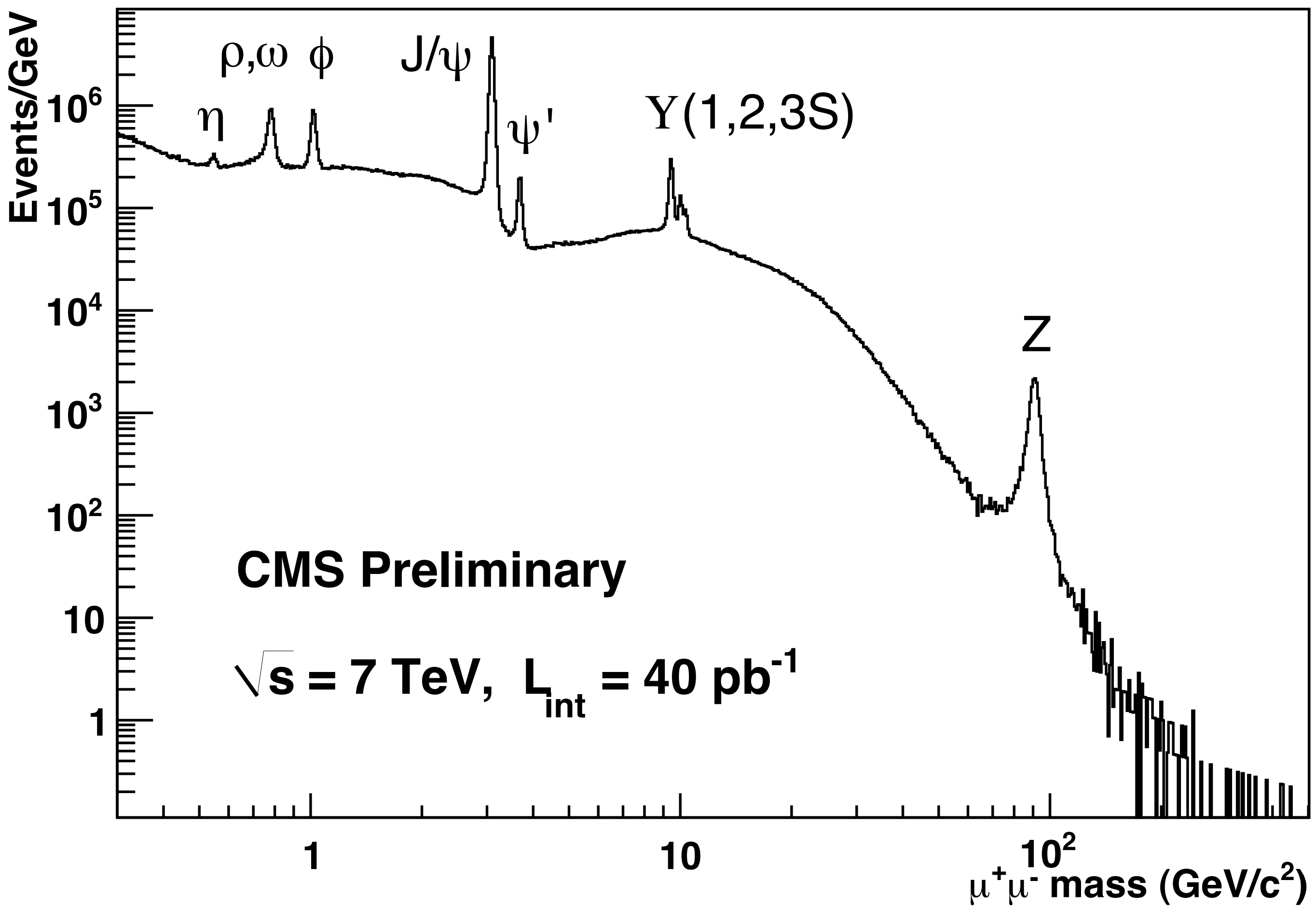
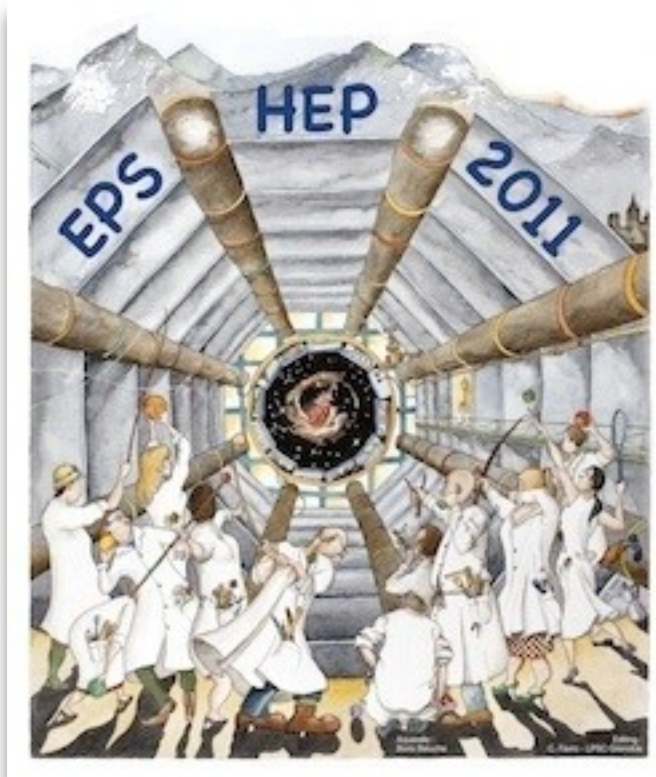




Measurement of J/ψ and ψ(2S) production at $\sqrt{s}$=7 TeV with the CMS experiment

Fabrizio Palla
INFN - Pisa

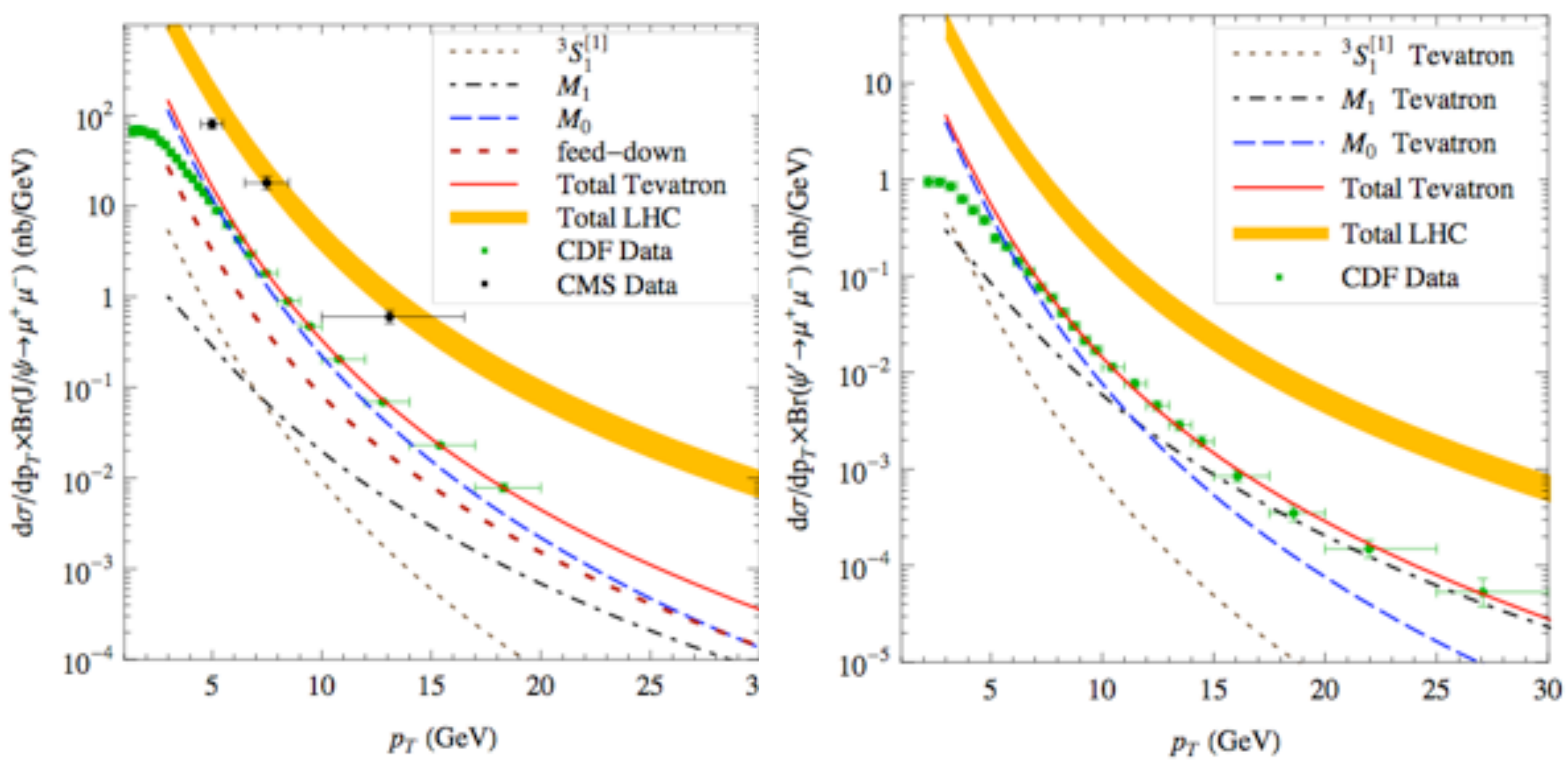
(on behalf of the CMS Collaboration)

EPS 2011
Grenoble

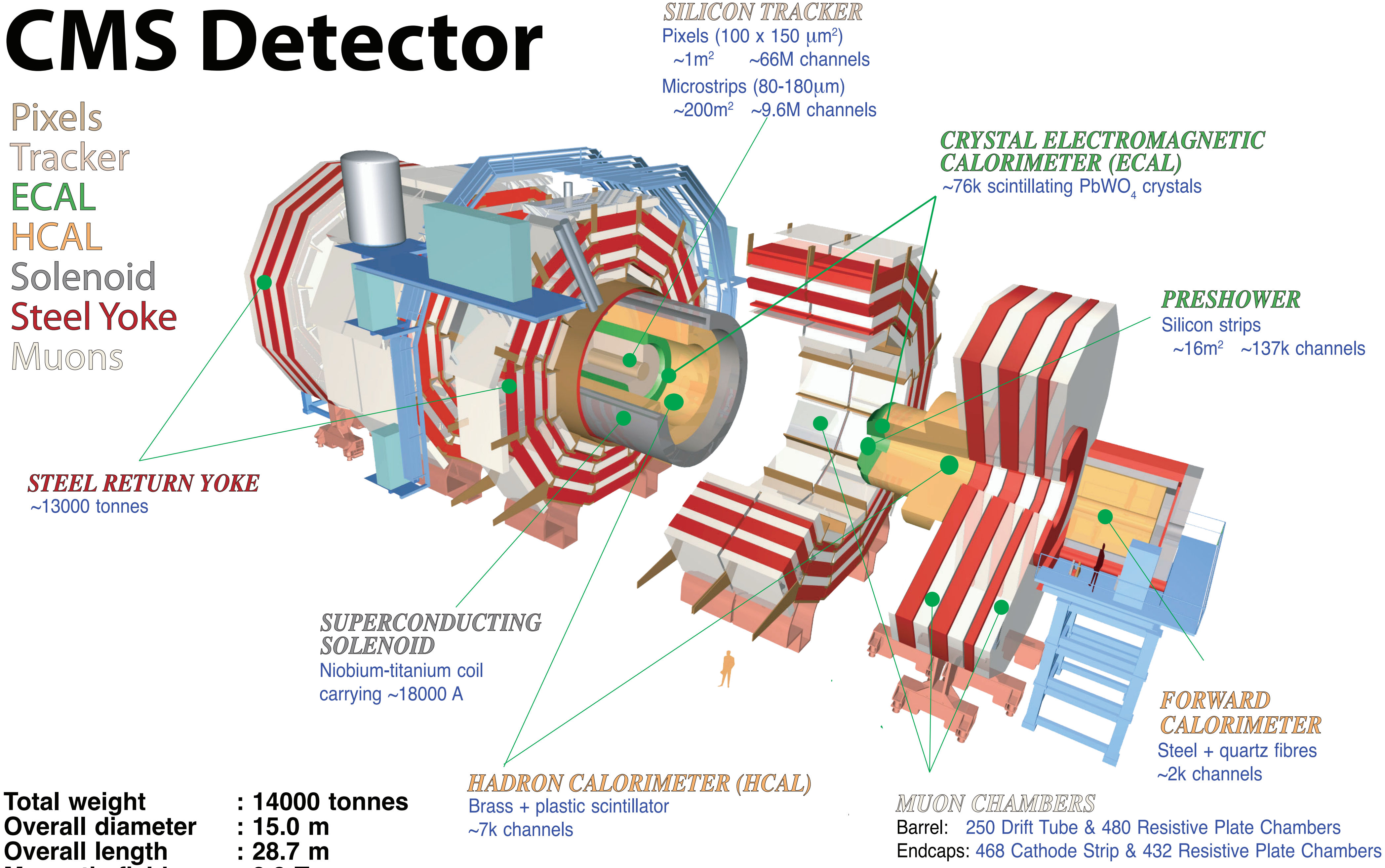
Motivations

- **Production of charmonium states provides a test of QCD**
  - **Production mechanism with a preponderance of color octet over color singlet contributions seems to work for Tevatron and first LHC data. Important to test the high p_T region.**
    - **The J/ψ prompt yield has a large fraction of feed-down contributions from ψ(2S) and χ_c decays. High p_T region up to now tested by ATLAS.**
    - **ψ(2S) has no “indirect” contribution from heavier charmonia. Up to now, only LHCb measurements at LHC, which cover the region $2<y\leq4.5$.**
    - **Measuring the ψ(2S) to J/ψ ratio most of the experimental uncertainties cancel.**

Y. Q. Ma, Y. J. Zhang and K. T. Chao
Phys. Rev. Lett. 106:042002, 2011



CMS Detector



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

J/ψ and ψ(2S) reconstruction mainly exploits

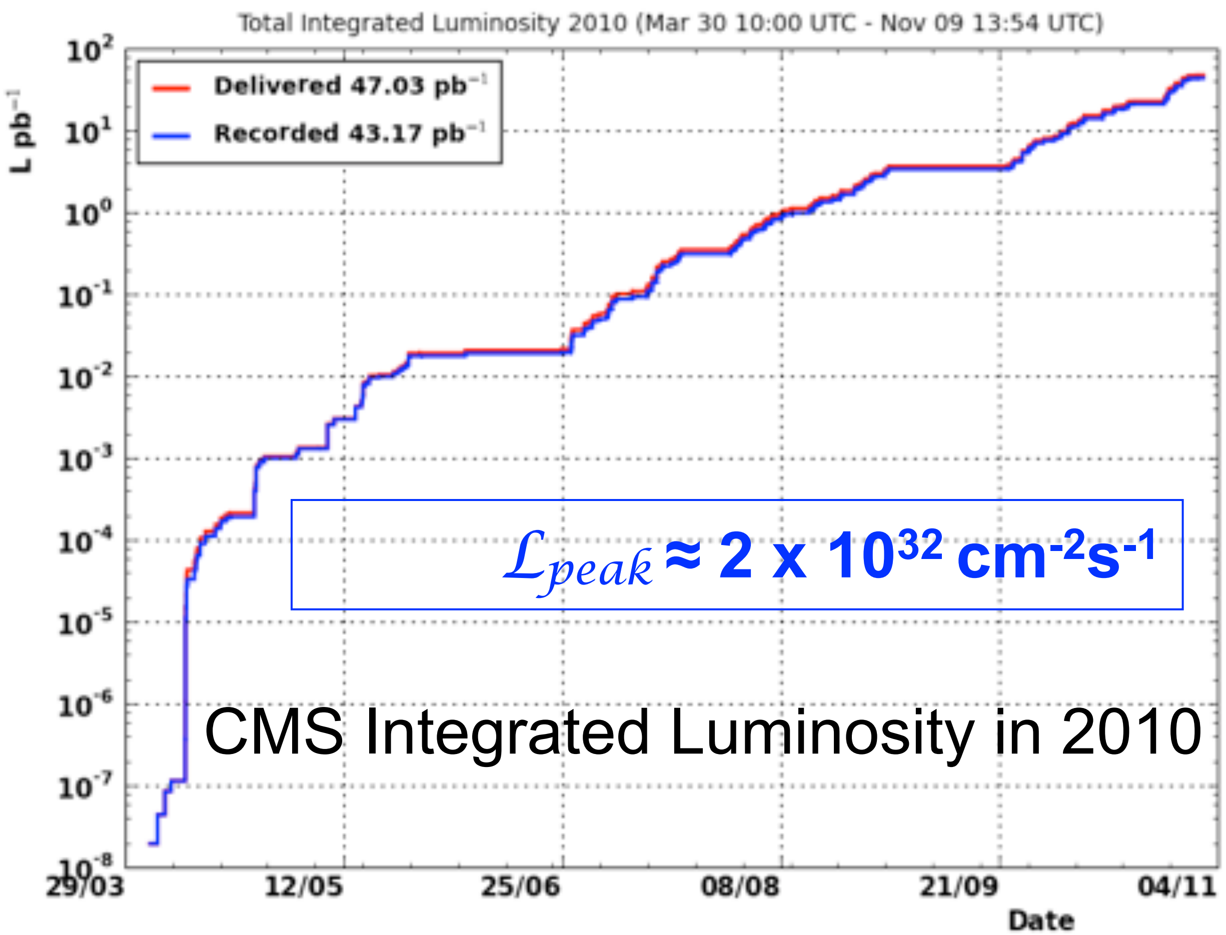
Muon detectors for high purity muon identification and trigger

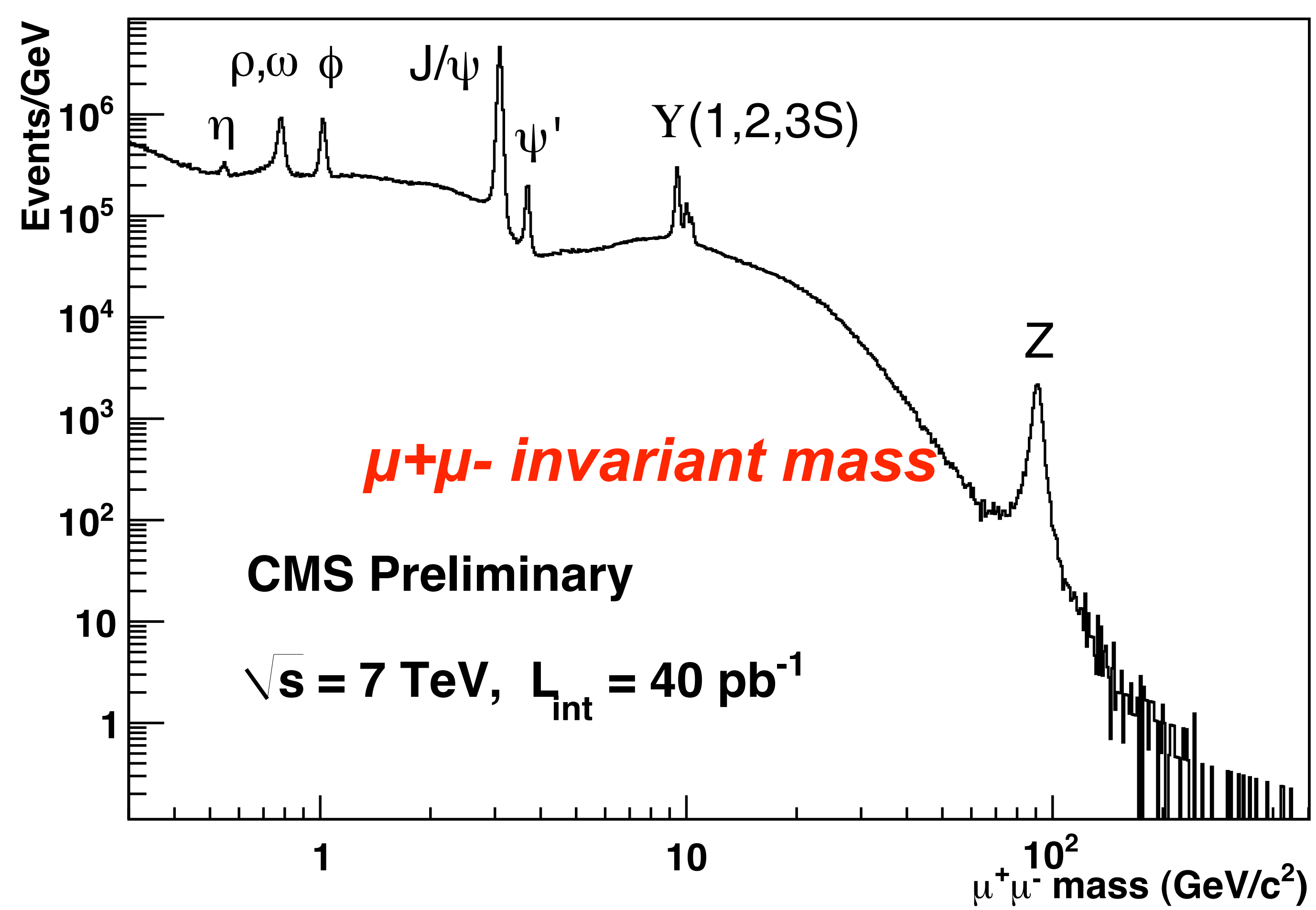
Silicon Tracker detector for long lifetime and good di-muon mass resolution

The LHC accelerator

- CMS integrated around 43 pb^{-1} by the end of the 2010 pp run with an overall data taking efficiency better than 90%. Analysis is based on 36.7 pb^{-1}.

- **Low p_T dimuon triggers in 2010 optimized for J/ψ and Upsilon**



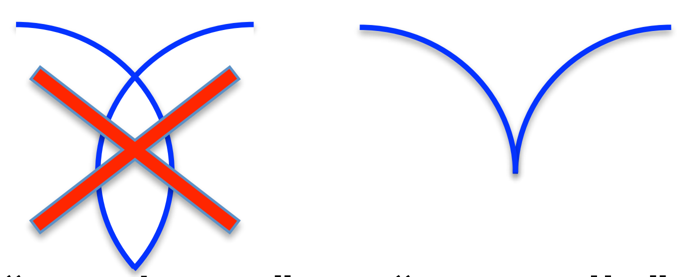


Double Muon Triggers

L1: hardware
muon system and calorimeters only

HLT: software
matching of different sub-detectors. Fast local tracker reconstruction for muons

- **Trigger requirements changing with increasing luminosity:**
  - **L1 requirements at the startup had no p_T threshold (not prescaled until 10^{31} Hz cm^{-2})**
    allows to go down to zero quarkonium p_T in the forward region - used for the first CMS paper based on 314 nb^{-1}
  - **At higher luminosities, smart strategies adopted for quarkonia (combination of L1 and HLT muons, or HLT muon and track in specific invariant mass regions… etc.)**
    effective p_T thresholds were ~3 GeV
  - "veto cone" at Level-1 (to reduce the rate from single muons faking two signal μ) induces correlations.
  - Offline rejection for "cowboy" like dimuons in the forward



"cowboys" "seagulls"

Cross section in a nutshell

$$\frac{d^2\sigma}{dp_T dy}(\psi)\times \mathrm{BR}(\psi\to\mu\mu)=\frac{\mathrm{N}_{fit}(\psi)\left\langle\frac{1}{A\cdot\varepsilon}\right\rangle}{\int L\,dt\cdot\Delta p_T\cdot\Delta y}$$

- **N_{fit} = signal yield from fit to dimuon invariant mass distributions**
- **$\int Ldt$ = integrated luminosity (4% uncertainty)**
- **A = geometrical and kinematical acceptance**
  - **strongly dependent on production polarization, mostly dictated by the thresholds on efficiency triggers**

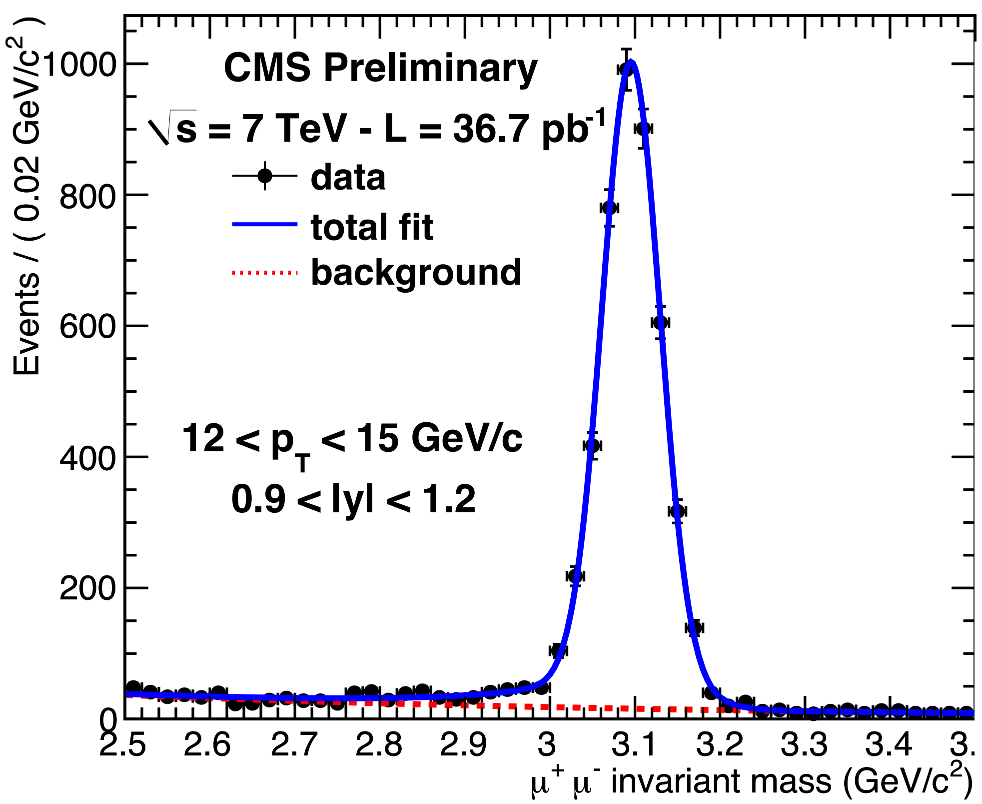
$$\begin{array}{rcl} |\eta^\mu| < 1.2 & \rightarrow & p_T^\mu > 4\ \mathrm{GeV}/c \\ 1.2 < |\eta^\mu| < 2.4 & \rightarrow & p_T^\mu > 3.3\ \mathrm{GeV}/c \end{array}$$

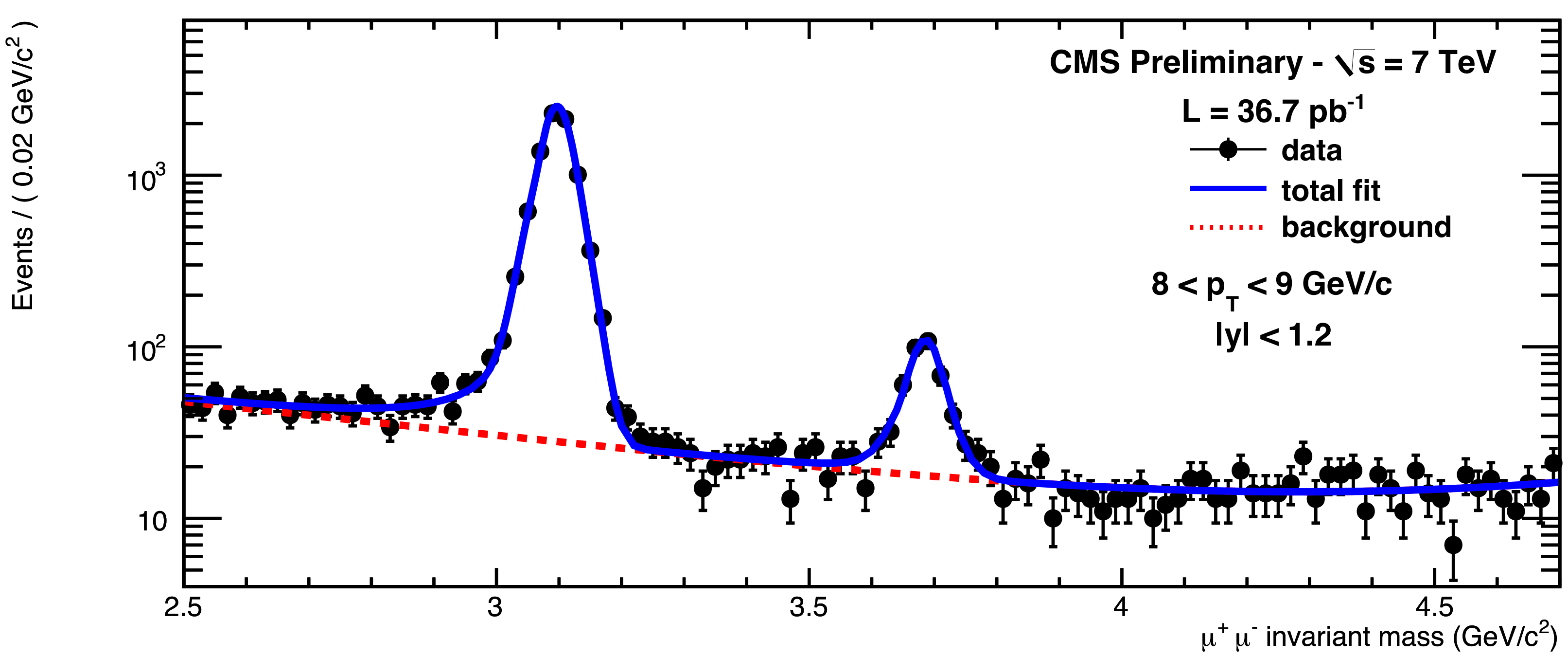
- **ε = dimuon efficiency=** $\epsilon(\mu^+)\cdot\epsilon(\mu^-)\cdot\rho\cdot\epsilon_{\mathrm{vertex}}$
  - **single muon trigger and reconstruction efficiencies, from Tag & Probe method**
  - **Vertexing of opposite sign dimuons (Prob>1%)**
  - **High quality tracks associated to muon segments: cuts on n_{Hits}, χ^2, d_{xy}, d_z**

J/ψ and ψ(2S) yields

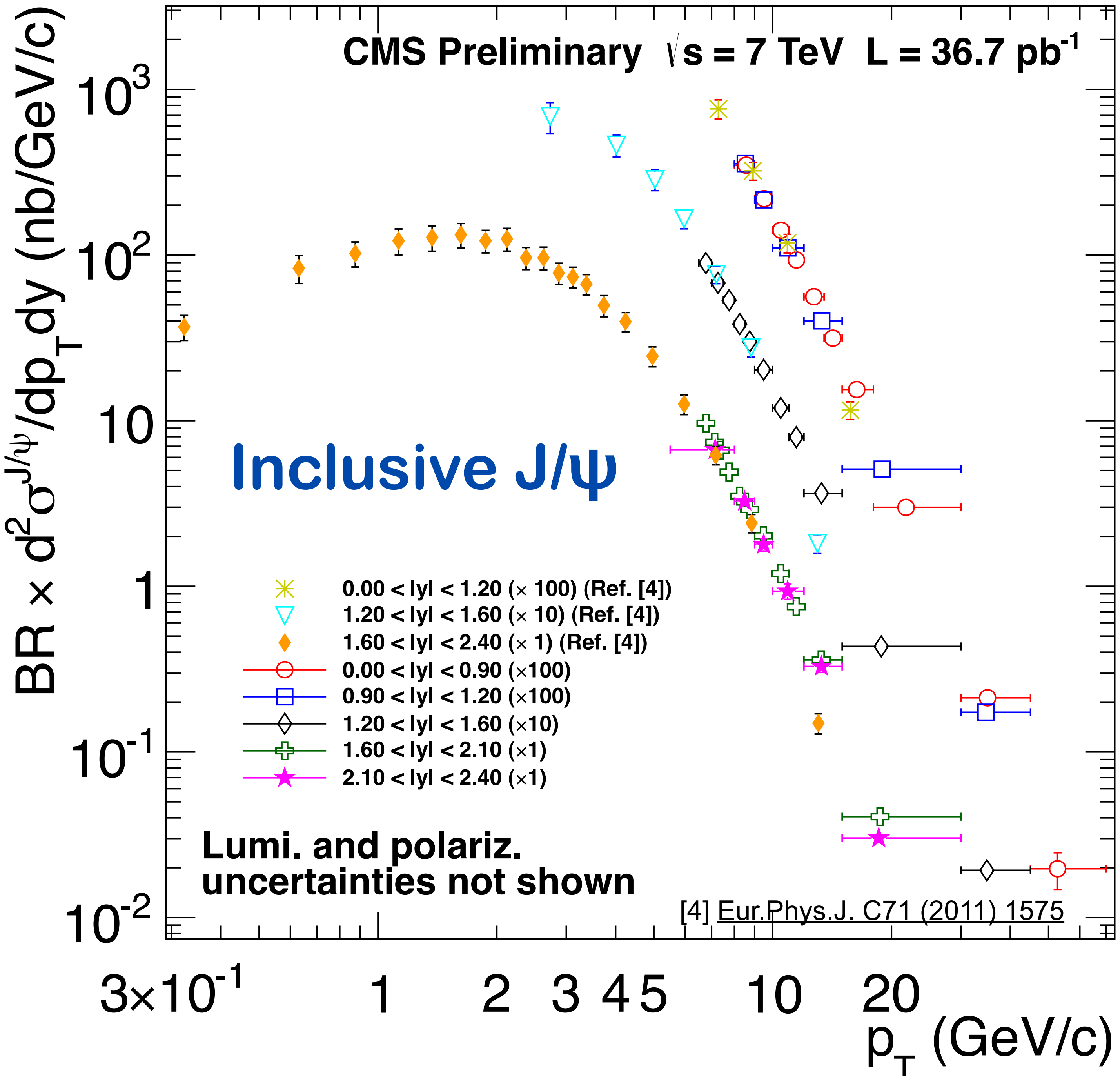
Yield extraction: UML fit to invariant mass distributions

- J/ψ in five rapidity bins ~200K events
  - Crystal Ball+ Gaussian + exponential bkg
- ψ(2S) in three rapidity bins ~8K events
  - Simultaneous fit to ψ and J/ψ + 2 exp bkg
    - CB tail parameters and resolution (scaled by mass) in common
    - mass mean difference fixed from PDG
- Mass resolution ~20 MeV for |y|<0.5, ~50 MeV |y|>2.1





Inclusive J/ψ cross section



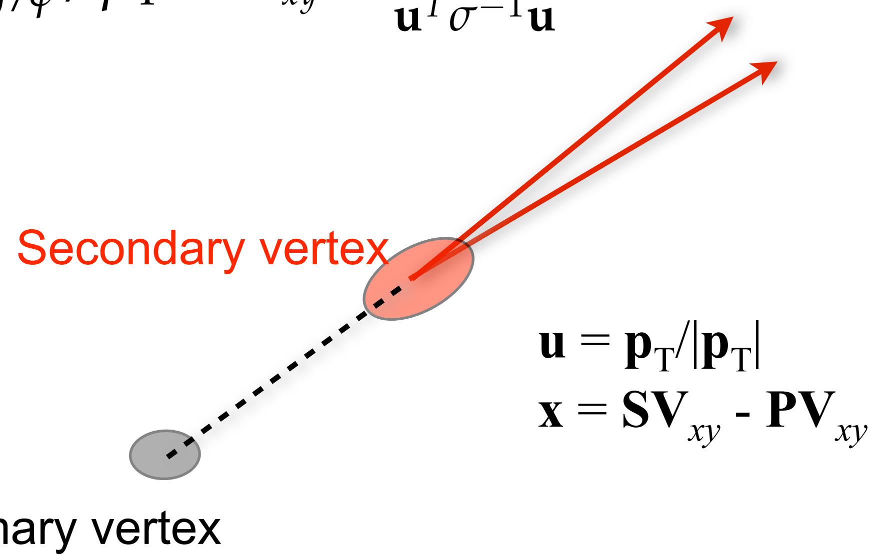
Null polarization scenario

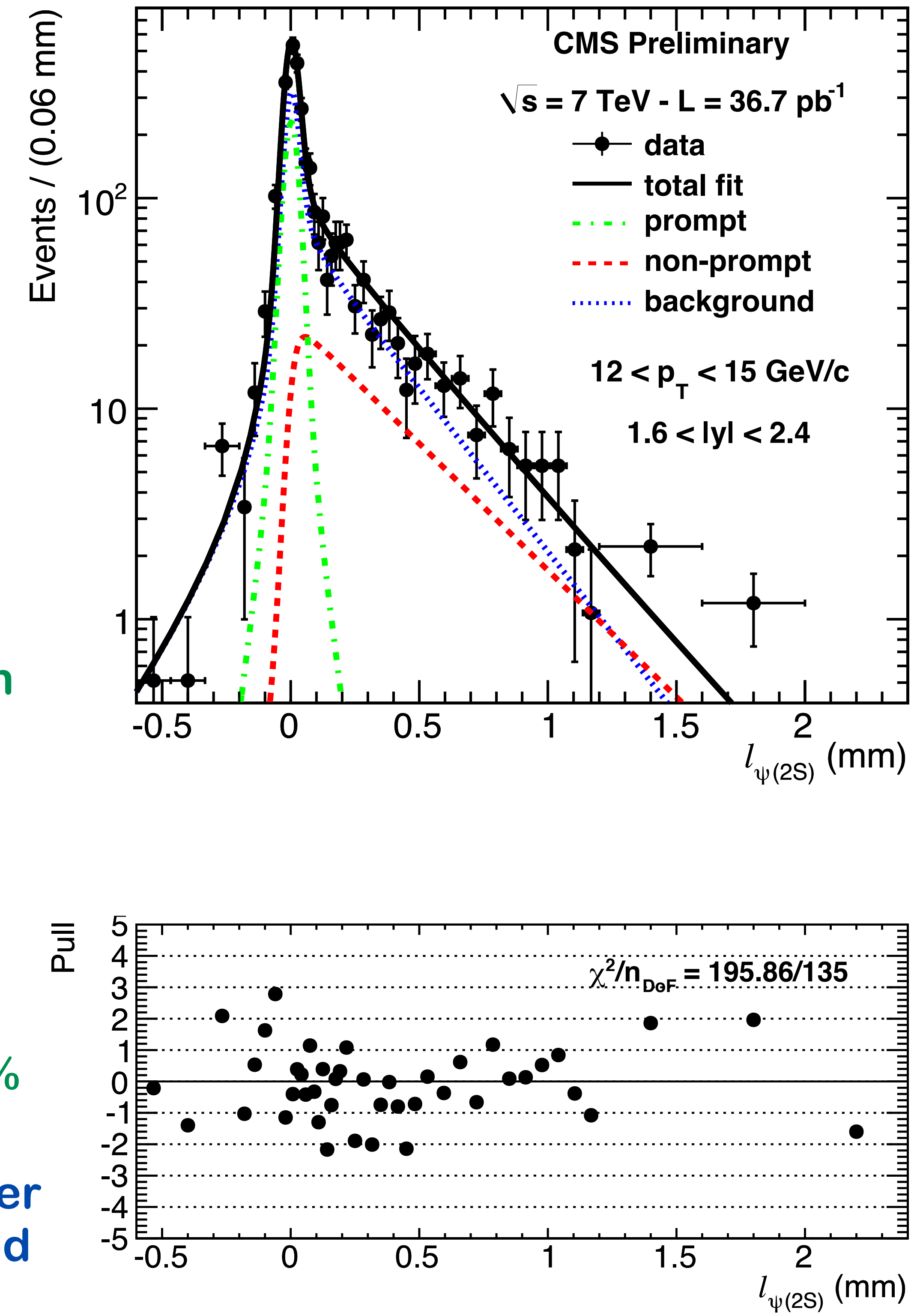
- Merging with the published CMS results, we have a J/ψ cross-section measurement from 0 to 70 GeV/c
- Nice agreement among different triggers/methods
- Statistical errors 2 to 9%
- Systematics mostly below 1% (except polarization)
  - the largest systematics occur at the boundary of the acceptance or for very high p_T, where the correlation between two muons is large.

Non prompt J/ψ fraction

Pseudo proper decay length

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





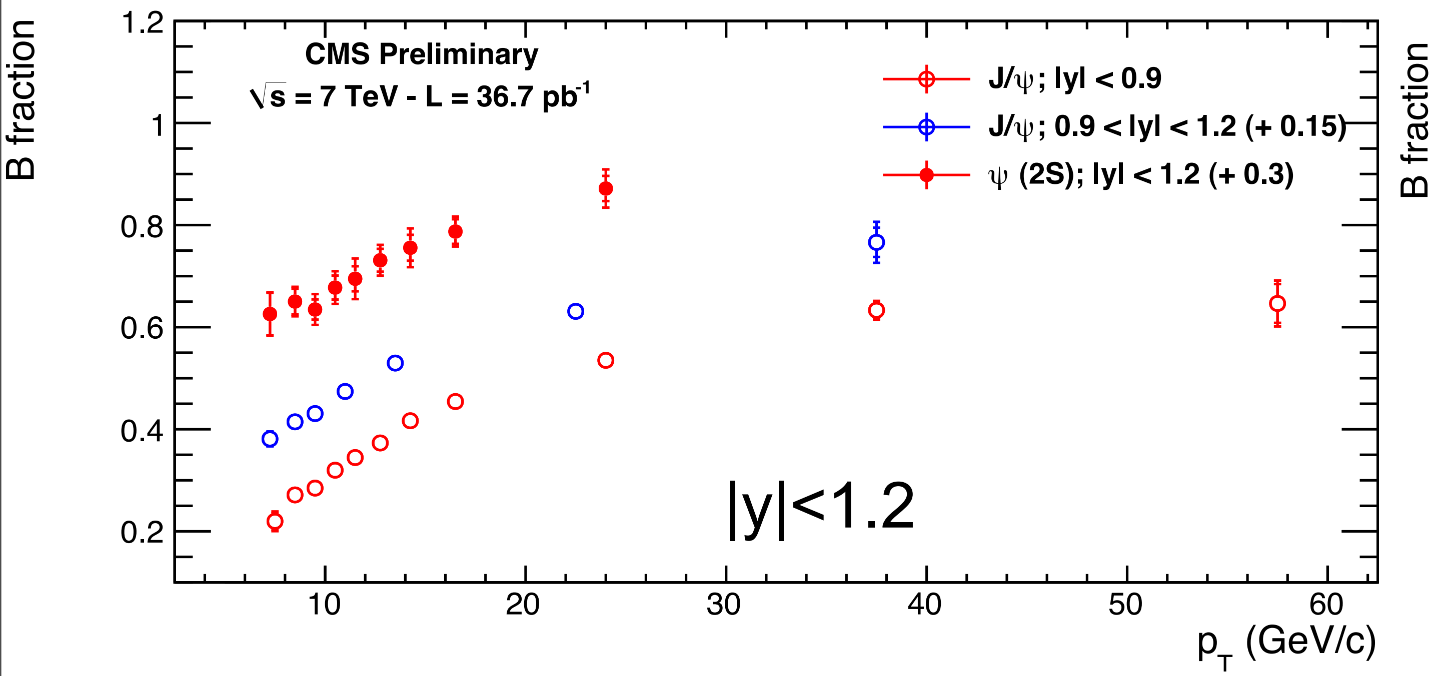
Decay length parameterization :

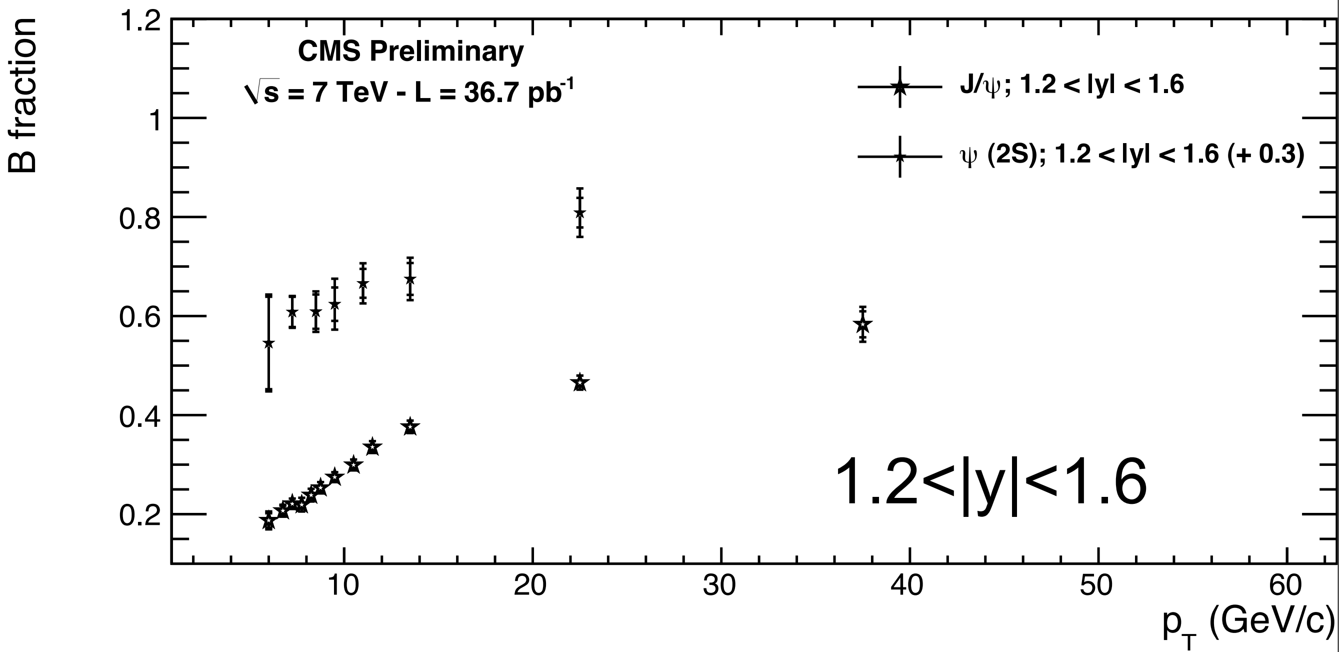
- Prompt : δ-function convoluted with a resolution function
- Non-prompt : effective exponential convoluted with a resolution function
- Background: generic superposition of different contributions from the side-bands

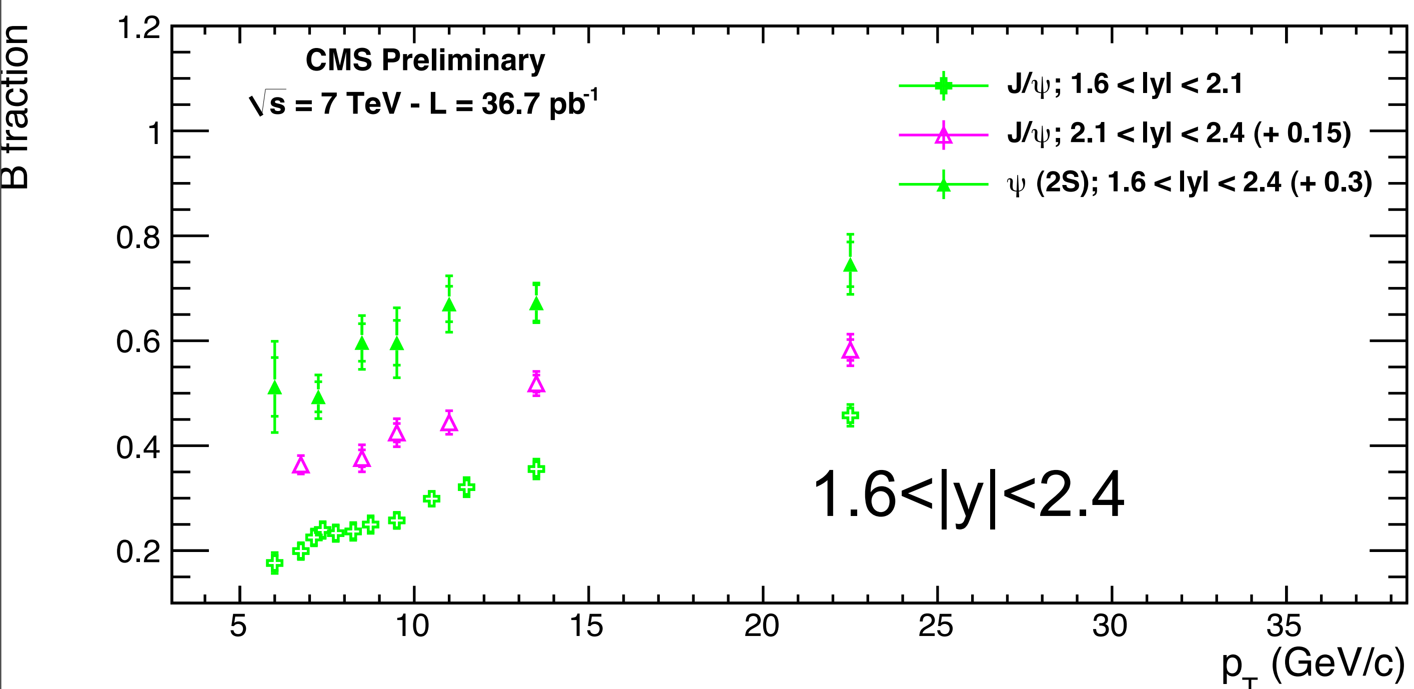
Fit technique

- Core resolution function given by one Gaussian (plus <1% of a second Gaussian) using "per event error"
- In the ψ(2S) case, a simultaneous fit is performed together with the J/ψ, using some constraints (same resolution and mean, same effective background lifetimes)

B fraction results

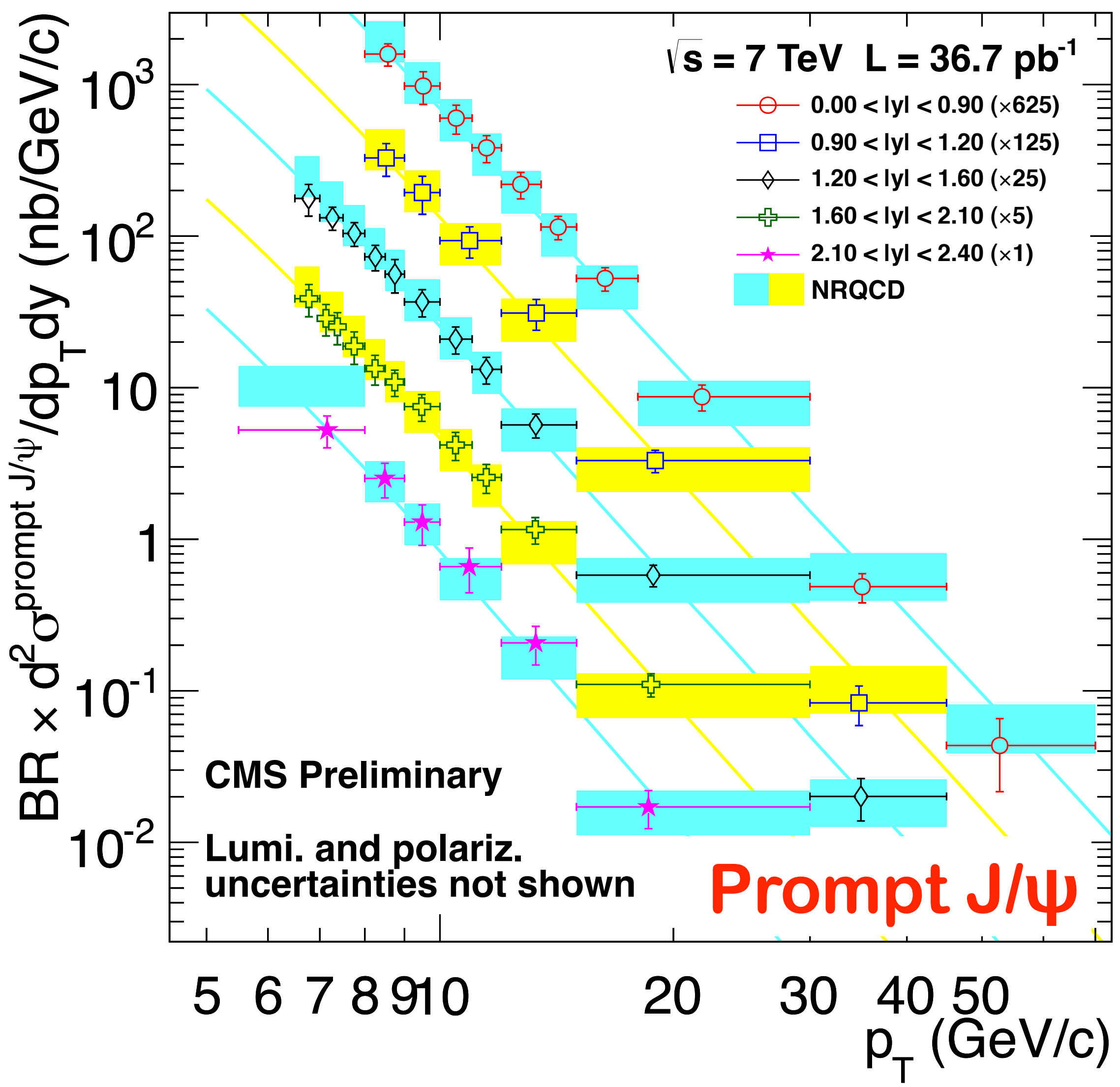


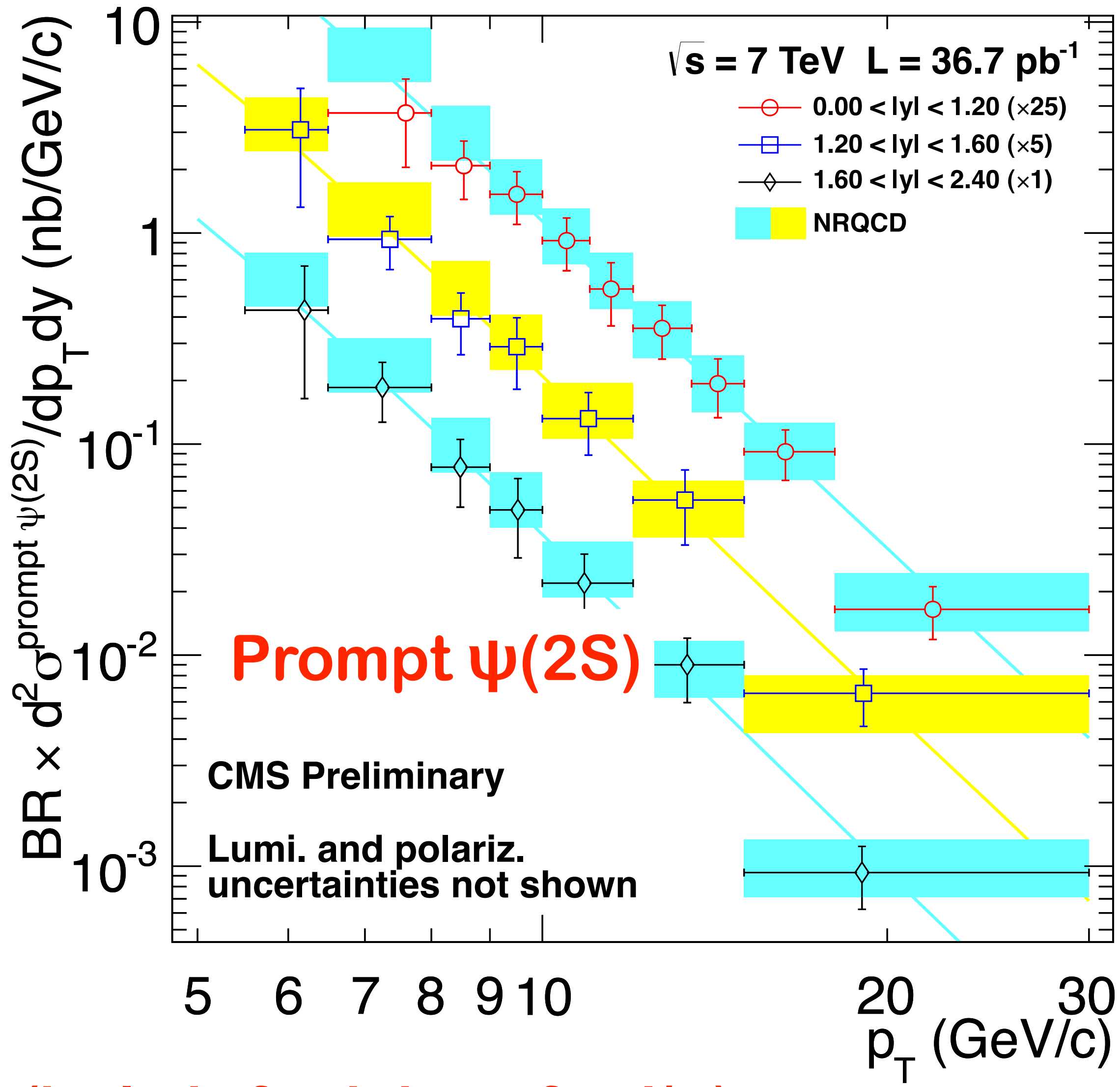




- Increasing monotonically with p_T

Prompt cross-sections



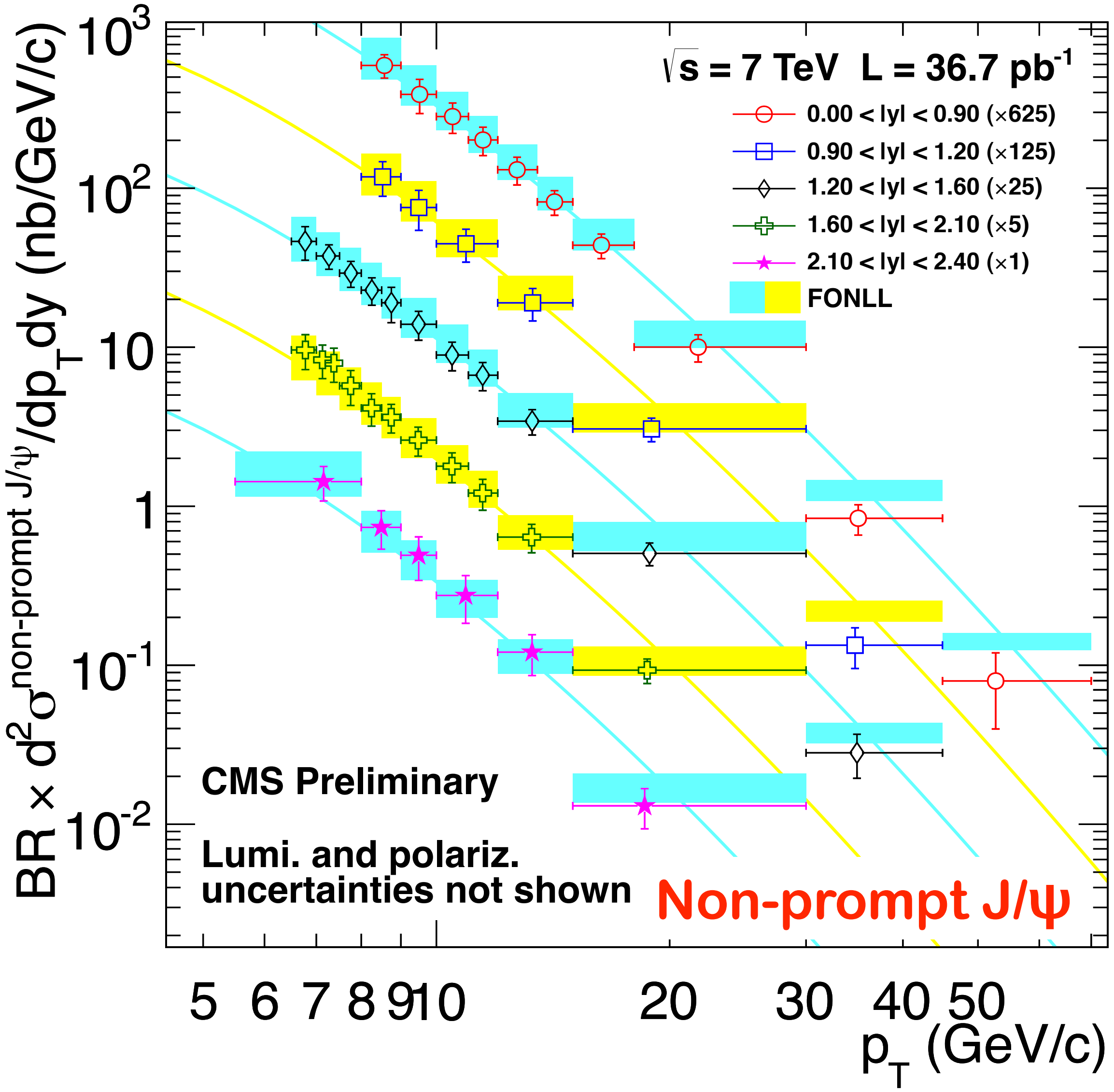


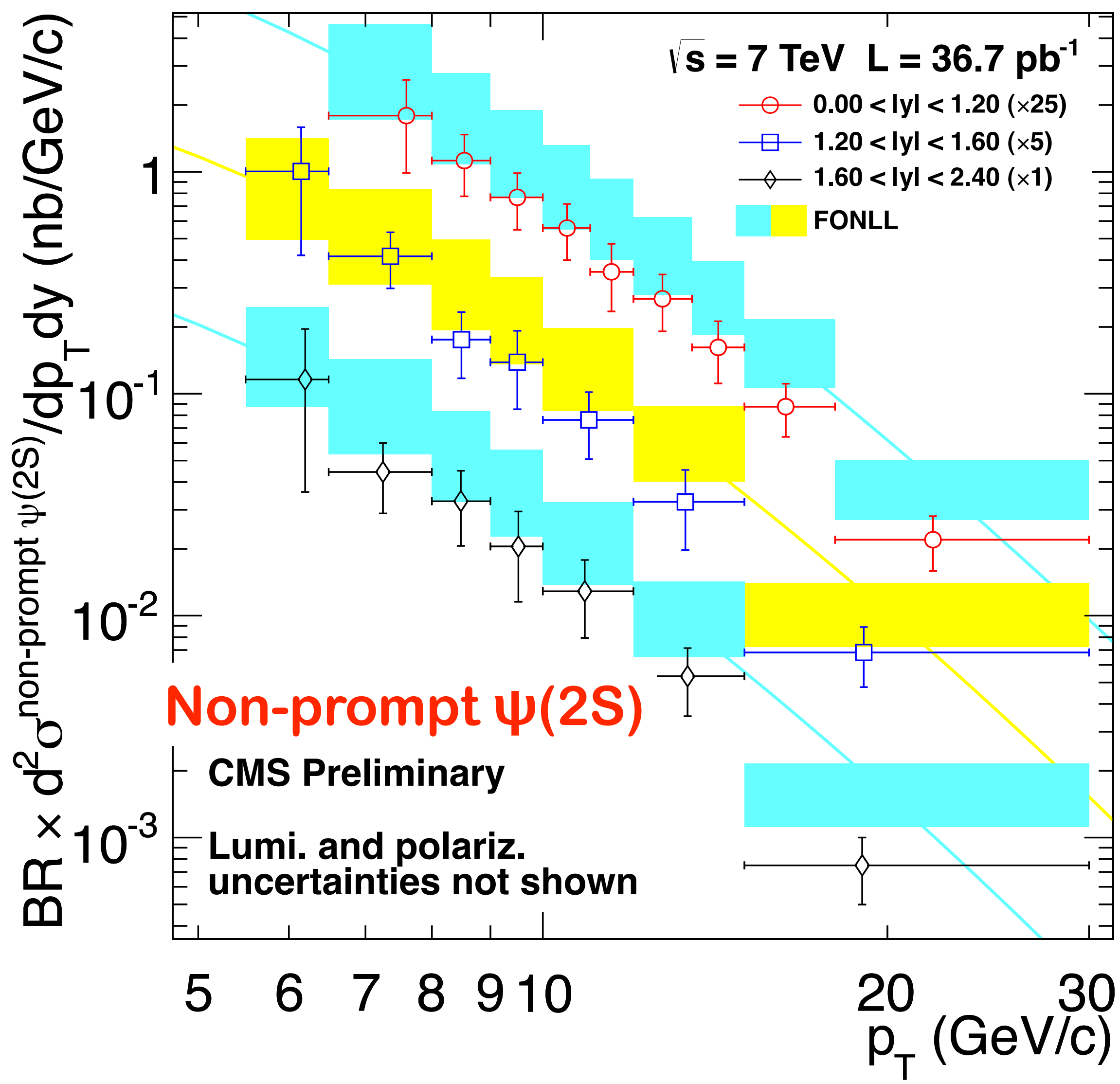
NRQCD predictions in excellent agreement (include feed-down for J/ψ)
(K.T. Chao et al.) [Phys. Rev. Lett.106:042002, 2011]

J/ψ [ψ(2S)] polarization uncertainties as in *Eur. Phys. J. C71 (2011) 1575*:

- **+18% [+25%] (fully transverse in helicity frame)**
- **-20% [-28%] (fully longitudinal helicity frame)**

Non-prompt cross-sections





Excellent comparison with FONLL predictions for J/ψ
(M. Cacciari et al.) [JHEP 0103 (2001) 006]

Largest systematics from ρ-factors (for the J/ψ) and background lifetime (for ψ(2S)).

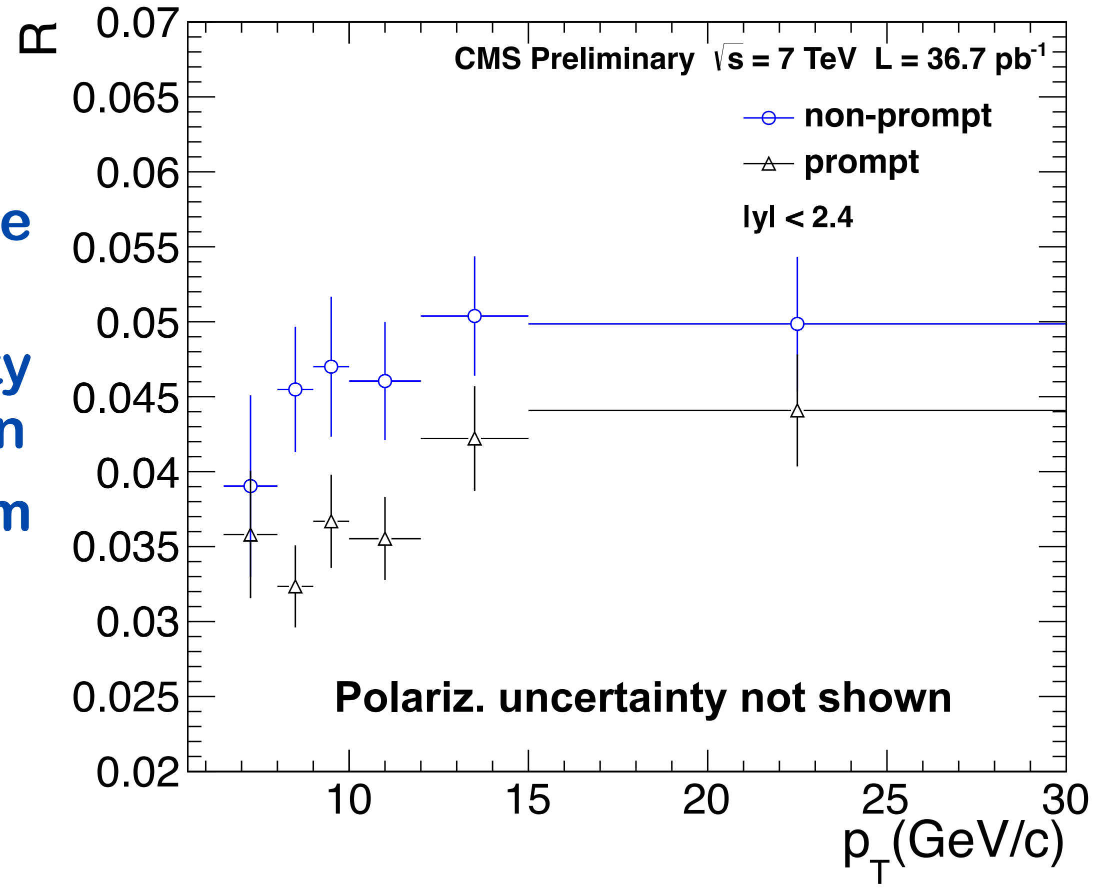
- **Overall shift for predictions for ψ(2S)**
- **ψ(2S) spectrum falls more rapidly at high p_T than the predictions**

Cross-sections ratios

- Ratio of the differential cross sections is appealing since most of the systematic uncertainties cancel

$$R(p_T,|y|) = \frac{\frac{d^2\sigma}{dp_T dy}(\psi(2S)) \cdot BR(\psi(2S) \to \mu^+\mu^-)}{\frac{d^2\sigma}{dp_T dy}(J/\psi) \cdot BR(J/\psi \to \mu^+\mu^-)} = \frac{N_{corr}(\psi(2S))}{N_{corr}(J/\psi)}.$$

- Ratio is constant over rapidity bins, hence the result is given averaged within $|y|<2.4$.
- Statistical errors ~3 to 5%, systematic uncertainty ~10% (acceptance dominated) - except polarization
- The polarization uncertainty on R ranges from 12% to 20%



Conclusions

- Absolute differential cross-sections in p_T and $|y|$ of J/ψ and $\psi(2S)$ mesons and ratio of the cross sections
  - All separately for prompt and non-prompt contributions
- Measurement of J/ψ cross section from 0 to 70 GeV/c
- Typical uncertainties (statistical + systematic)
  - ~5 (20)% on J/ψ ($\psi(2S)$) x-sections, ~10% on ratios
  - Maximum polarization uncertainties for the prompt cross sections range from ~18% (for J/ψ) to 28% (for $\psi(2S)$)
- Results compared with NRQCD and FONLL predictions
  - Excellent agreement for prompt case J/ψ and $\psi(2S)$, as well as for non-prompt J/ψ.
  - Overall $\psi(2S)$ normalization (and spectrum at very high p_T) show differences with respect to the non-prompt predictions

Backup

J/ψ Systematics

$\lvert y \rvert$ range		0 – 0.9	0.9 – 1.2	1.2 – 1.6	1.6 – 2.1	2.1 – 2.4
Quantity affected	Source	Relative uncertainty (in %)				
$m_{\mu\mu}$ fits	Statistical	1.2 – 8.9	1.5 – 7.1	1.6 – 8.4	1.2 – 3.2	2.3 – 3.9
$\ell_{J/\psi}$ fits	Statistical	1.0 – 5.9	1.4 – 4.7	1.4 – 7.6	2.1 – 8.3	4.4 – 7.1
Acceptance	FSR	0.0 – 1.5	0.0 – 2.5	0.0 – 4.2	0.7 – 8.0	0.5 – 3.5
	p_T calibration	0.0 – 0.6	0.0 – 0.6	0.0 – 0.8	0.1 – 0.6	0.0 – 0.8
	Kinematical spectra	0.0 – 0.3	0.0 – 0.7	0.0 – 0.7	0.7 – 3.8	0.4 – 5.3
	B polarization	0.0 – 0.5	0.0 – 0.4	0.0 – 0.5	0.1 – 0.8	0.3 – 1.3
Efficiency	Single-muon efficiency	0.3 – 0.9	0.2 – 1.6	0.1 – 1.4	0.2 – 1.0	0.6 – 1.4
	ρ factor	1.9 – 23.2	1.2 – 7.6	0.7 – 5.7	0.8 – 5.4	3.7 – 6.8
Yields	Fit functions	0.6 – 3.4	0.4 – 2.8	0.5 – 2.8	0.8 – 2.2	1.0 – 4.2
Luminosity	Luminosity	4	4	4	4	4
b-fraction	Tracker misalignment	0.1 – 2.1	0.1 – 0.8	0.0 – 1.5	0.2 – 3.2	0.2 – 5.1
	b-lifetime model	0.1 – 3.0	0.1 – 3.4	0.1 – 3.7	0.2 – 2.6	0.2 – 6.6
	Vertex estimation	0.1 – 0.7	0.7 – 3.0	0.4 – 3.7	1.5 – 4.6	2.3 – 5.0
	Background fit	0.0 – 0.2	0.1 – 1.4	0.1 – 1.0	0.0 – 2.5	0.1 – 1.2
	Resolution model	0.2 – 3.5	0.0 – 4.2	0.8 – 3.5	1.1 – 5.0	1.1 – 4.4
	Efficiency	0.4 – 2.1	0.9 – 3.3	0.5 – 9.9	0.3 – 3.3	1.6 – 10.5

ψ (2S) systematics

$\lvert y \rvert$ range		0 – 1.2	1.2 – 1.6	1.6 – 2.4
Quantity affected	Source	Relative uncertainty (in %)		
$m_{\mu\mu}$ fits	Statistical	5.6 – 14.8	7.5 – 31.7	7.3 – 24.1
$\ell_{\psi(2S)}$ fits	Statistical	4.3 – 12.7	5.9 – 38.0	9.1 – 26.4
Acceptance	FSR	0.0 – 3.9	0.5 – 3.4	0.3 – 4.1
	p_T calibration	0.2 – 0.5	0.3 – 0.5	0.3 – 0.5
	Kinematical spectra	0.1 – 1.2	0.0 – 0.9	0.7 – 2.0
	B polarization	0.1 – 0.8	0.0 – 0.6	0.2 – 1.7
Efficiency	Single-muon efficiency	0.1 – 0.5	0.1 – 0.6	0.2 – 0.9
	ρ factor	0.7 – 13.1	2.1 – 6.6	2.3 – 9.8
Yields	Fit functions	1.2 – 3.7	0.6 – 12.1	3.1 – 10.0
Luminosity	Luminosity	4	4	4
b-fraction	Tracker misalignment	0.3 – 2.6	1.5 – 7.1	1.8 – 11.1
	b-lifetime model	0.0 – 2.5	0.4 – 7.6	0.0 – 2.9
	Vertex estimation	0.0 – 1.7	0.2 – 3.5	1.2 – 4.2
	Background fit	1.0 – 6.8	2.2 – 10.0	2.5 – 15.3
	Resolution model	0.5 – 3.5	0.1 – 4.6	0.9 – 24.9
	Efficiency	0.5 – 7.8	0.9 – 6.3	0.5 – 13.8

Systematics on B-fraction

- **Tracker misalignment:** data re-reconstructed in 3 “weak-mode” alignment scenarios and taking the maximum deviation as systematics
- **B-lifetime model:** “MC template” method used as alternative non-prompt PDF model
- **Background fit:** varying mass limits for the sideband fit which determines l_{qq} background parameters
- **Pile-up:** different choice criteria in case of multiple PVs
- **Resolution model:** double Gaussian → single Gaussian
- **Different prompt/non-prompt efficiencies:** evaluated from MC

Systematics from polarization in the cross section ratio

- The polarization uncertainty is lower wrt cross-sections (see P. Faccioli talk at Quarkonium Production Workshop 2011, Vienna), but dominant
  - The polarization of the J/ψ from $\psi(2S)$ decays practically coincides.
  - The only difference comes from the polarization of the ~30% feed-down P-wave states (χ_{c1} and χ_{c2}), which is constrained by theory.

Systematics

- **Mass fits systematics:**
  - changing
    - ➨Crystal Ball + Gaussian to a single Crystal Ball
    - ➨Exponential to a linear
  - and taking the maximum variation per bin
- **Acceptance Systematics :**
  - To estimate effect of the FSR MC model (PHOTOS) generate events w/ and w/o FSR and compare
  - pT calibration: muon momenta are smeared according to the uncertainties of the momentum scale corrections
  - Kinematical distributions: alternative pT spectra used to average inside a small bin
  - Non-prompt polarization: difference between partially measured value (Babar) and EvtGen predictions

Published J/ψ cross section

- **Muons well within acceptance window**
- **Track quality:**
  - number of hits in full tracker
  - number of hits in pixel layers
  - track fit χ^2
- **Muon quality:**
  - fit χ^2
  - track-muon matching
- **Di-muon vertex quality**
- **~27000 events selected**

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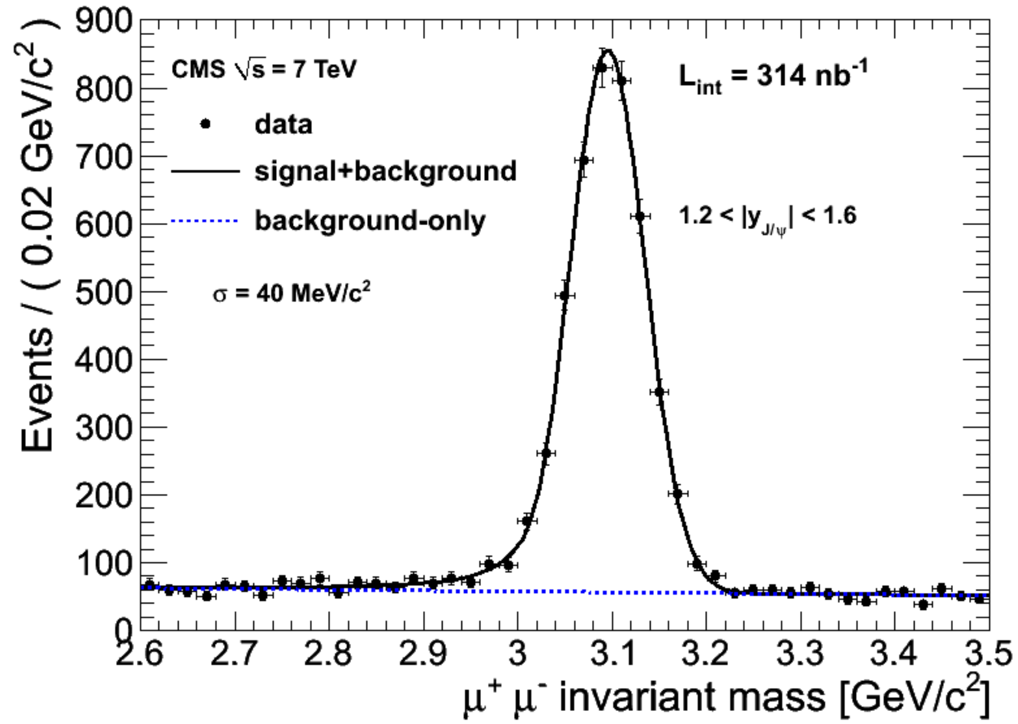
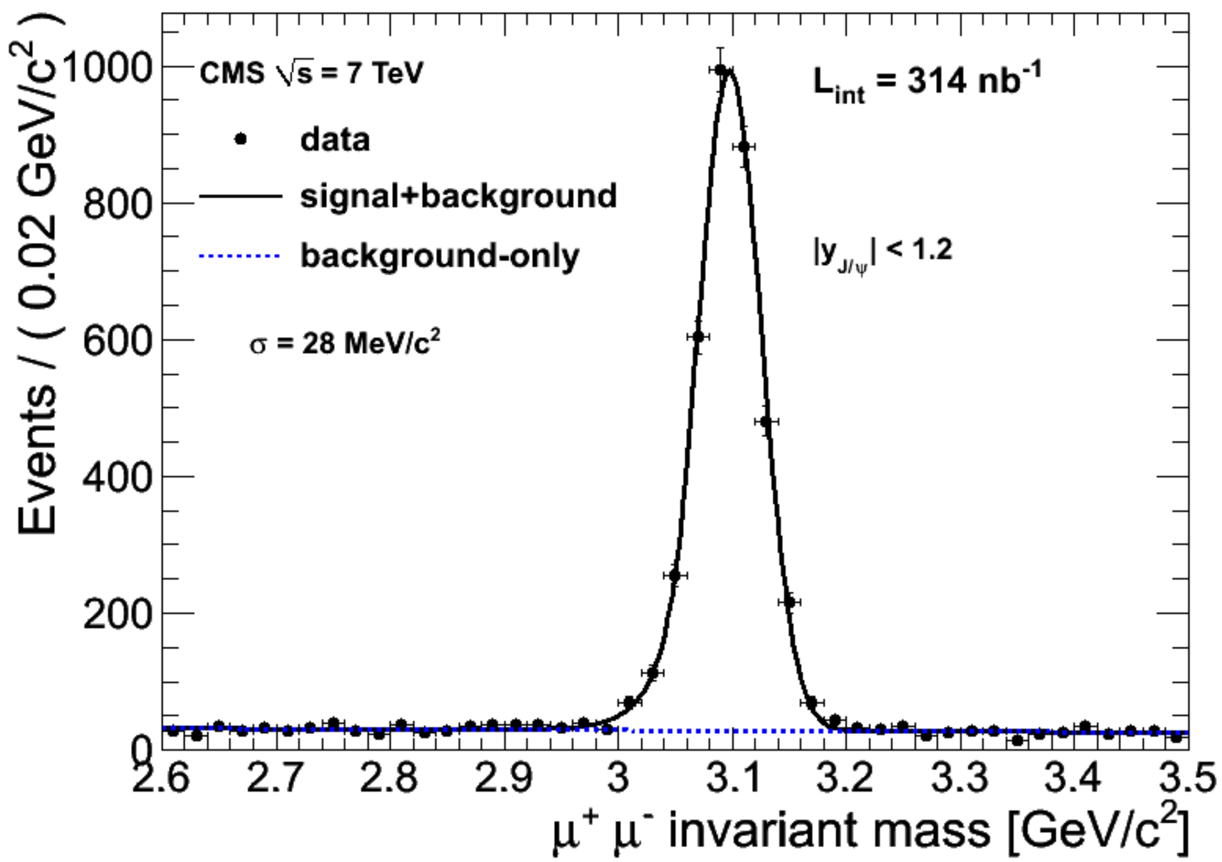
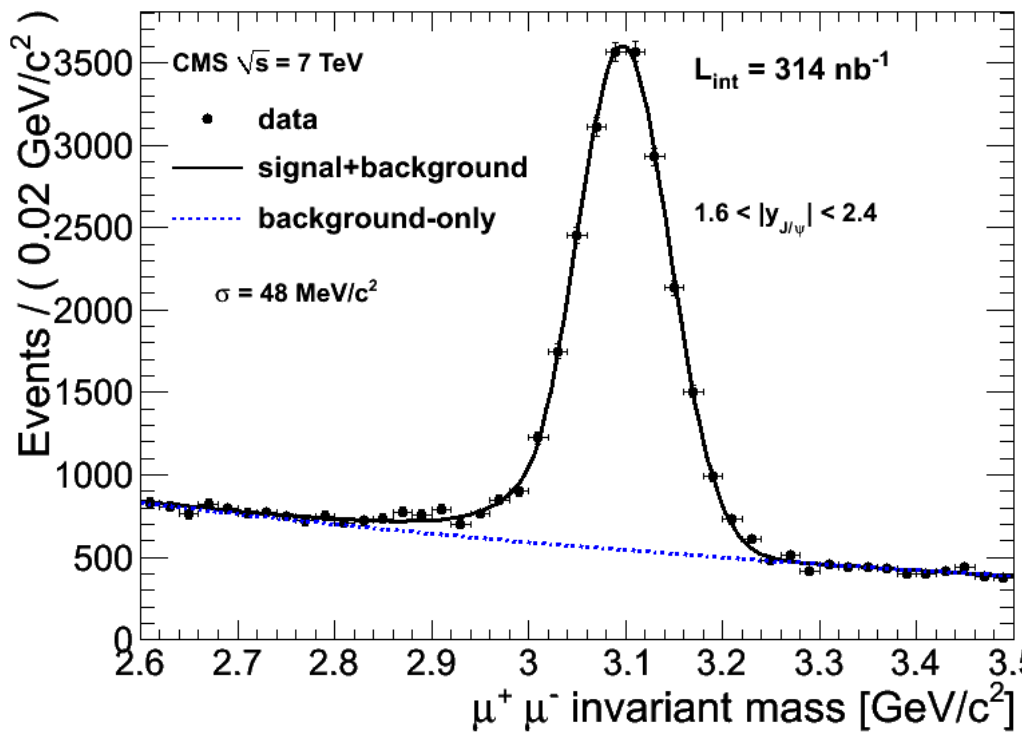
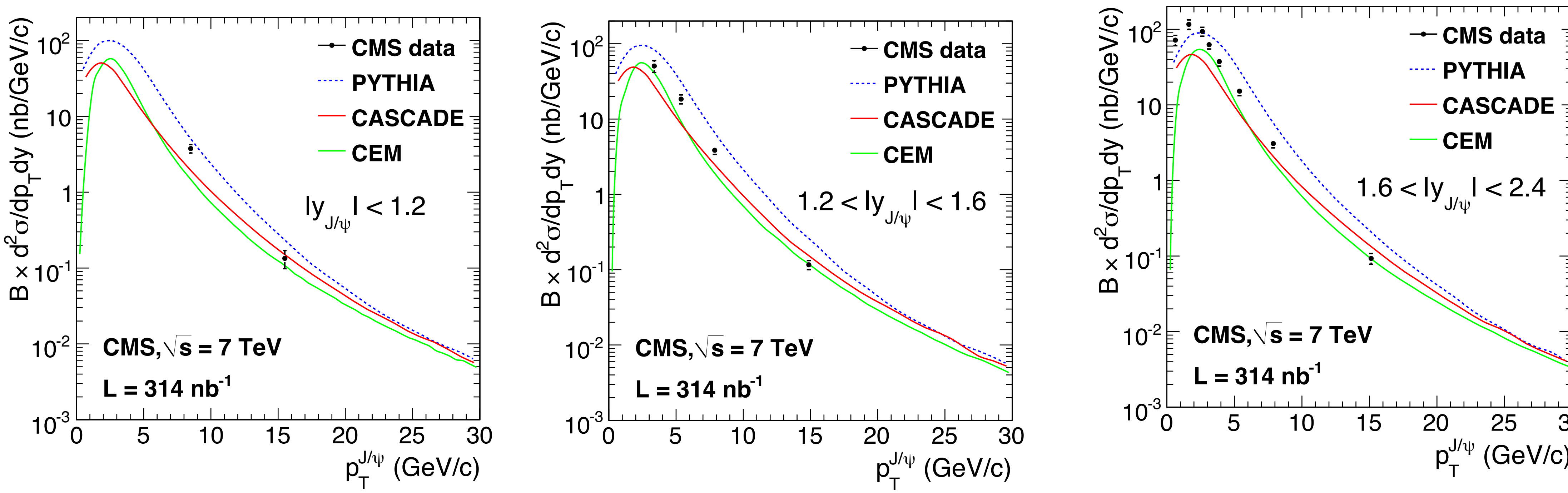






Comparison with theory



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

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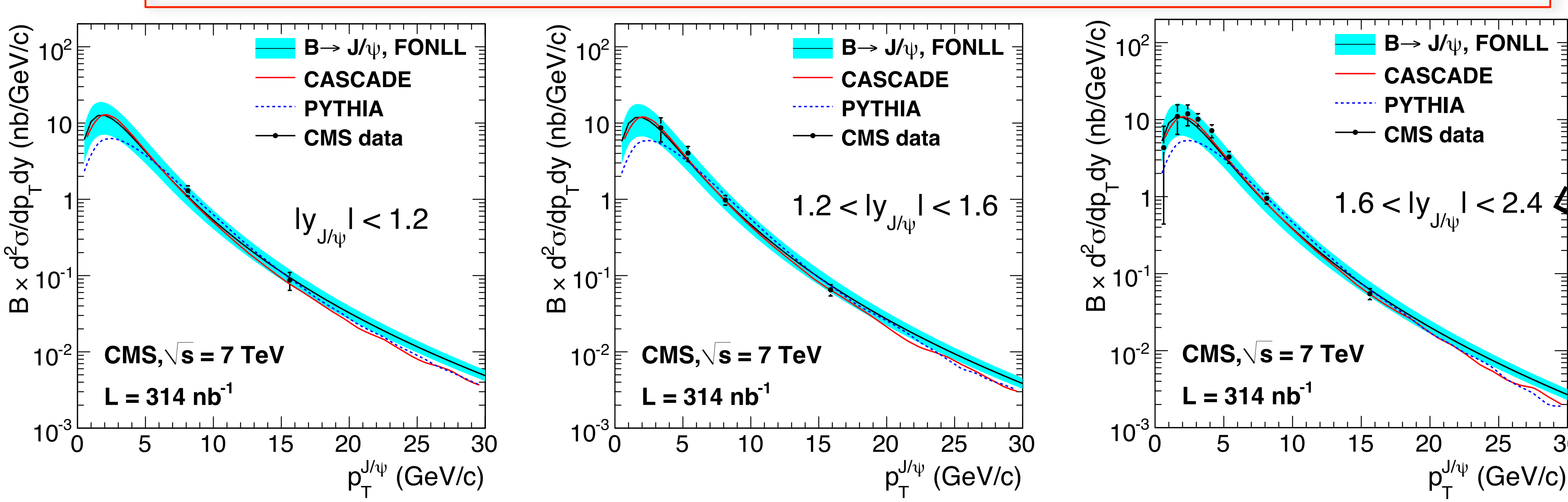
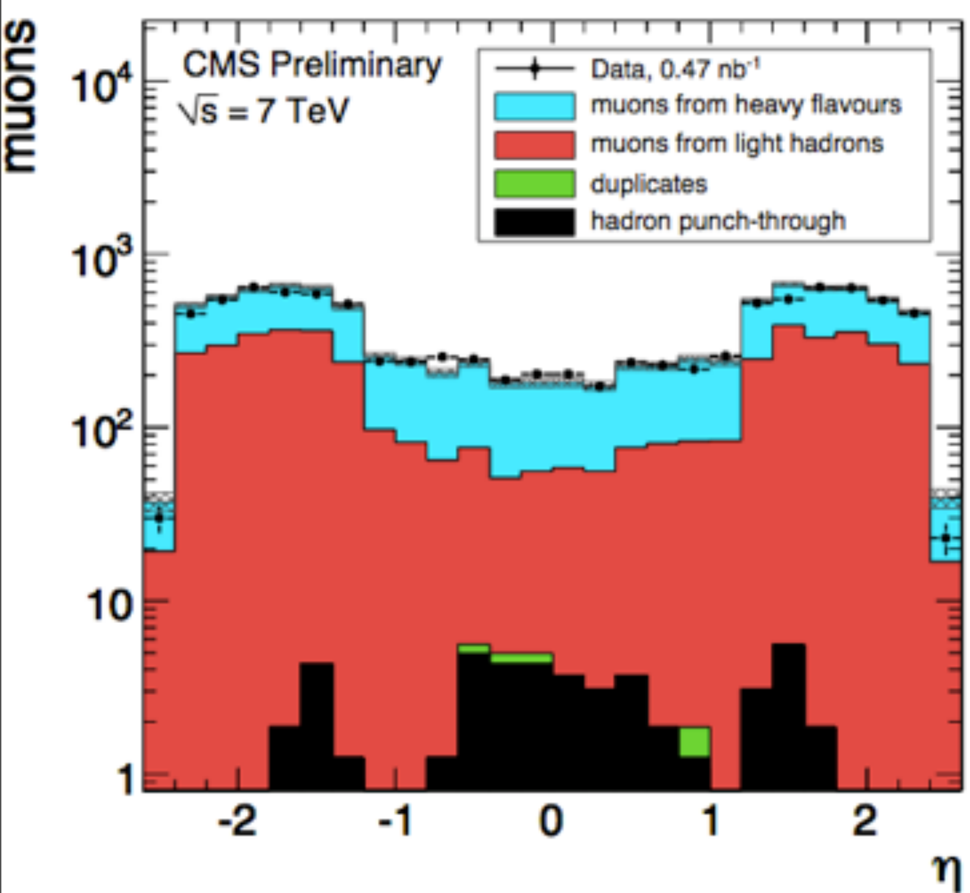


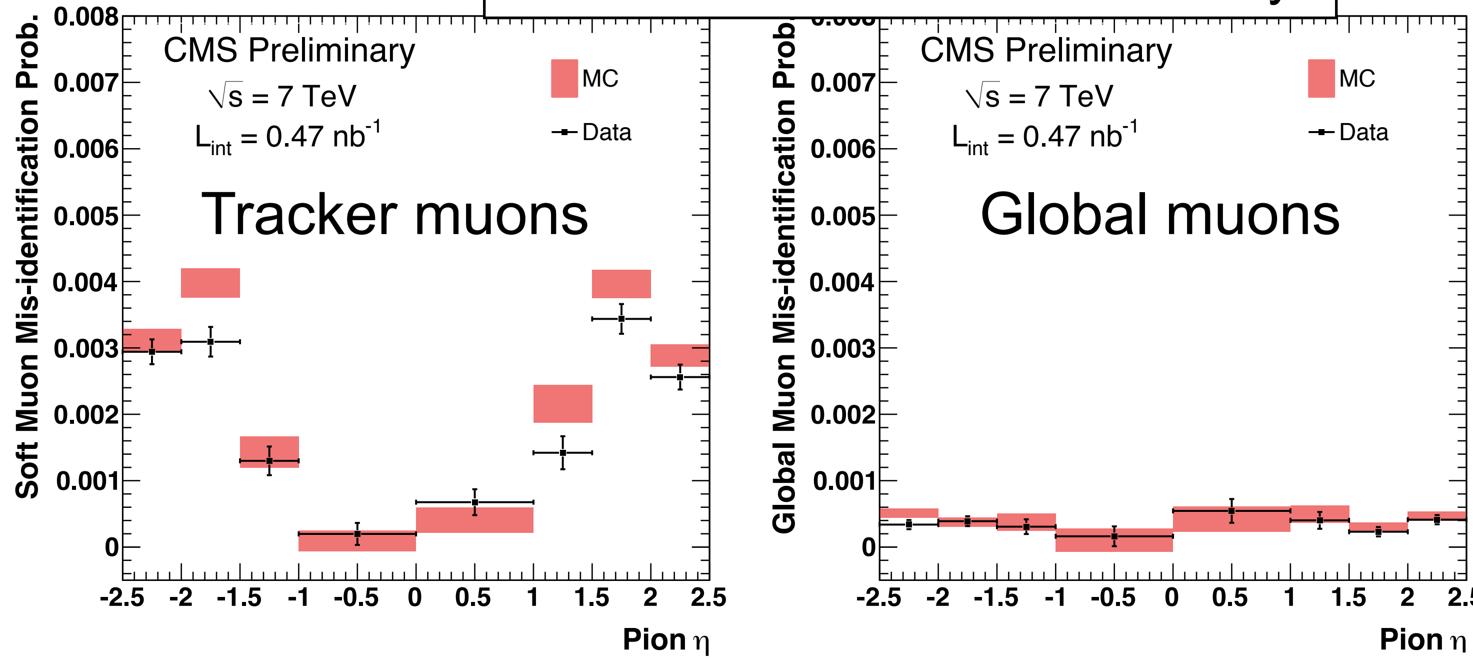
$$\sigma(pp \to bX \to J/\psi X) \cdot BR(J/\psi \to \mu^+\mu^-) = 26.0 \pm 1.4\ (\text{stat}) \pm 1.6\ (\text{syst}) \pm 2.9\ (\text{luminosity})\ \text{nb}$$

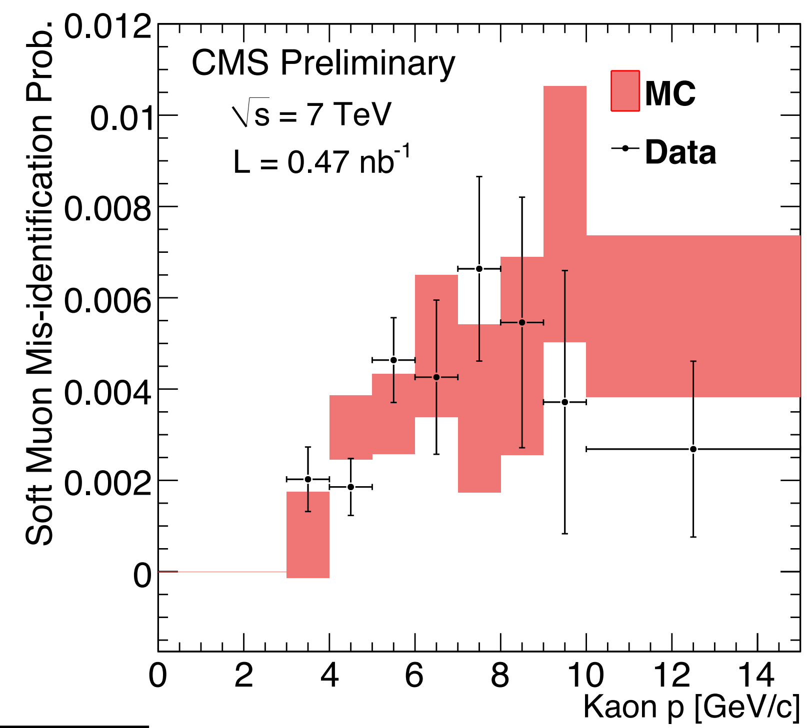
Muon reconstruction quality

Muons in min-bias events
CMS-PAS-MUO-10-002



π misidentification from K_S decays

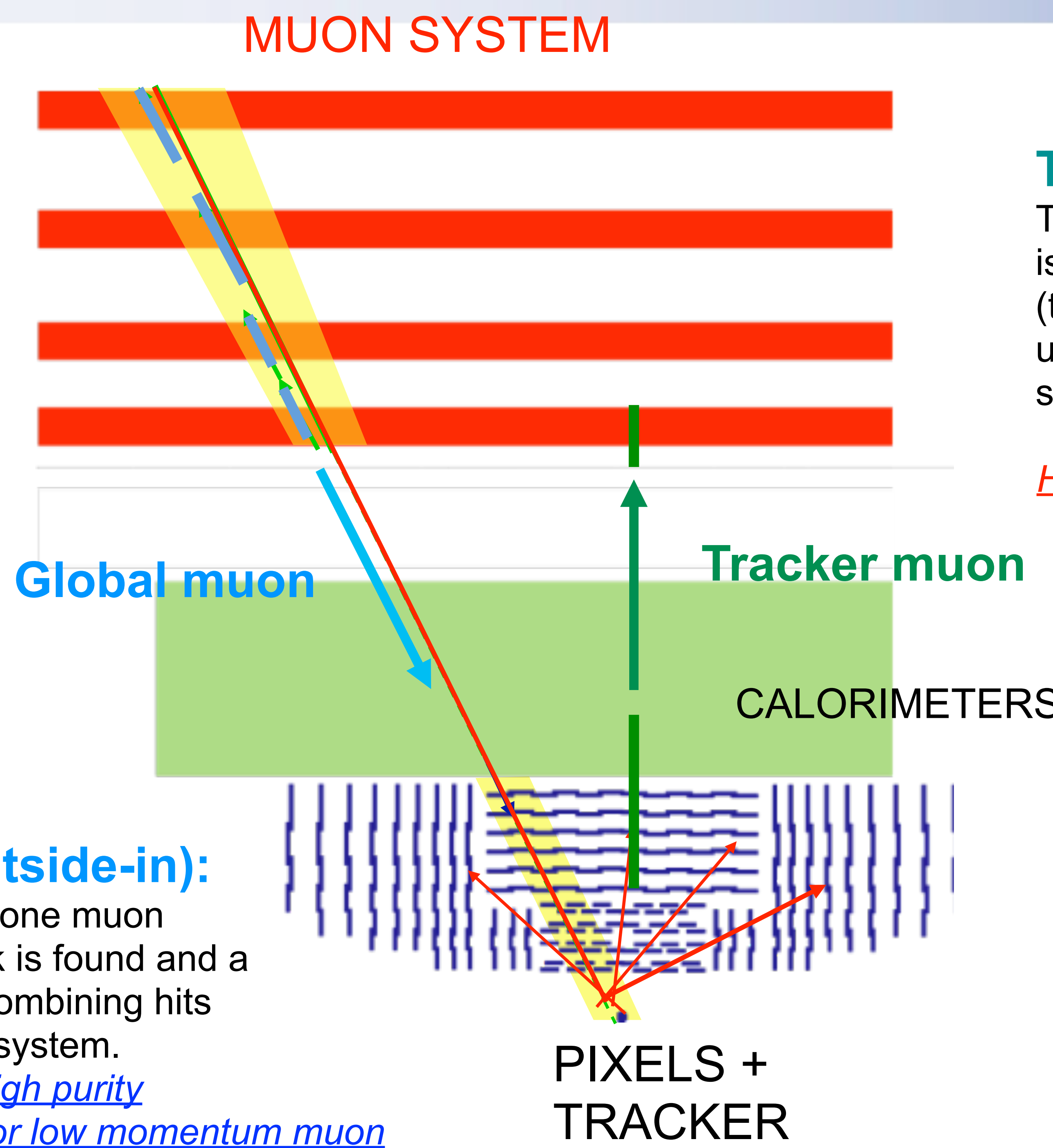




K misidentification from ϕ decays

Excellent performance thanks to early detector commissioning using cosmic muons in 2008 and 2009.

Muon identification



Tracker muon (inside-out):

Tracker track (pt>0.5 GeV,p>2.5 GeV) is extrapolated to the muon system (taking into account energy loss, MS uncertainty) at least one muon segment matches track in position.

Fake muon level high

Higher efficiency low momentum muon

Global muon (outside-in):

starting from a stand-alone muon a matching tracker track is found and a global fit is performed combining hits from tracker and muon system.

High purity

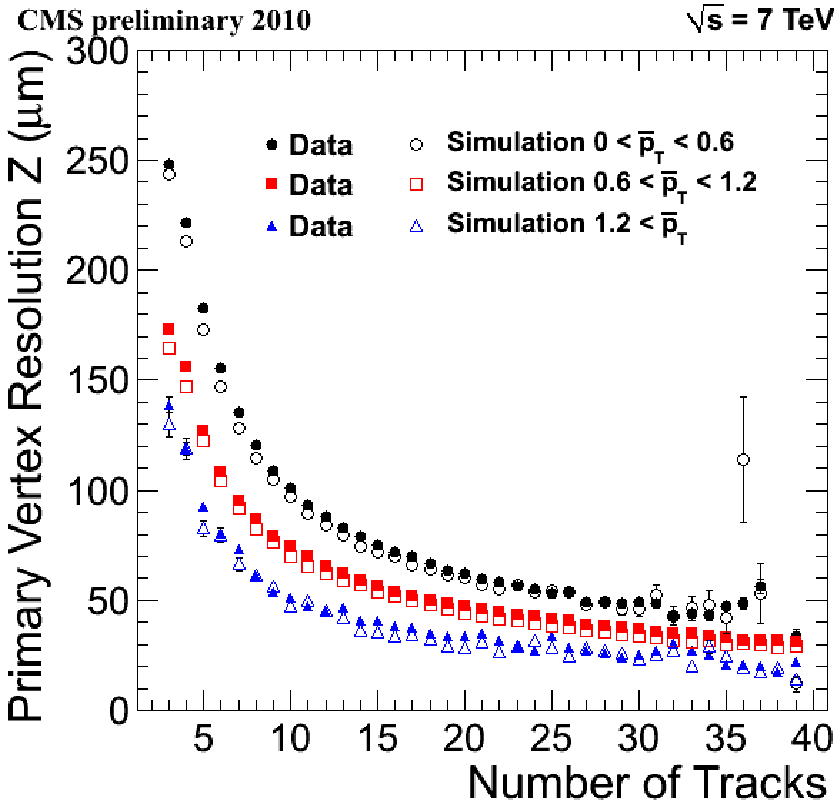
Low efficiency for low momentum muon

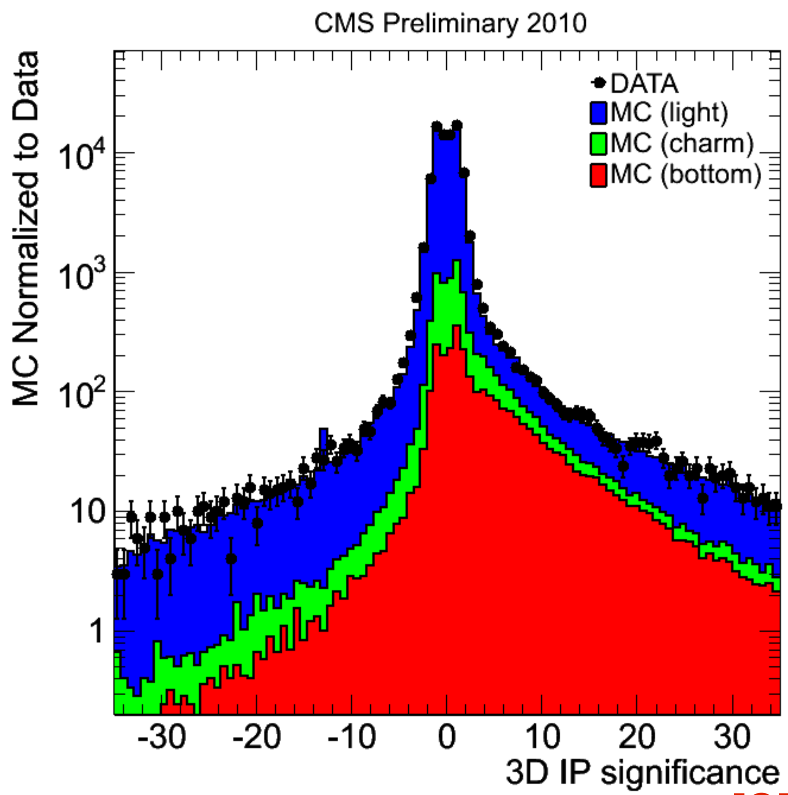
Tracker performance

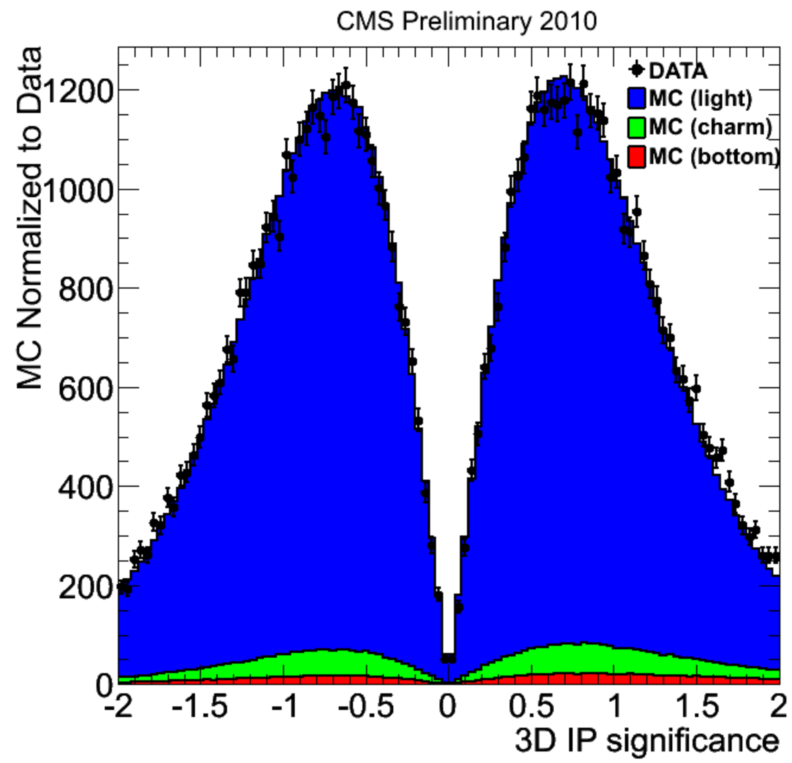
- **Tracker performance well understood**
  - Performance in agreement with the simulation
  - Excellent level of detector alignment

DMR	Data 7 TeV RMS [μm]	MC startup RMS [μm]	MC no misalignment RMS [μm]
BPIX (u')	1.6	3.1	0.9
BPIX (v')	5.5	8.9	1.8
FPIX (u')	5.7	10.7	2.5
FPIX (v')	7.3	14.4	6.1
TIB (u')	5.1	10.1	3.2
TOB (u')	7.5	11.1	7.5
TID (u')	4.0	10.4	2.4
TEC (u')	10.1	22.1	2.9

[CMS PAS TRK-10-001]

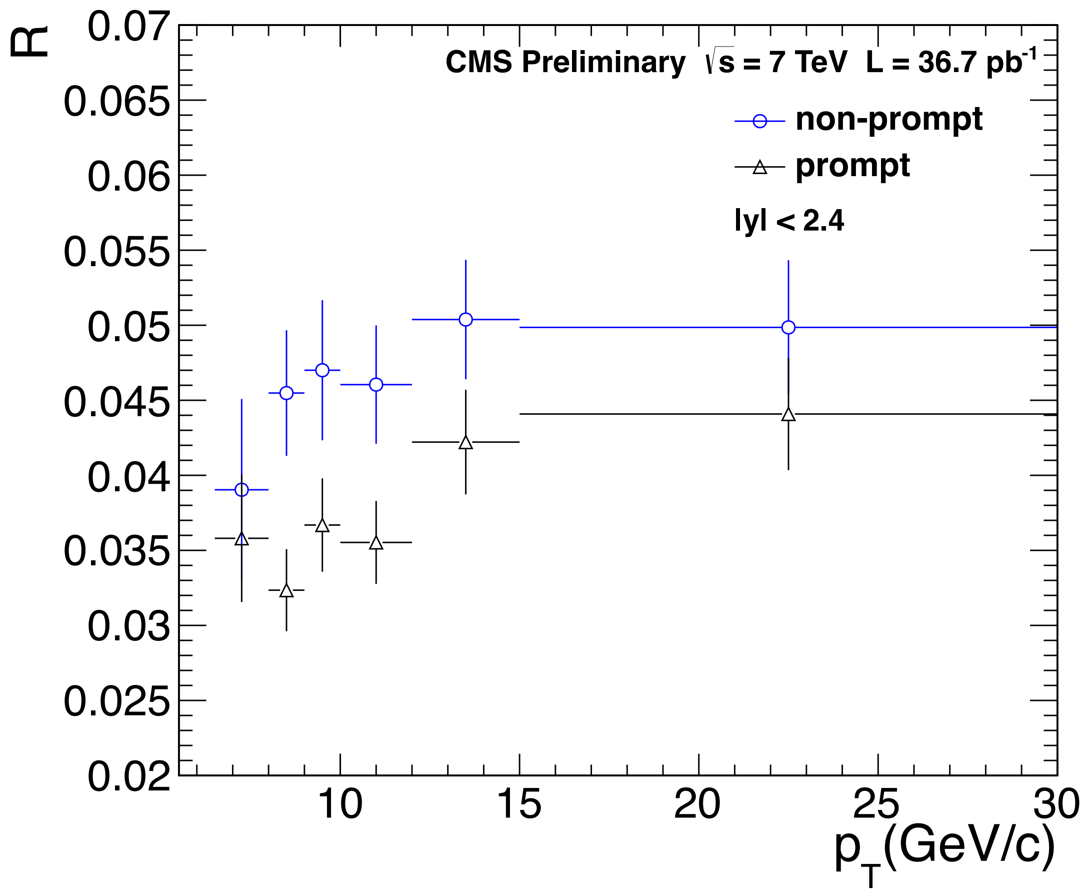






[CMS PAS BTV-10-001]

Comparison with CDF



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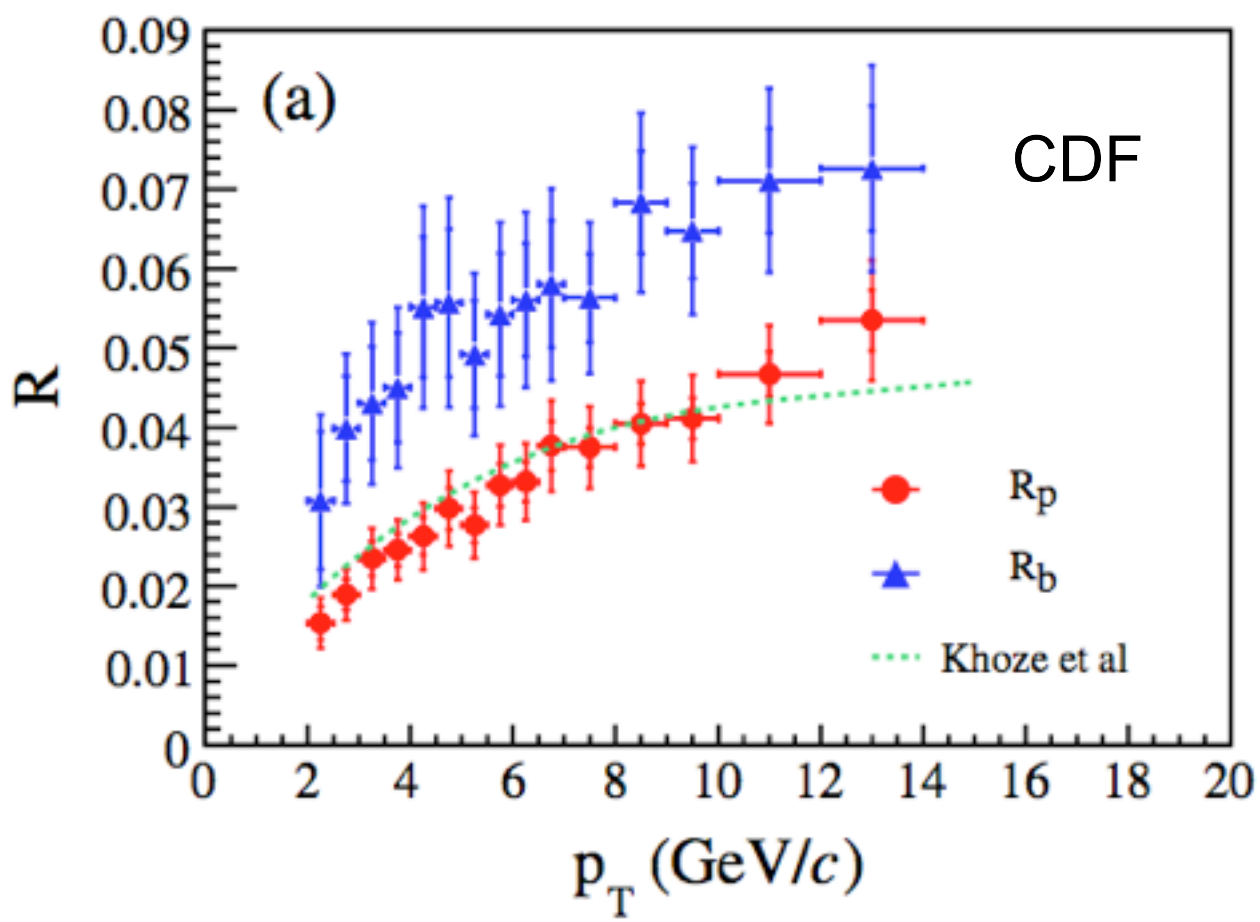

Theory systematics

- The NRQCD theoretical errors include uncertainties on feed-down contributions and on the color-octet long distance matrix elements determined from fits to the Tevatron data.

- The FONLL theoretical errors include renormalization and factorization scale, b and c quark mass, and PDF uncertainties.

  - In the non-prompt ψ(2S) theory predictions figures, a 50% error from the PDG value of the BR(B→ψ(2S)X), has been included.