CMS B Physics Results and prospects for the future

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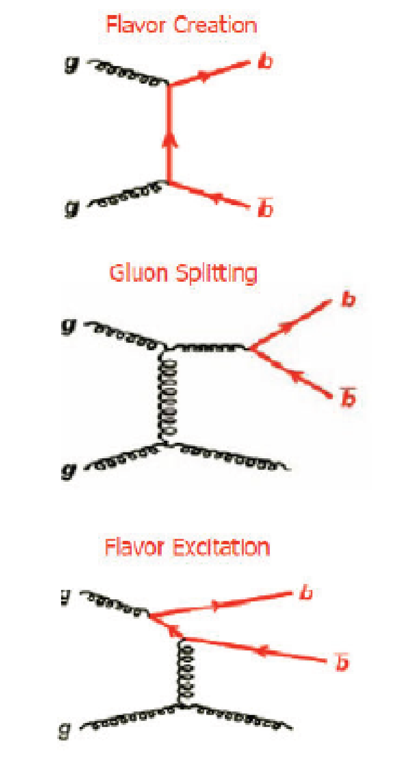
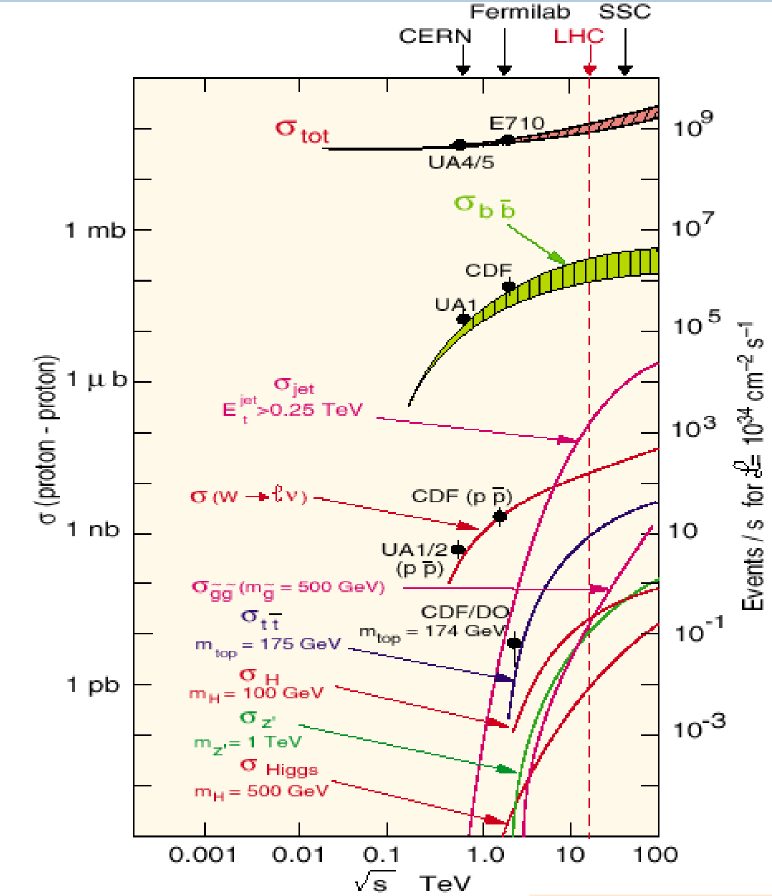
On behalf of
The CMS Collaboration

B physics at LHC

- b quark in pp collisions:
  - high cross section
  - efficient tagging possibilities
  - provide a test of QCD higher order corrections (production mechanism)
  - weak (production and) decay:
    - tool for testing also the weak sector





B physics at LHC

- Early B physics at CMS (low luminosity):
  - Quarkonia production
  - inclusive b-jet production
- Later, with higher statistics:
  - exclusive b-hadron decays
    - test SM and BSM physics (CP, rare decays)
- Main tools:
  - muons (semileptonic b, quarkonia ID)
  - secondary vertexing (b-jet tagging)

LHC and CMS performance

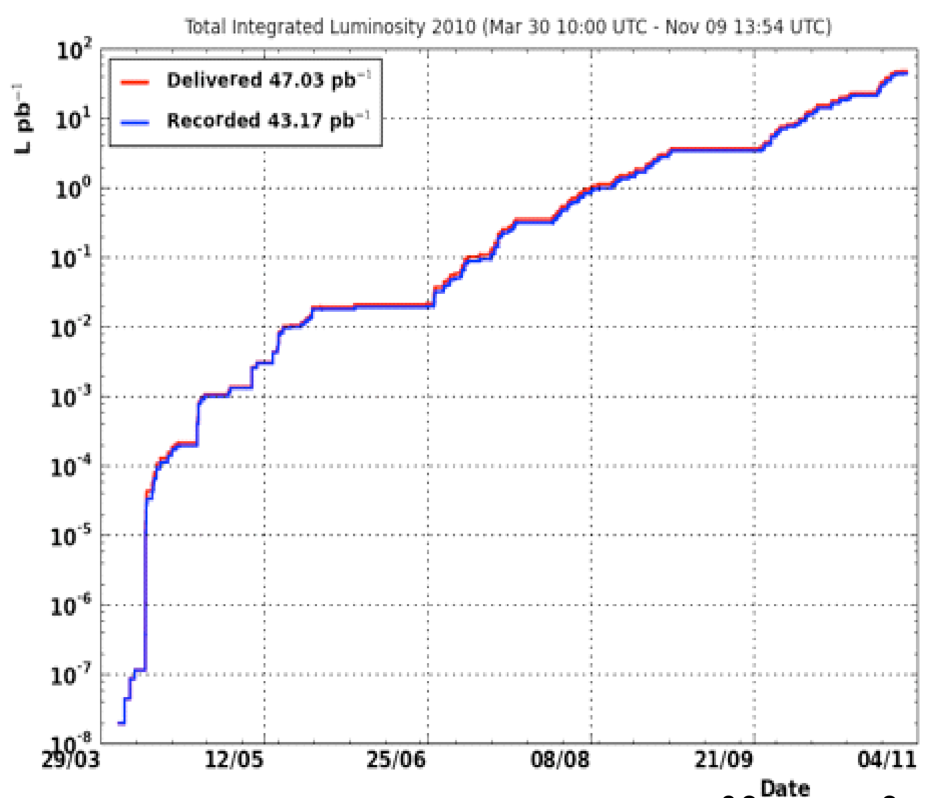
Very good LHC performance and rapid Improvement

LHC instantaneous pp luminosity $2\times10^{32}\ cm^{-2}s^{-1}$

end of 2010 pp run:

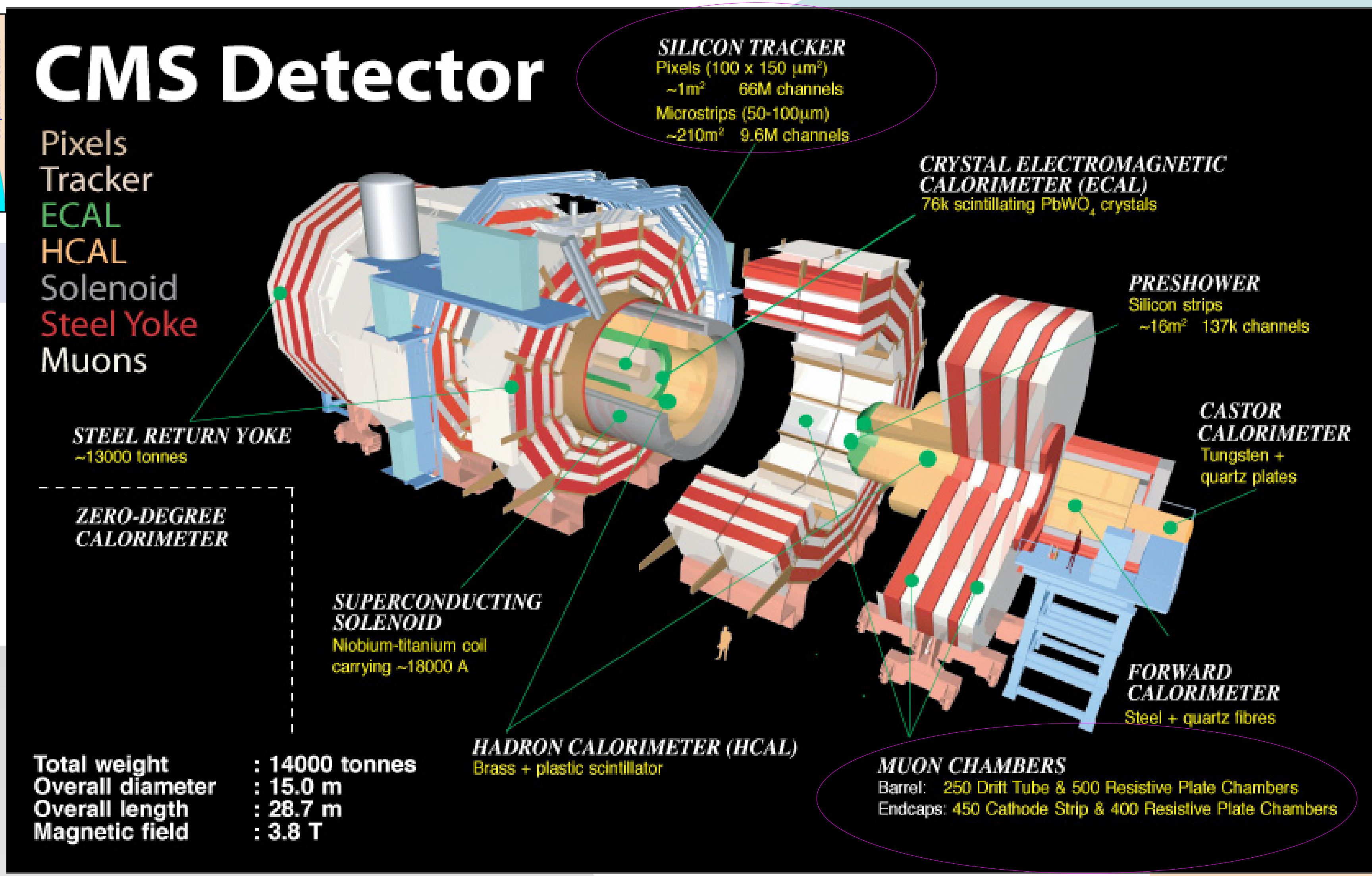
43 pb^{-1} collected by CMS

Low p_T dimuon triggers initially optimized for J/ψ and Upsilon



$$L \simeq 2\times10^{32}\ cm^{-2}s^{-1}$$

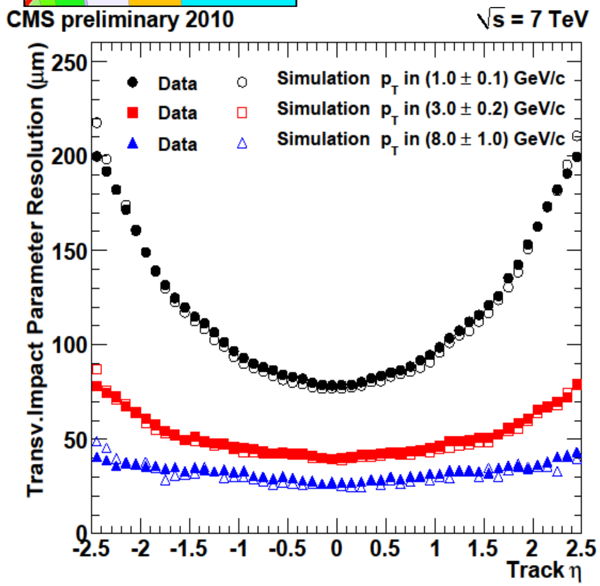
Only a fraction of the collected data is used for the results presented here

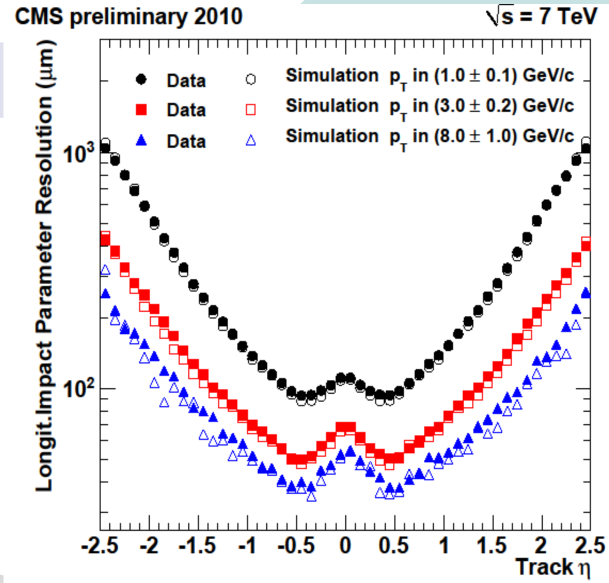


relevant detectors for B physics
(b-tagging and quarkonium detection):

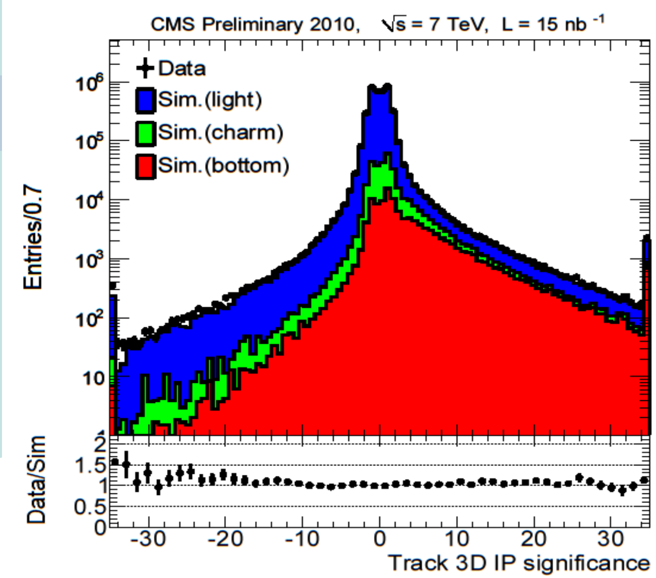
- **Silicon Tracker**
- **Muon Chambers**

tracker performance

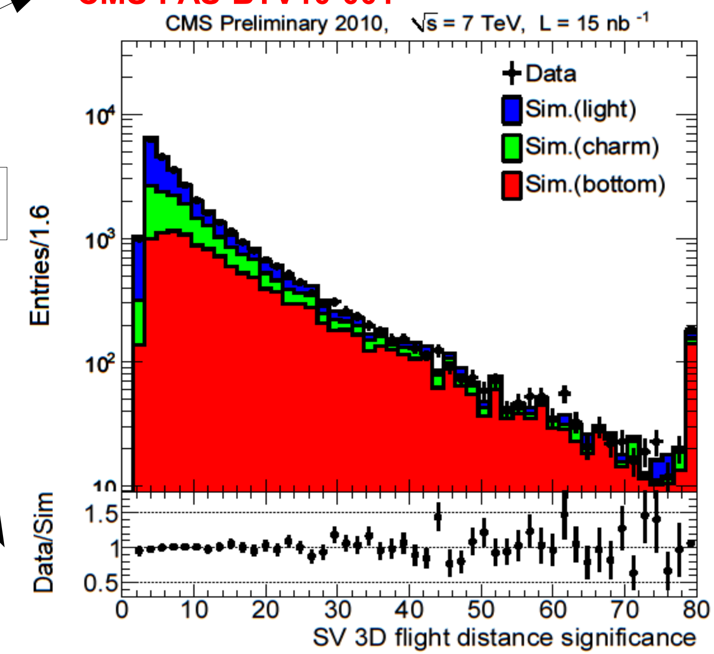




CMS-PAS-TRK-10-005



CMS-PAS-BTV10-001



impact parameter resolution

impact parameter significance

very good data/MC agreement

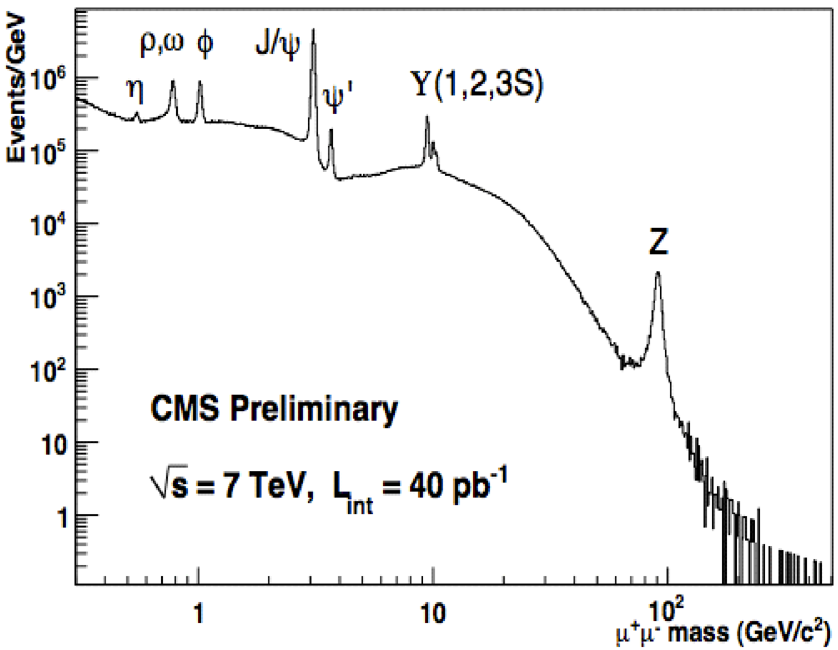
secondary vertex displacement significance

Di-lepton invariant mass

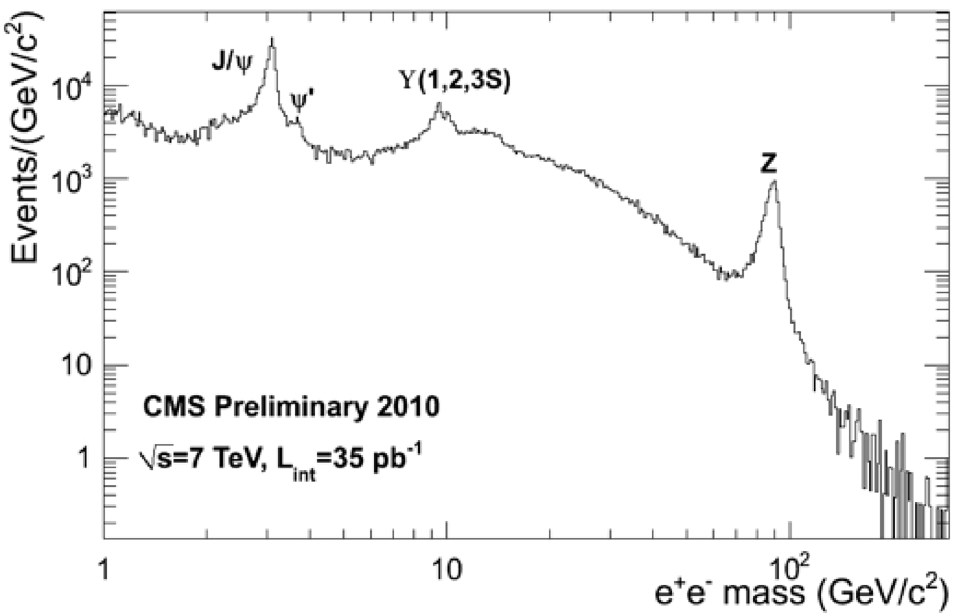
Level-1 and HLT trigger:
high capability and flexibility

down to low masses and p_T,
(especially low p_T muon triggers)

(lower instantaneous luminosities
at LHC start-up)



Stricter triggers now in place to
limit storage rates.



Muon Trigger

- Two trigger levels
  - Level 1 (hardware)
    - (fast) based on calorimeters & muon system (not combined)
  - High Level Trigger (software)
    - matches different subdetectors
    - based on fast local tracking for muons

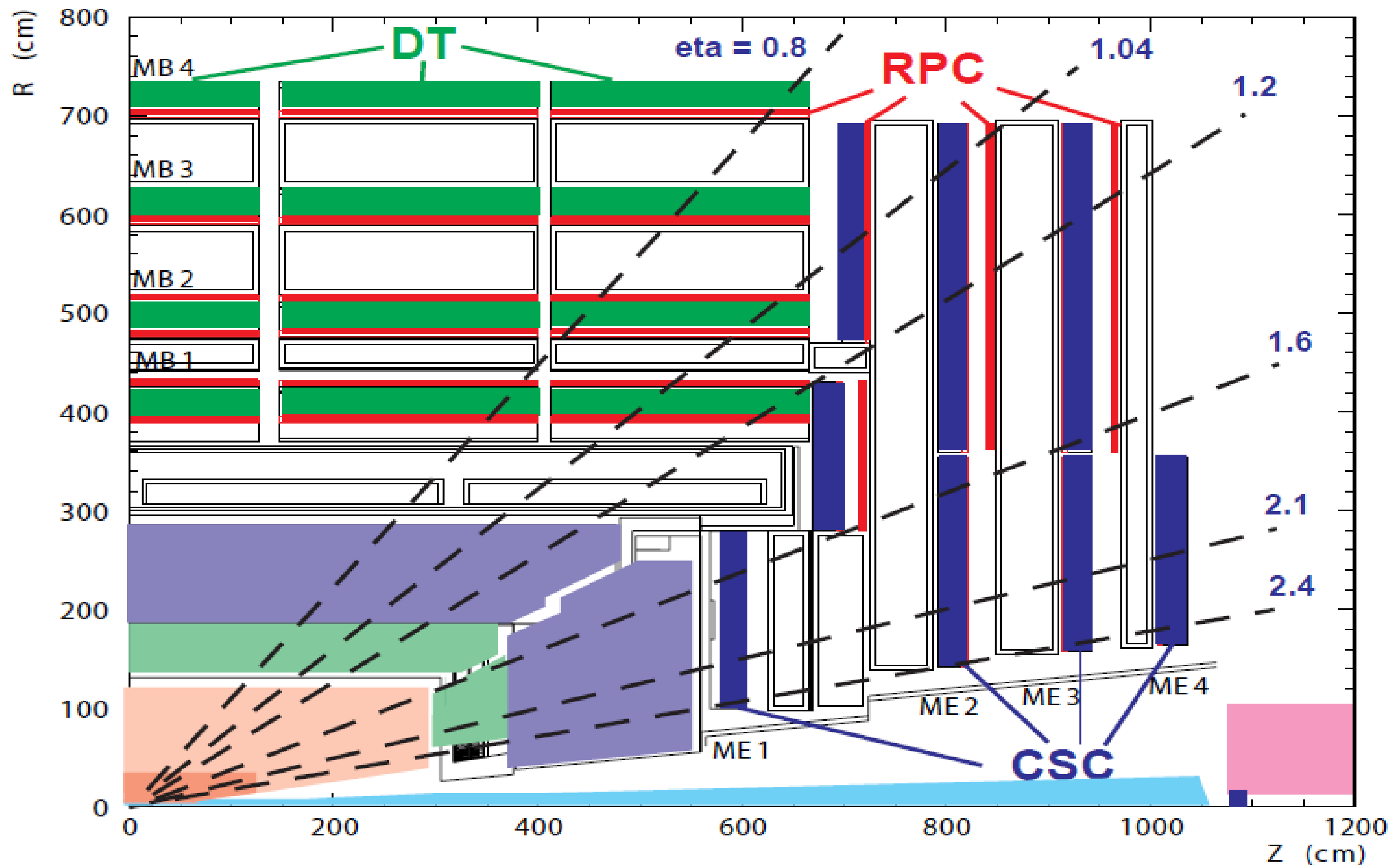
- trigger requirements **changing** with increasing luminosity (due to total rate issues)
  - Single muon:
    - $p_T > 3$ GeV at start-up

      increasing to
    - $p_T > 7$ GeV at $L \approx 10^{31}$ cm^{-2}s^{-1}
  - Double muon:
    - No p_T threshold at start-up!
    - at $L \approx 10^{31}$ cm^{-2}s^{-1} ad-hoc strategies for quarkonia (combination of different single muon triggers)

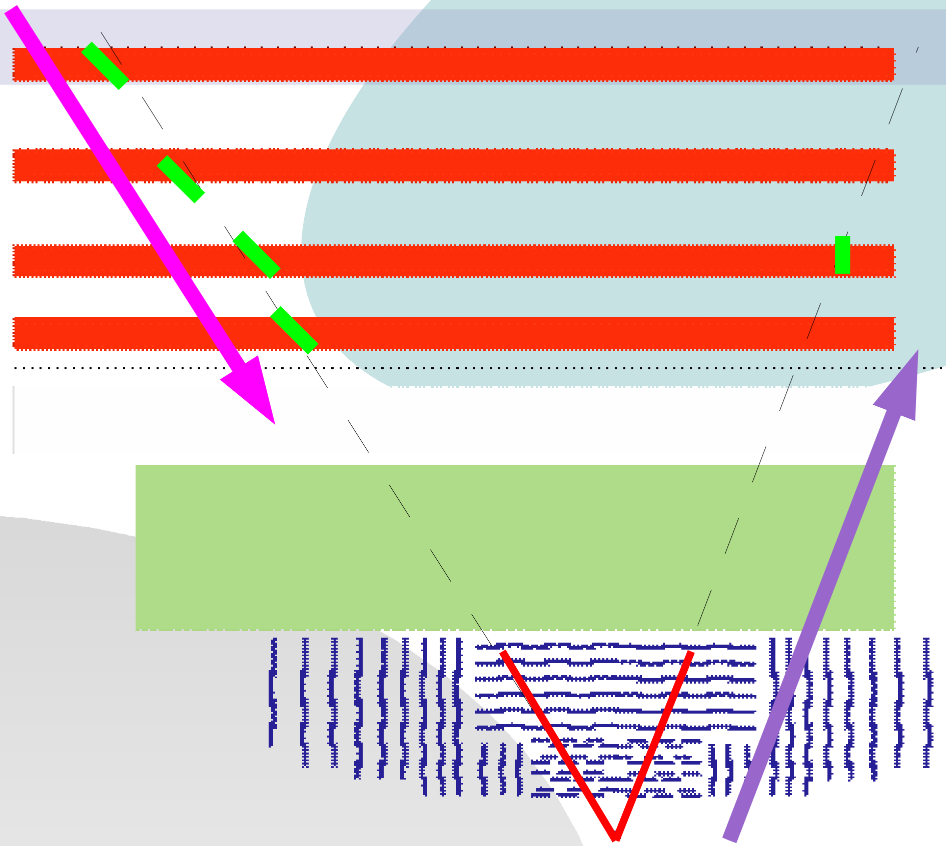
allows detection of low-p_T quarkonia

CMS muon detectors

pseudorapidity reach



Muon identification



Global muon (outside-in):

Muon reconstructed in Muon detectors

matched to

reconstructed track

High purity
Low efficiency for low momentum muon

Tracker muon (inside-out):

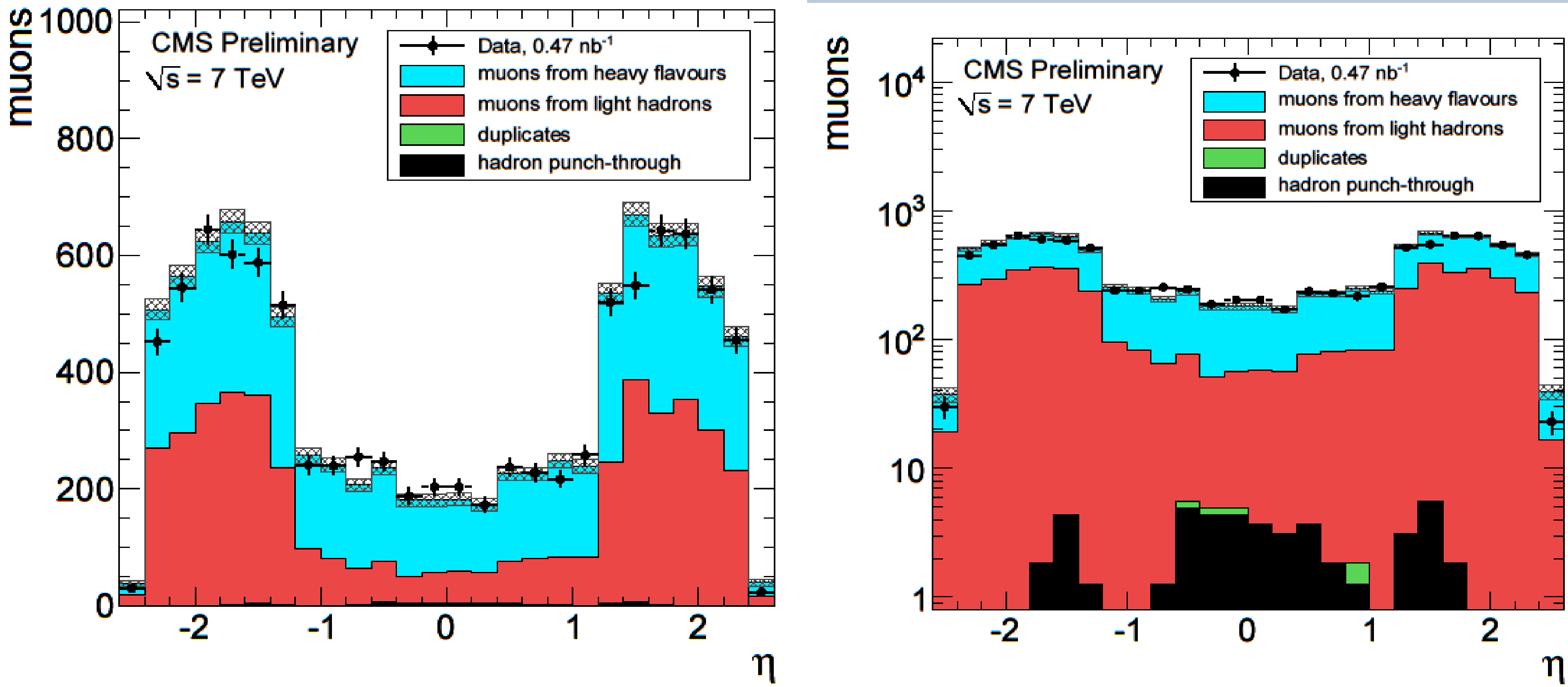
Track reconstructed in Silicon detectors

matched to

Track element in Muon detectors

lower purity (high fake rate)
Higher efficiency for low momentum muon

muon identification performance



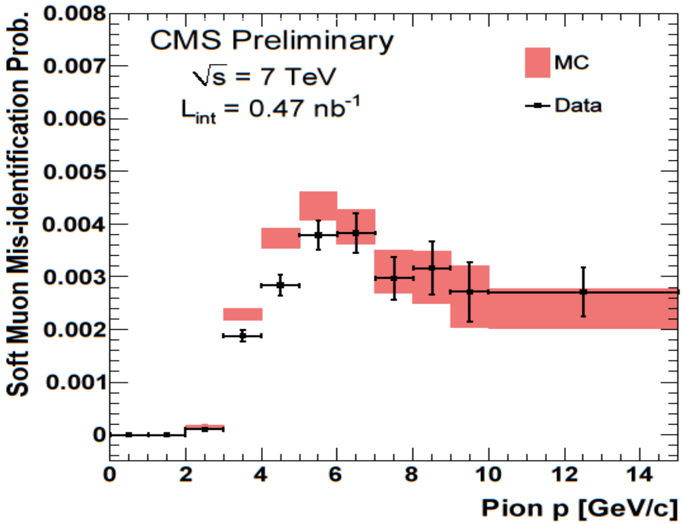
CMS-PAS-MUO-10-002

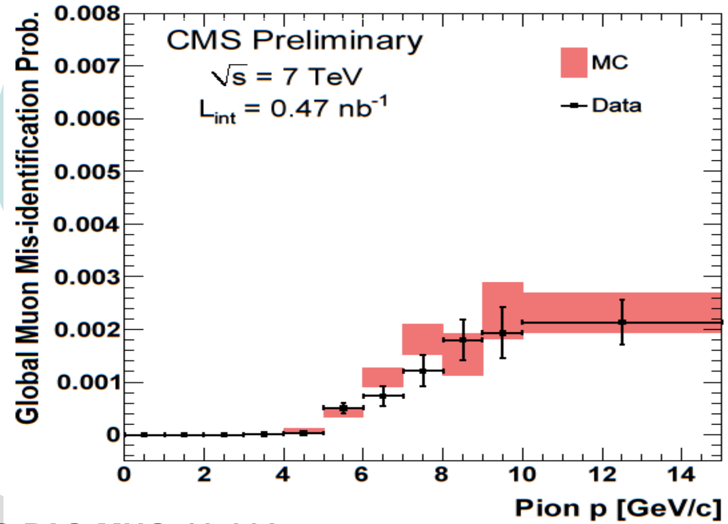
detectors commissioned with cosmic runs in 2008 in 2009

Muons from minimum bias events

muon identification performance

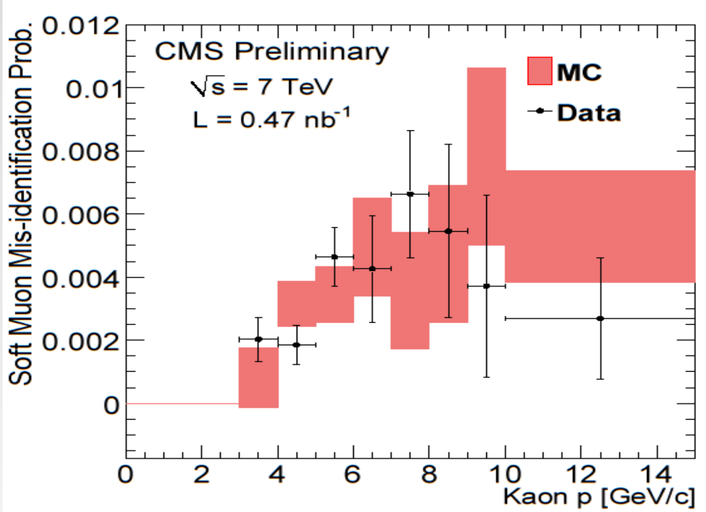
Tracker Muons | **Global Muons**

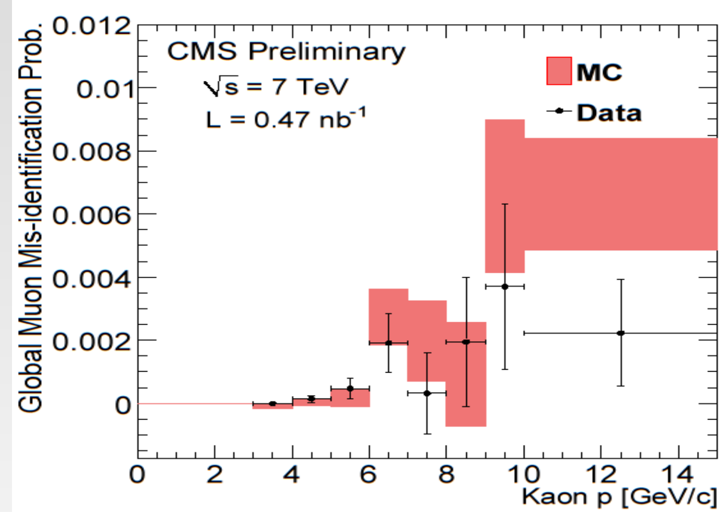




pion misidentification probability from K_s decays

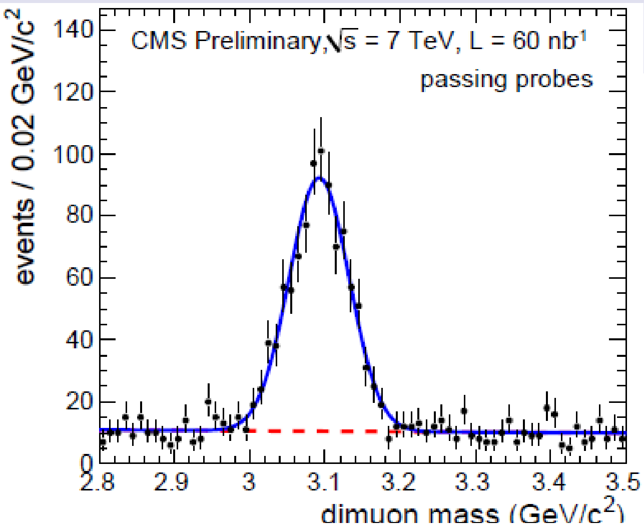
CMS-PAS-MUO-10-002

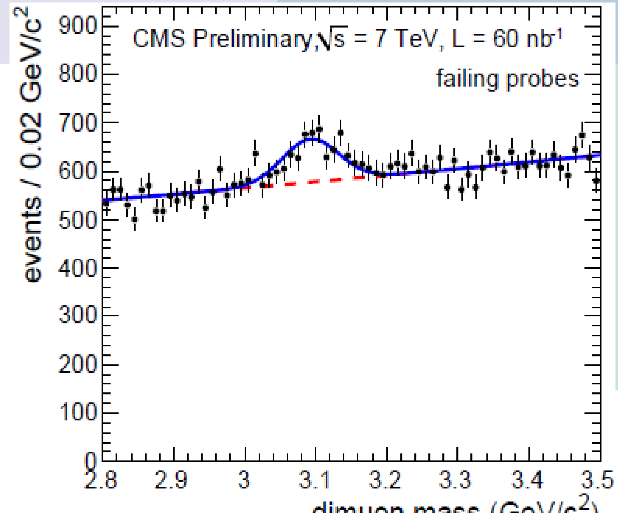




kaon misidentification probability from φ decays

muon efficiencies: Tag & Probe method



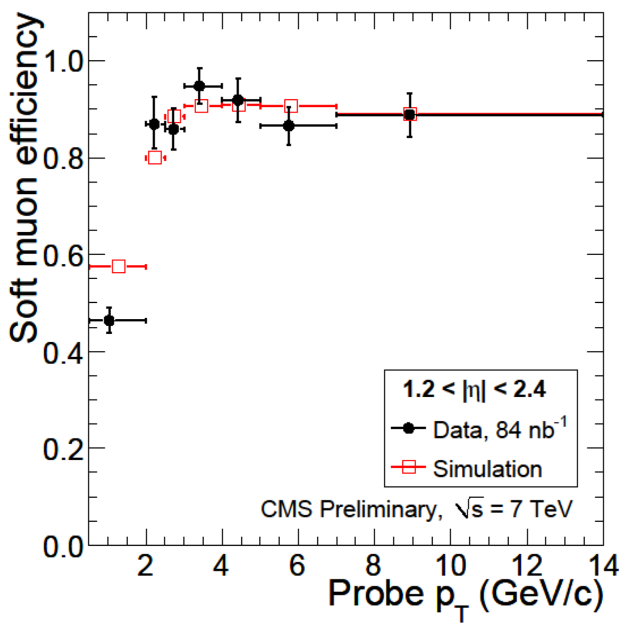


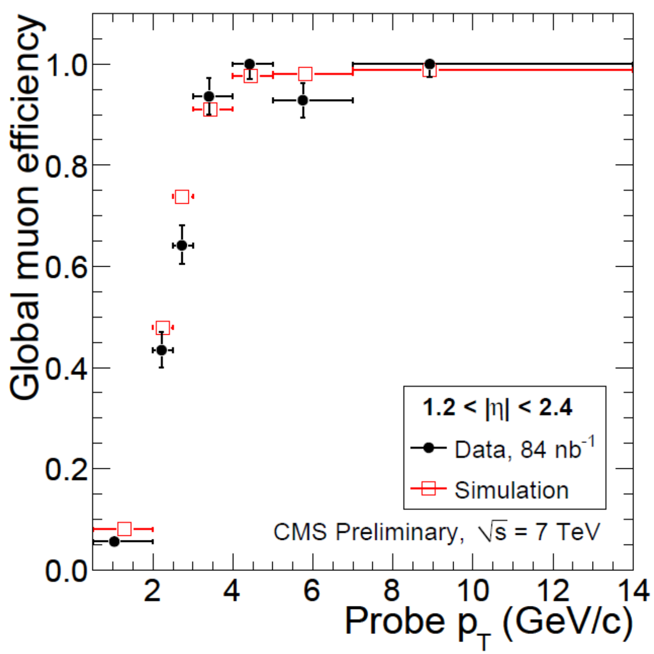
CMS-PAS-MUO-10-002

exploit **J/Ψ→ μμ** mass peak

tag muon: strictly identified

probe muon: used to measure efficiency





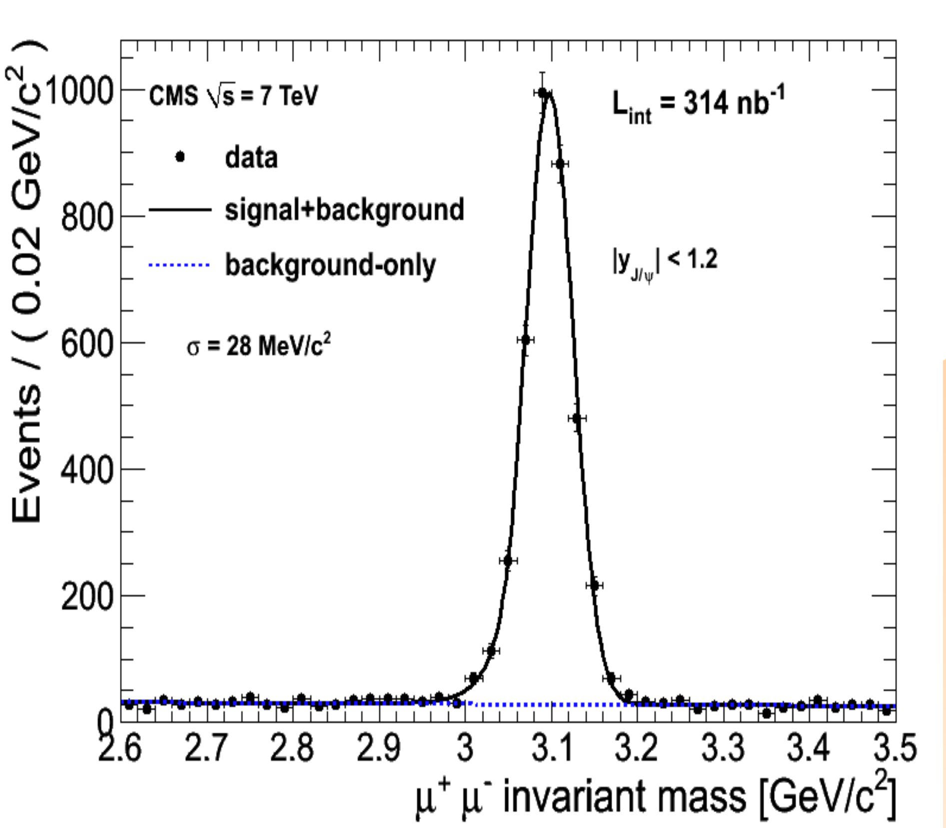
can be used to measure on data different efficiencies:

muon-ID
trigger
track quality cuts

prompt and non-prompt J/ψ production

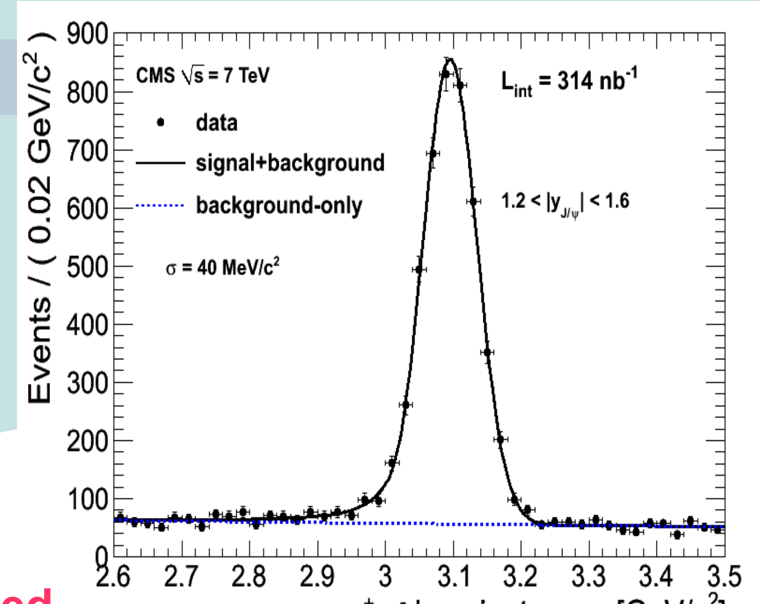
- motivations:
  - prompt production:
    - test theoretical models (e.g. color singlet vs octet)
    - historical discrepancies with Tevatron data
  - non prompt: from b hadron decays
    - test B production and decay models at high energies
    - test QCD and PDFs

CERN-PH-EP/2010-046
18 Nov 2010
Submitted to EPJC
arXiv:1011.4193



prompt and non-prompt J/ψ production

vertexing and tracking allow separation between prompt and non-prompt production

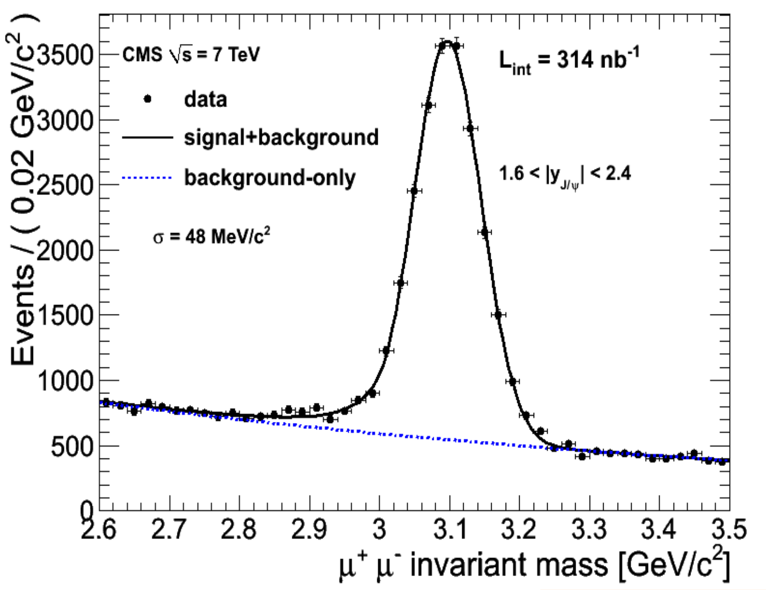


CMS Analysis:
(first 314 nb^{-1})

- **Acceptance window for muons**

- **Track quality:**
  - number of hits in full tracker
  - number of hits in pixel layers
  - track fit χ2

~27000 events selected



- **Muon quality:**
  - fit χ2
  - track-muon matching

- **Di-muon vertex quality**

prompt J/ψ cross section

invariant mass fit in pre-defined p_T and y regions

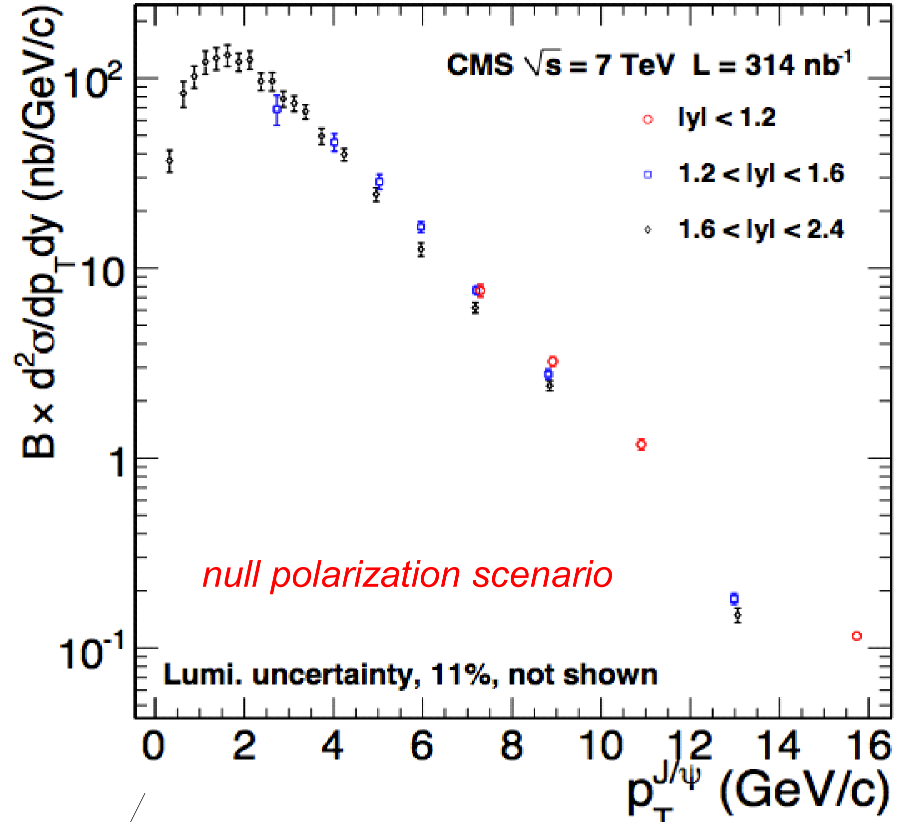
measured yield is corrected for

acceptance and **efficiency**

acceptance → kinematics and decay spectrum **from MC**

efficiency → linked to detector performance **from data (T&P)**

depends on the **polarization** of the J/ψ: computed for 5 «extreme» cases



in the MC:

prompt J/ψ: **unpolarized** (isotropic decay)
non-prompt: polarized as predicted by **EvtGen**

prompt cross section

$$\sigma(pp \to J/\psi + X) \cdot \mathrm{BR}(J/\psi \to \mu^+\mu^-) = 97.5 \pm 1.5(\mathrm{stat}) \pm 3.4(\mathrm{syst}) \pm 10.7(\mathrm{luminosity})\ \mathrm{nb}$$

J/ψ: acceptance

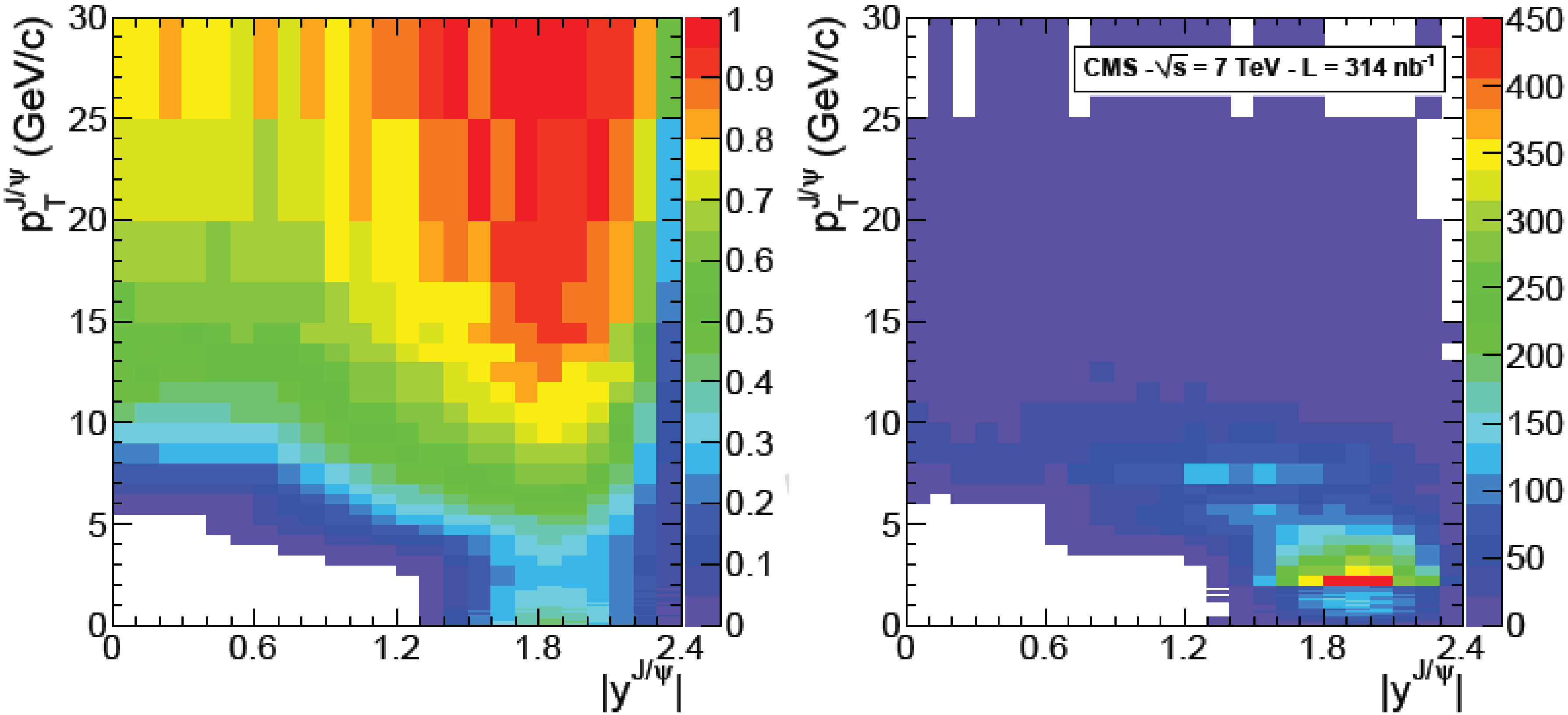
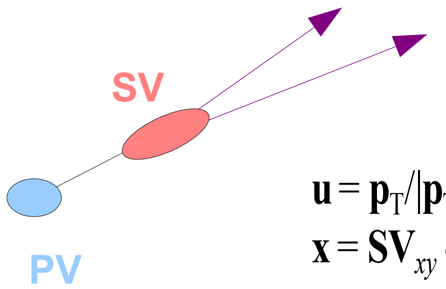
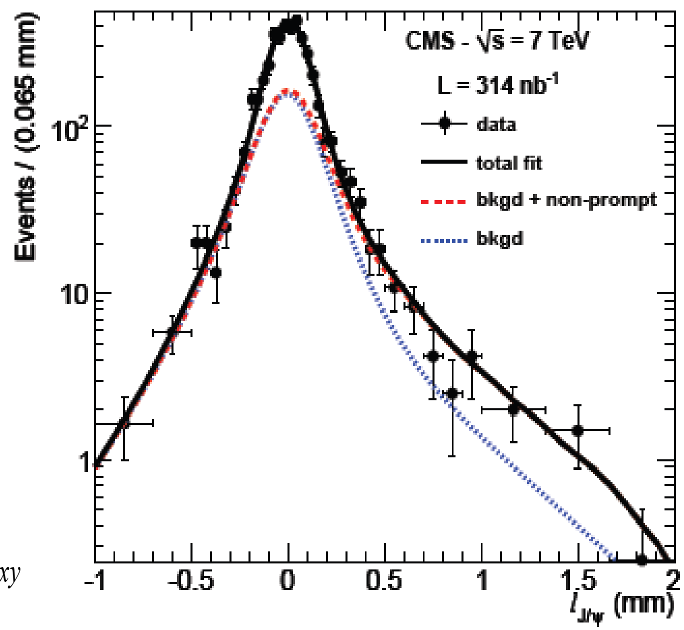


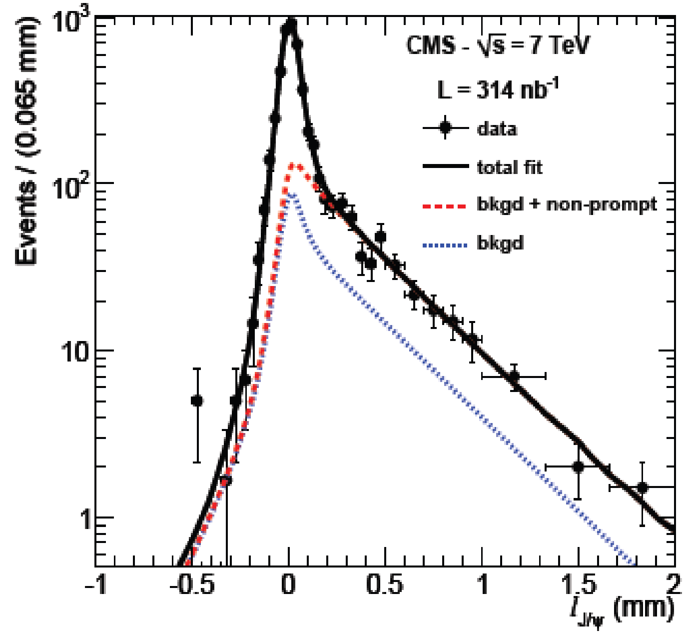
Figure 2: Left: Acceptance as a function of the J/ψ p_T and rapidity. Right: Number of muon pairs within ± 100 MeV$/c^2$ of the nominal J/ψ mass, in bins of p_T and $|y|$.

non-prompt J/ψ cross section



$\mathbf{u} = \mathbf{p}_T / |\mathbf{p}_T|$
$\mathbf{x} = \mathbf{SV}_{xy} - \mathbf{PV}_{xy}$





Pseudo proper decay length

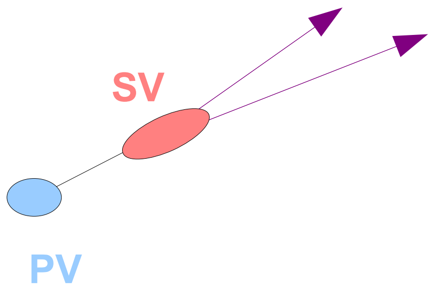
$$\ell_{J/\psi} = L_{xy} \cdot m_{J/\psi} / p_T \qquad L_{xy} = \frac{\mathbf{u}^T \sigma^{-1} \mathbf{x}}{\mathbf{u}^T \sigma^{-1} \mathbf{u}}$$

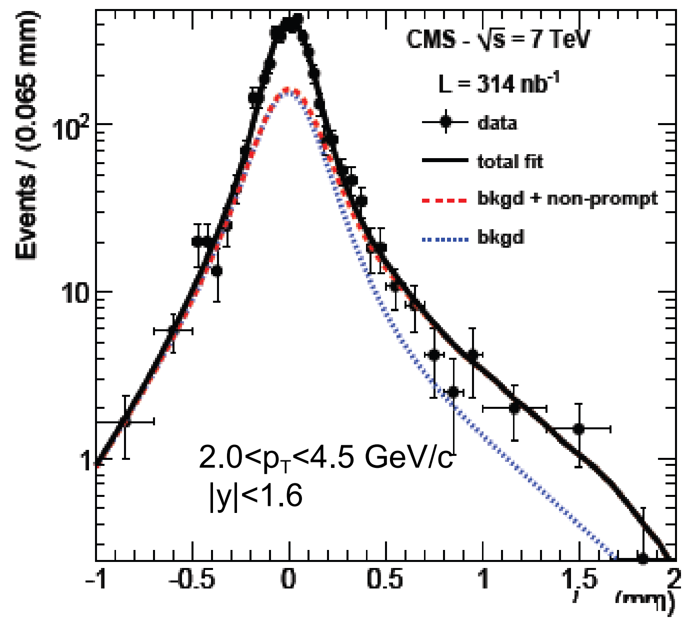
projection of measured vertex distance onto momentum direction

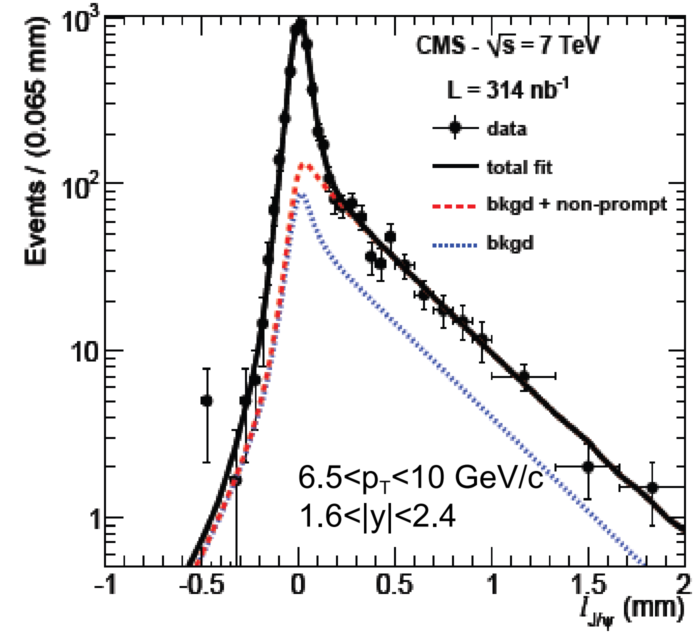
Decay length l_{xy} resolutions depend on the p_T and mildly on the rapidity
p_T (J/Psi) 0-2 GeV/c ~250 µm
p_T (J/Psi) 10-30 GeV/c ~35 µm

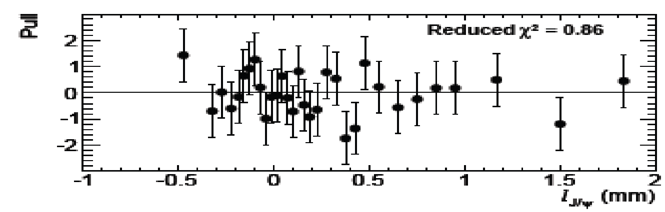
Decay length parametrization :
Prompt : δ-function
Non-prompt : MC templates
all convoluted with a 3-Gaussian resolution

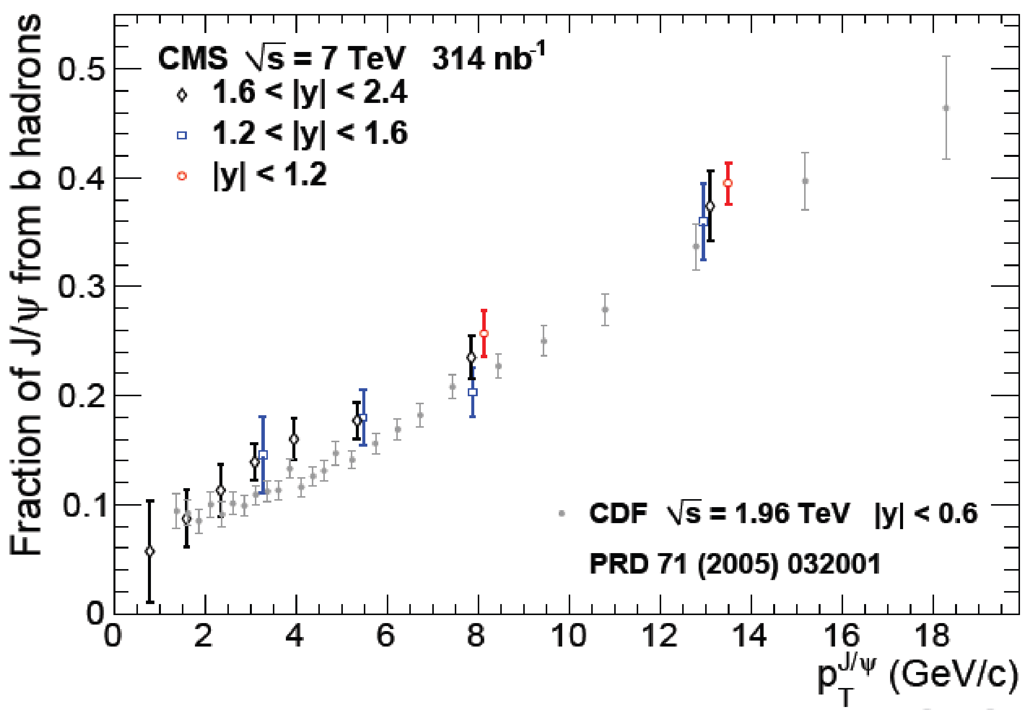
non-prompt J/ψ cross section







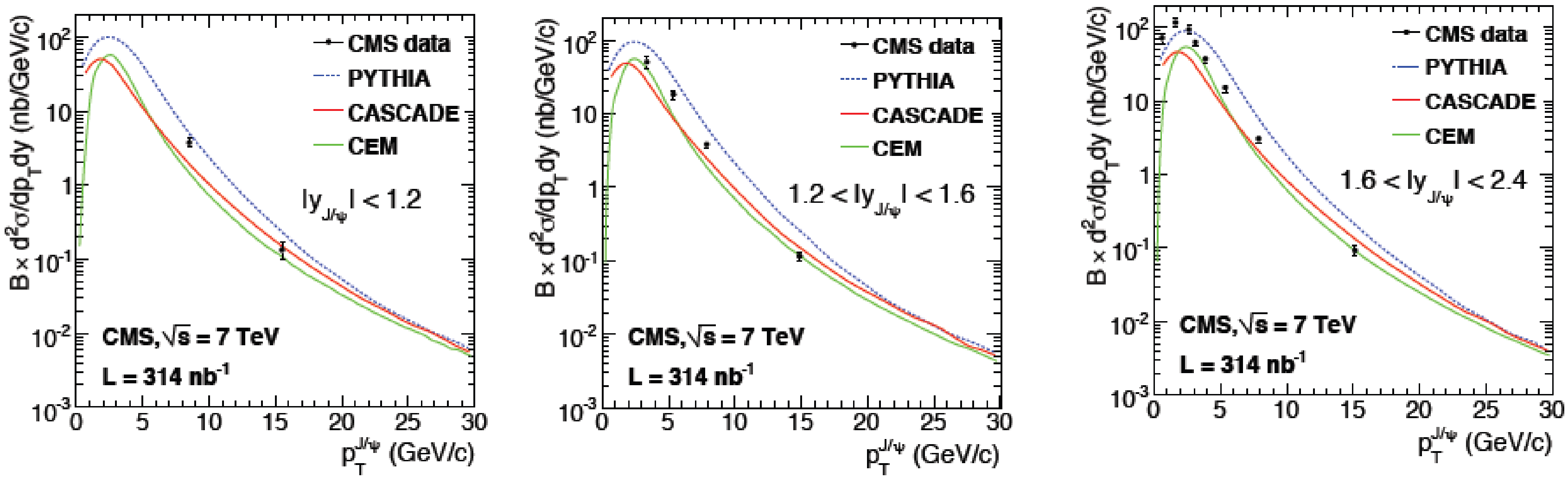




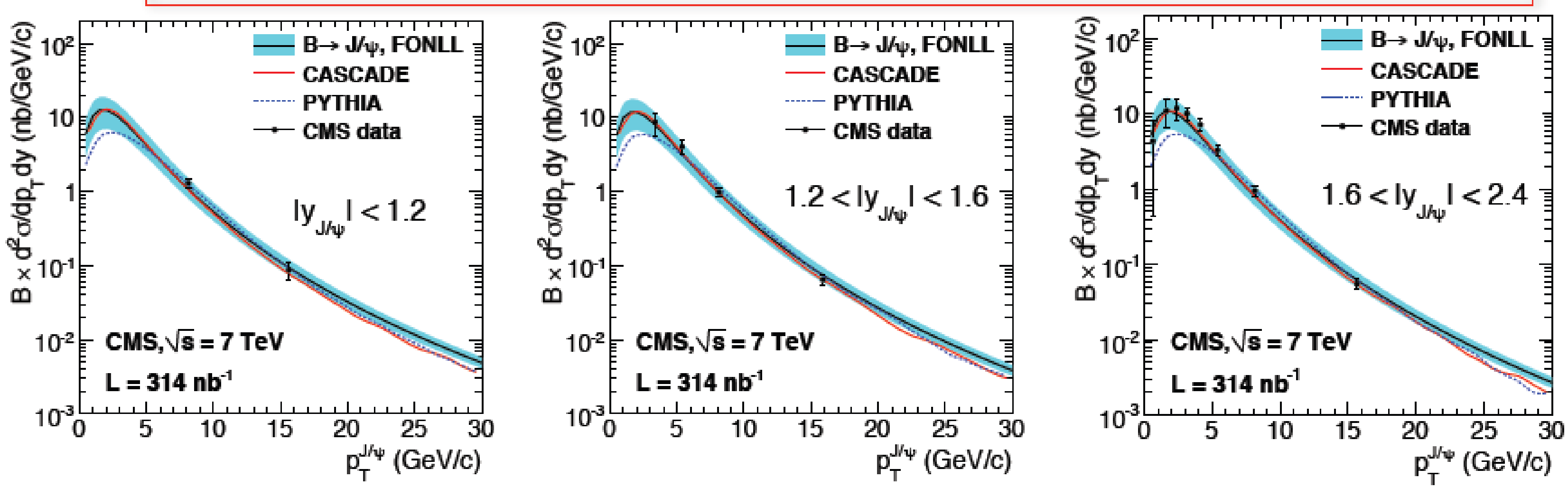
relative error (in %)

	$\lvert y\rvert < 1.2$	$1.2 < \lvert y\rvert < 1.6$	$1.6 < \lvert y\rvert < 2.4$
Tracker misalignment	0.5 – 0.7	0.9 – 4.6	0.7 – 9.1
b-lifetime model	0.0 – 0.1	0.5 – 4.8	0.5 – 11.2
Vertex estimation	0.3	1.0 – 12.3	0.9 – 65.8
Background fit	0.1 – 4.7	0.5 – 9.5	0.2 – 14.8
Resolution model	0.8 – 2.8	1.3 – 13.0	0.4 – 30.2
Efficiency	0.1 – 1.1	0.3 – 1.3	0.2 – 2.4

prompt and non-prompt J/ψ: comparison with theory



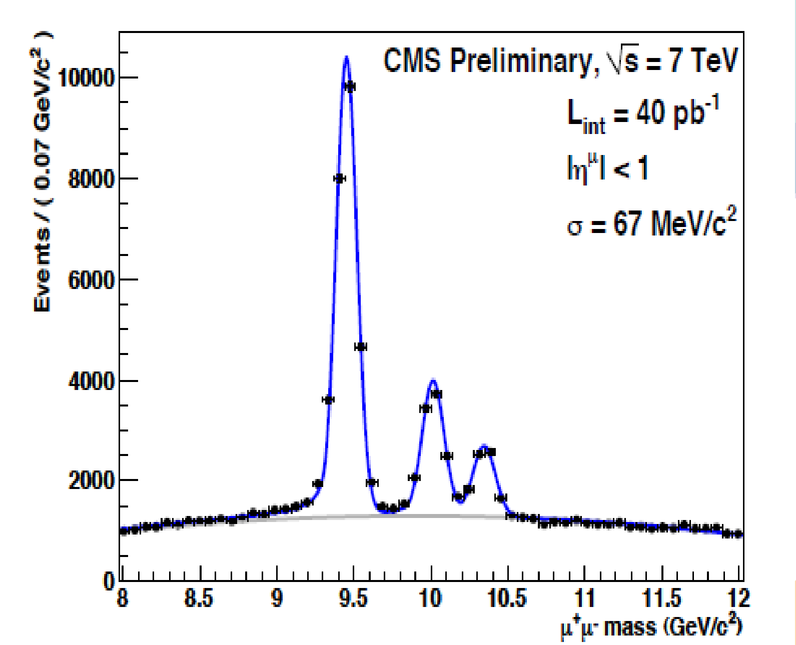
$$\sigma(pp \rightarrow \mathrm{J}/\psi + \mathrm{X}) \cdot \mathrm{BR}(\mathrm{J}/\psi \rightarrow \mu^+\mu^-) = 70.9 \pm 2.1(\mathrm{stat}) \pm 3.0(\mathrm{syst}) \pm 7.8(\mathrm{luminosity})\ \mathrm{nb}$$



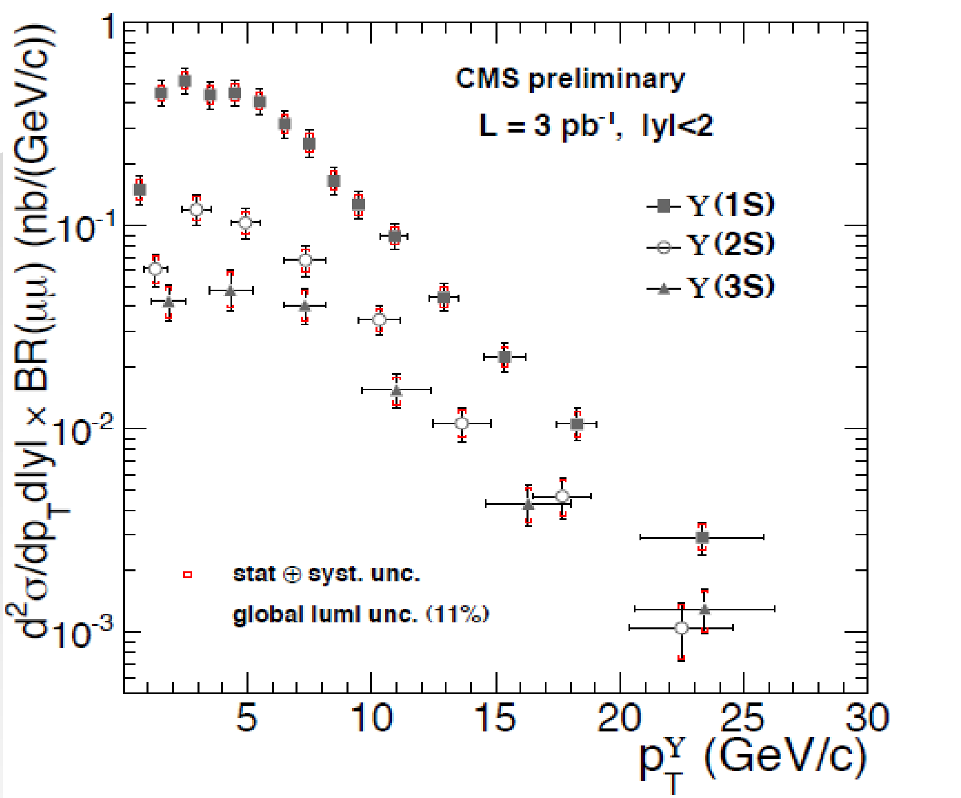
$$\sigma(\mathrm{pp} \rightarrow bX \rightarrow \mathrm{J}/\psi X) \cdot \mathrm{BR}(\mathrm{J}/\psi \rightarrow \mu^+\mu^-) = 26.0 \pm 1.4\ (\mathrm{stat}) \pm 1.6\ (\mathrm{syst}) \pm 2.9\ (\mathrm{luminosity})\ \mathrm{nb}$$

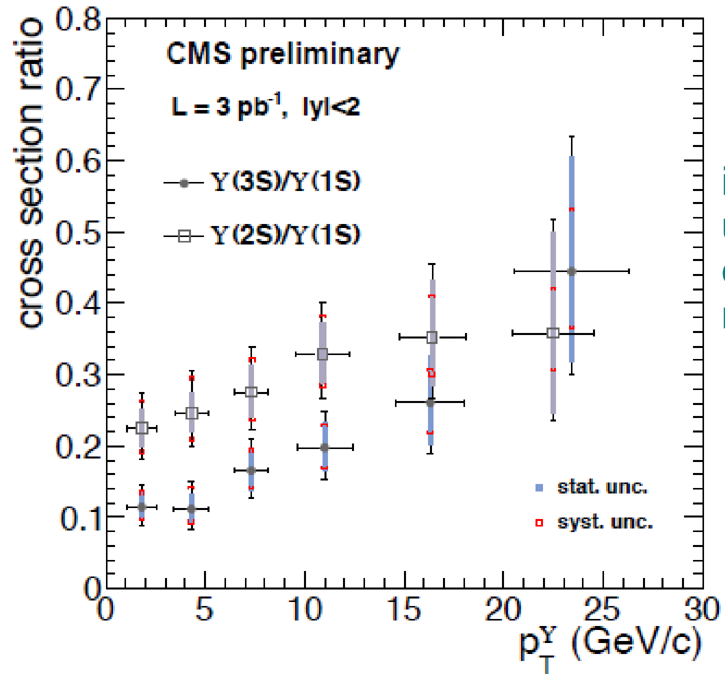
Y(nS) production

- Similar selection as J/ψ:
- acceptance from MC
- efficiencies from data (T&P)
- fit to 3 Crystal Ball functions + linear background
- main systematics from efficiency



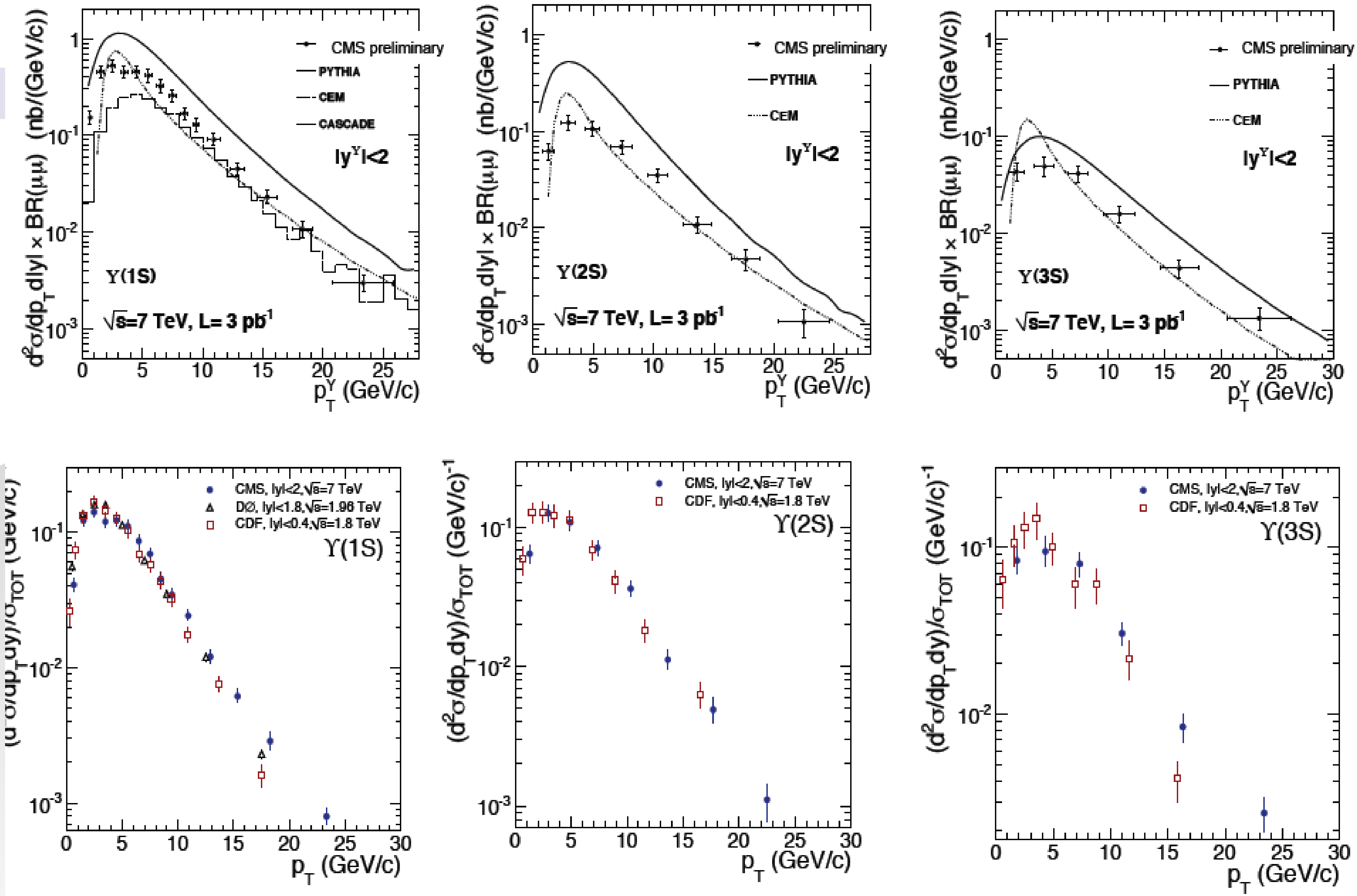
X-section result depends on assumed polarization (~20% variation between 5 extreme scenarios)





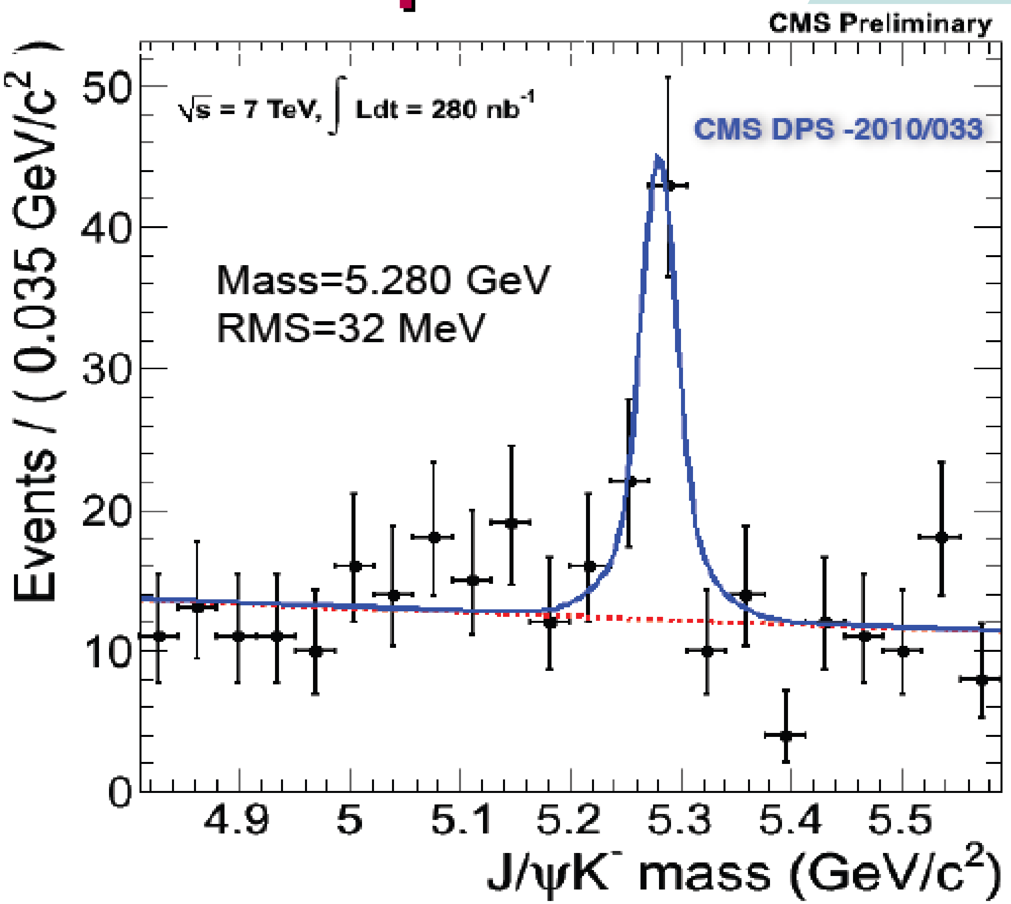
important systematic uncertainties cancel out in the ratio

Υ(nS) production: comparison with theory and Tevatron



exclusive B channels

$B^{\pm} \to J/\psi\ K^{\pm}$



Analysis ongoing,
based on larger statistics
(measuring differential cross section)

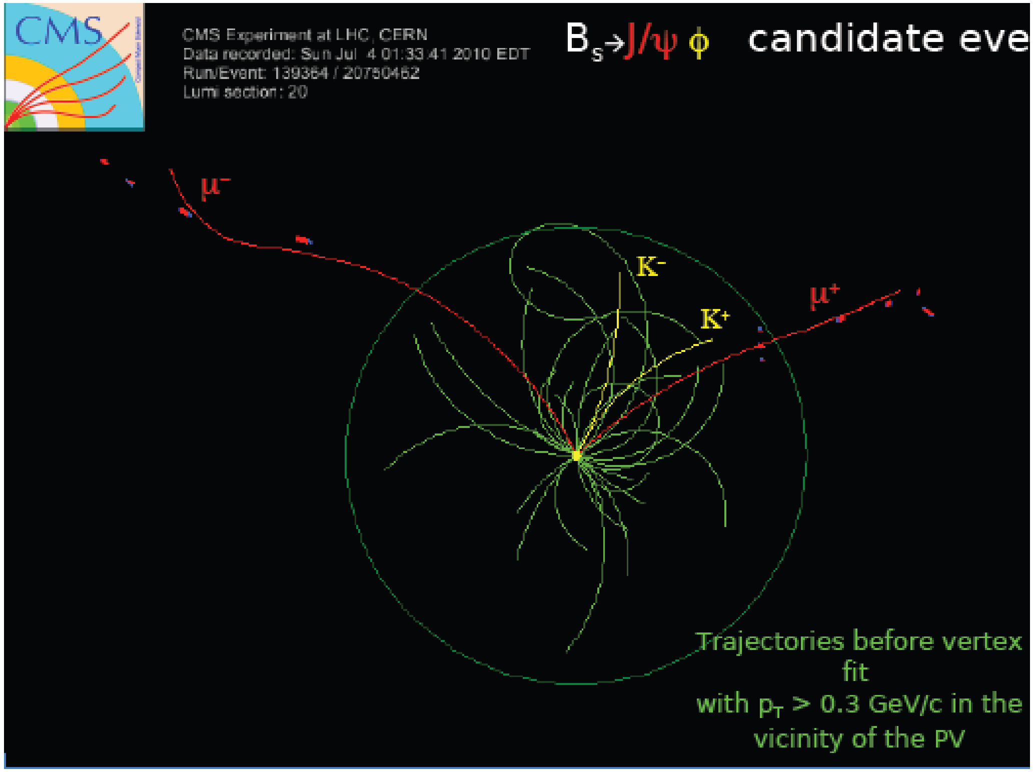
fit: 3 gaussians + exponential bkg

Also:

$B^0 \to J/\psi\ K^0_S$

$B^0 \to J/\psi\ K^{*0}$

$B_s \rightarrow J/\psi\ \varphi$



Fit results:

$\mu_{gauss} = 5.3670 \pm 1.2\text{e-}03$ GeV/c^2

$\sigma_{gauss} = 16.4 \pm 1.2$ MeV/c^2

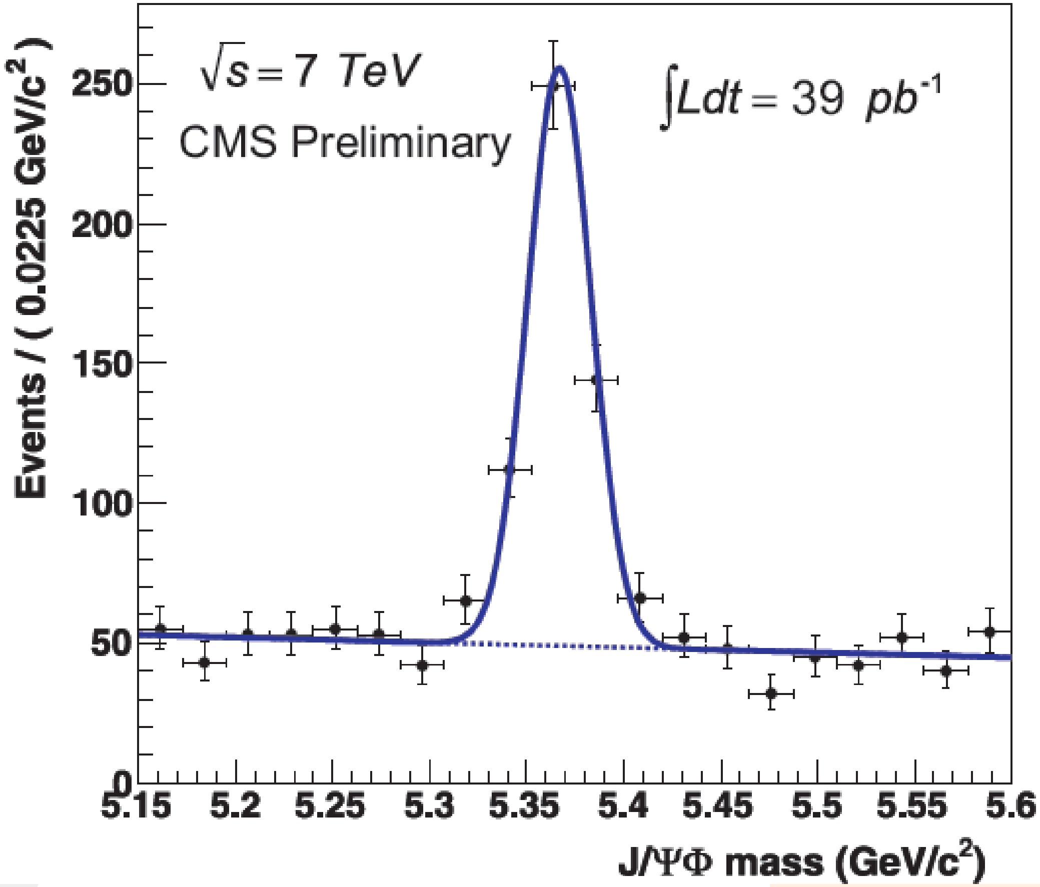
$N_{signal} = 377 \pm 26$

$N_{BG} = 978 \pm 36$

$\chi^2/ndof = 0.91$

$S/\sqrt{(S+B)} \approx 10$

$S/B \approx 0.4$



b semileptonic decays

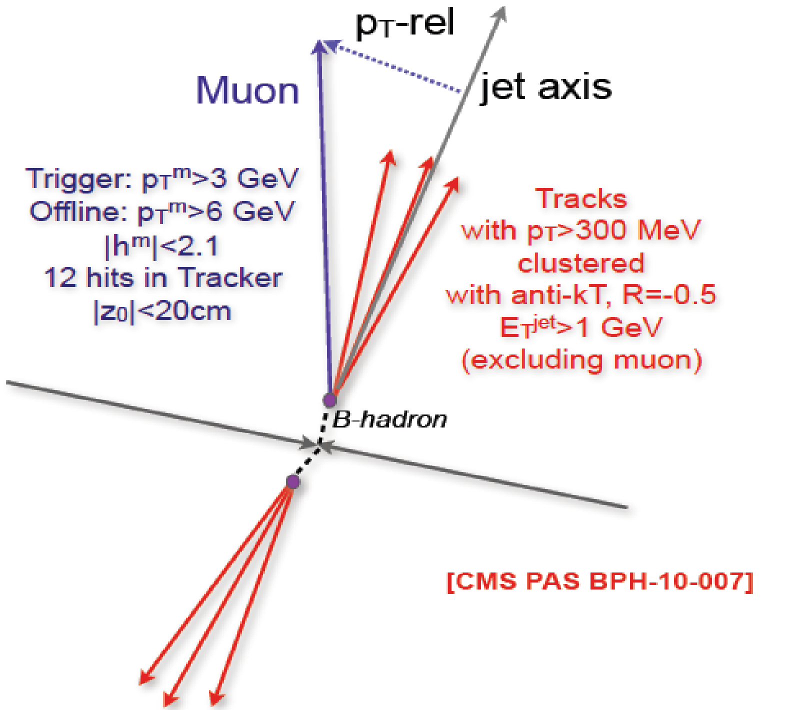
larger transverse momentum relative to jet axis than with lighter flavour

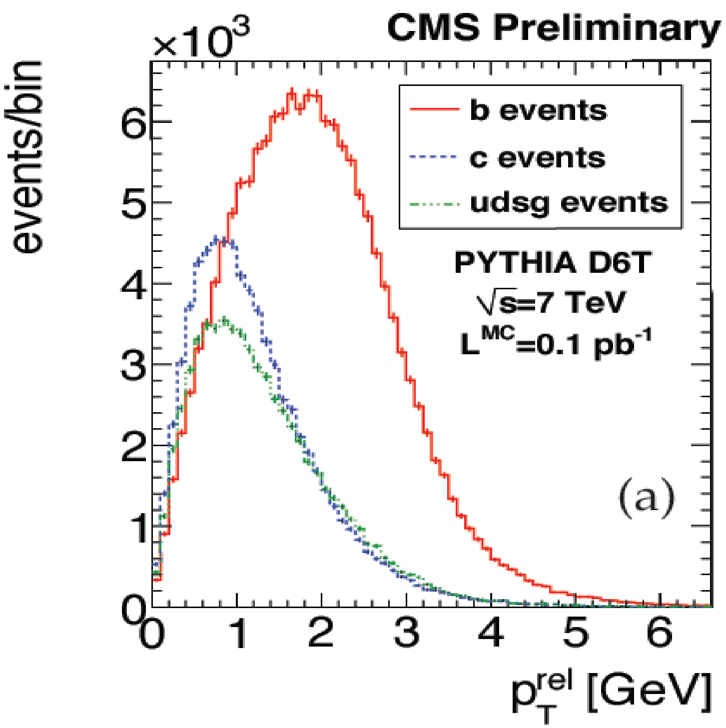
use p_T^{rel} template shapes to fit for the b fraction in the selected events

signal template: MC validated on data with b-enriched sample

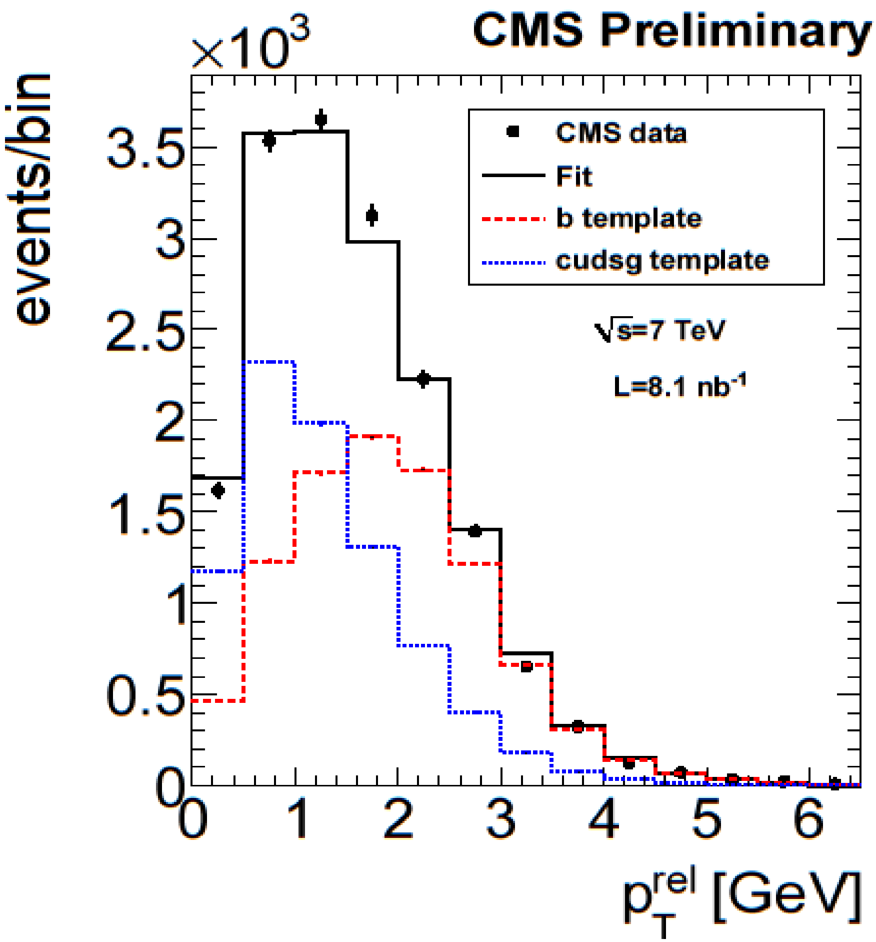
light flavour templates: from hadron spectra in data combined with muon faking probability from MC

charm template: from MC





b semileptonic decays



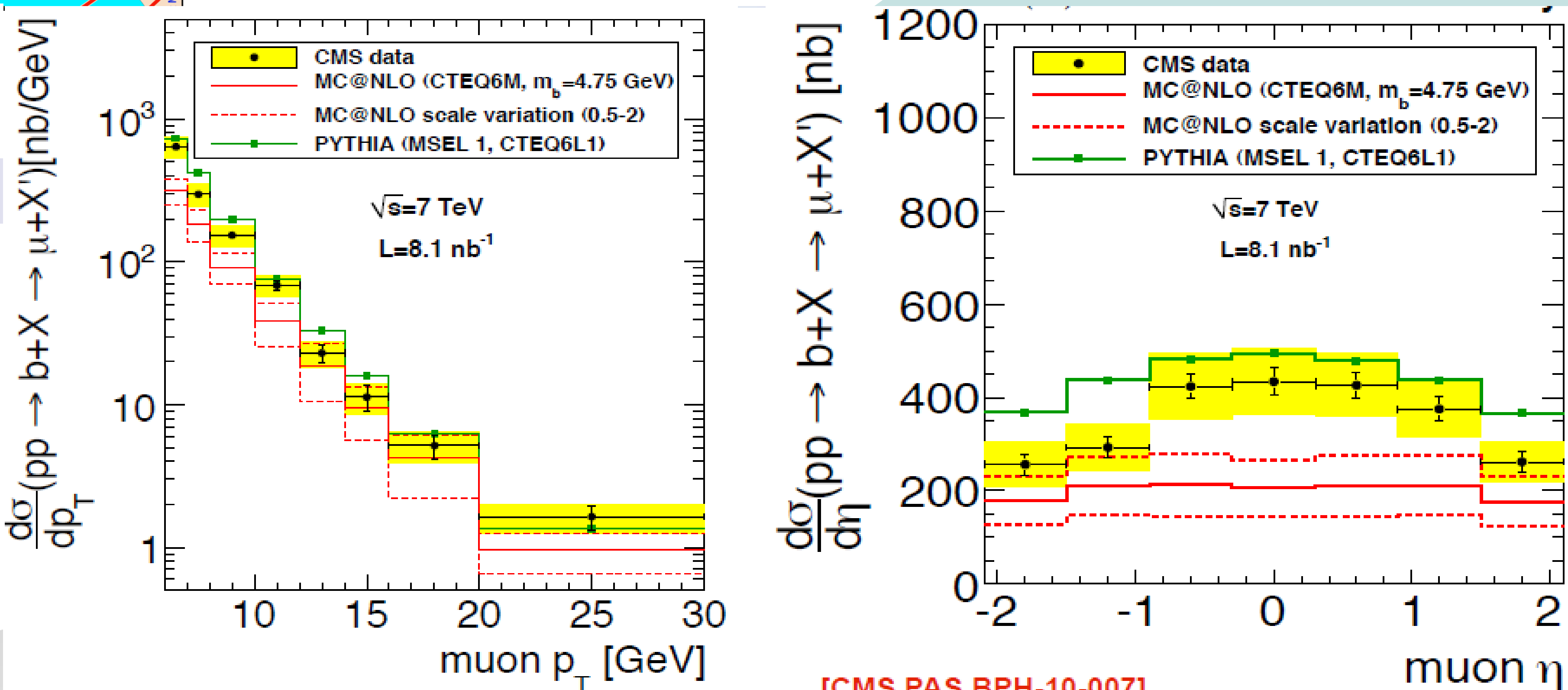
charm and light-flavours merged into a single template (shapes too similar)

binned log-likelihood fit (bins of muon p_T and η)

non-lumi systematics 11-16% dominated by

- underlying event simulation
- light flavour template shape

b semileptonic decays



[CMS PAS BPH-10-007]

Measured visible cross section

$$\sigma = (1.48 \pm 0.04_{\text{stat}} \pm 0.22_{\text{syst}} \pm 0.16_{\text{lumi}})\ \mu\text{b}$$

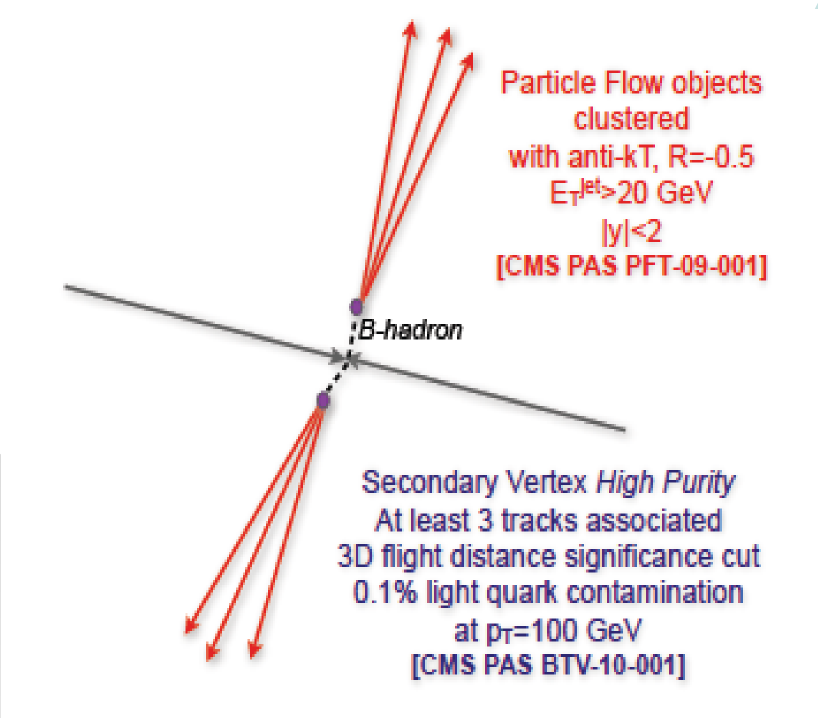
$$\sigma_{\text{PYTHIA}} = 1.8\ \mu\text{b}$$

$$\sigma_{\text{MC@NLO}} = [0.84^{+0.36}_{-0.19}(\text{scale}) \pm 0.08(m_b) \pm 0.04(\text{pdf})]\ \mu\text{b} \quad (m_F=m_R=p_T)$$

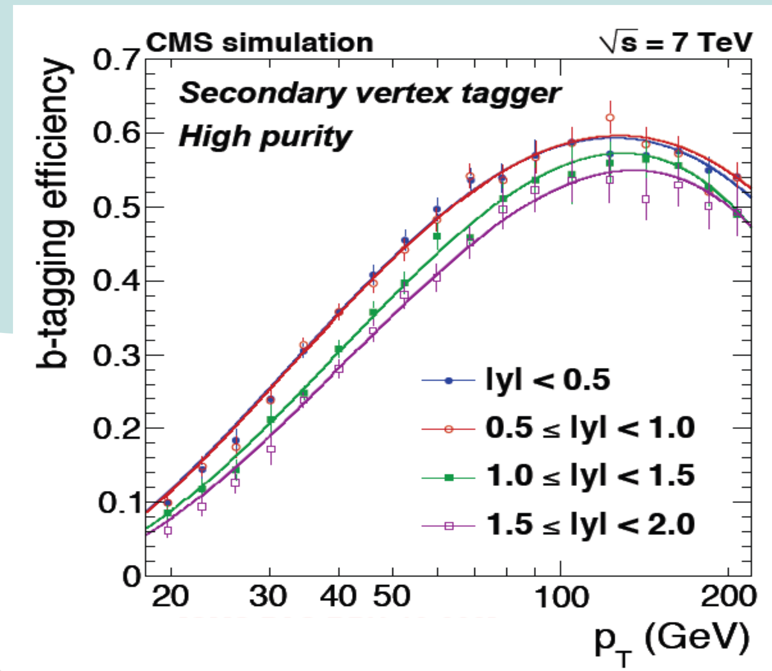
MC@NLO consistently underestimates the cross section
larger discrepancies in the central region and at low transverse momentum

Inclusive b-jet production

b-jet tagging exploiting secondary vertices (pixel detector)



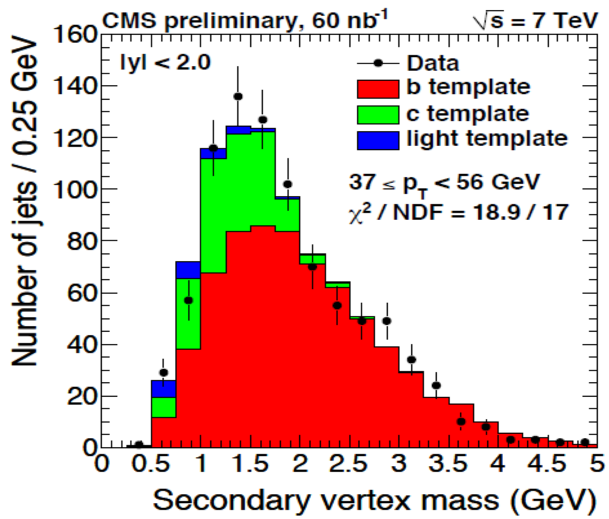
complementary to semileptonic tagging
(different systematics)

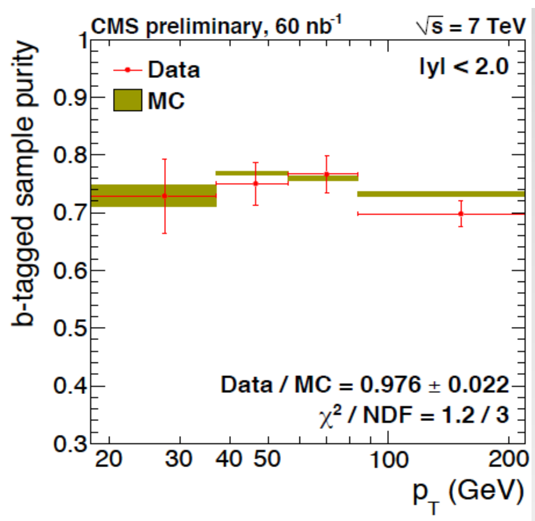


b-tagging efficiency validated on data
using semi-leptonic decays:

data/MC = 0.98±0.08(stat)±0.08(syst)

Inclusive b-jet production





$$\frac{d^2\sigma_{b-\text{jets}}}{dp_T dy} = \frac{N_{\text{tagged}} f_b C_{\text{smear}}}{\epsilon_{\text{jet}} \epsilon_b \Delta p_T \Delta y \mathcal{L}}$$

jet efficiency

b-tagging efficiency

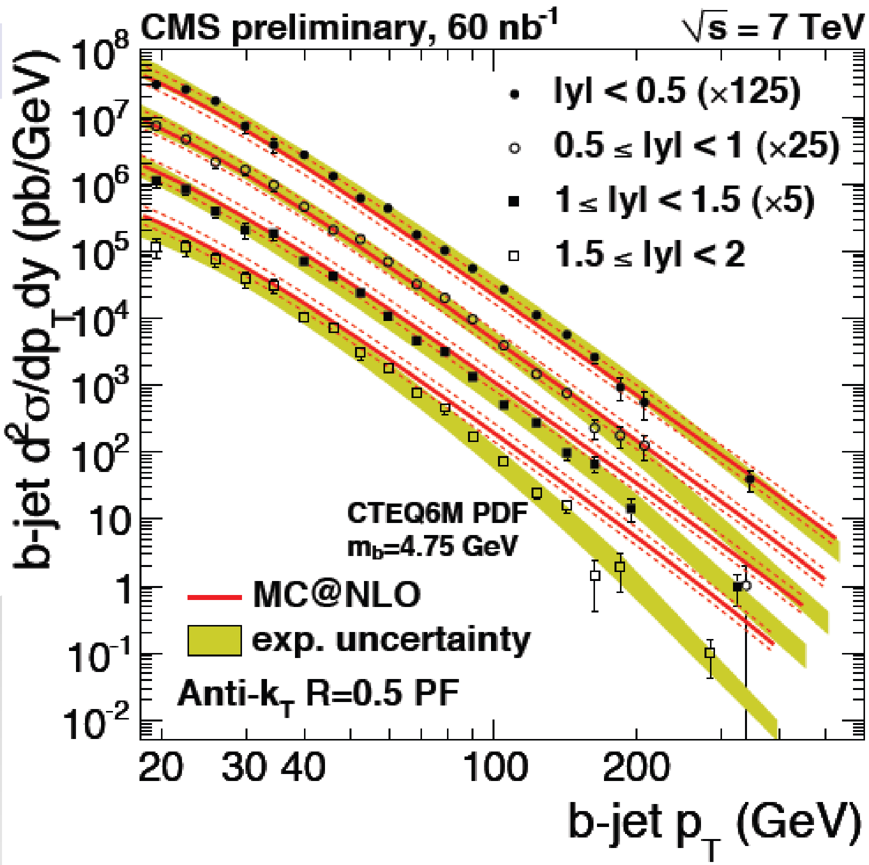
purity

unfolding factor

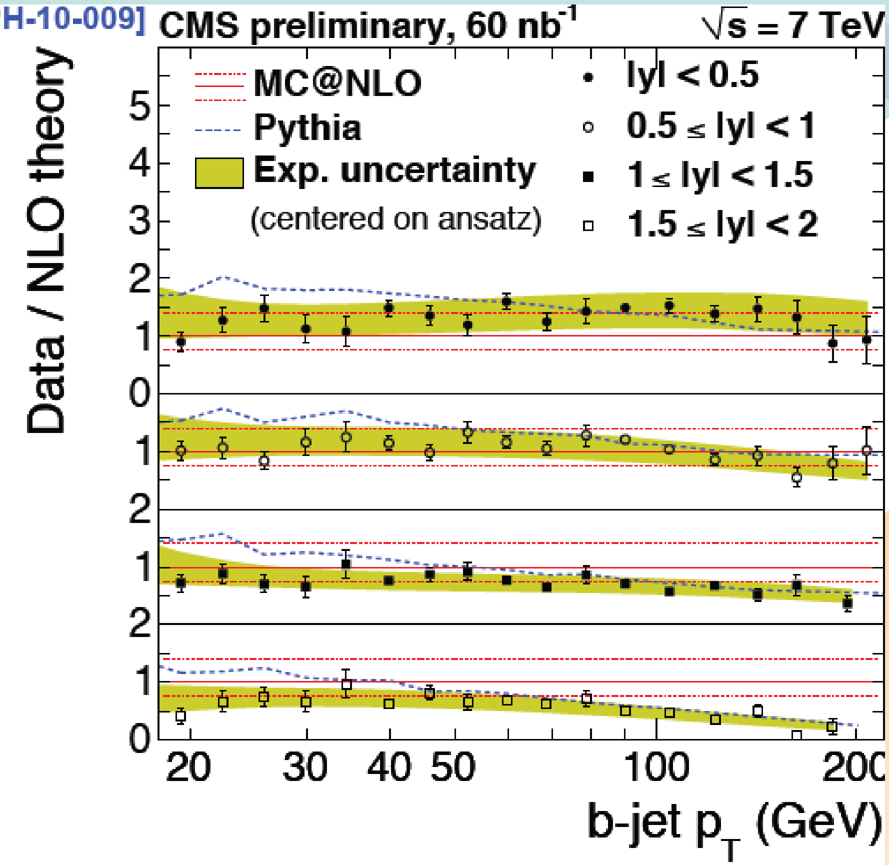
sample purity validated on data using

- vertex mass fit
- MC fake rates and measured signal efficiency

Inclusive b-jet production



[CMS PAS BPH-10-009]



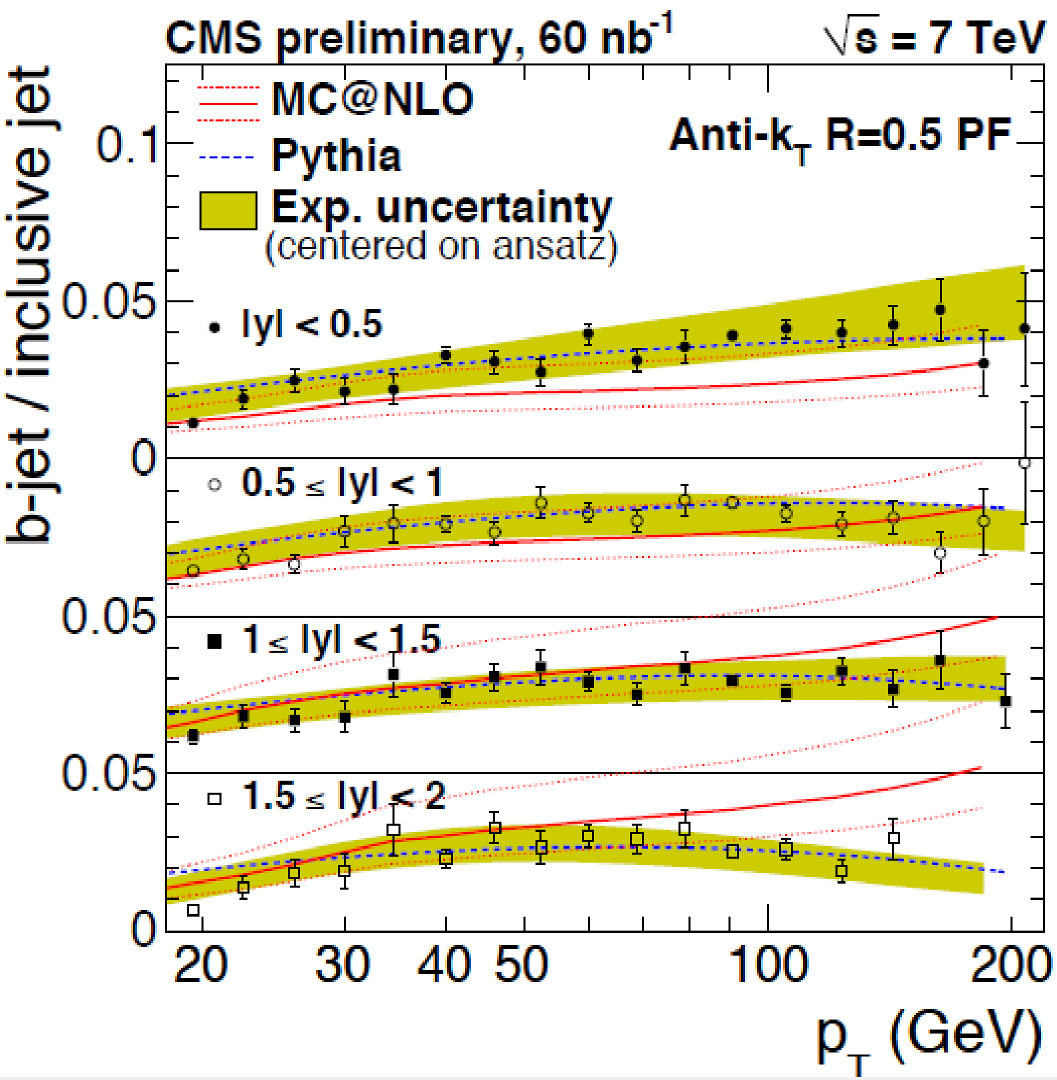
Experimental uncertainties (~20%) dominated by b-tagging efficiency and jet energy scale (~5%)

MC@NLO uncertainties dominated by scale variations (+40%,-25%) and b-quark mass (+17%,-14%)

good agreement with Pythia at high Pt

discrepancy with MC@NLO at high pt and rapidity

Inclusive b-jet production



Ratio of b-jet to all jets.

Jet energy corrections and luminosity systematic uncertainties **cancel out**

Pythia in perfect agreement in measured range

Indicates shape discrepancies with NLOJet++ (used to generate inclusive jets) to MC@NLO ratio

Prospects

- Analysis of the entire 2010 data set going on
- Many results expected:
  - b-jet angular correlations to study **production mechanism**
  - quarkonia production updates and **polarization** measurements (smaller systematics, also from increased statistics and finer binning)
  - integrated B meson mixing parameter
  - χ_c observation
  - b hadron exclusive decays: ($B^+ \to J/\psi K^+$, $B^0 \to J/\psi K_S$, $B_s \to J/\psi \phi$, $\Lambda_b \to J/\psi \Lambda$)

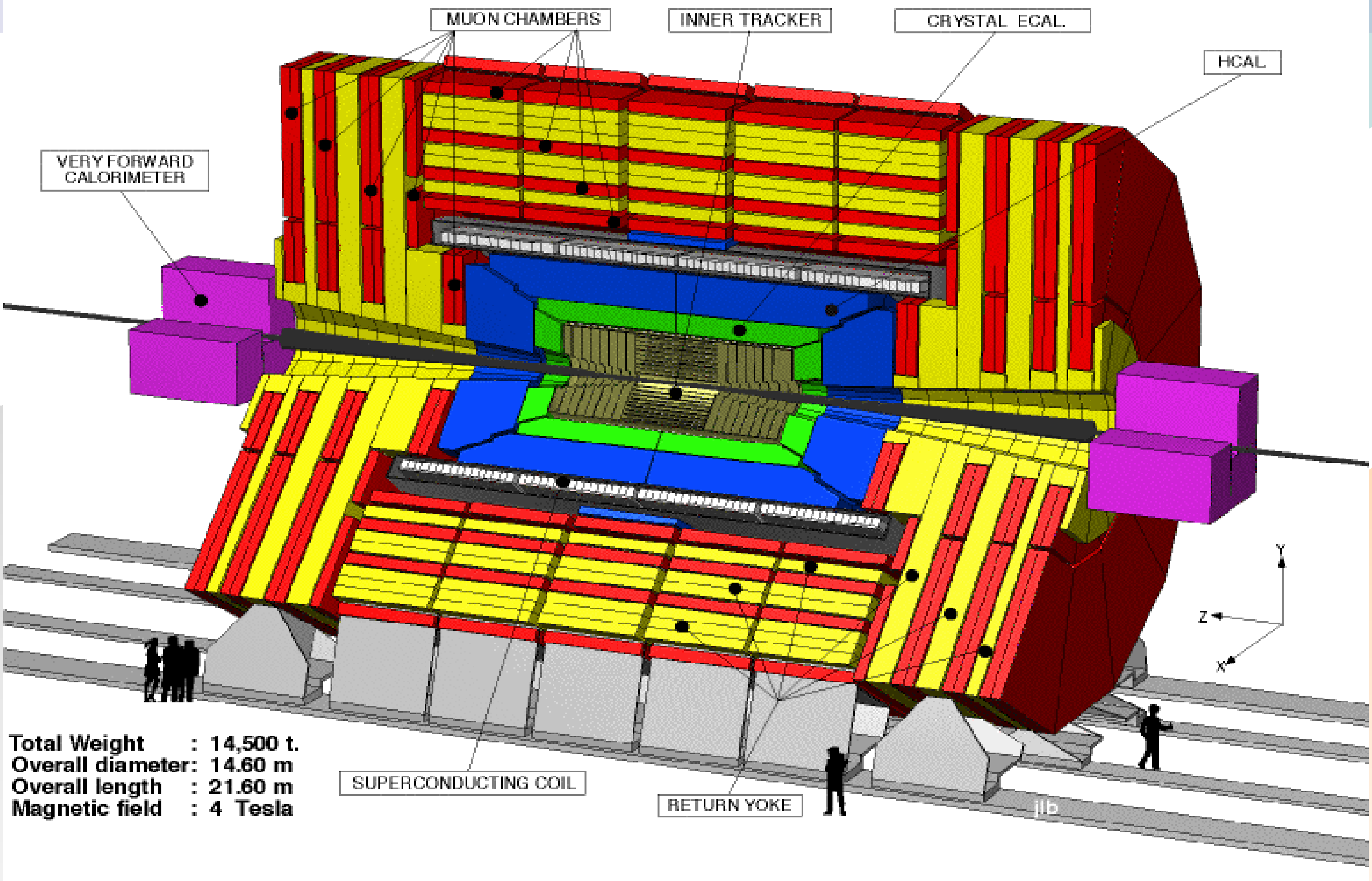
($\Delta\Gamma/\Gamma$, CP violation)

Conclusions

- CMS has recorded more than 40pb^{-1} of data at $\sqrt{s}$ = 7 TeV
- only a fraction used for the results shown here (basically data collected before the summer)
- Quarkonia production measurements already allow the comparison with theoretical models and with other experiments
  - systematics will go down with increasing statistics
- b quark inclusive production measured with complementary techniques: semileptonic decays and secondary vertexing
  - hints of discrepancies with theoretical models (errors comparable)
- some exclusive decays reconstructed
- more results to come with full 2010 statistics!

Backup

CMS detector



J/ψ: acceptance

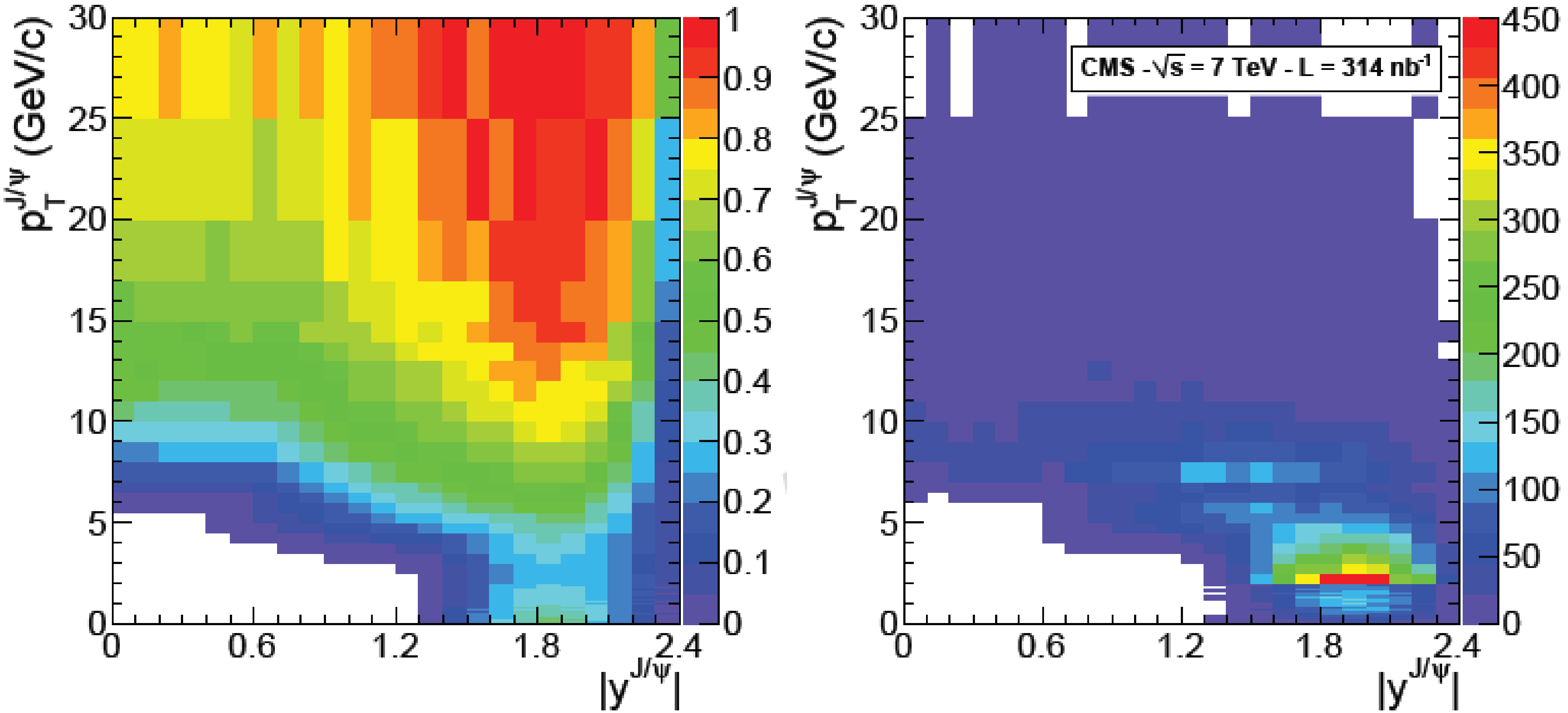
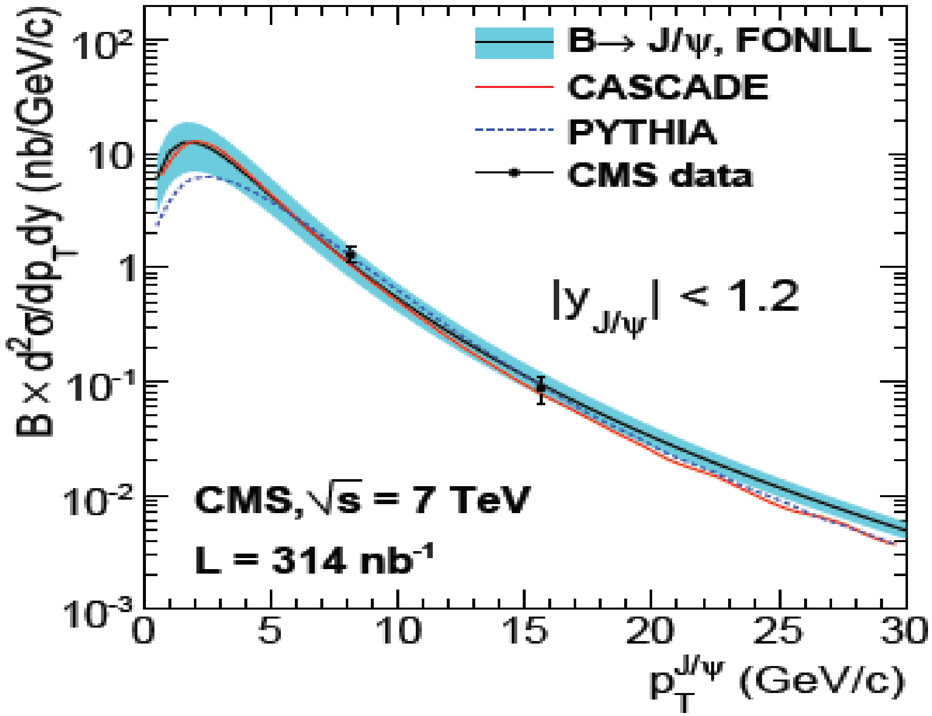
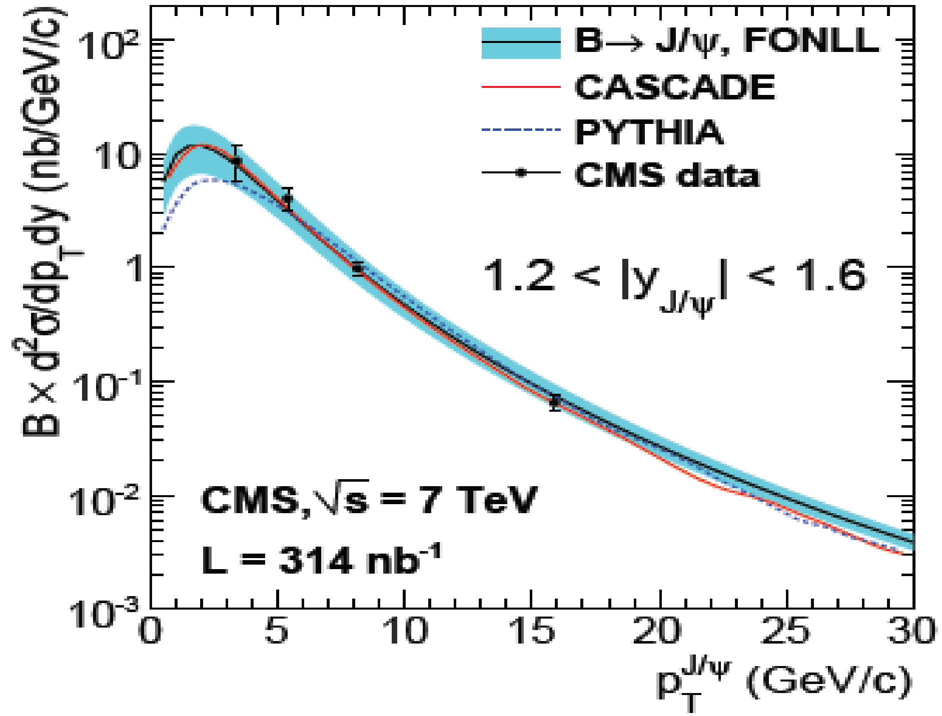
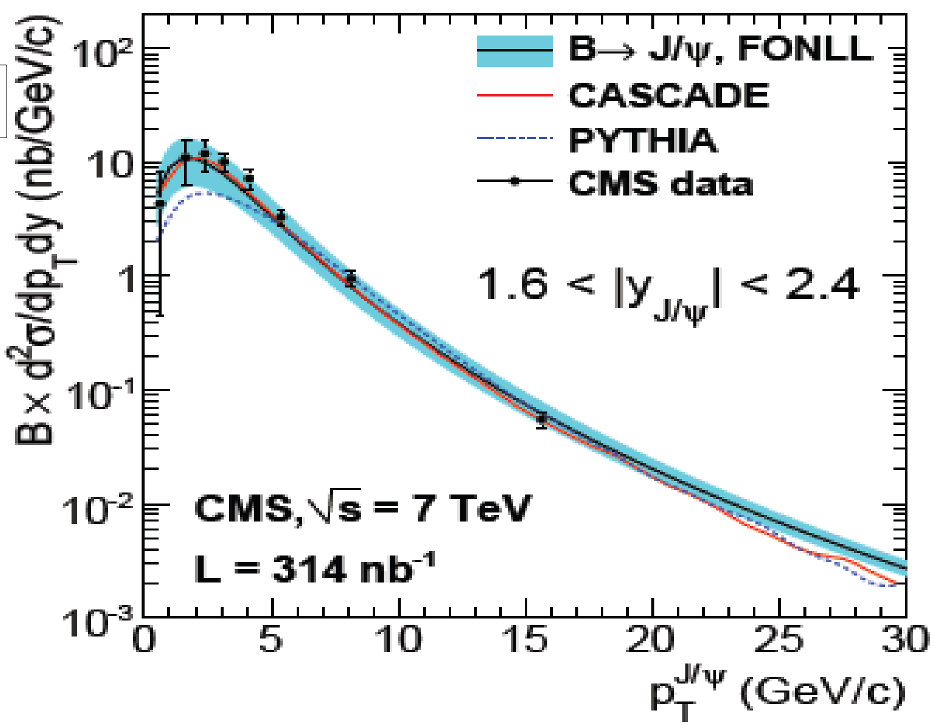


Figure 2: Left: Acceptance as a function of the J/ψ p_T and rapidity. Right: Number of muon pairs within ± 100 MeV$/c^2$ of the nominal J/ψ mass, in bins of p_T and $|y|$.

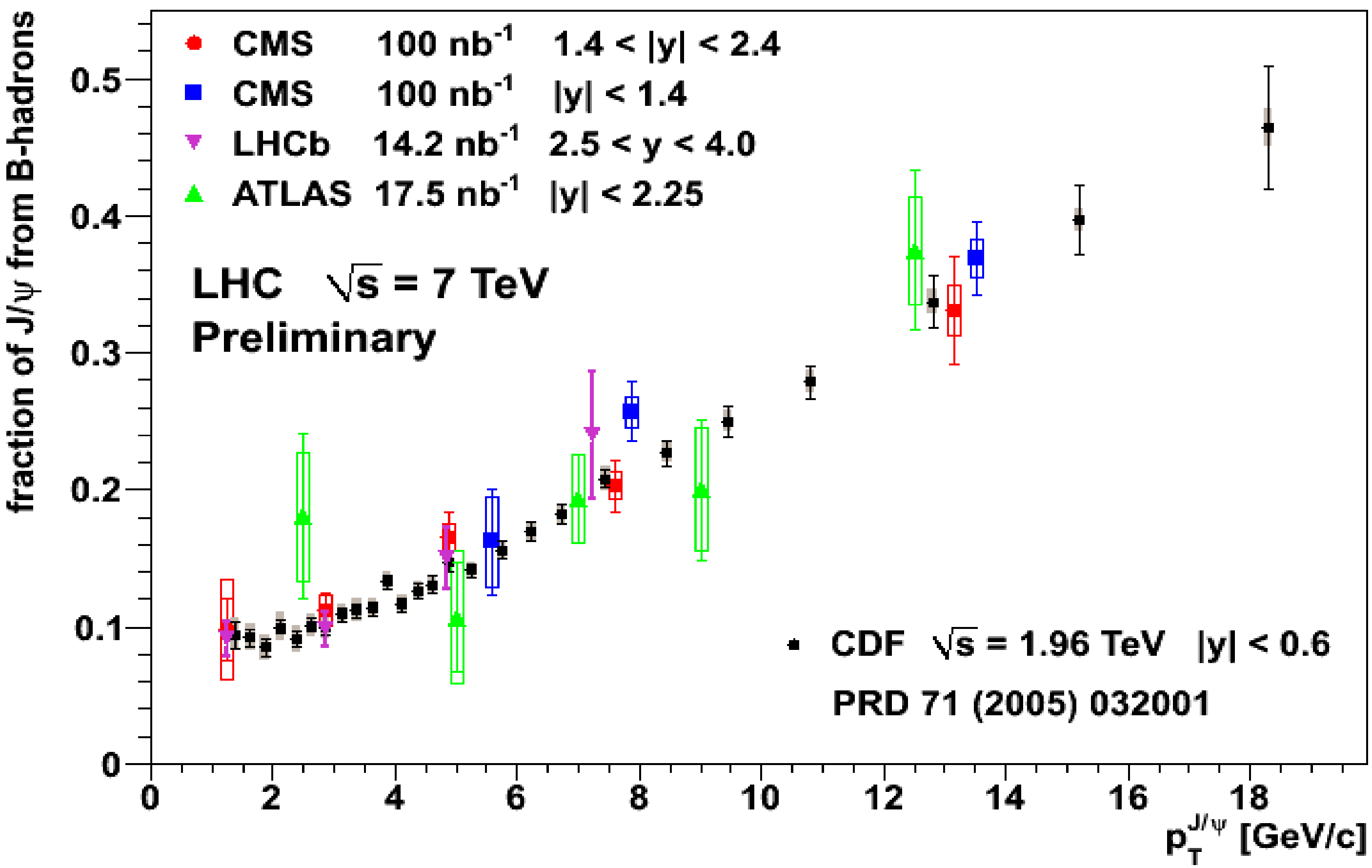




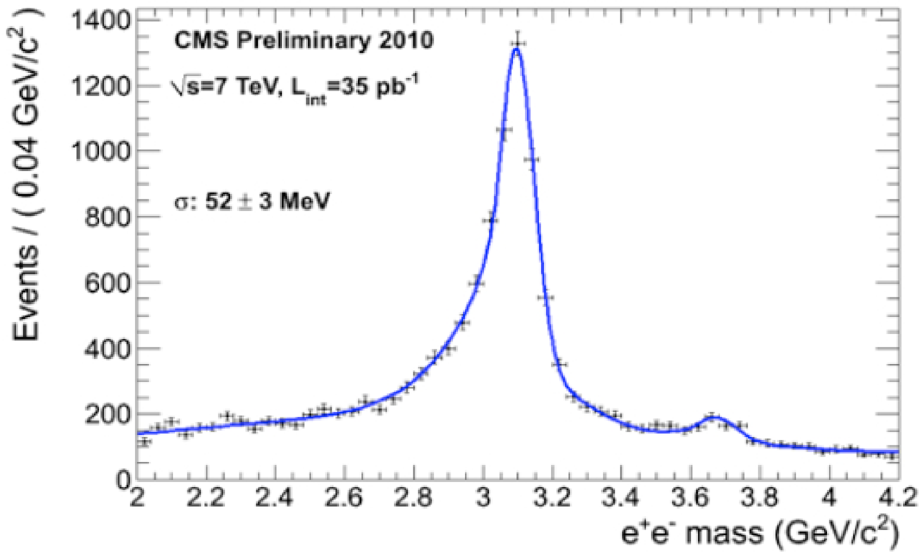
J/Psi from b hadrons

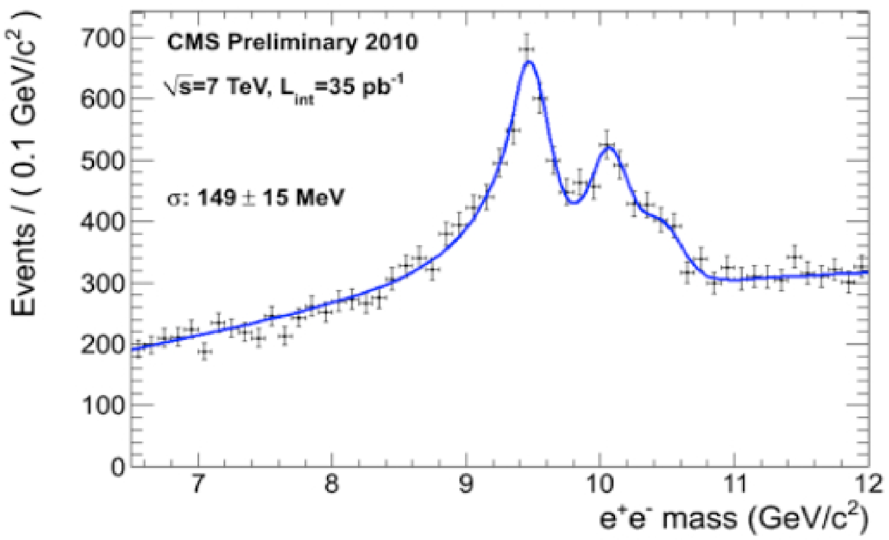


J/ψ from b-hadrons: comparison with other LHC experiments and with Tevatron

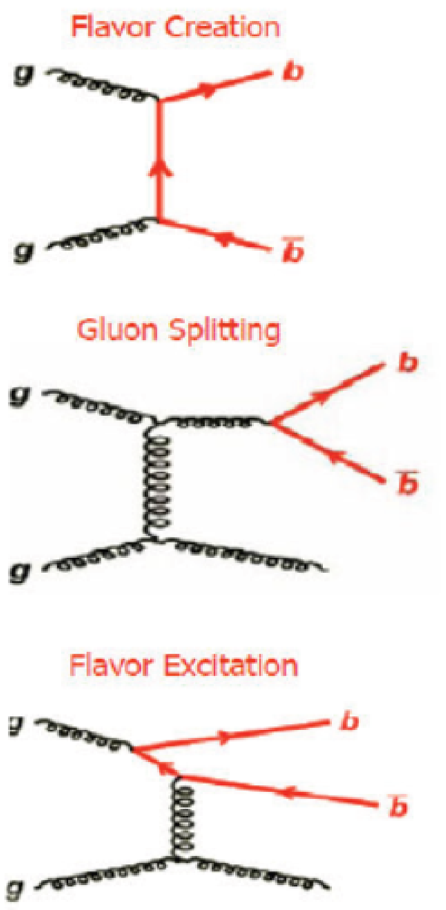


quarkonia to electrons

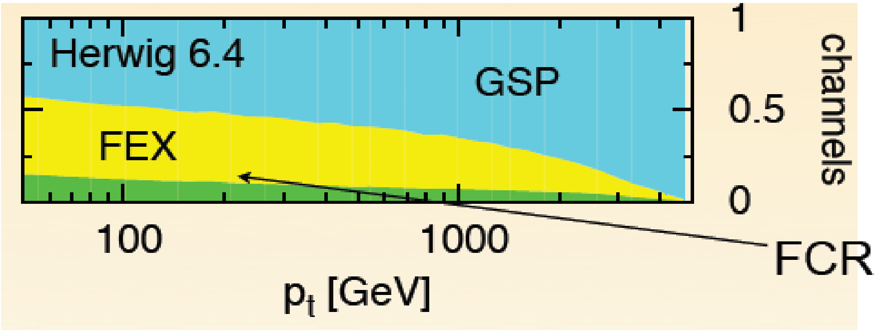




b quark production mechanisms



- **LO:**
  - Flavour creation
- **Large NLO contributions:**
  - Flavour Excitation
  - Gluon splitting
- **Test benchmark for perturbative QCD, MC tools and detector performance**
  - Long standing problems with lower energy data resolved
  - Measurements could have smaller errors than NLO QCD predictions currently available



b-jet ansatz fit

assumed jet production shape:

$$f(p_T) = N_0\,(p_T/\,\mathrm{GeV}\,)^{-\alpha}\left(1-\frac{2p_T\cosh(y_{\min})}{\sqrt{s}}\right)^{\beta}\exp(-\gamma/p_T).$$

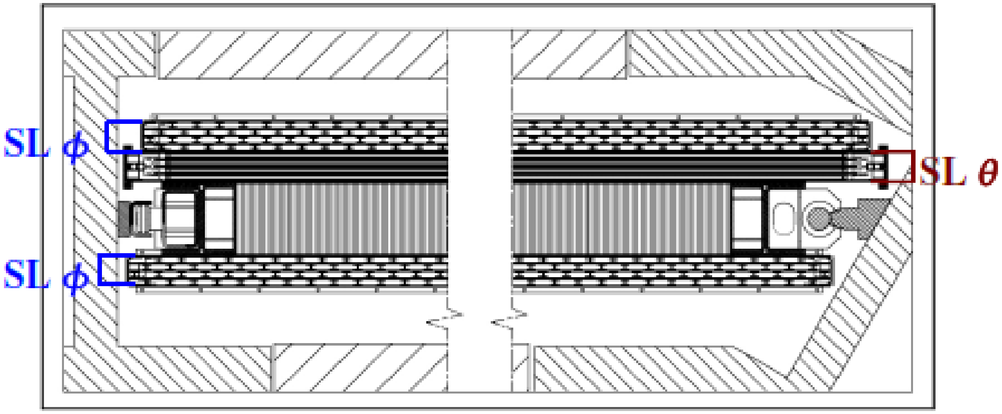
smeared with a gaussian resolution function

$$F(p_T^{\mathrm{meas}}) = \int_0^{\infty} f(p_T^{\mathrm{gen}}, y; p_i)\,g(p_T^{\mathrm{meas}} - p_T^{\mathrm{gen}}, y; \sigma)\,dp_T^{\mathrm{gen}}$$

unfolding correction

$$C_{\mathrm{smear}}(p_T) = \frac{f(p_T)}{F(p_T)}$$

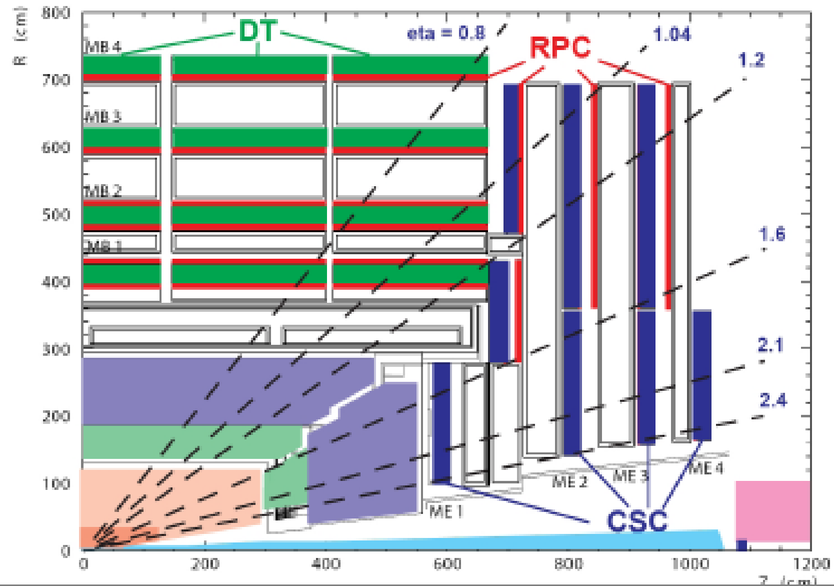
CMS muon system

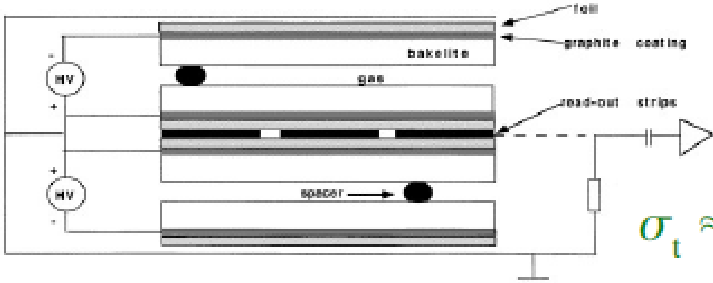


3 Super Layer (2ϕ and 1θ) for the first 3 stations

2 Super Layer (2ϕ) for the last station **DT**

4 Layer for each Super Layer $\sigma_x \approx 200\ \mu m$



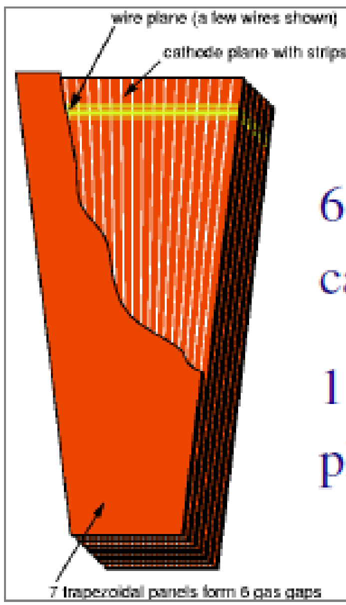


RPC

$\sigma_t \approx 2$ ns

2 RPC chamber for the first 2 DT stations

1 RPC chamber for the last 2 DT stations and for the CSC chamber till $|\eta|<1.6$



CSC

6 gaps (Layers) for each camber

1 wire plane and 1 cathode plane with strips

$\sigma_x \approx 100\text{-}240\ \mu m$

J/psi B fraction absolute systematics

$p_T^{J/\psi}$ (GeV/c)	Misalign-ment	B-lifetime model	Vertex estimation	Background fit	Resolution model	Efficiency
			$\lvert y\rvert < 1.2$			
4.5 – 6.5	0.0045	0.0041	0.0038	0.0007	0.0129	0.0020
6.5 – 10.0	0.0017	0.0000	0.0008	0.0120	0.0073	0.0010
10.0 – 30.0	0.0021	0.0004	0.0012	0.0004	0.0032	0.0036
			$1.2 < \lvert y\rvert < 1.6$			
2.0 – 4.5	0.0067	0.0040	0.0181	0.0032	0.0191	0.0019
4.5 – 6.5	0.0020	0.0086	0.0002	0.0169	0.0024	0.0007
6.5 – 10.0	0.0019	0.0006	0.0027	0.0000	0.0002	0.0010
10.0 – 30.0	0.0056	0.0004	0.0101	0.0051	0.0098	0.0011
			$1.6 < \lvert y\rvert < 2.4$			
0.00 – 1.25	0.0052	0.0064	0.0375	0.0022	0.0172	0.0001
1.25 – 2.00	0.0051	0.0041	0.0206	0.0011	0.0049	0.0002
2.00 – 2.75	0.0044	0.0047	0.0085	0.0168	0.0027	0.0001
2.75 – 3.50	0.0019	0.0061	0.0004	0.0001	0.0068	0.0011
3.50 – 4.50	0.0017	0.0024	0.0043	0.0027	0.0109	0.0018
4.50 – 6.50	0.0067	0.0003	0.0016	0.0021	0.0083	0.0041
6.50 – 10.00	0.0017	0.0035	0.0033	0.0004	0.0105	0.0040
10.00 – 30.00	0.0057	0.0008	0.0045	0.0008	0.0015	0.0019

LHC in 2011

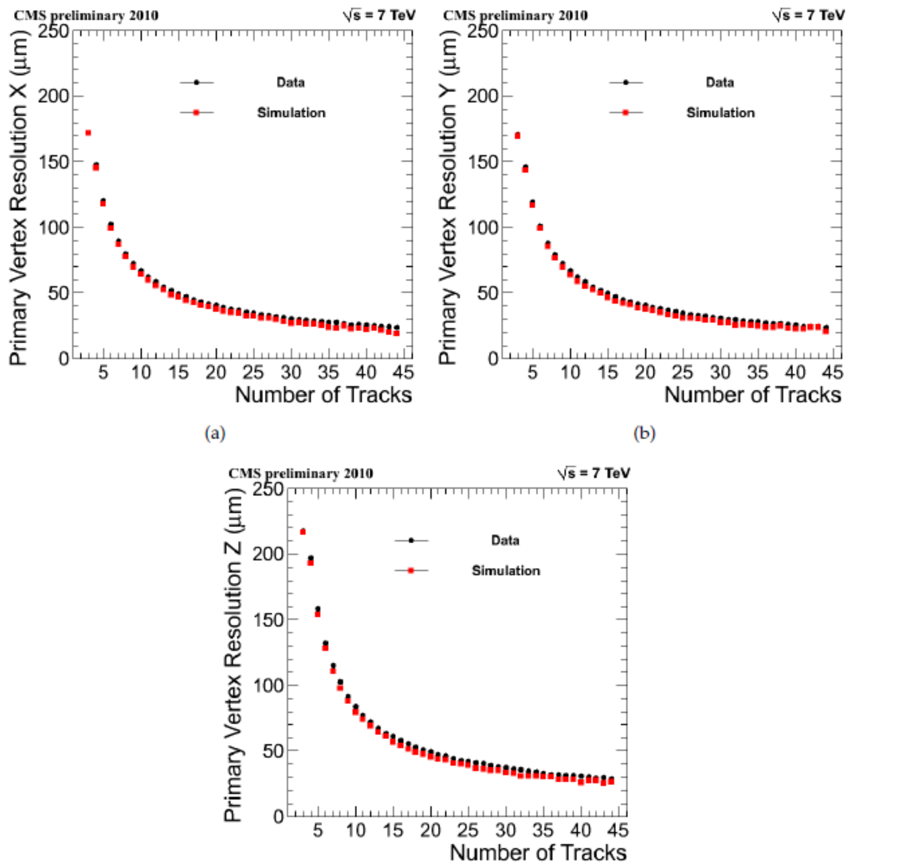
2011: “reasonable” numbers

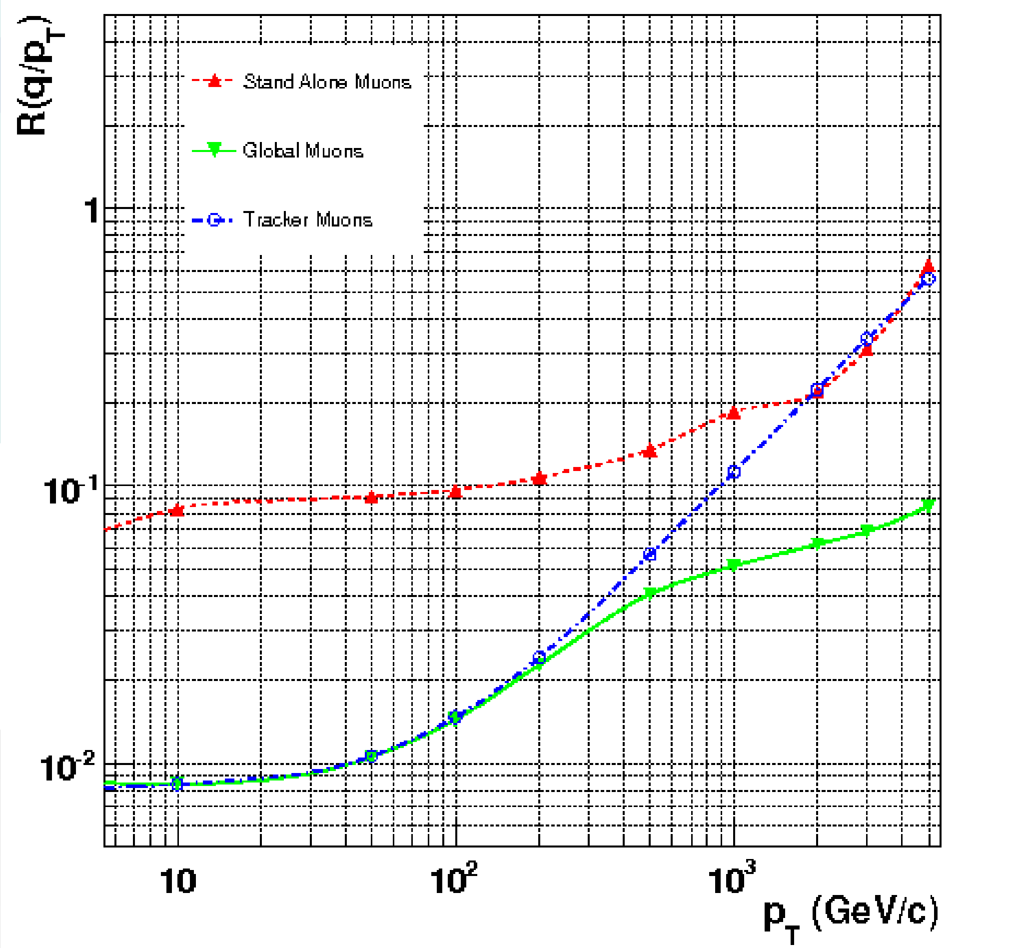
- 4 TeV (to be discussed at Chamonix)
- 936 bunches (75 ns)
- 3 micron emittance
- 1.2 x 10^{11} protons/bunch
- beta* = 2.5 m, nominal crossing angle
- Hubner factor 0.2

Peak luminosity	6.4 x 10^{32}
Integrated per day	11 pb^{-1}
200 days	2.2 fb^{-1}
Stored energy	72 MJ

Usual warnings apply – see problems, problems above

tracker resolutions





primary vertex resolution: 25, 20 μm

$B^{\pm} \rightarrow J/\psi K^{\pm}$

- Select opposite sign di-muon combinations,
- Select combination/event with mass closest to the J/psi mass
- Select events with a di-muon vertex Probability >0.1%
- Muons satisfying quality criteria (require a muon chamber segment matching in position and direction with the prediction of the associated track extrapolation)
- At least one muon required to fire the trigger
- Both muons required to have p_T(mu)>3 GeV/c, |eta(mu)|<2.4
- Combine J/psi candidate with tracks (p_T>0.9 GeV/c)
- Kinematic fit with J/psi mass constraint
- Require vertex probability > 0.1%
- If multiple candidates/event, choose highest p_T B^- candidate

Single Muon trigger
(p_T >3 GeV/c cut at HLT level)
ct/$sigma_{ct}$ >1

ct:transverse decay length of J/psiK^- vertex relative to primary vertex
$sigma_{ct}$=error on transverse decay length

1-d fit to J/psiK^- invariant mass:
- Signal: sum of three Gaussians (means and widths fixed to MC)
- Mean: 5.280 GeV/c^2
- Resolution = 32 MeV/c^2 (weighted sum of gaussian resolutions)
- Background is fitted with exponential function (slope floated in the fit)
- N_sig = 48 ± 8

$B_s \to J/\Psi\varphi$ mass peak

Only certified BPAG good runs [140042 - 149442].
Scraping and GoodVertex filters on each event applied;

Triggers: HLT_doubleMu0 OR HLT_DoubleMu0_Quarkonium_v1;

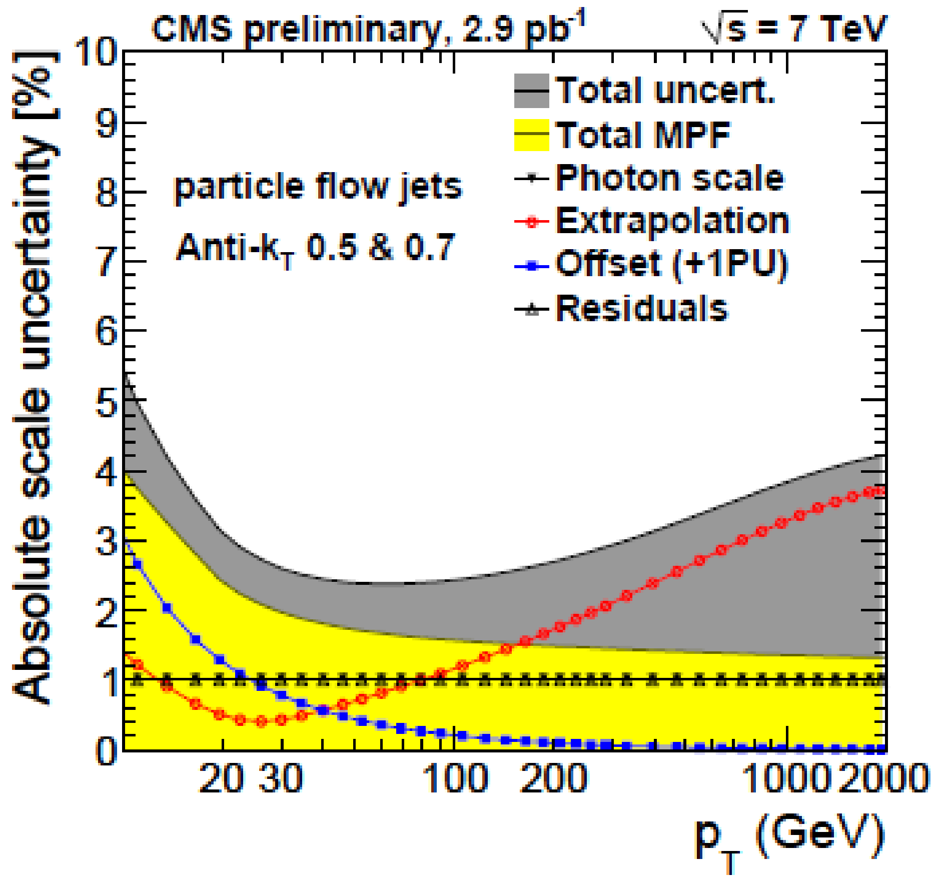
Muons: used Global or Tracker, if Tracker muon arbitration/selection TMLastStationOptimizedBarrelLowPtTight is applied, $p(\mu)>3$ GeV/c and $|\eta|<2.4$;

Selected a pair of opposite-sign muons, both muons required to fire the trigger. Track/muon and muon/muon overlaps removed;
J/ψ: candidate mass within 150 MeV/c^2 around the J/ψ mass PDG value, $p_T(J/\psi)>0.5$ GeV/c;

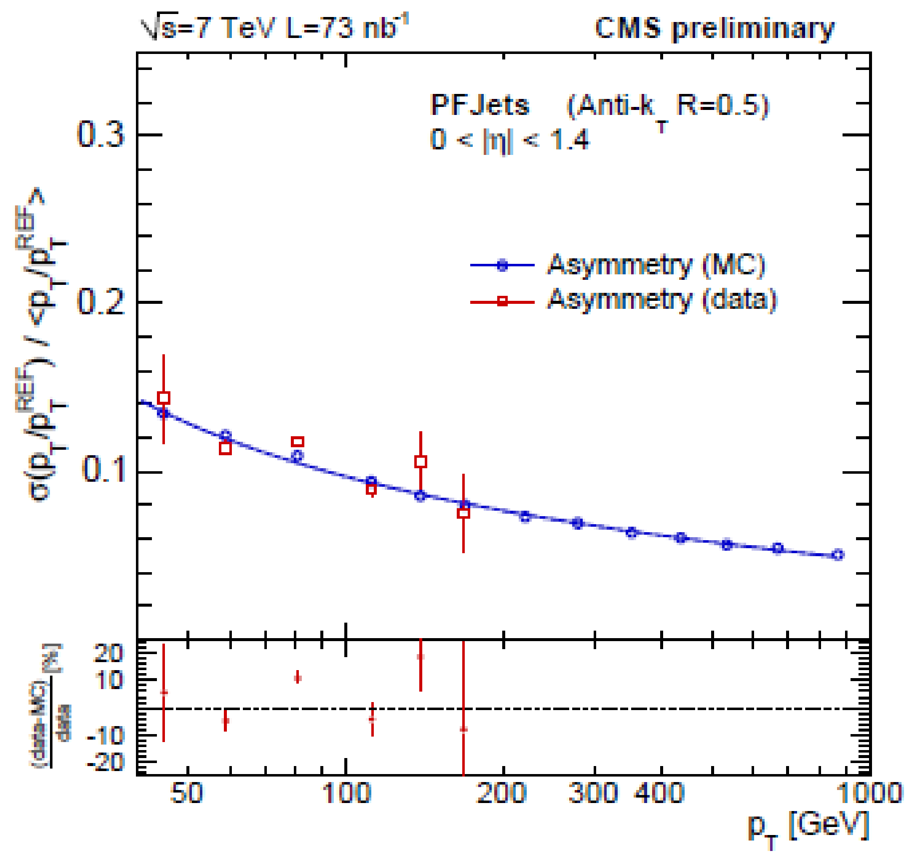
Kaons: transverse momentum p_T (K)>0.6 GeV/c and $|\eta|<2.5$;
φ: candidate mass within 10 MeV/c^2 around the mass PDG value;

Kinematic fit of the four tracks with the J/ψ PDG mass constraint, cut on vertex probability > 2%;
Significance cut $c\tau_{2D}/\sigma_{2D}>3$, where $c\tau_{2D}$ is transverse decay length of J/ψφ vertex relative to primary vertex and σ_{2D} is the error on transverse decay length;

JES & JER



CMS preliminary, 2.9 pb-1
√s = 7 TeV
Absolute scale uncertainty [%]
particle flow jets
Anti-kT 0.5 & 0.7
Total uncert.
Total MPF
Photon scale
Extrapolation
Offset (+1PU)
Residuals
pT (GeV)



√s=7 TeV L=73 nb-1
CMS preliminary
PFJets (Anti-kT R=0.5)
0 < |η| < 1.4
Asymmetry (MC)
Asymmetry (data)
σ(pT/pTREF) / <pT/pTREF>
(data-MC)/data [%]
pT [GeV]