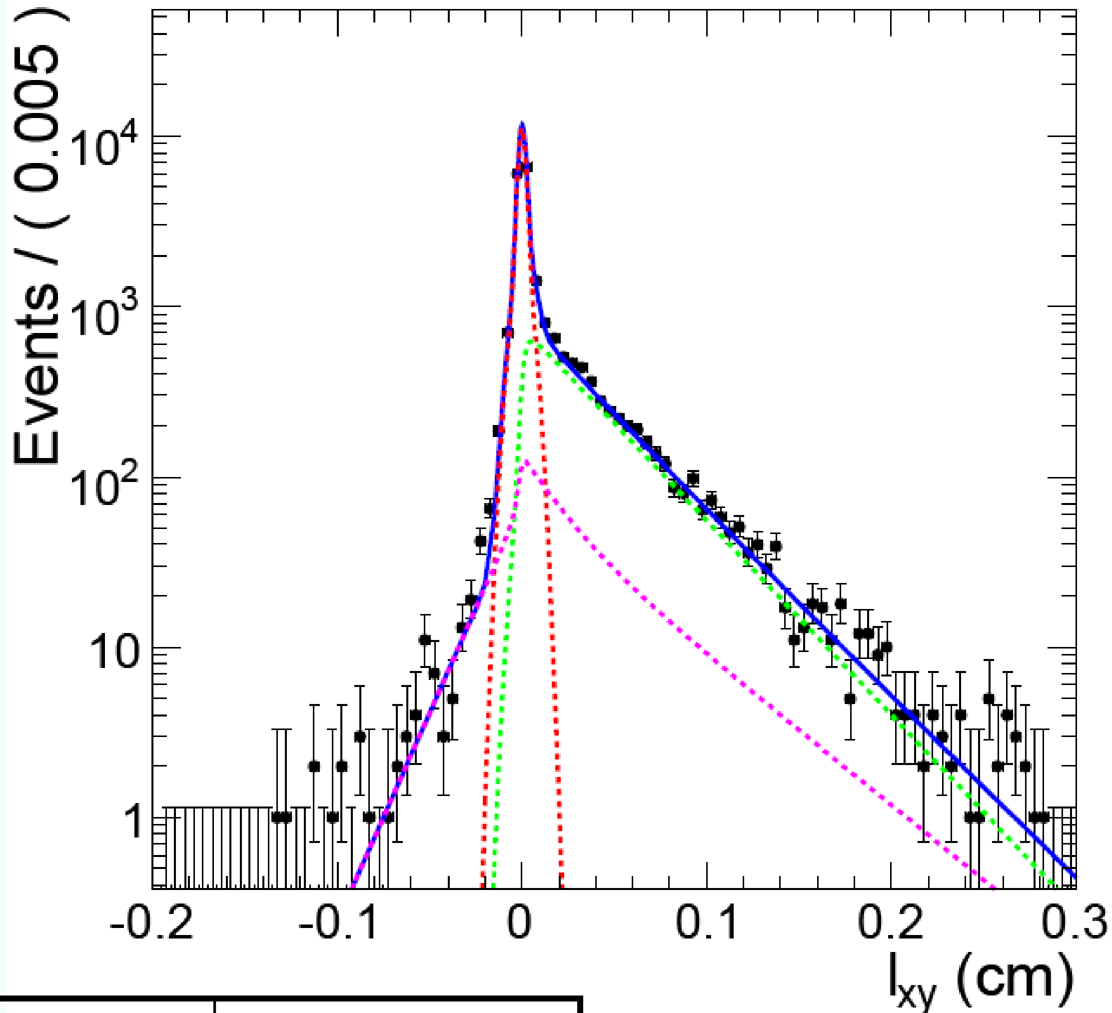
In pT bin 9-10 GeV/c, the background level S/B = 16.7



	fit (w bkg)	fit (w/o bkg)	MC input
f_b	0.296±0.0047	0.299±0.0045	0.295

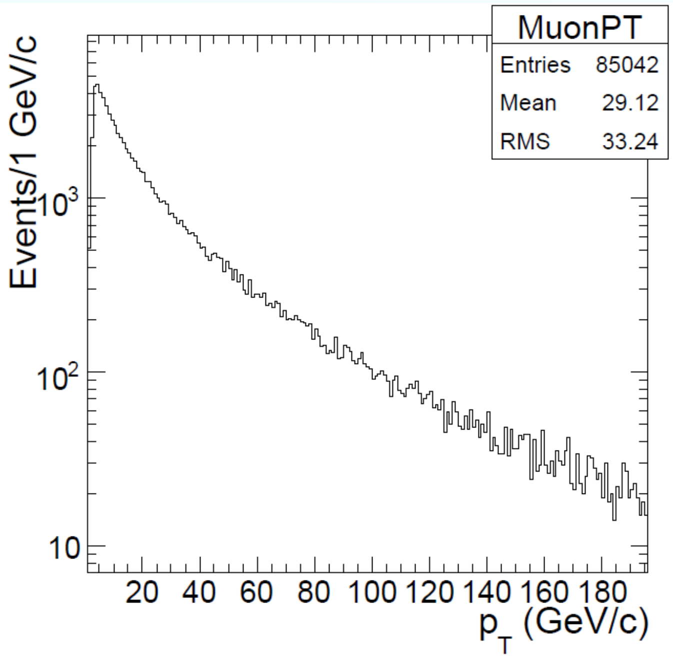
Update (5)

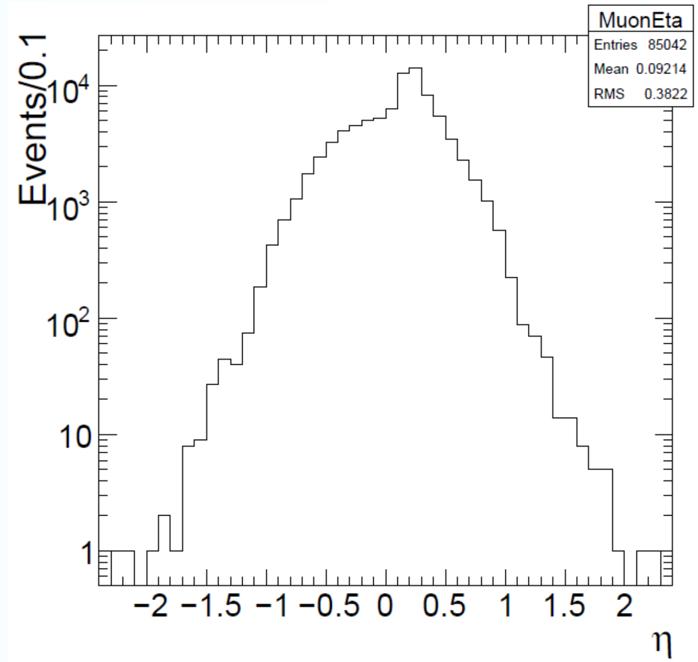
In pT bin 20-24 GeV/c, the background level S/B = 4.36

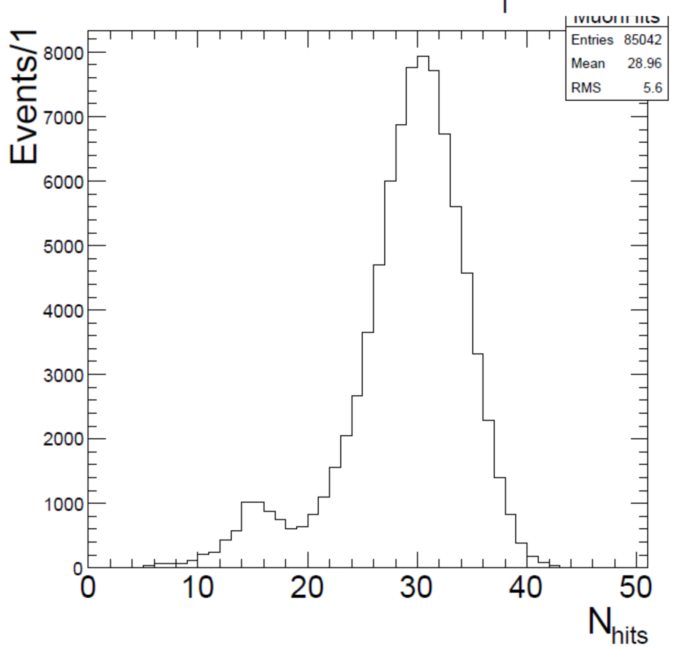


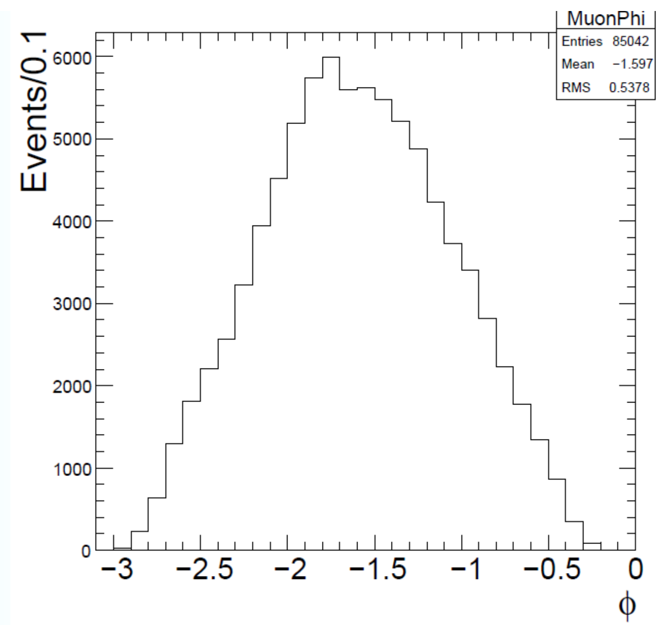
	fit (w bkg)	fit (w/o bkg)	MC input
f_b	0.454±0.011	0.458±0.009	0.457

Cosmic Muons



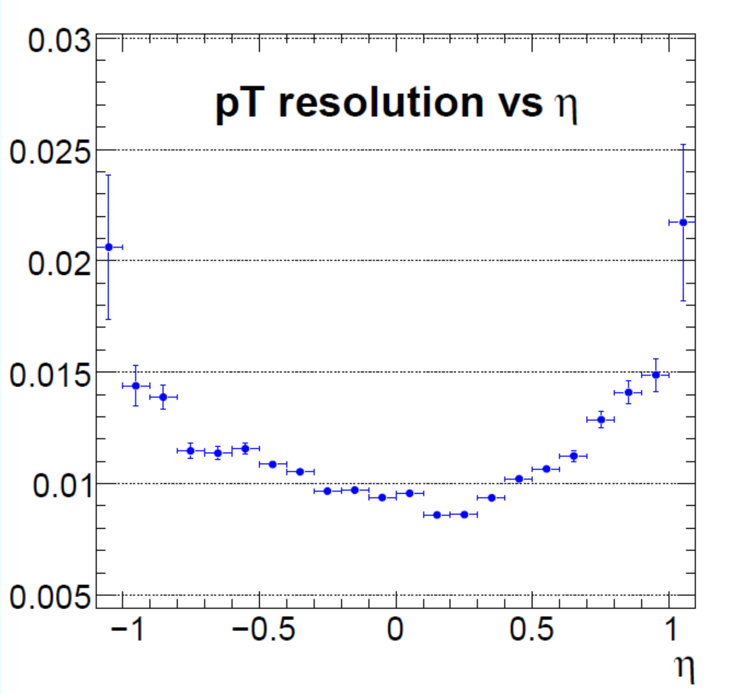


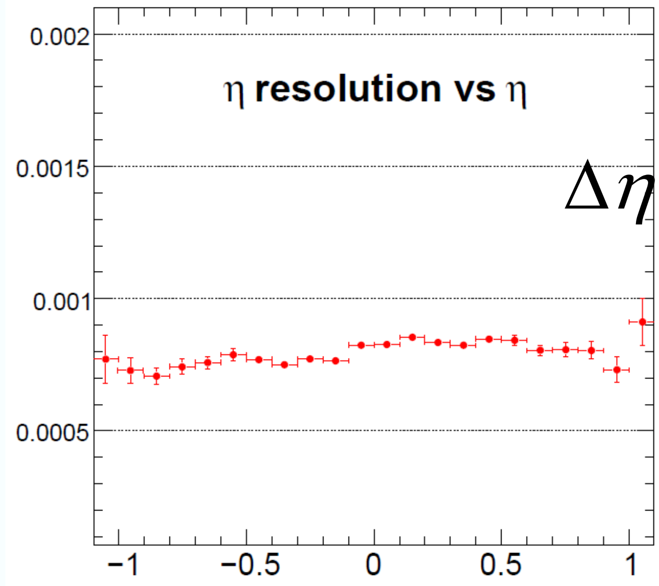




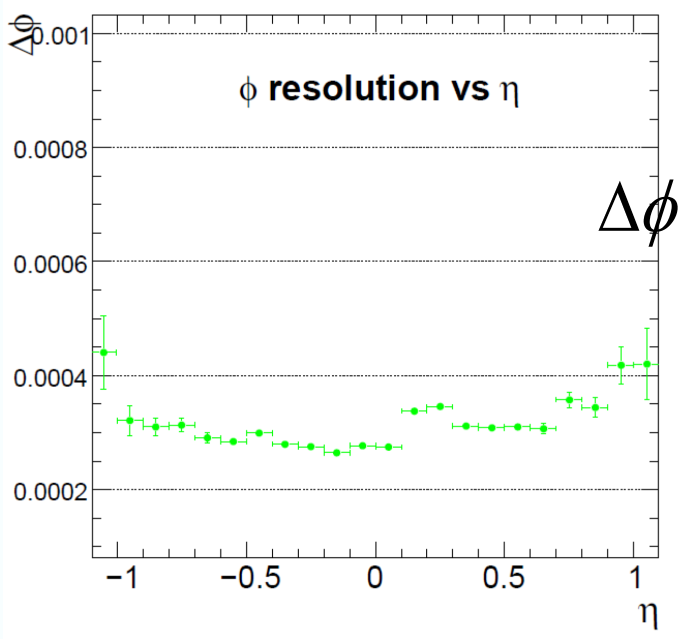
Muon resolution vs. η

$$\frac{\Delta p_T}{p_T}$$





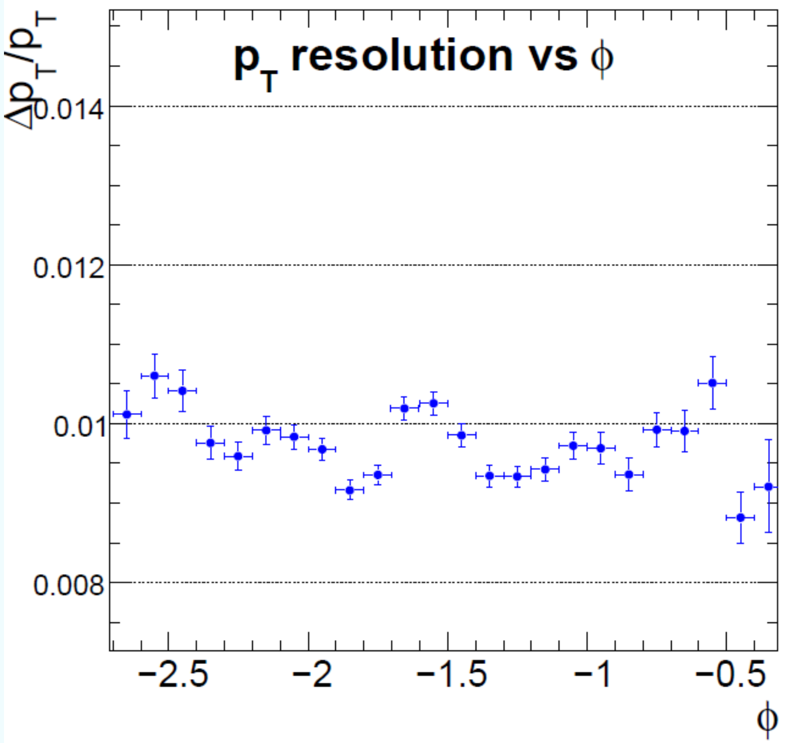
$\Delta\eta$

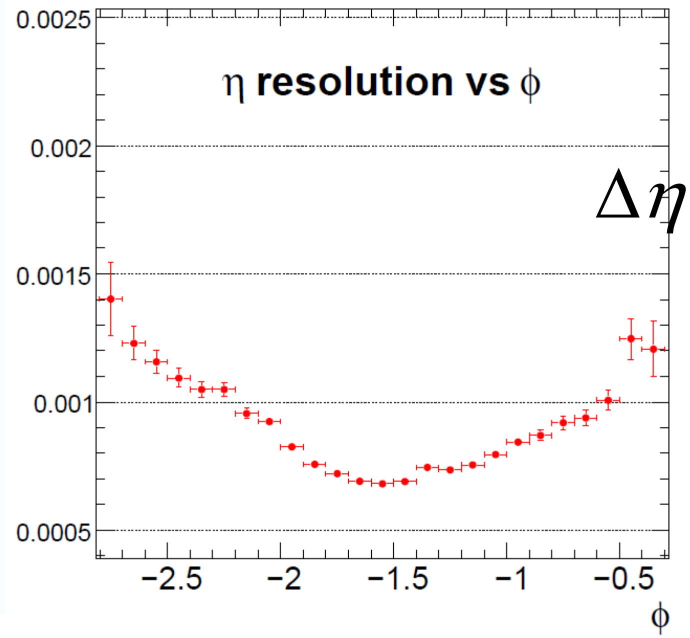


$\Delta\phi$

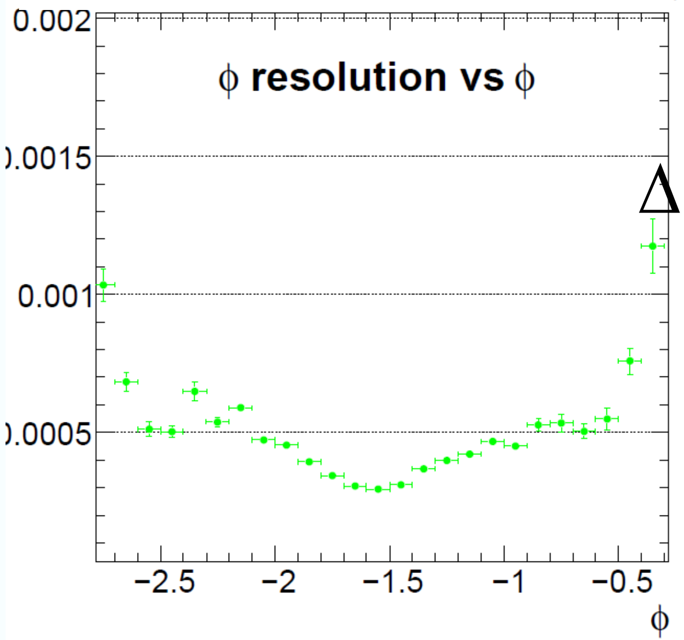
Muon resolution vs. η

$$\frac{\Delta p_T}{p_T}$$





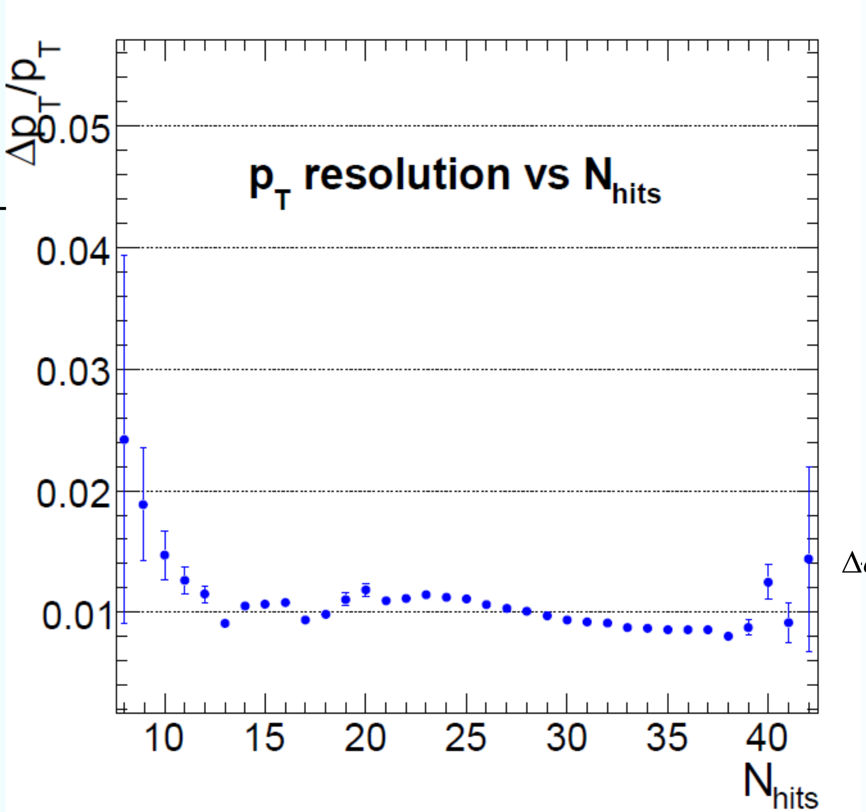
$\Delta\eta$



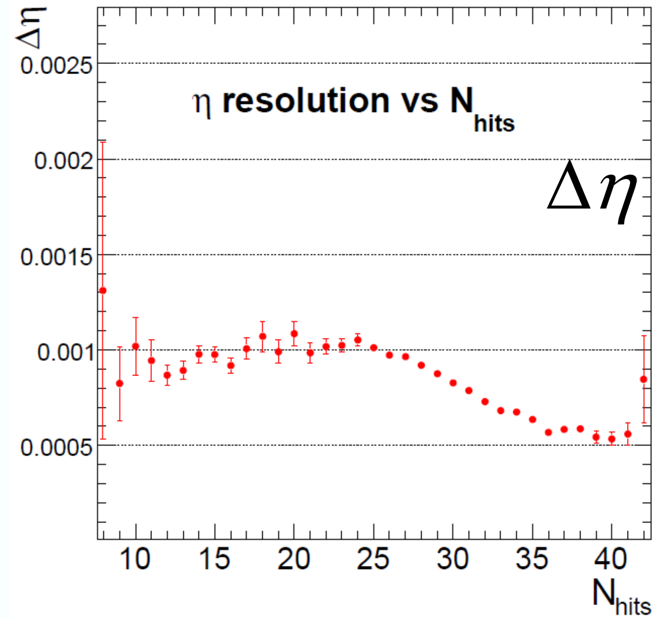
$\Delta\phi$

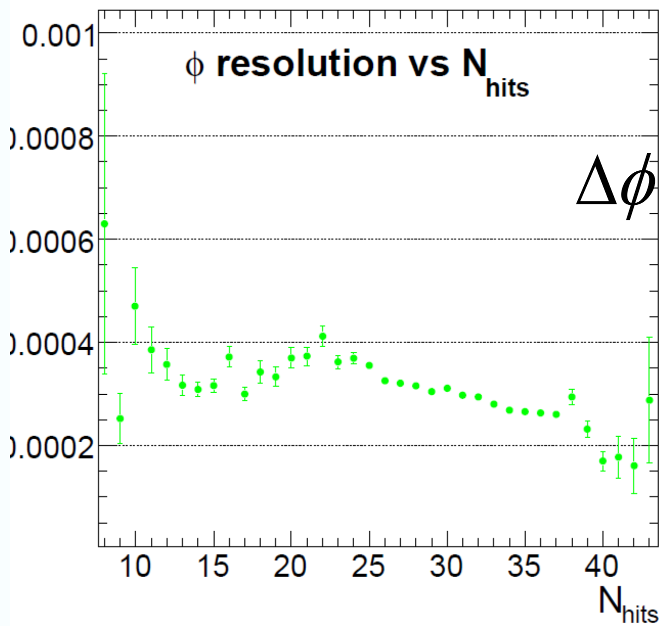
Muon resolution vs. N_{hits}

$$\frac{\Delta p_T}{p_T}$$



$\Delta\phi$





$$N_{hits}(\mu_{up}) + N_{hits}(\mu_{down}) \le N_{hits}(\mu_{one-leg})$$

The resolution as a function of η and ϕ is in the back-up slides