CMS results on quarkonia and open heavy-flavour

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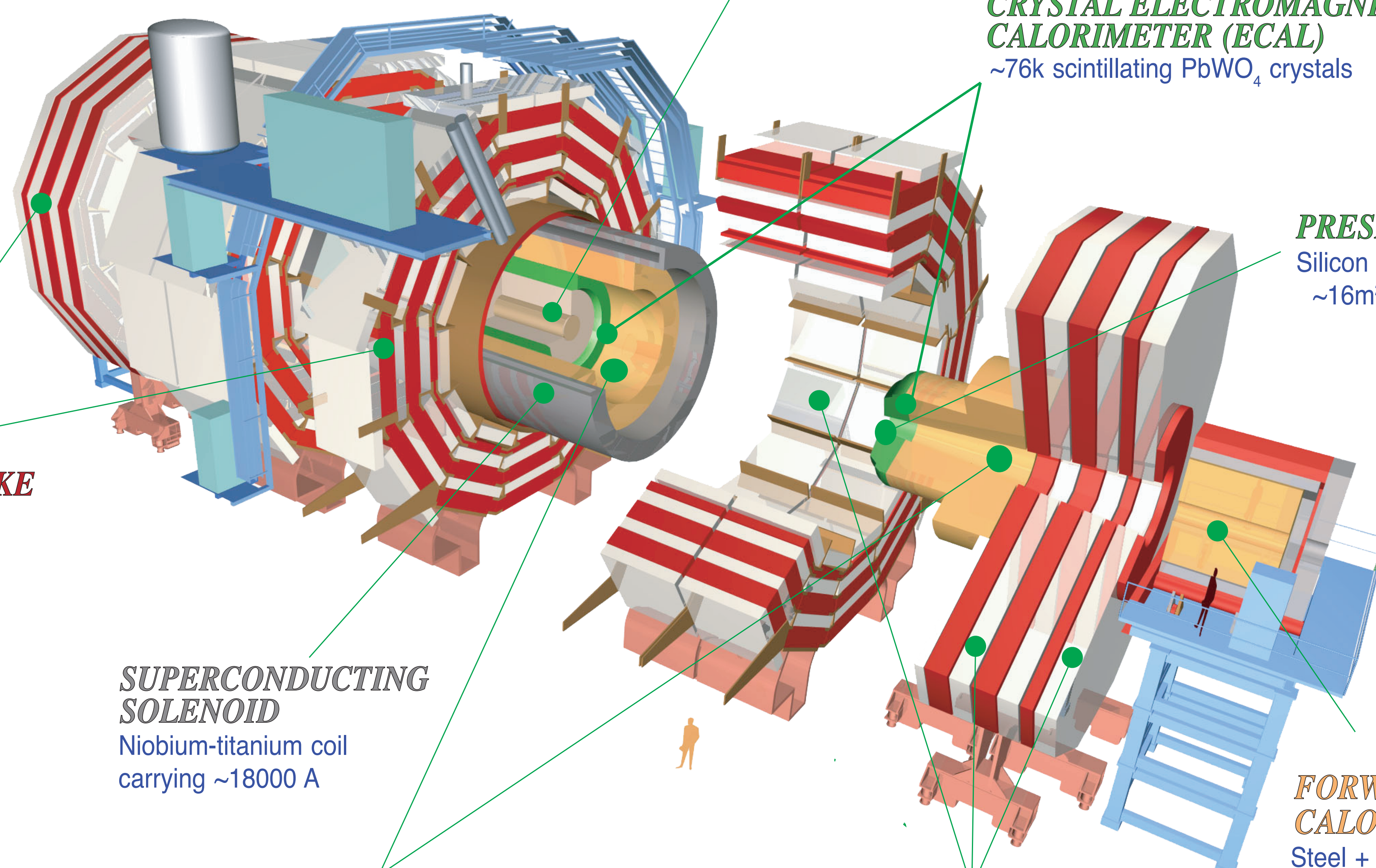
LLR - École Polytechnique
(for the CMS collaboration)

GDR PH-QCD Fall Meeting
October 18th, 2011

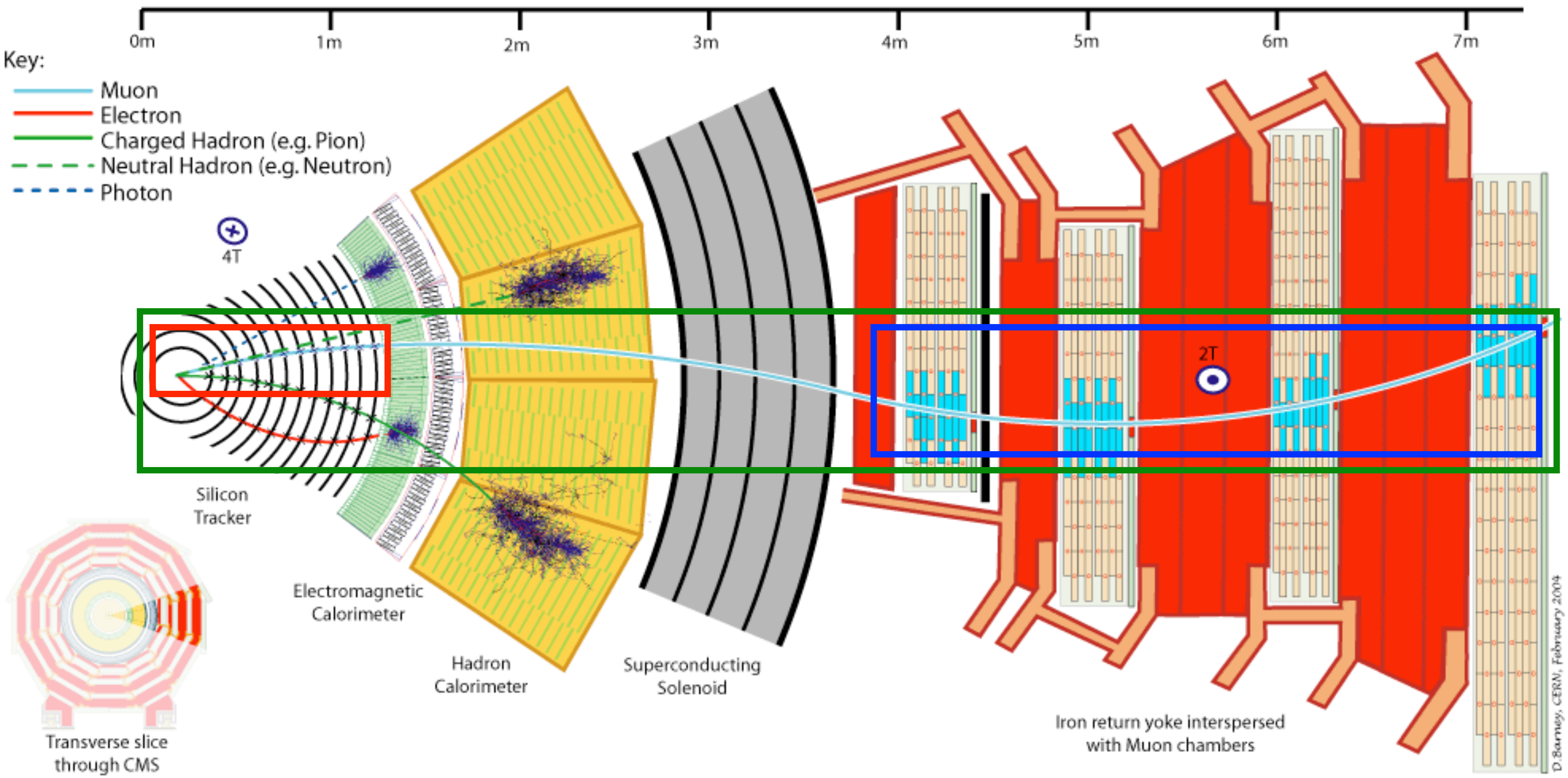
CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



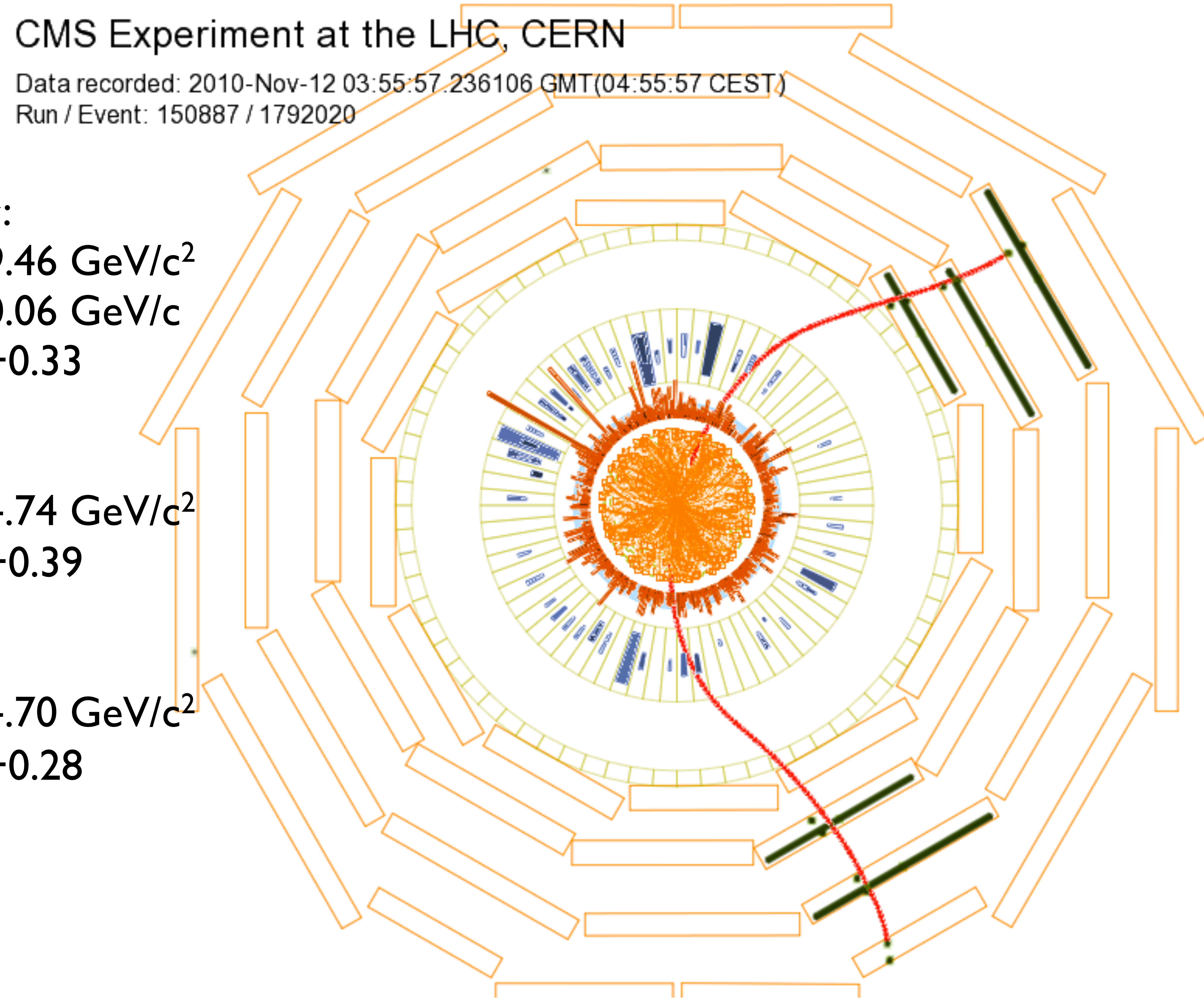
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Muon reconstruction in CMS



- Global muons reconstructed with information from tracker and muon stations
- Global muons need p ≳ 3 GeV to reach the muon station, but lose 2–3 GeV energy in the absorber → a minimum of ≈ 5 GeV total momentum required
- Further muon ID based on track quality (χ^2, # hits,…)

Υ candidate in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV



$\mu^+\mu^-$ pair:
mass: 9.46 GeV/c^2
p_T: 0.06 GeV/c
rapidity: −0.33

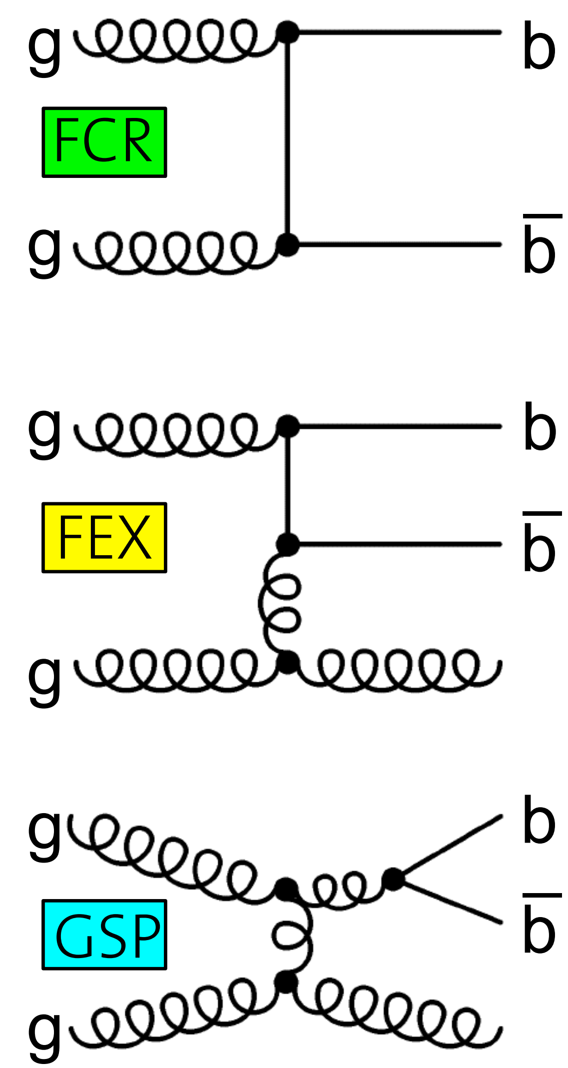
μ^+:
p_T = 4.74 GeV/c^2
η = −0.39

μ^-:
p_T = 4.70 GeV/c^2
η = −0.28

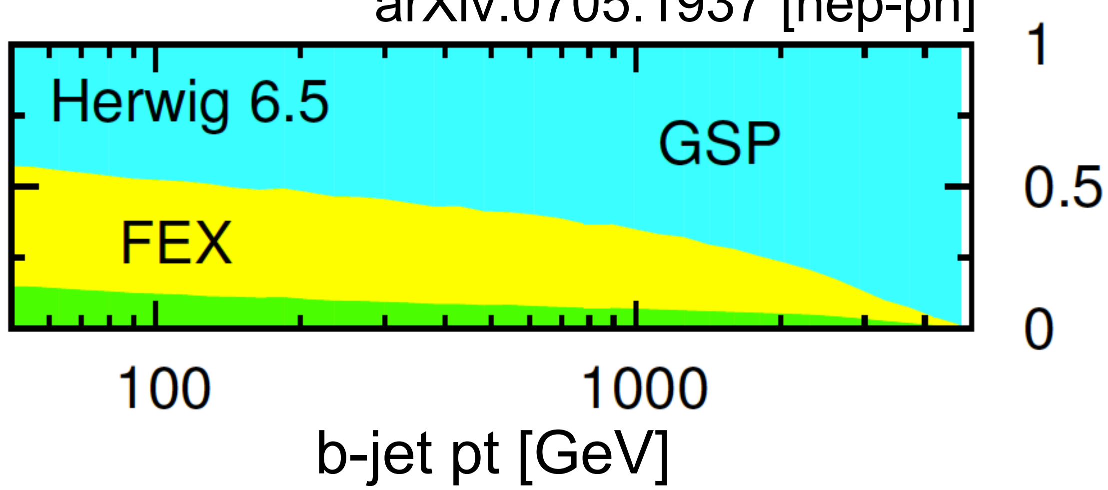
Open Heavy-Flavour

Identifying B mesons with CMS

- Leading order b quarks are produced back-to-back
  - Higher order contributions with different angular correlation varying importance with p_T
- Heavier and longer life time than light mesons
  - $B^{\pm}$ $c\tau = 491.1 \pm 3.2\ \mu m$
  - B^{0} $c\tau = 457.2 \pm 2.7\ \mu m$
- Semi-leptonic and hadronic decays
- CMS is very well suited for b-physics due to excellent tracking and muon detectors:
  - reconstruct secondary vertex with inner tracker
  - trigger and reconstruct muons with muon detectors down to low p_T
  - reconstruct secondary vertex of non-prompt J/ψ: $B \rightarrow J/\psi\ X \rightarrow \mu^{+}\mu^{-}\ X$

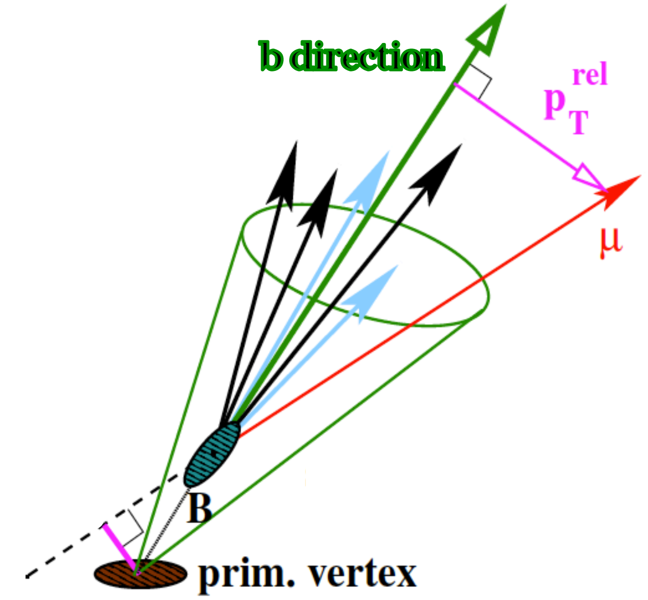


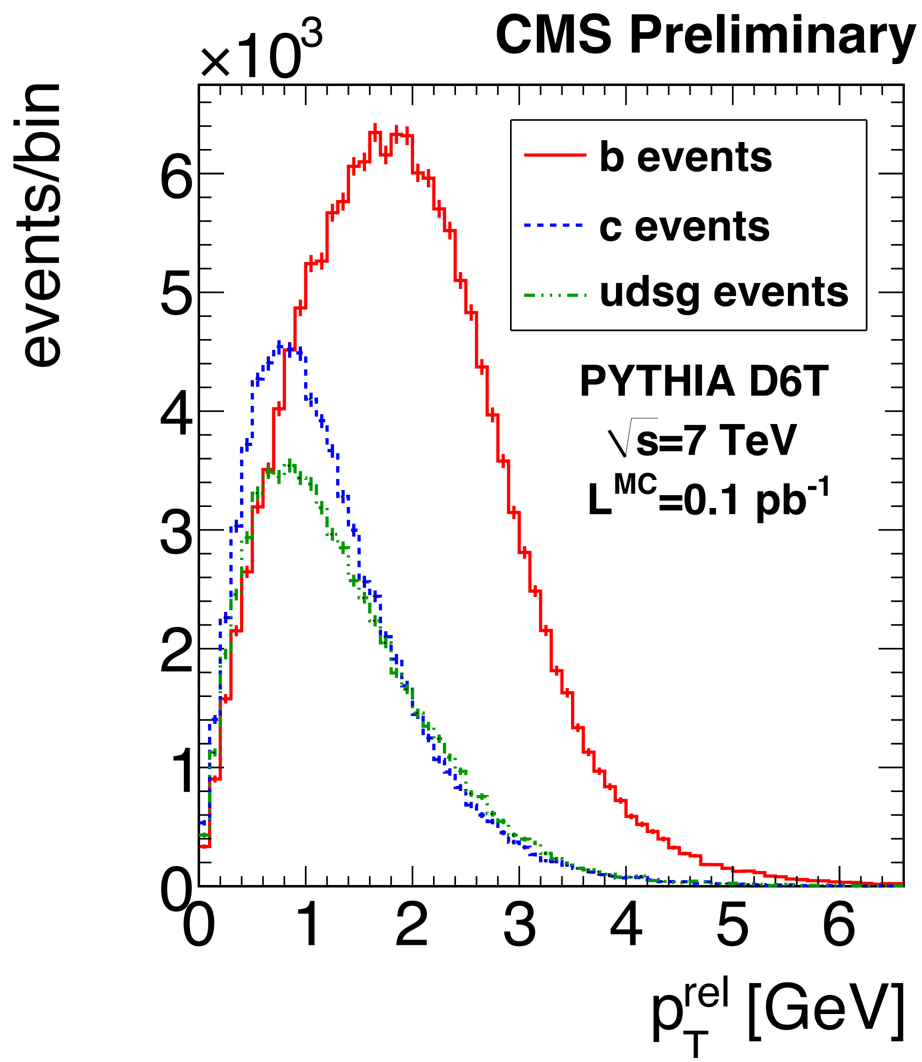
arXiv:0705.1937 [hep-ph]



Semi-leptonic B decays

- Trigger on single μ ($p_T > 3$ GeV/c)
- Require offline reconstructed μ with $p_T > 6$ GeV/c and $|\eta| < 2.1$
- Cluster all tracks into jets using anti-k_T algorithm (R=0.5)
  - Jet finding efficiency from 74% to almost 100% depending on μ p_T
  - Very good angular resolution (2–8%)
- Due to large B mass, muons from B decays have larger p_T^{rel} (p_T of μ relative to jet axis) than muons from c or light jets (udsg)
- Measurement of total cross section and differential cross section as a function of μ-p_T and η with $L_{int} = 85$ nb^{-1}





Inclusive b cross section at $\sqrt{s}$ = 7 TeV

- Binned maximum likelihood fit of p_T^{rel} distribution
- MC templates for b and c (signal template validated by b enriched data)
- Data driven template for udsg contribution (mostly from in-flight decays)
- Combined template for c and udsg contribution
- Templates for each μ-p_T and η bin
- Inclusive b cross section in kinematic range:

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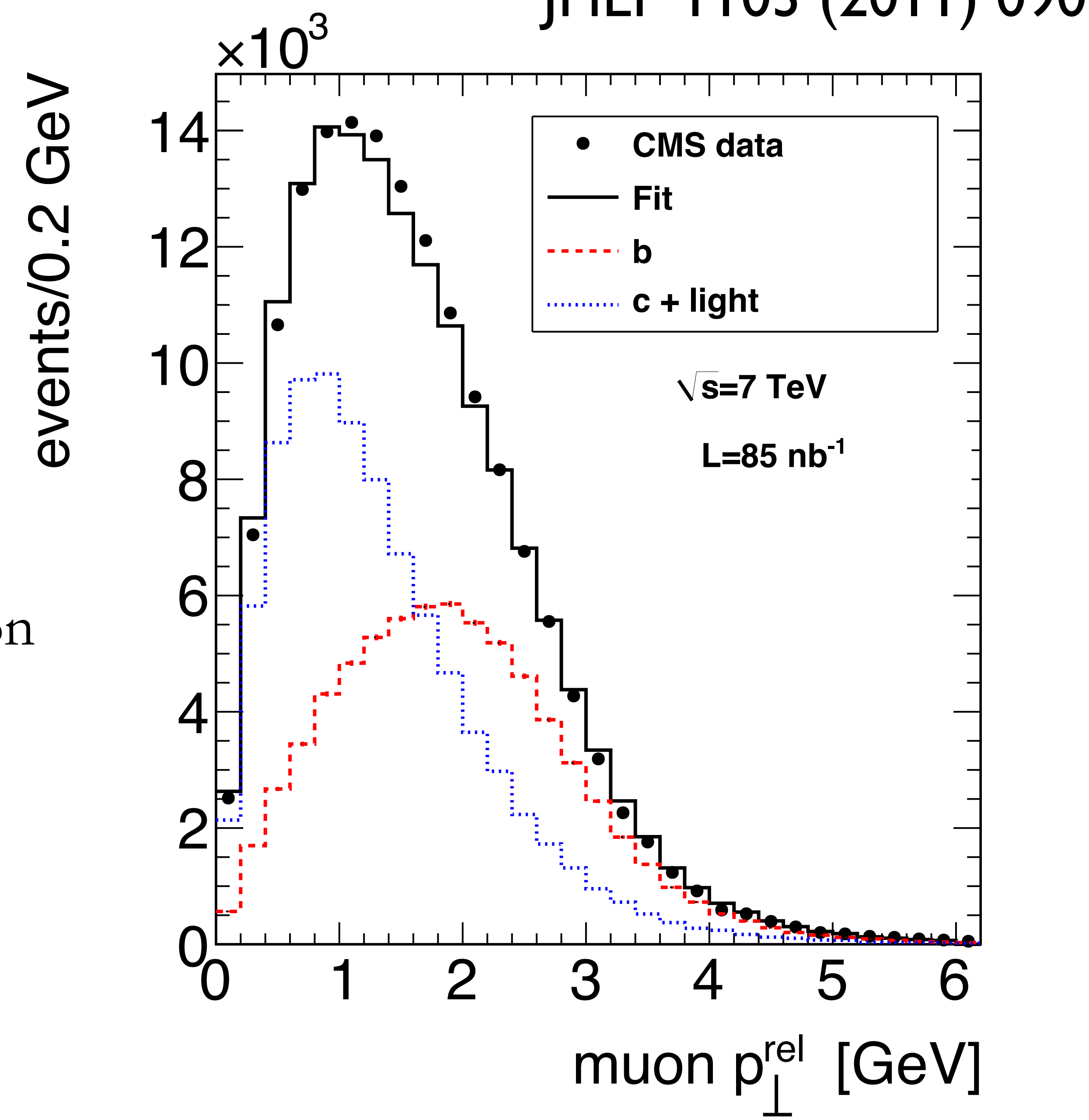
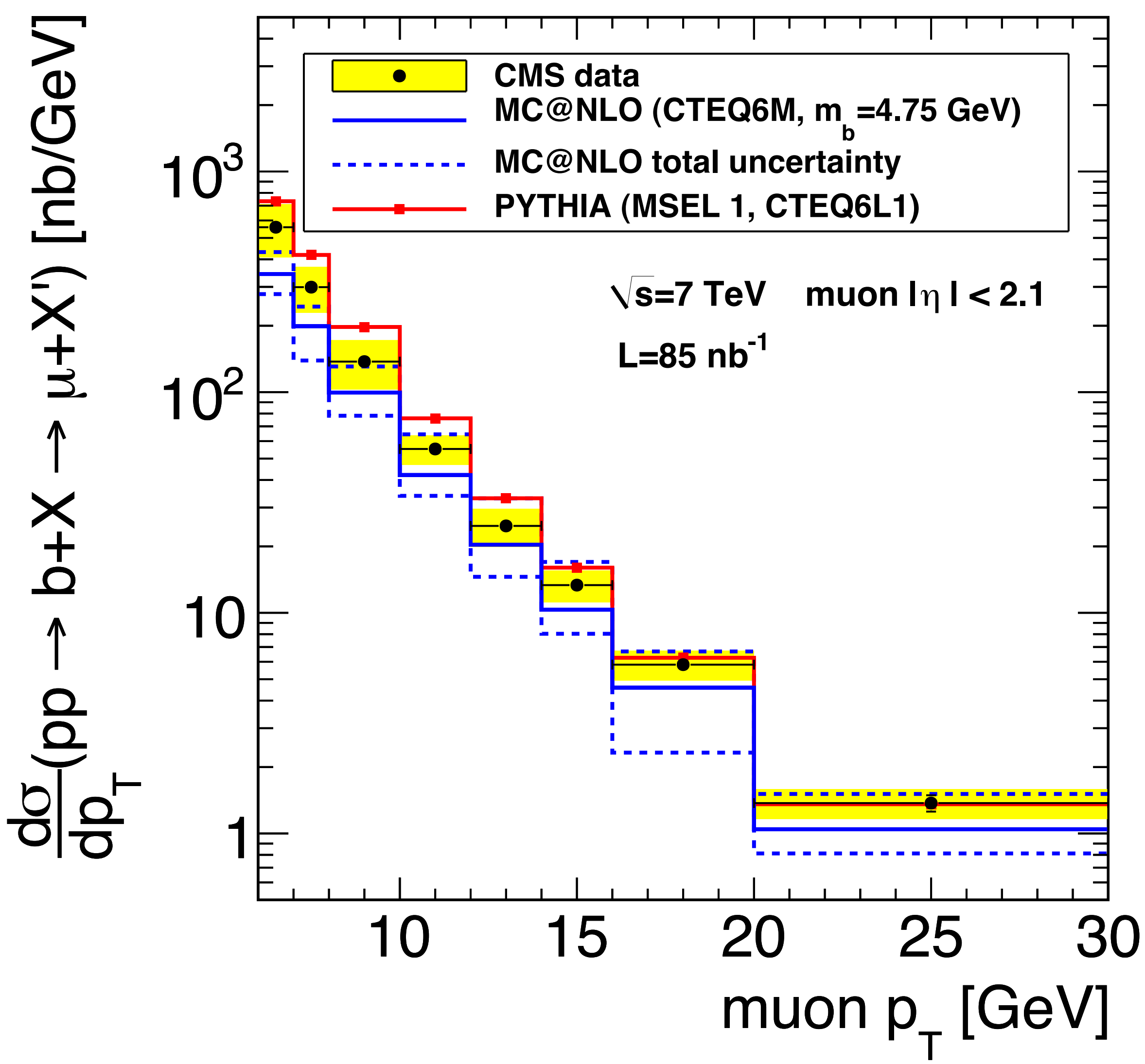


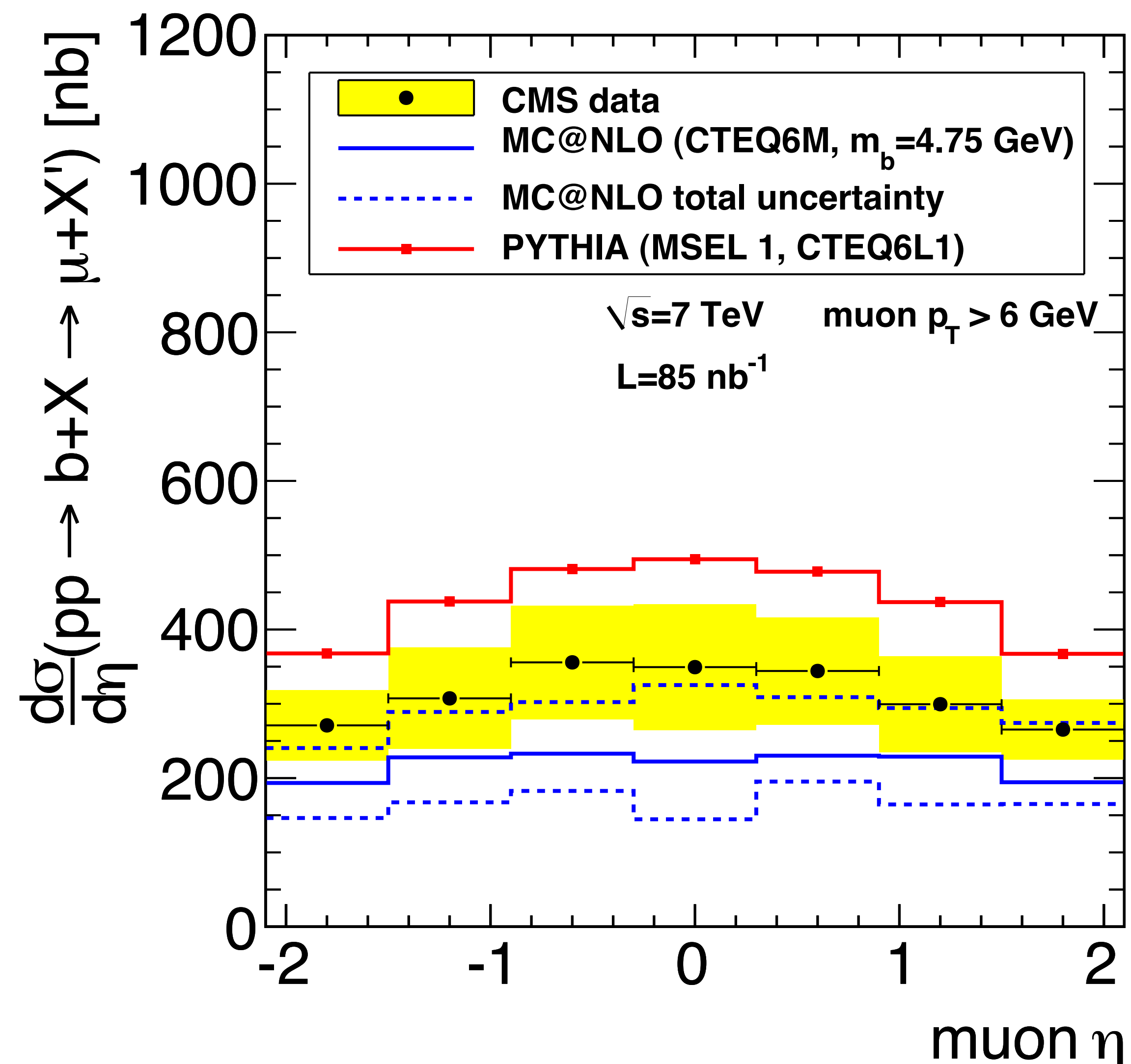
$$\sigma(pp \rightarrow b\ X \rightarrow \mu\ X',\ p_T^\mu > 6\ \mathrm{GeV}/c,\ |\eta^\mu| < 2.1)$$
$$= 1.32 \pm 0.01(\mathrm{stat}) \pm 0.30(\mathrm{syst}) \pm 0.15(\mathrm{lumi})\ \mu\mathrm{b}$$

$$\sigma_{\mathrm{MC@NLO}} = 0.95^{+0.41}_{-0.21}(\mathrm{scale}) \pm 0.09(m_b) \pm 0.05(\mathrm{pdf})\ \mu\mathrm{b}$$

Differential b cross sections

- Measurement in agreement with MC@NLO for $p_T > 12$ GeV/c integrated over η
- Above MC@NLO at mid-rapidity at low p_T





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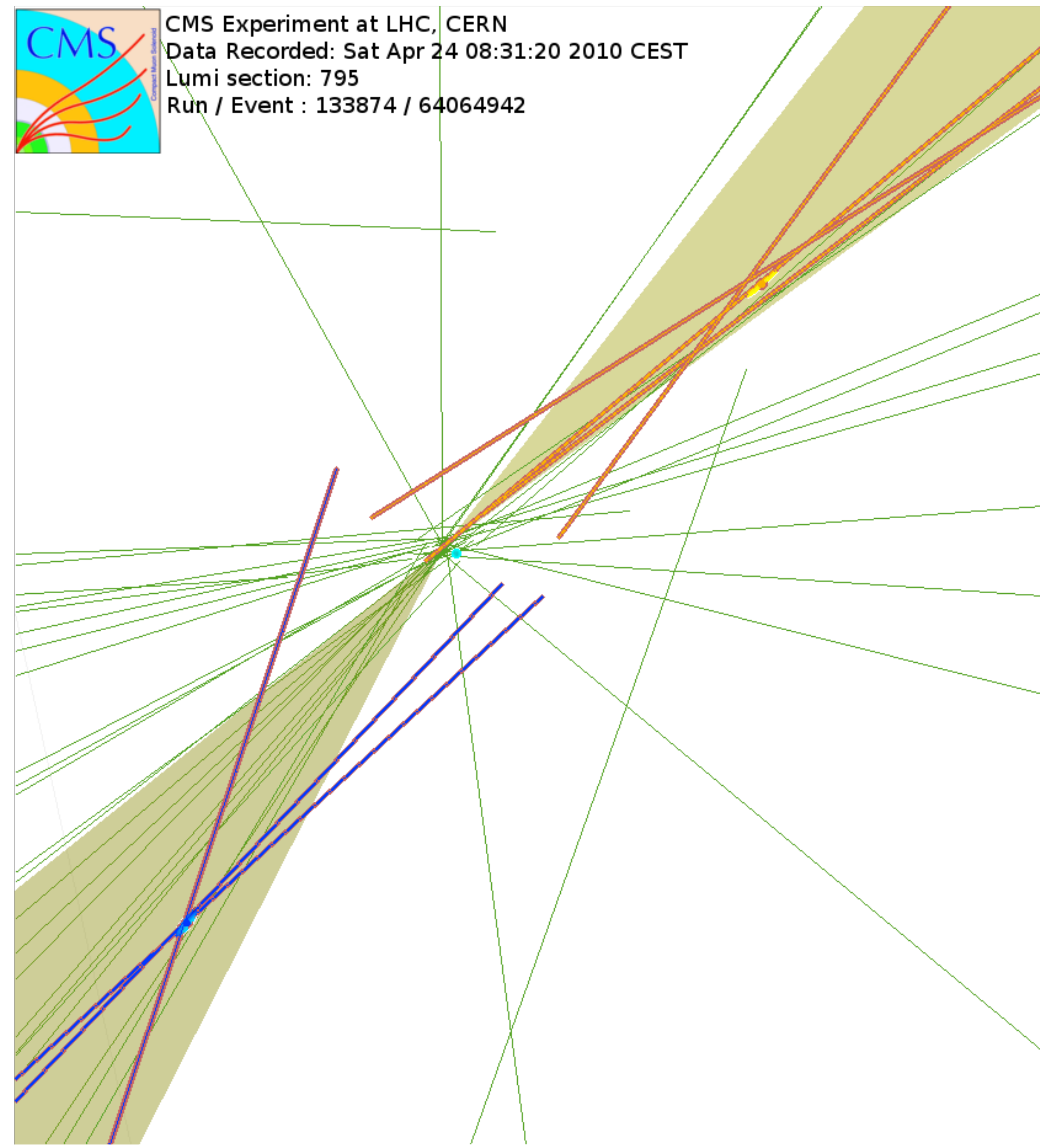
Inclusive b-jet production

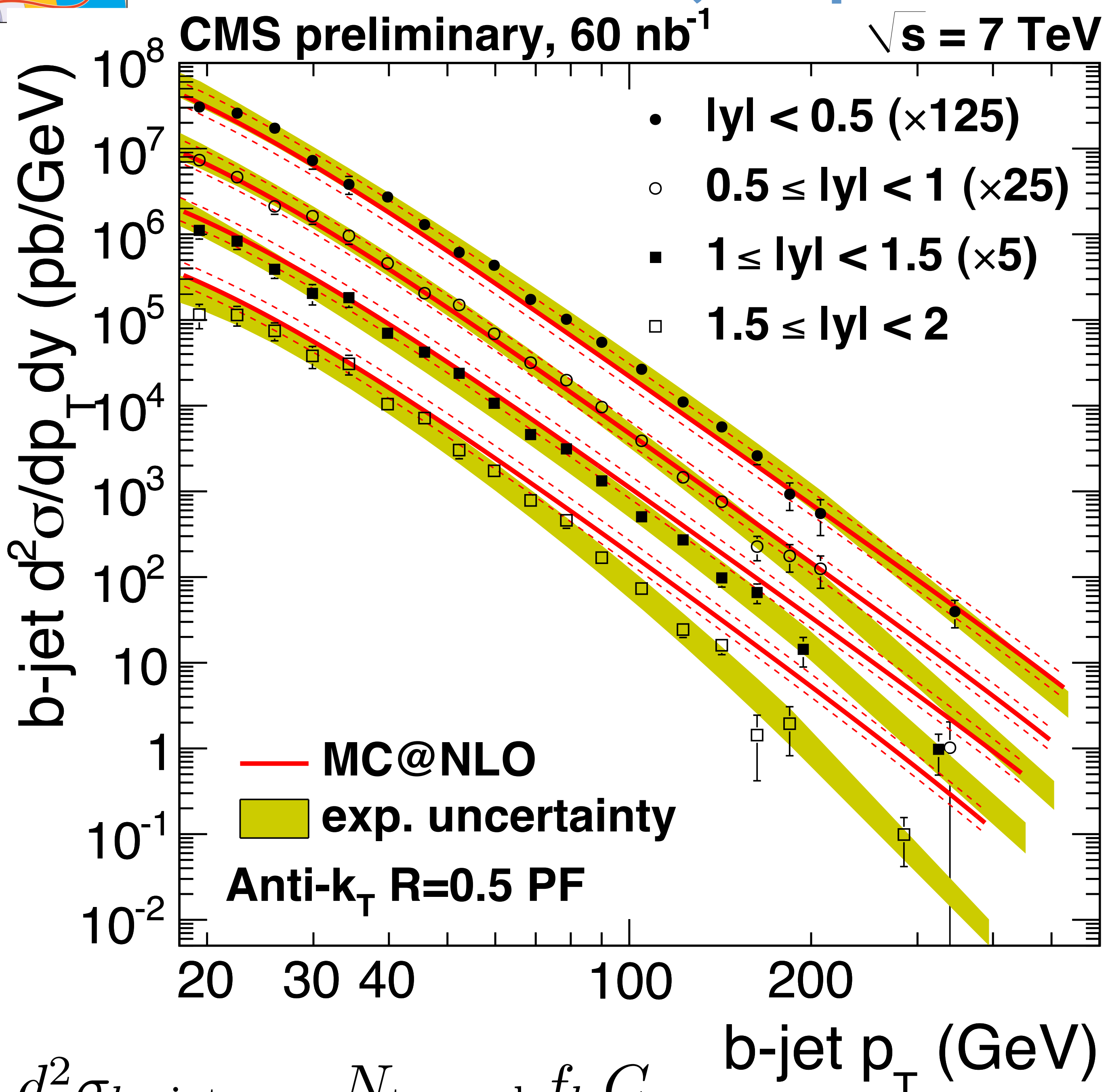
- Events collected with minimum bias and jet trigger
- Jets with $18 < p_T < 300$ GeV/c and $|y| < 2$ reconstructed with anti-k_T algorithm (R=0.5) using calorimeter and tracker information (Particle Flow)
- b-tagging based on secondary vertex reconstruction
  - Require secondary vertex with at least 3 tracks
  - b-tagging efficiency from MC, verified in subsample by measurement of scale factor using p_T^{rel}
  - Mistag rate from MC, constrained by data-driven negative tag discriminator

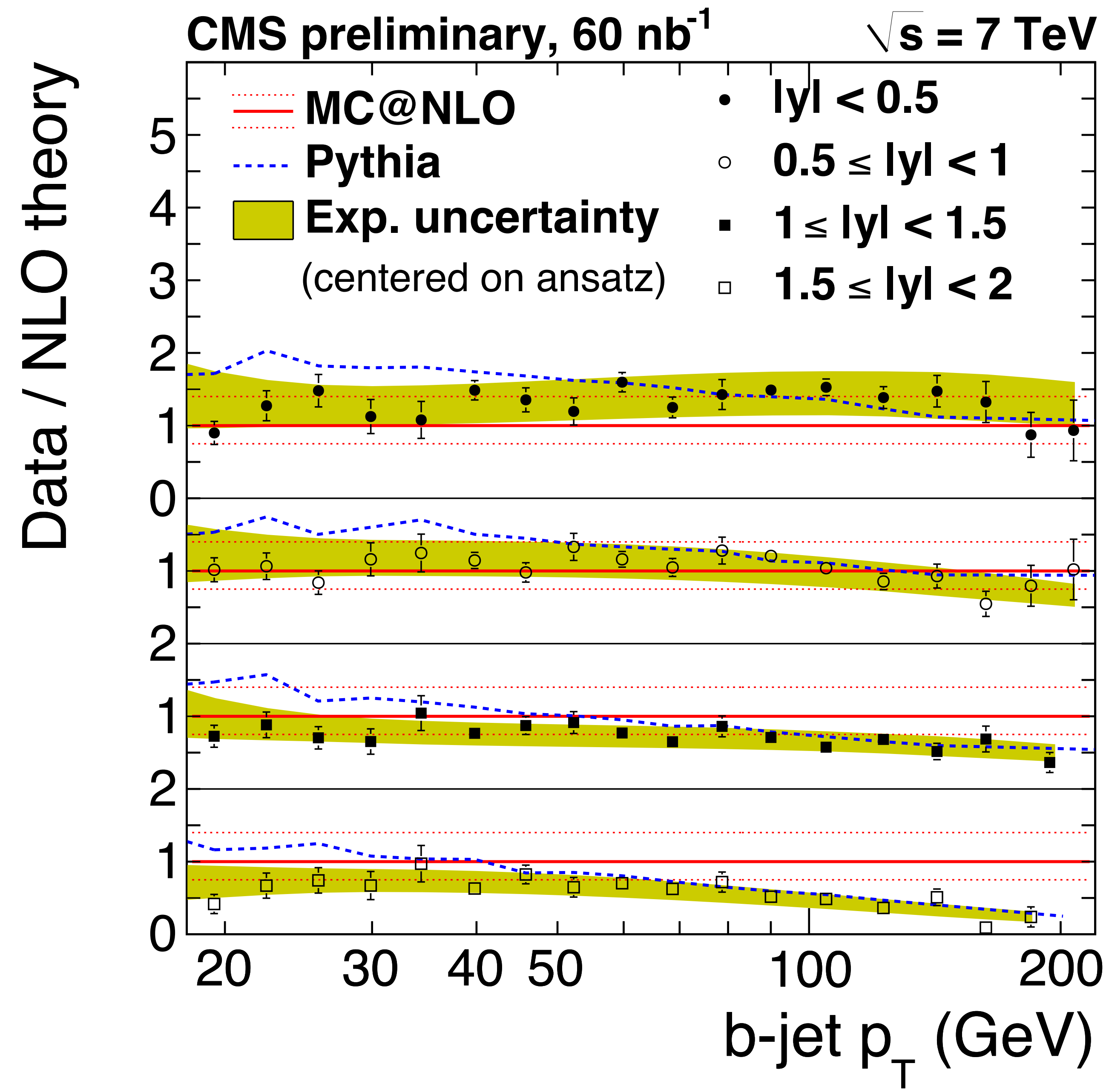
$$\varepsilon_b^{\mathrm{Data}} / \varepsilon_b^{\mathrm{MC}} = 0.98 \pm 0.08 \pm 0.18$$

Double b-jet candidate (CMS DPS-2010/015)



Inclusive b-jet production at $\sqrt{s}$ = 7 TeV





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

C_{smear}: unfolding correction

f_b: jet fraction containing b-hadrons

ε_{jet}: jet reconstruction efficiency

ε_b: b-tagging efficiency

CMS PAS BPH-10-009

BB(bar) angular correlations

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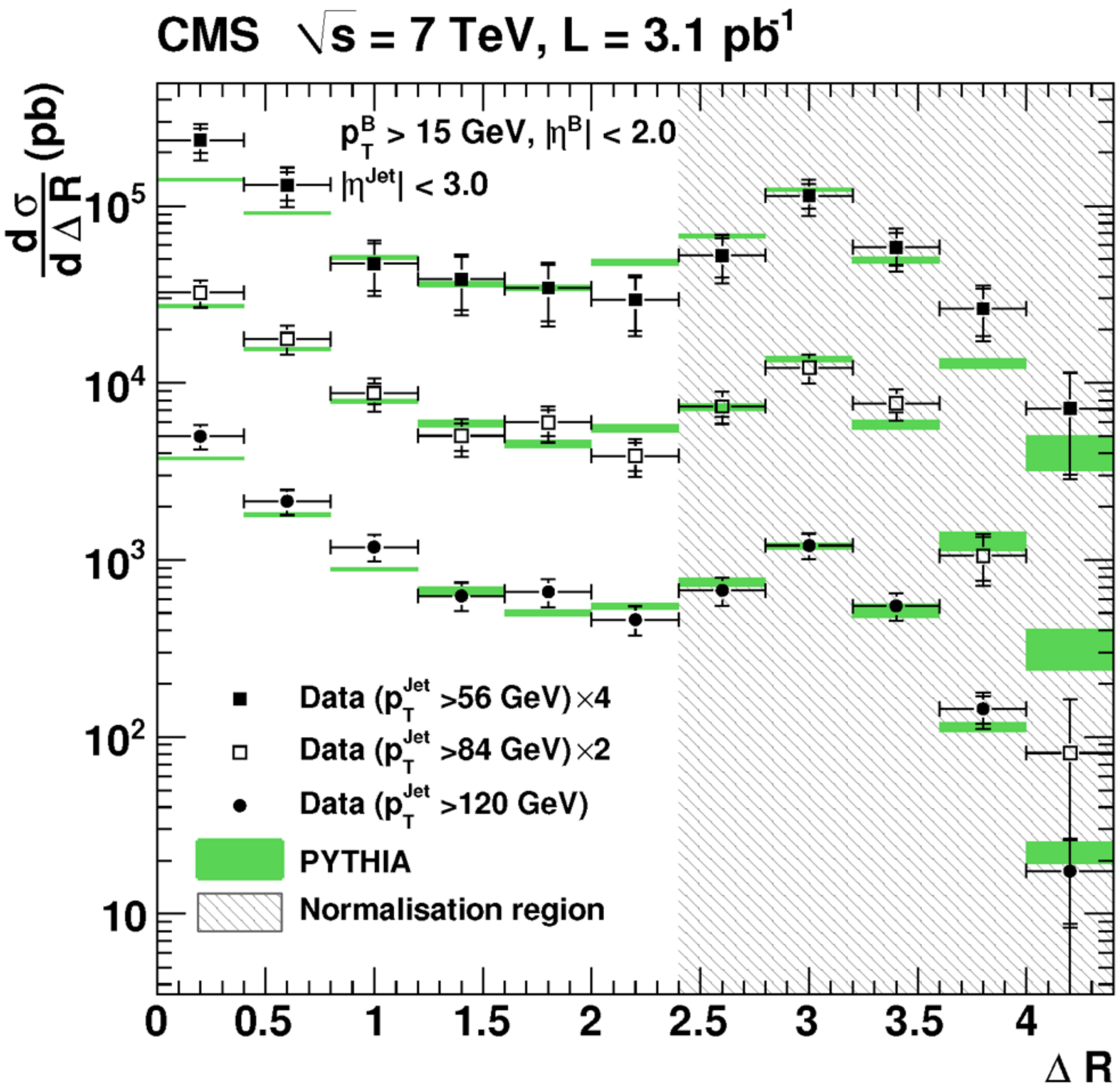

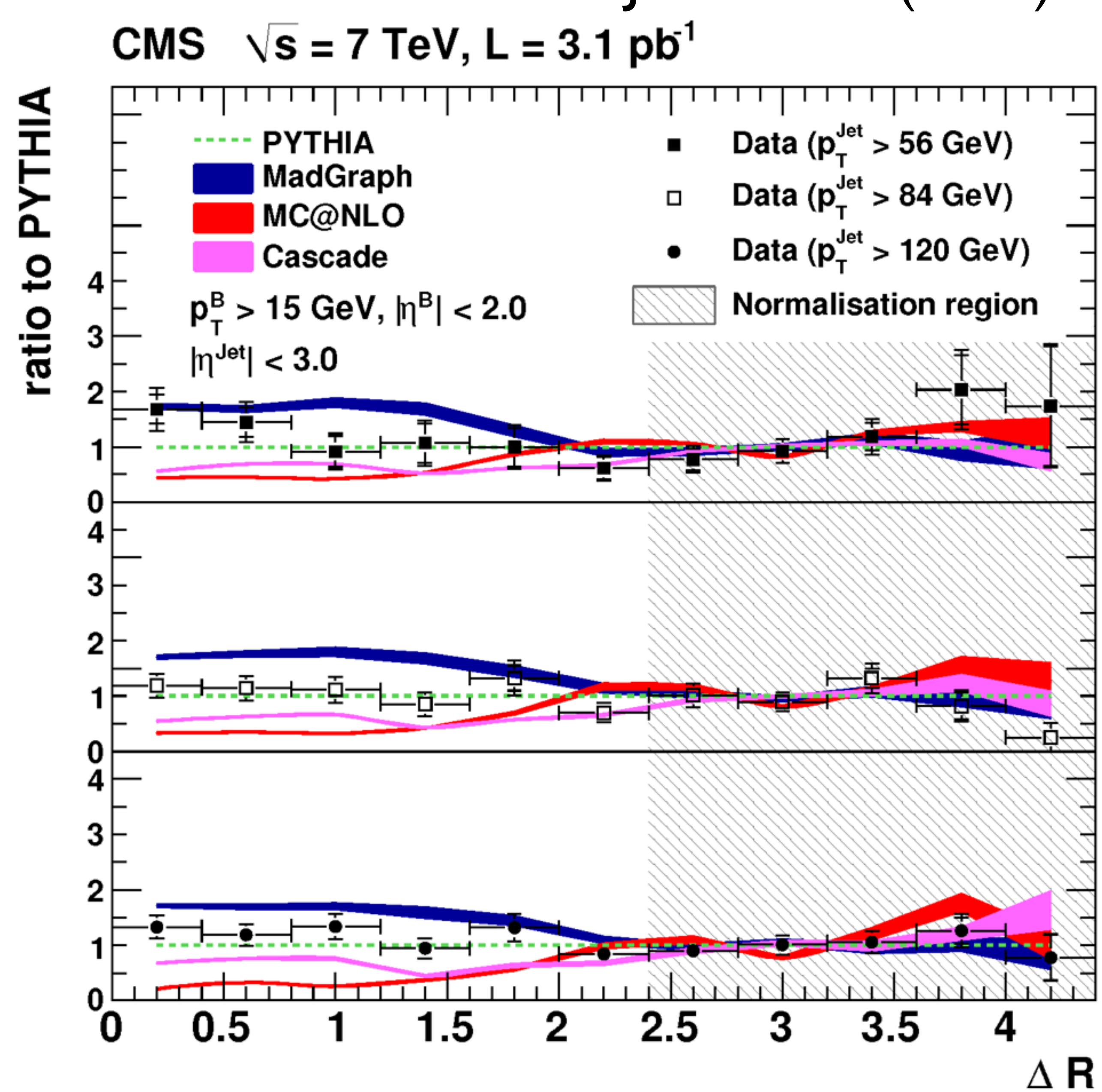

- Measure angular correlation between secondary vertices (does not need jet direction)
- MC normalised to data in $\Delta R > 2.4$
- MC does not described data at small ΔR: region dominated by gluon splitting
  - MadGraph over-predicts, all other models under-predict cross section

BB(bar) angular correlations

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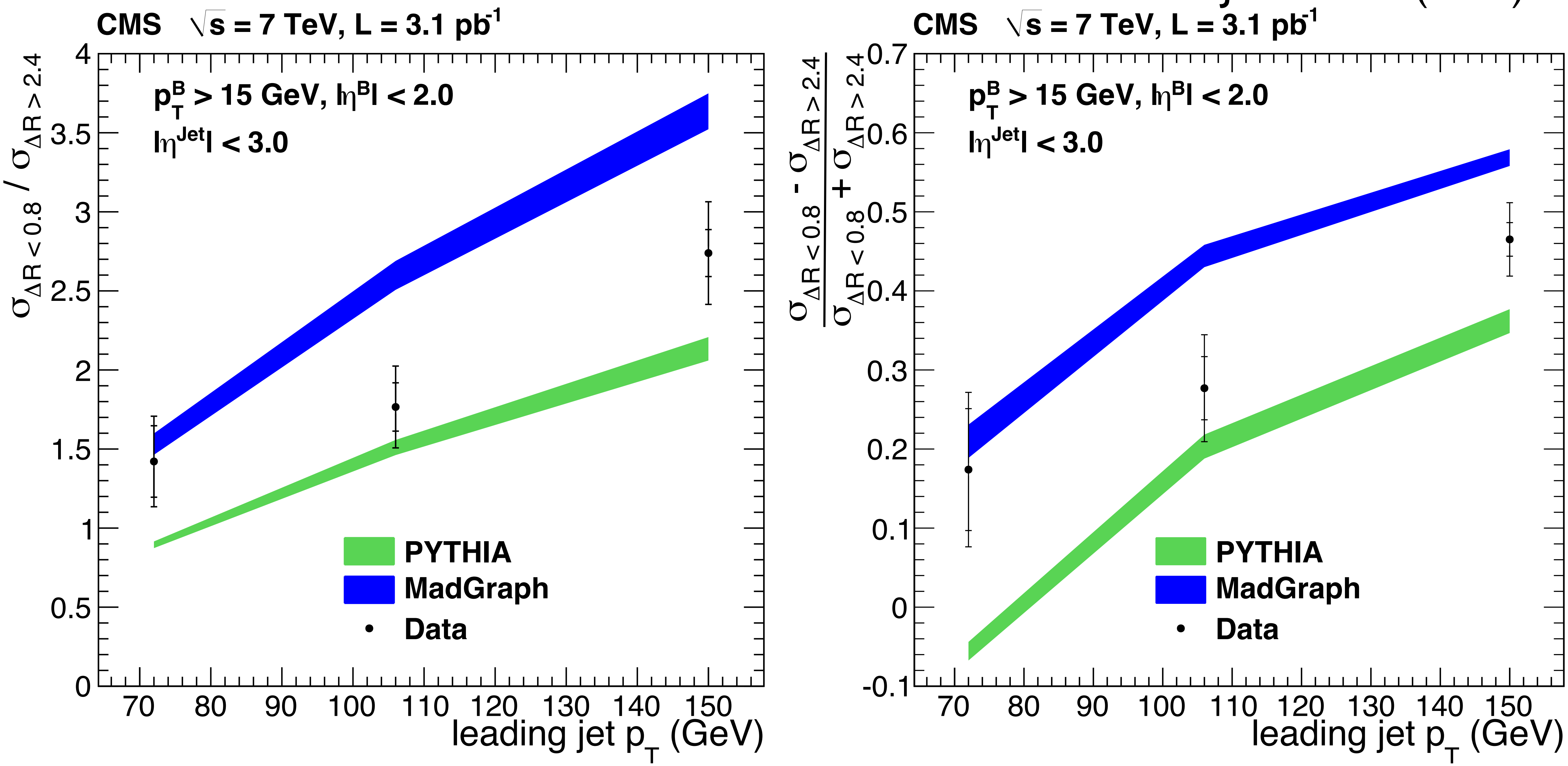
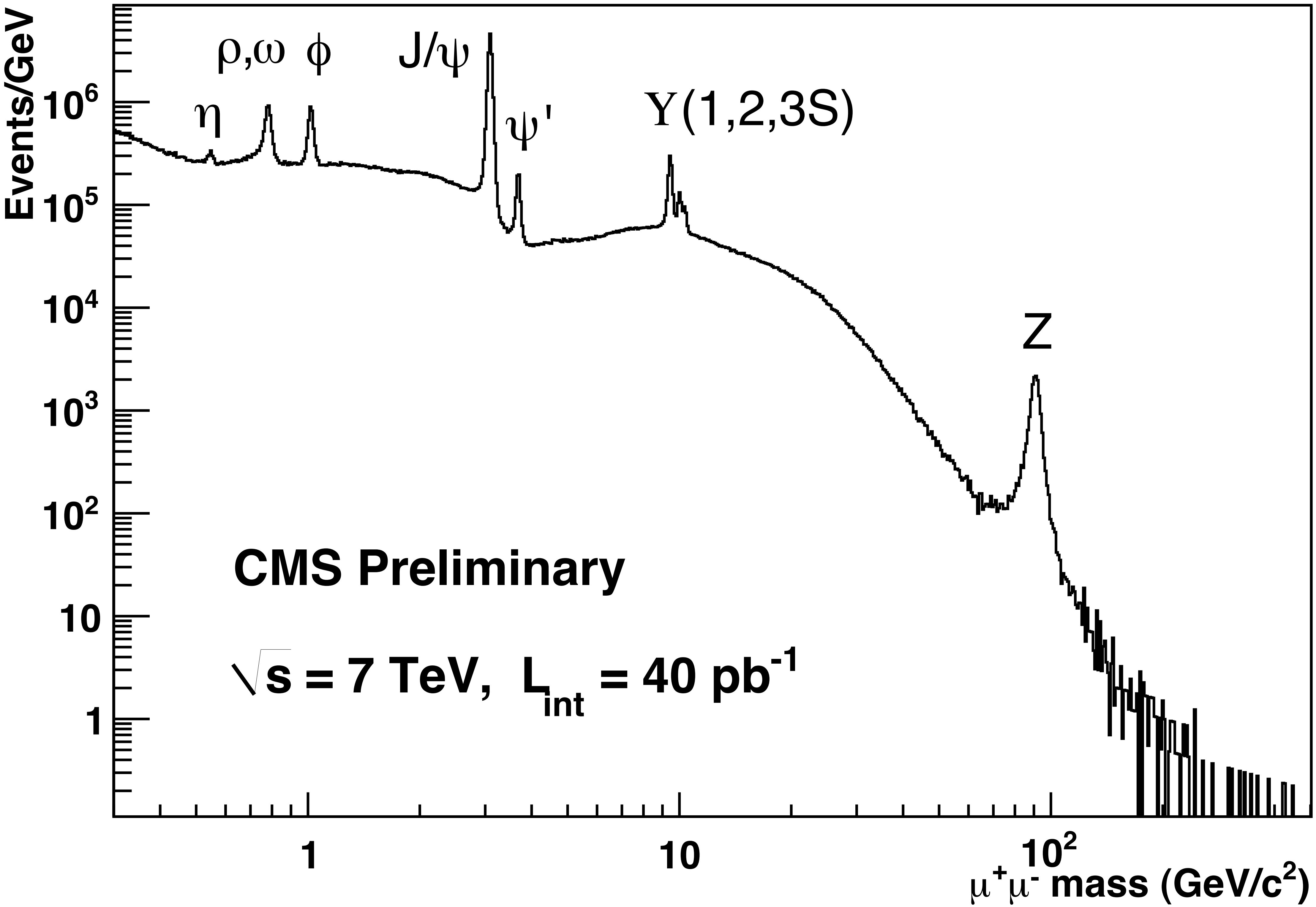


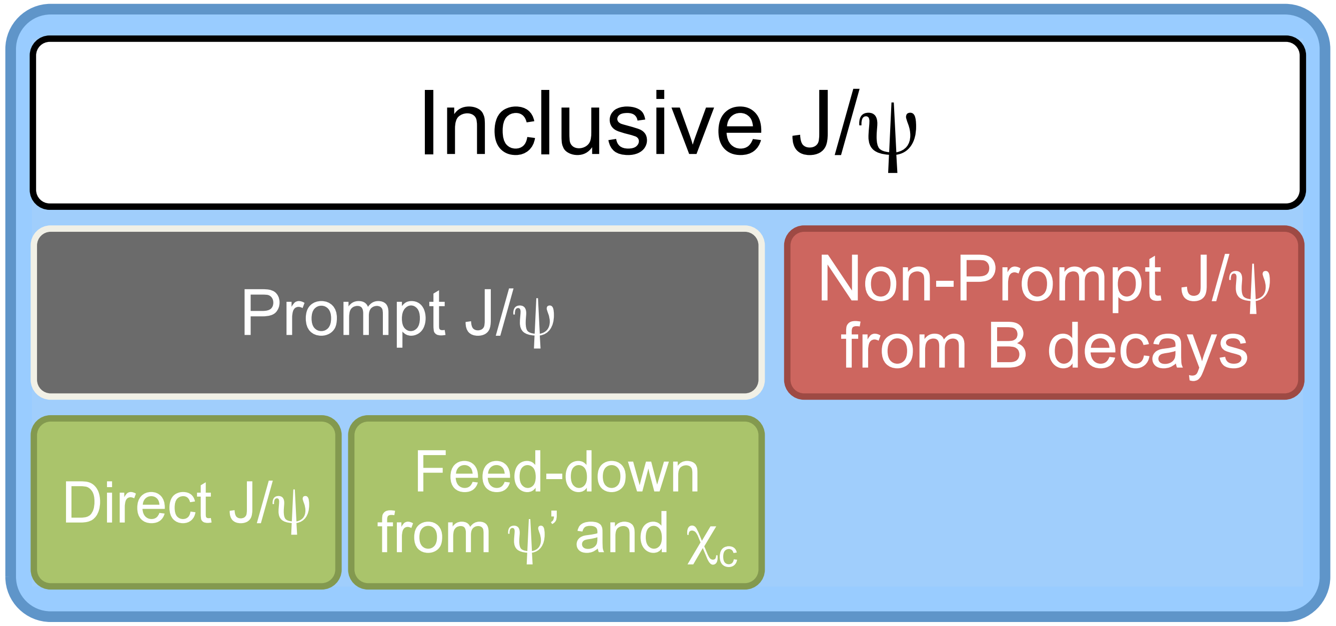
- Data in between PYTHIA and MadGraph
- Increase of contribution of collinear BB(bar) pairs with jet p_T
  - as expected for gluon splitting

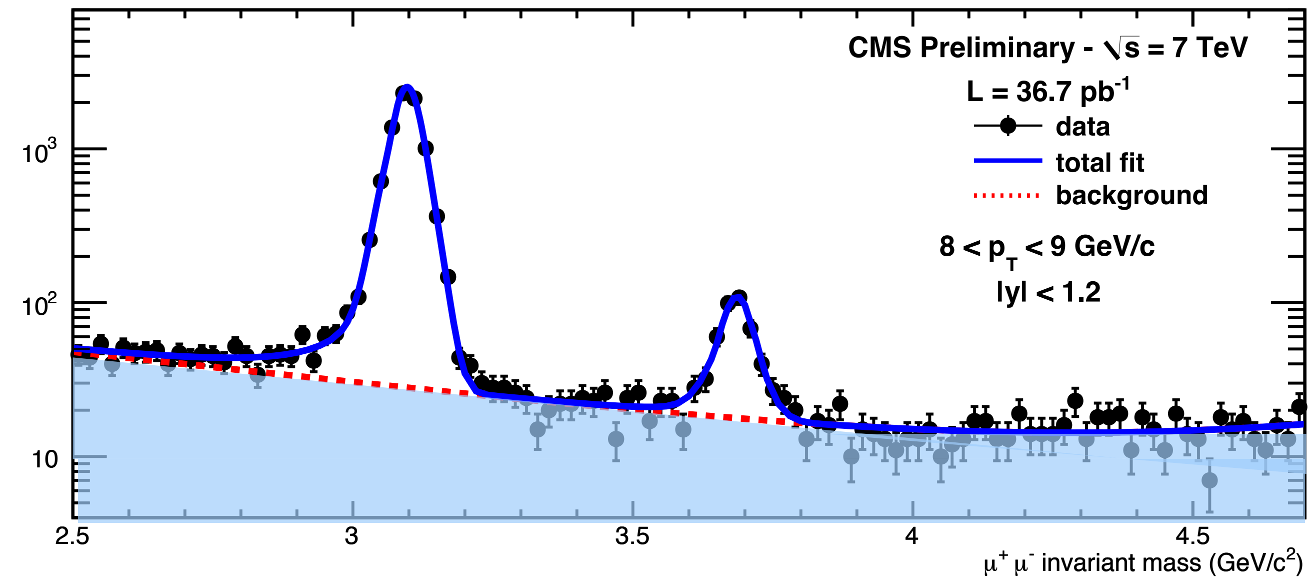
Quarkonia

Muon pairs in pp at $\sqrt{s}$ = 7 TeV



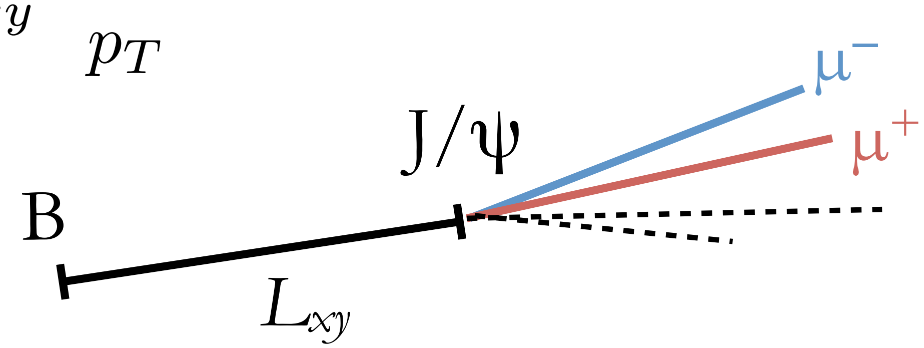
J/ψ in pp at $\sqrt{s}$ = 7 TeV

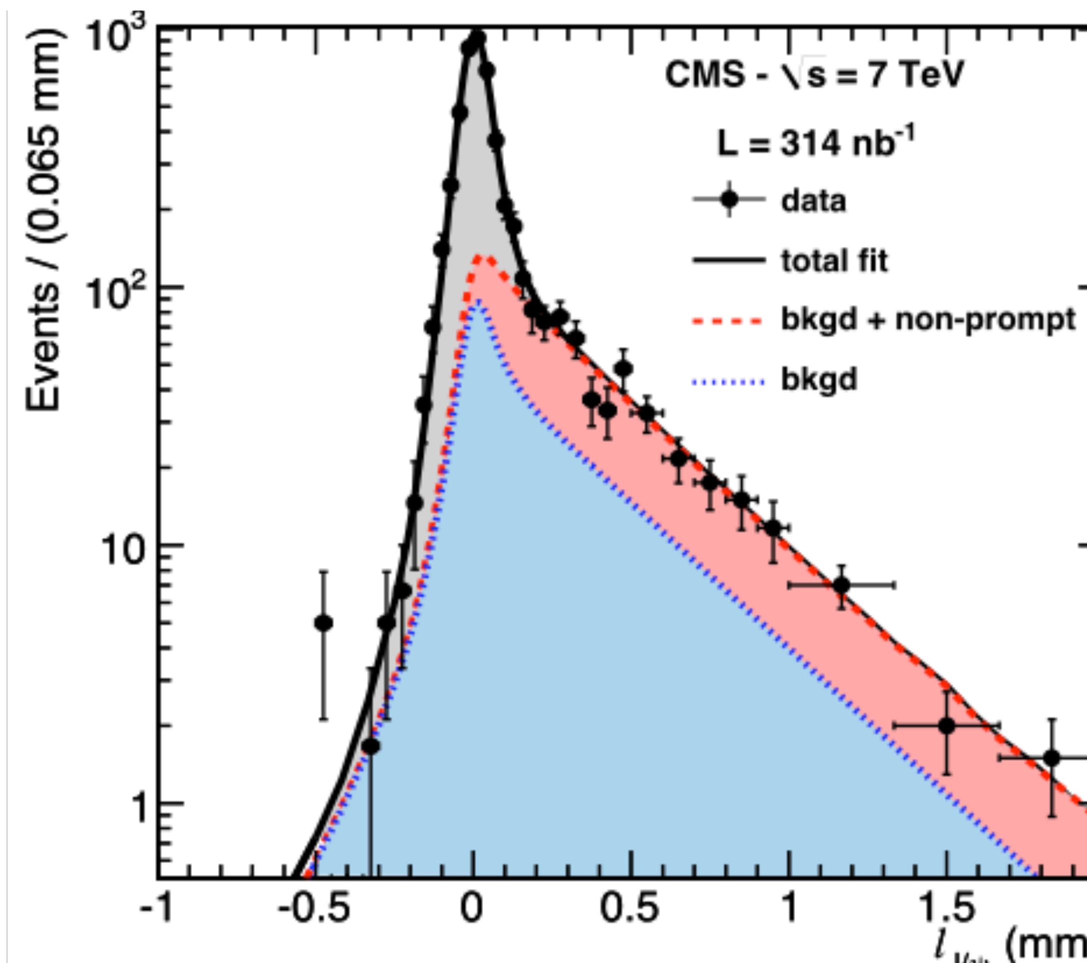




- Reconstruct $\mu^+\mu^-$ vertex
- Simultaneous fit of $\mu^+\mu^-$ mass and pseudo-proper decay length

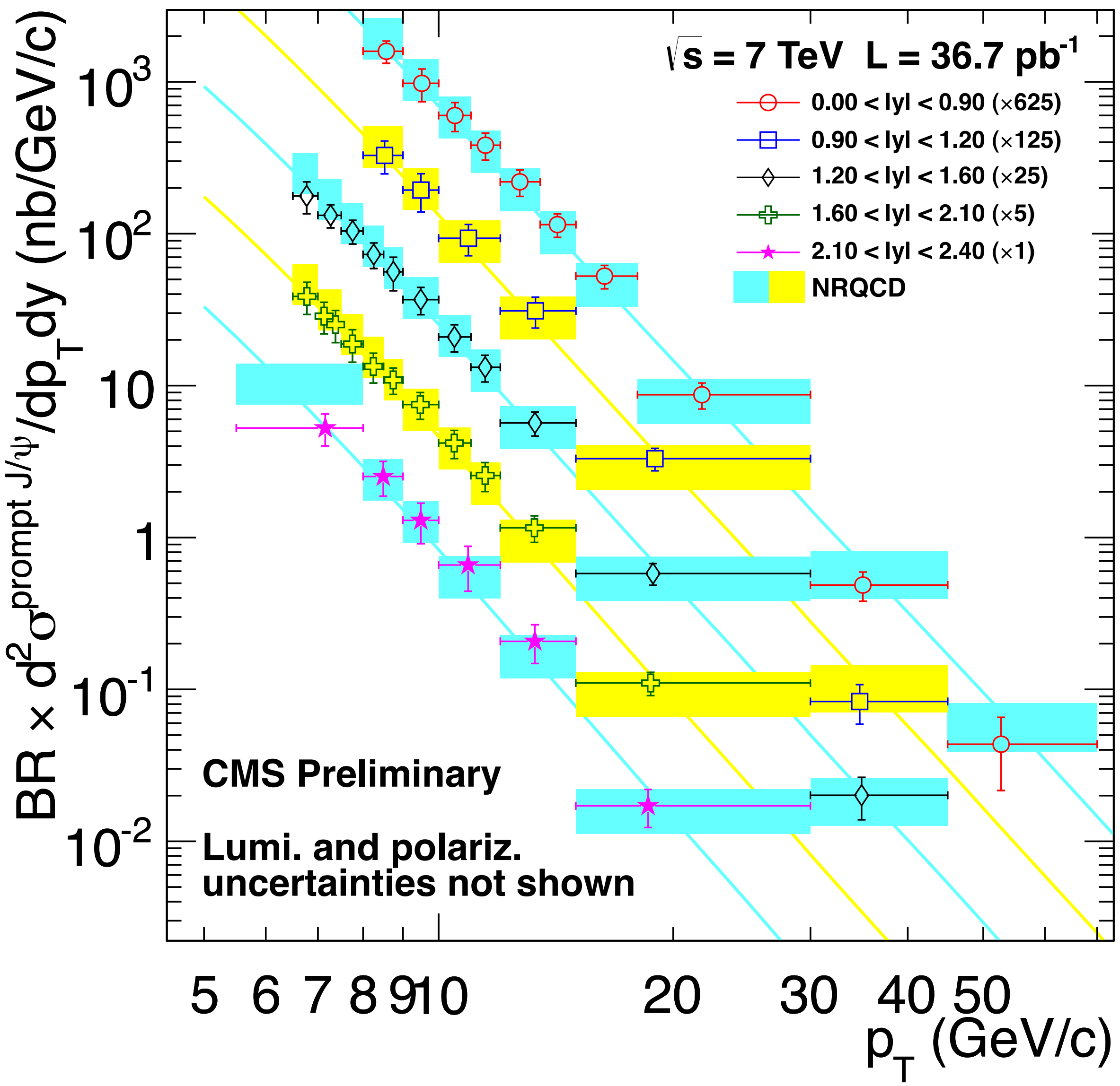
$$\ell_{J/\psi} = L_{xy}\frac{m_{J/\psi}}{p_T}$$

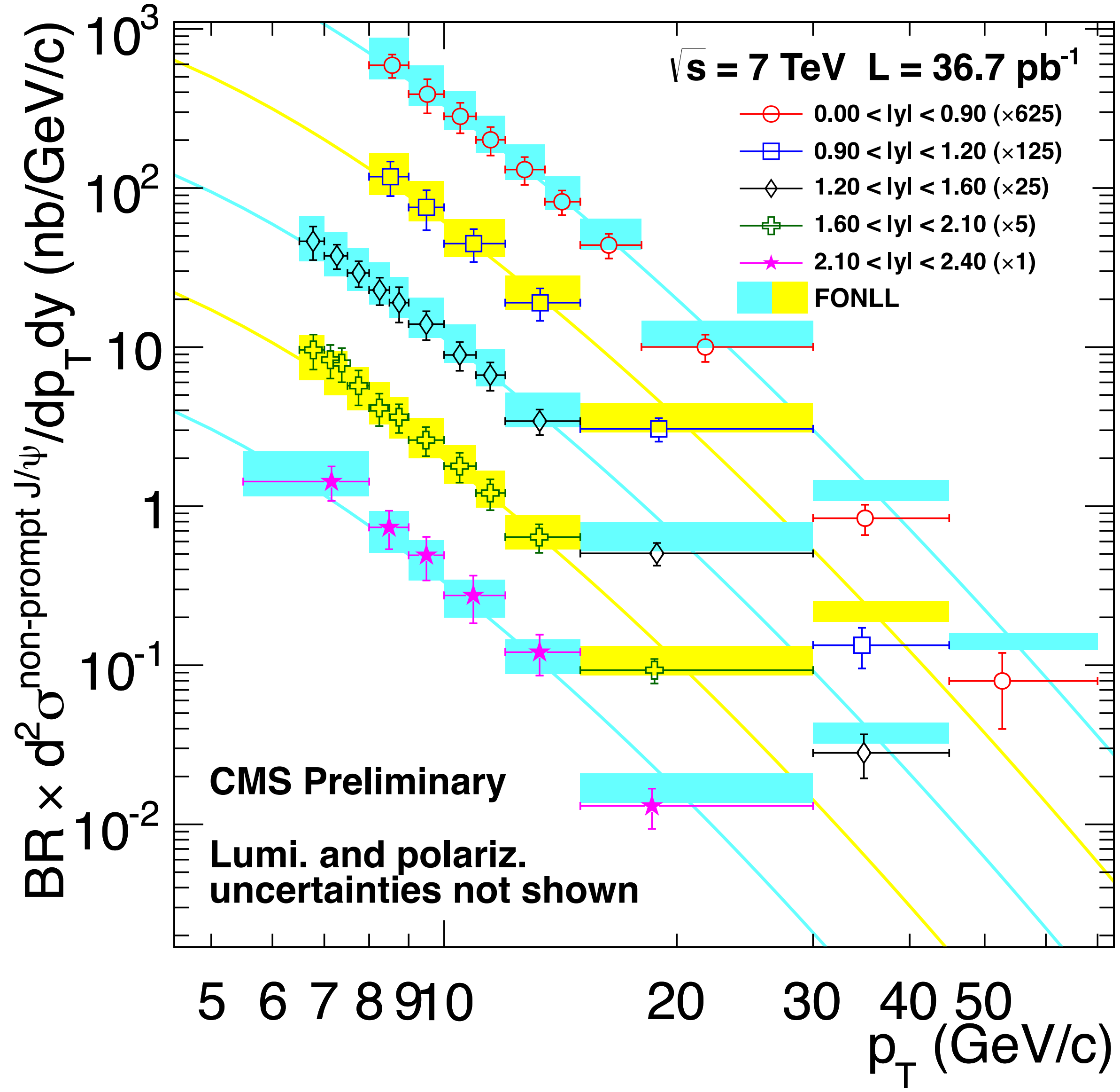




J/ψ in pp at $\sqrt{s}$ = 7 TeV

CMS PAS BPH-10-014

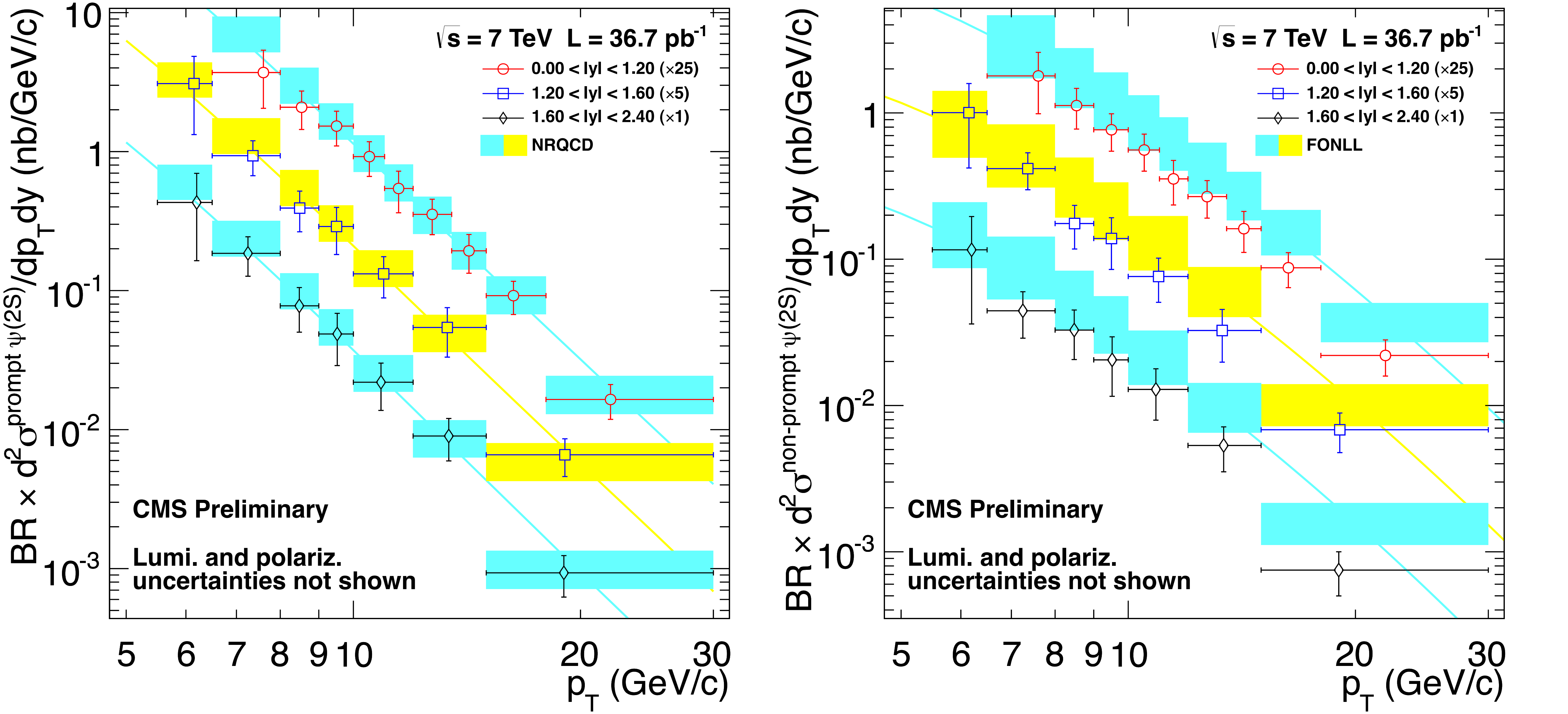




- Prompt J/ψ well described by NRQCD
- Open heavy-flavour:
  - Non-prompt J/ψ fall faster at high p_T than expected from FONLL

ψ(2S) in pp at $\sqrt{s}$ = 7 TeV

CMS PAS BPH-10-014

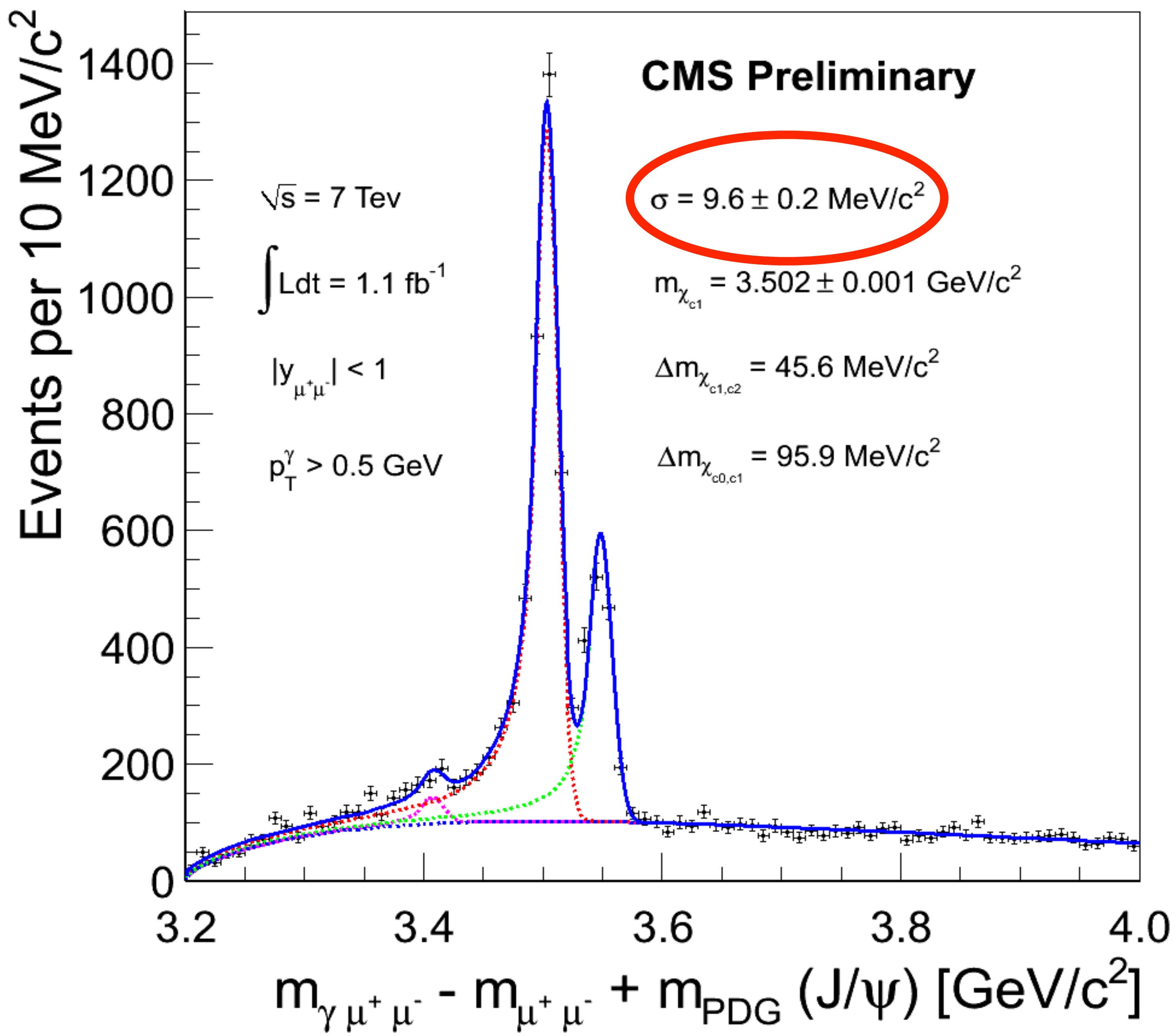


- Prompt ψ(2S) well described by NRQCD
- Open heavy-flavour:
  - Non-prompt ψ(2S) overestimated by FONLL
    - falls faster with p_T than expected from FONLL

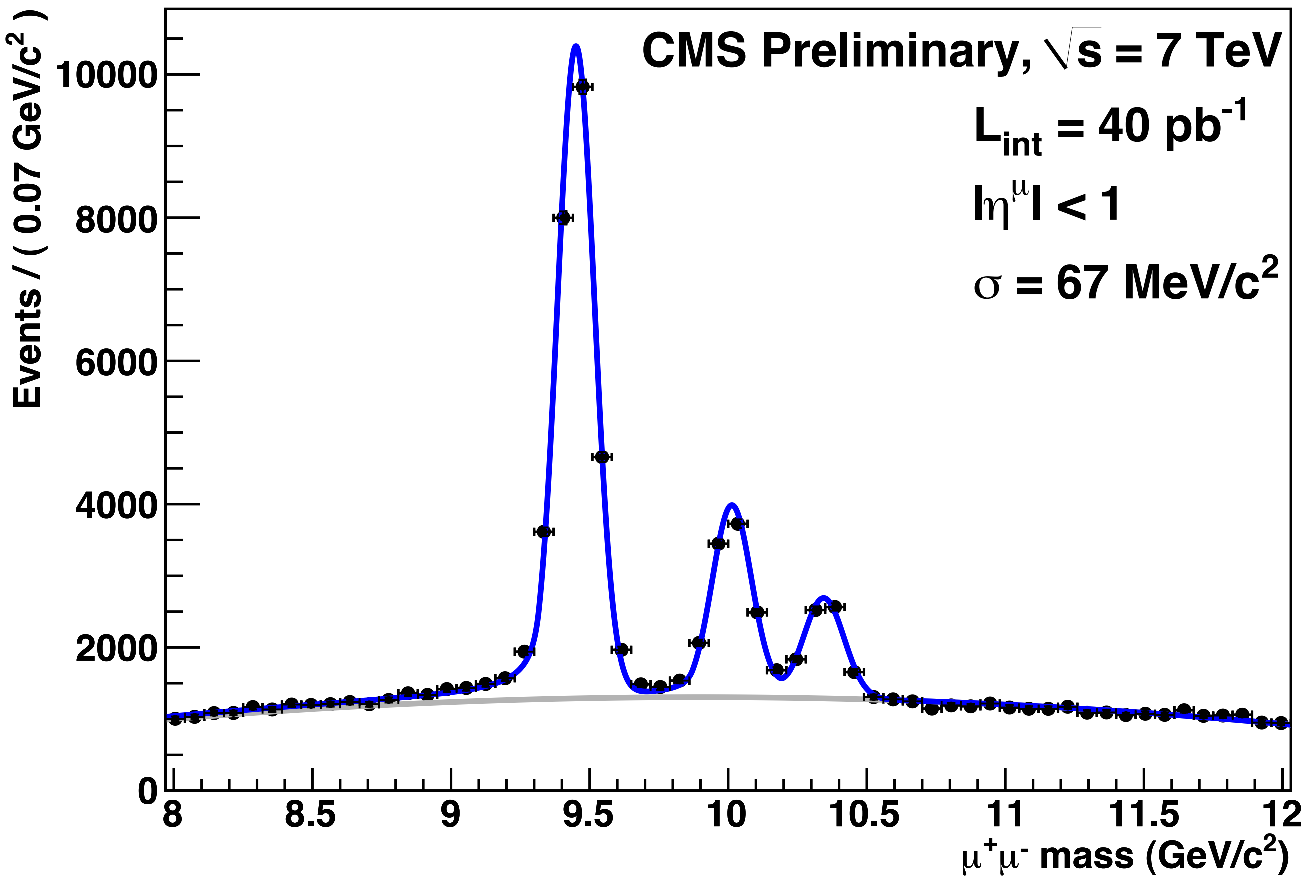
χ_c in pp at $\sqrt{s}$ = 7 TeV

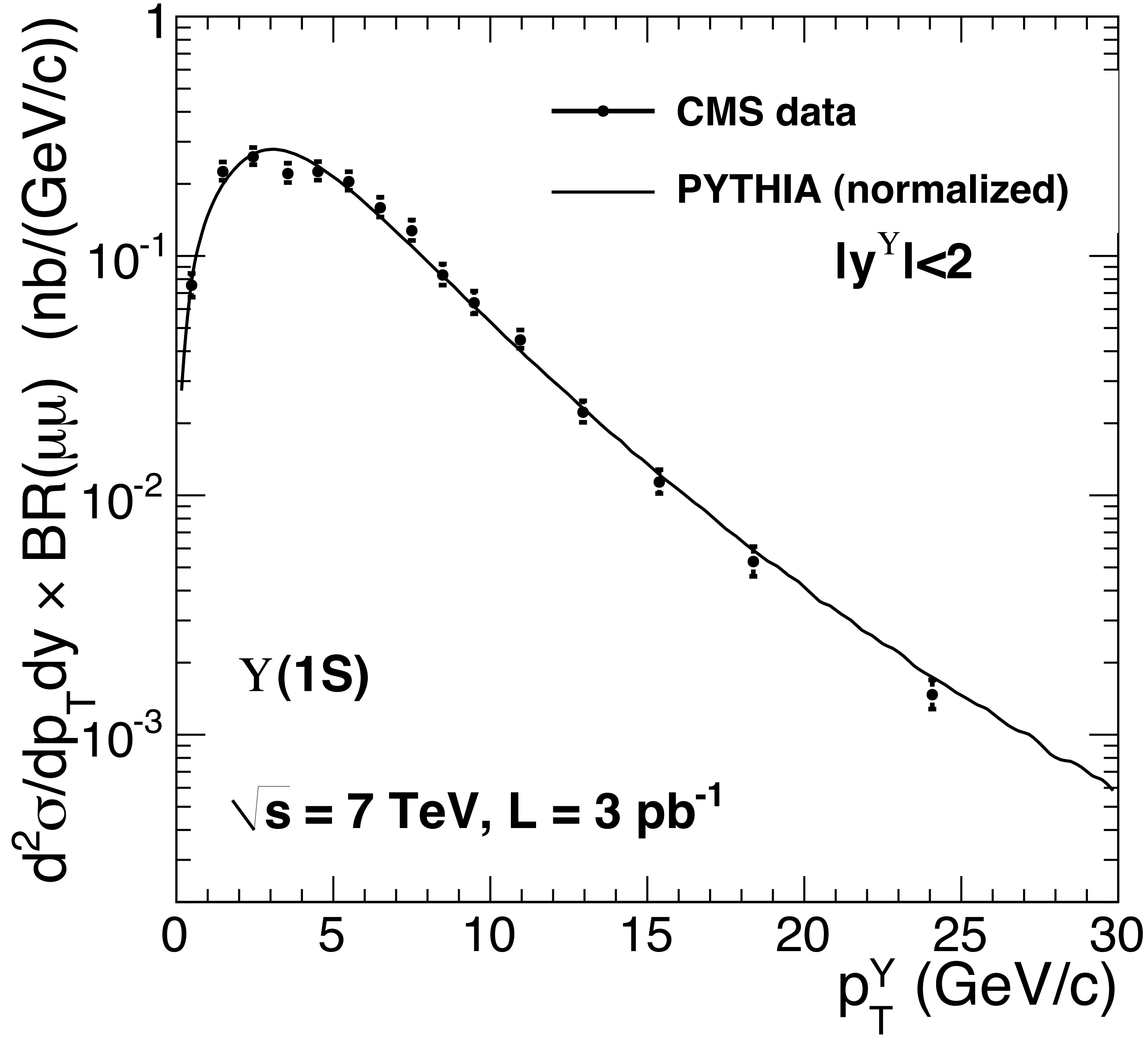
CMS DPS 2011-011

- Measured radiative decay: $\chi_c \rightarrow J/\psi\ \gamma$
- Photon measured by reconstructing e^+e^- conversion pairs
  - Excellent mass resolution $\rightarrow$ separating χ_{c1} and χ_{c2}
  - Hint of χ_{c0}



Υ(nS) in pp at √s = 7 TeV





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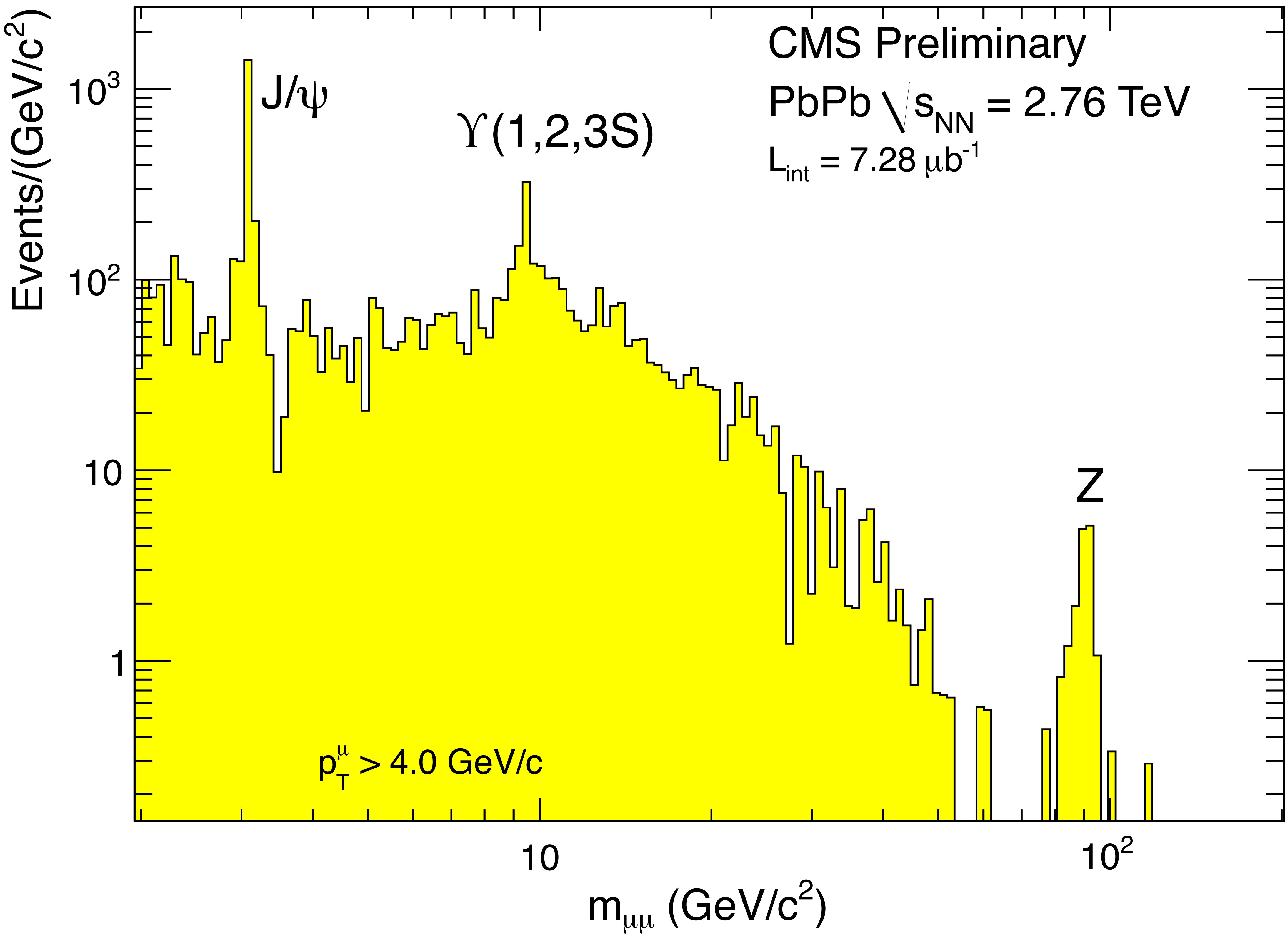
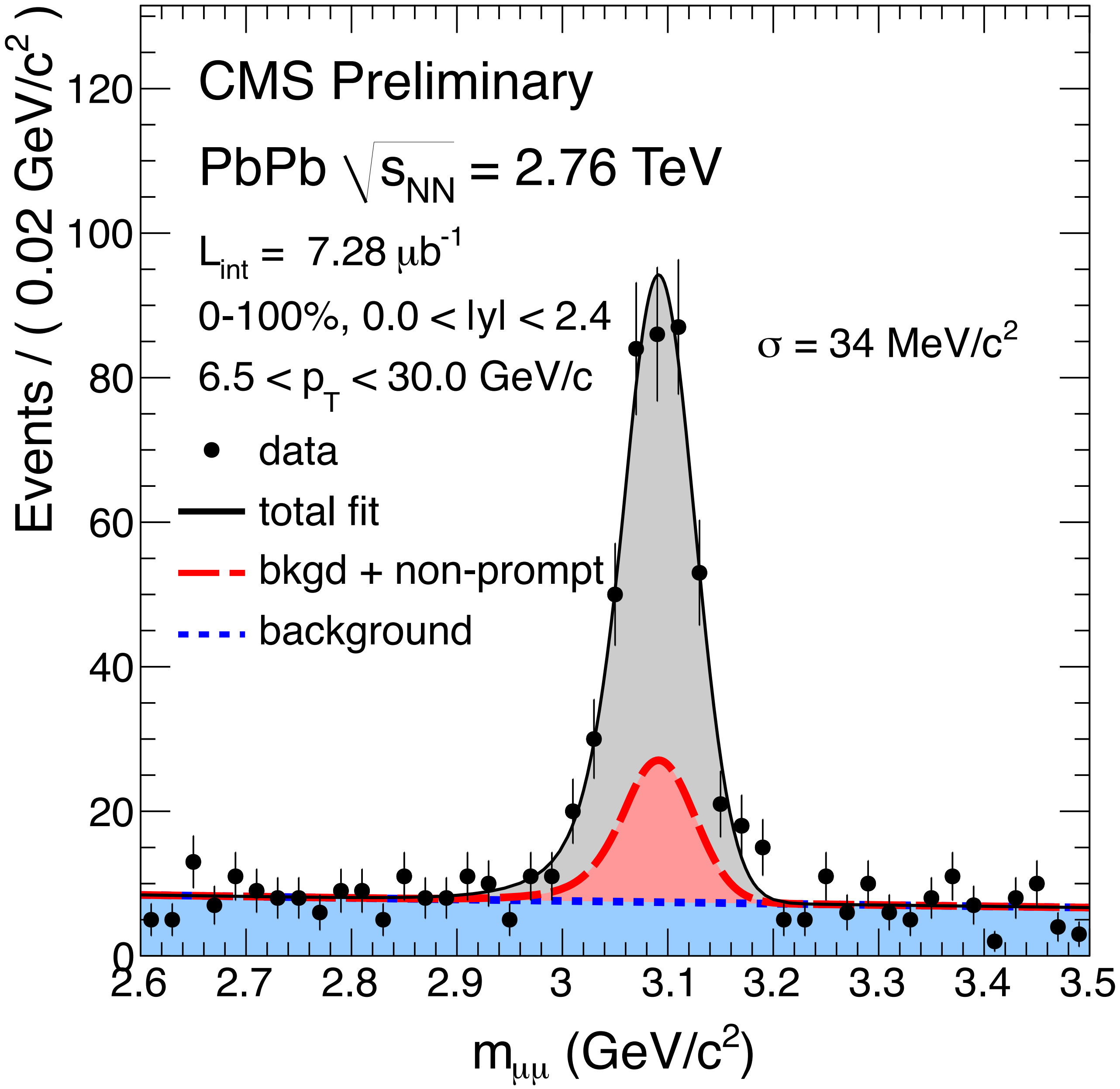
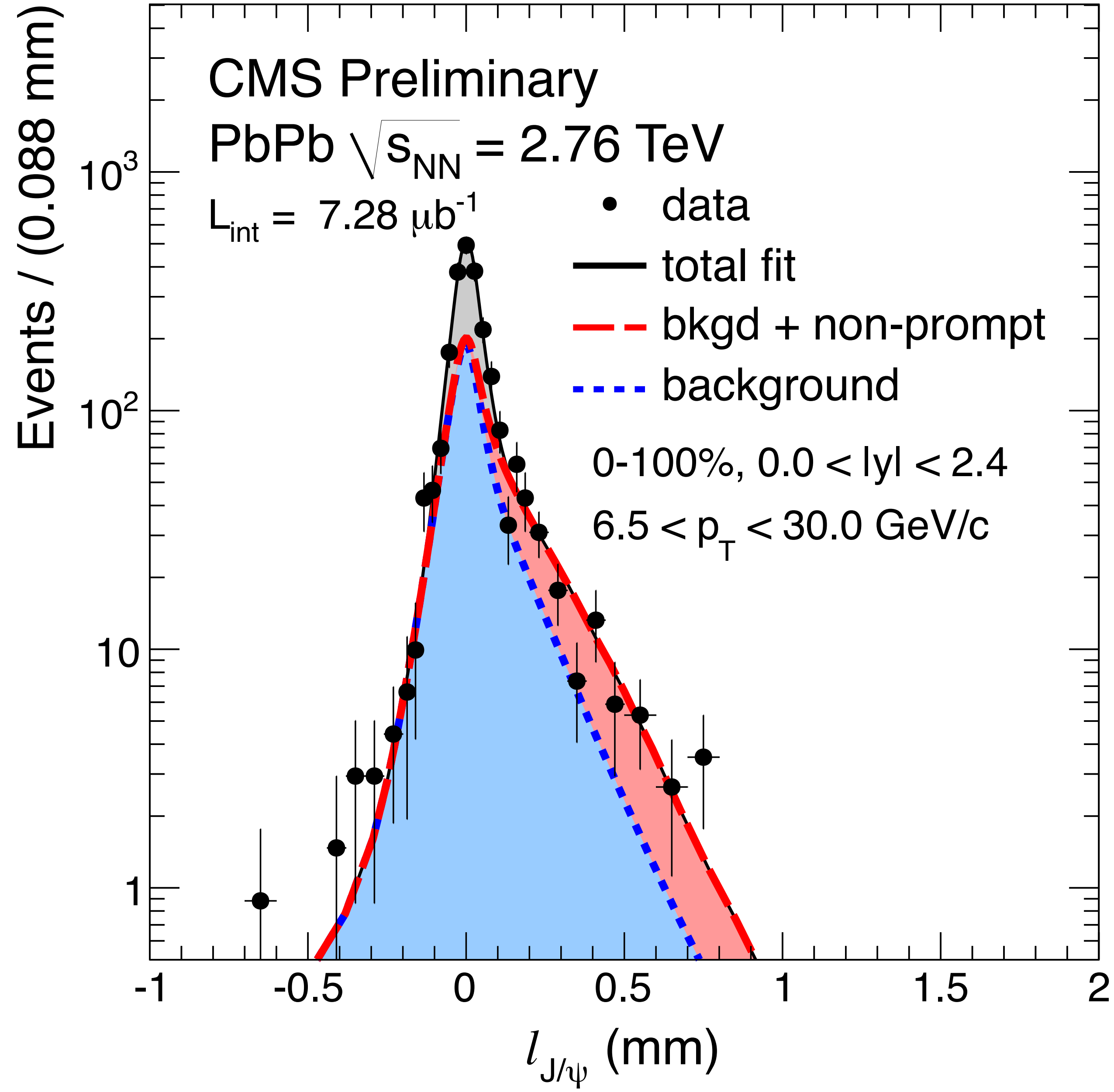
- Separation of the 3 Υ states with good mass resolution
- PYTHIA agrees in shape, but not in normalisation
  - Total cross section overestimated by about a factor 2

Muon pairs in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV



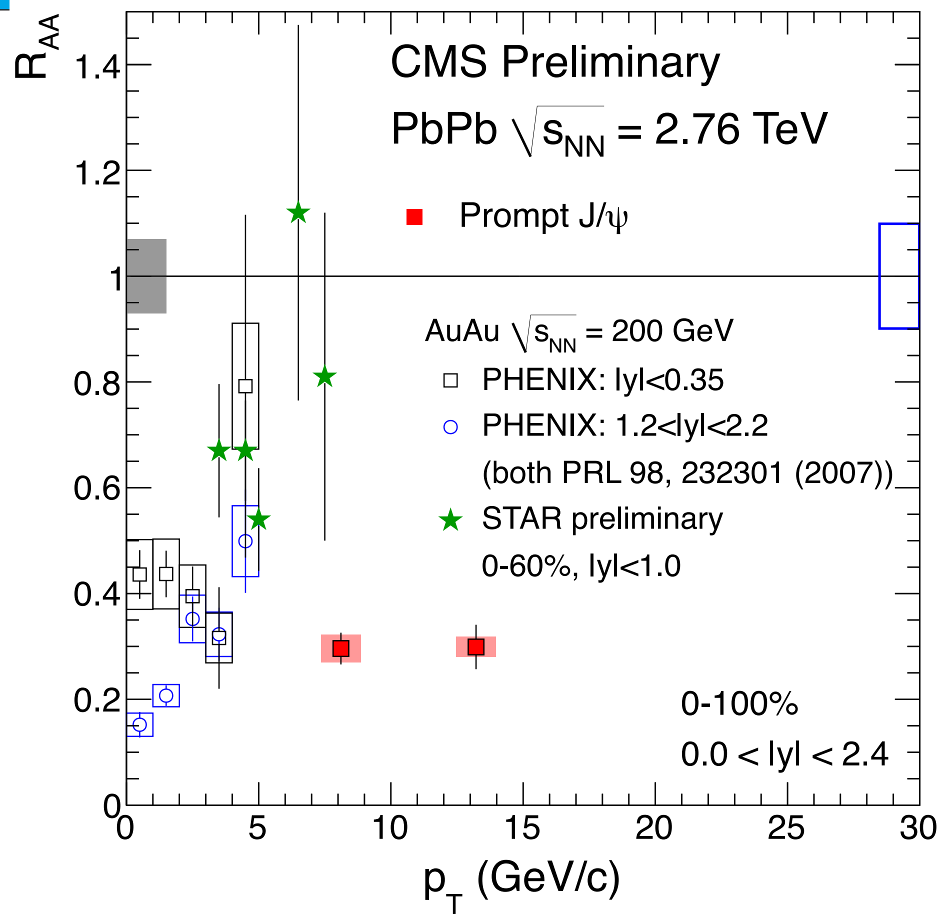
Prompt vs. non-prompt J/ψ in PbPb

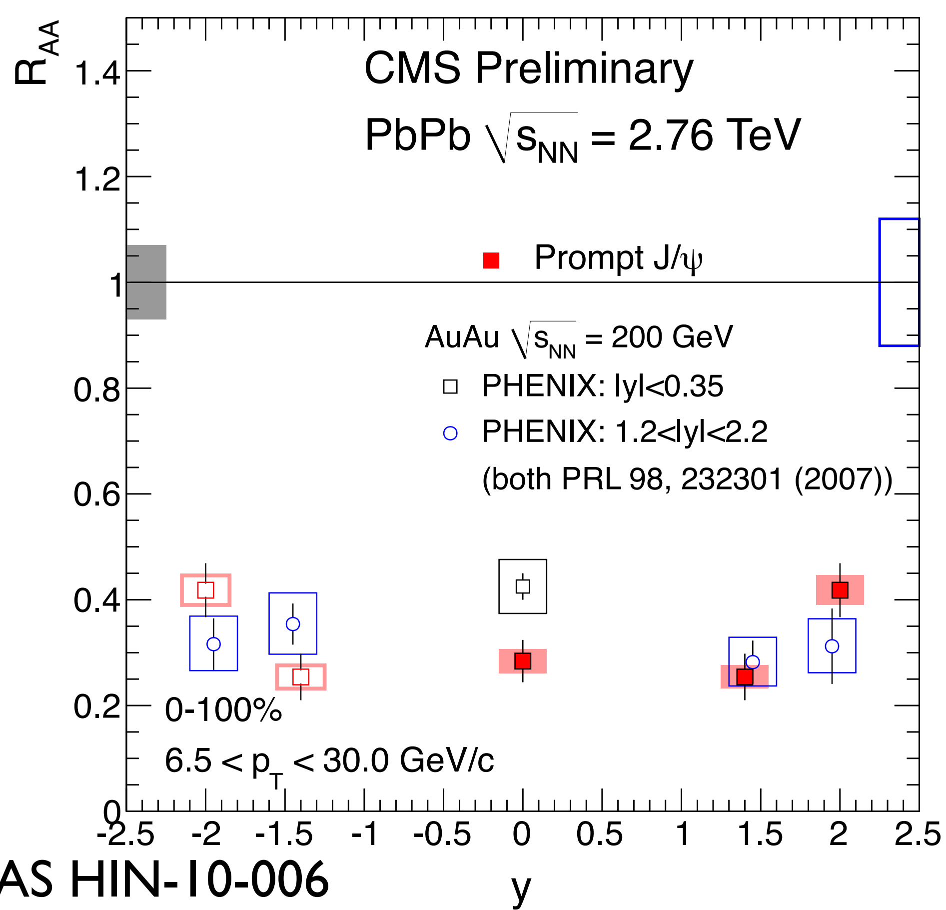




First time that prompt and non-prompt J/ψ have been separated in heavy ion collisions

Prompt J/ψ R_{AA} vs. p_T and y



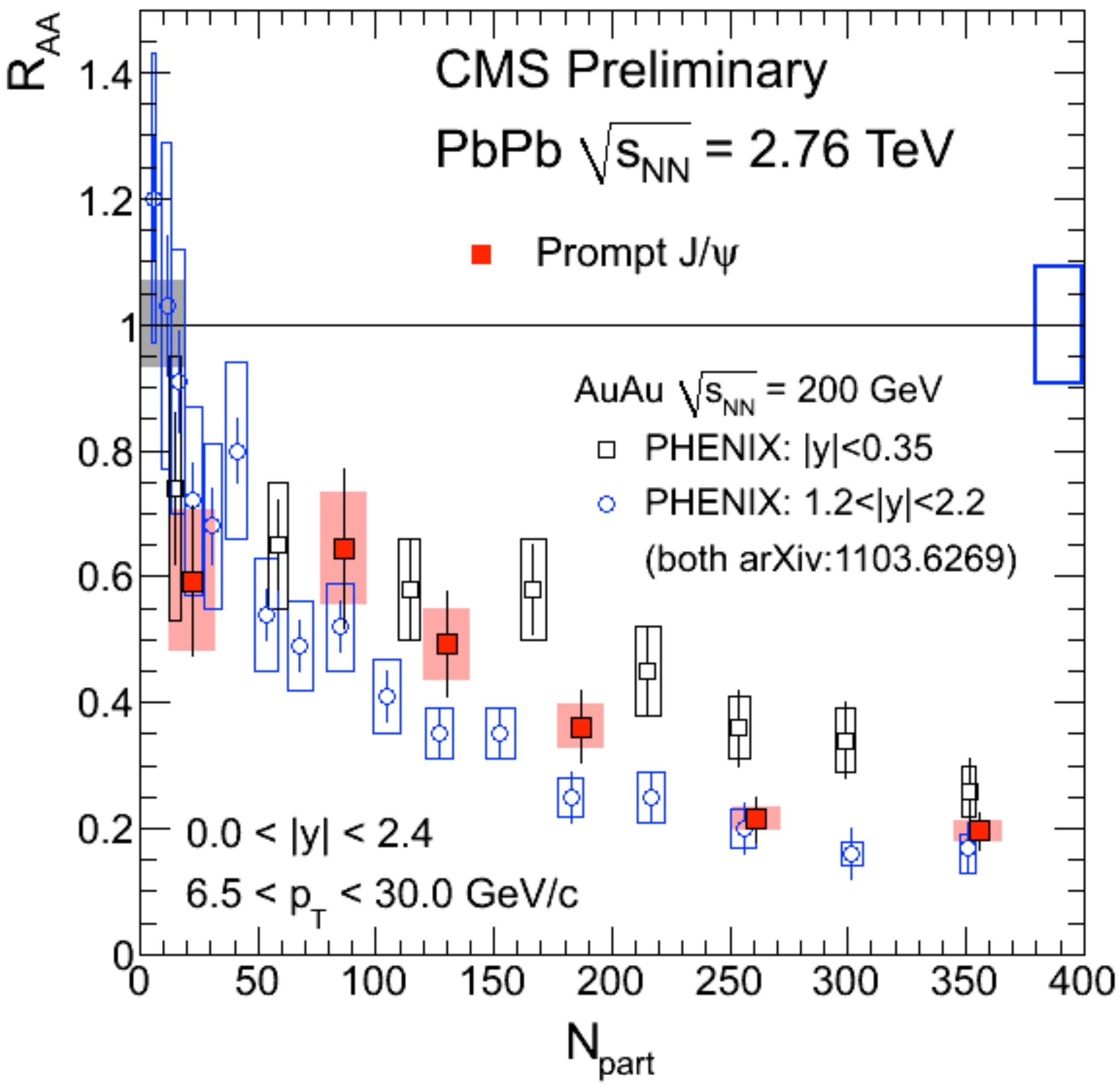


CMS PAS HIN-10-006

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA}N_{\rm MB}} \frac{N_{\rm PbPb}(J/\psi)}{N_{pp}(J/\psi)} \frac{\varepsilon_{pp}}{\varepsilon_{\rm PbPb}(\rm cent)}$$

- CMS: $p_T > 6.5$ GeV/c
  - Factor 3 suppression for $p_T > 6.5$ GeV/c and at $y = 0$
  - Trend to less suppression at forward rapidity
- STAR: no suppression at high p_T
- PHENIX: lower p_T
  - opposite rapidity dependence
- ALICE: inclusive J/ψ, $p_T > 0$ GeV/c, 0–80%
  - $R_{AA} = 0.49 \pm 0.03 \pm 0.11$ (Pillot, QM2011)
- Careful when comparing R_{AA} of prompt J/ψ (CMS) and inclusive J/ψ (ALICE)
  - In pp at low p_T: ~10% b-fraction
  - From RHIC we know that open charm cross section is unmodified
    (can assume the same for open bottom)
  - non-prompt J/ψ could shift R_{AA} by 10%

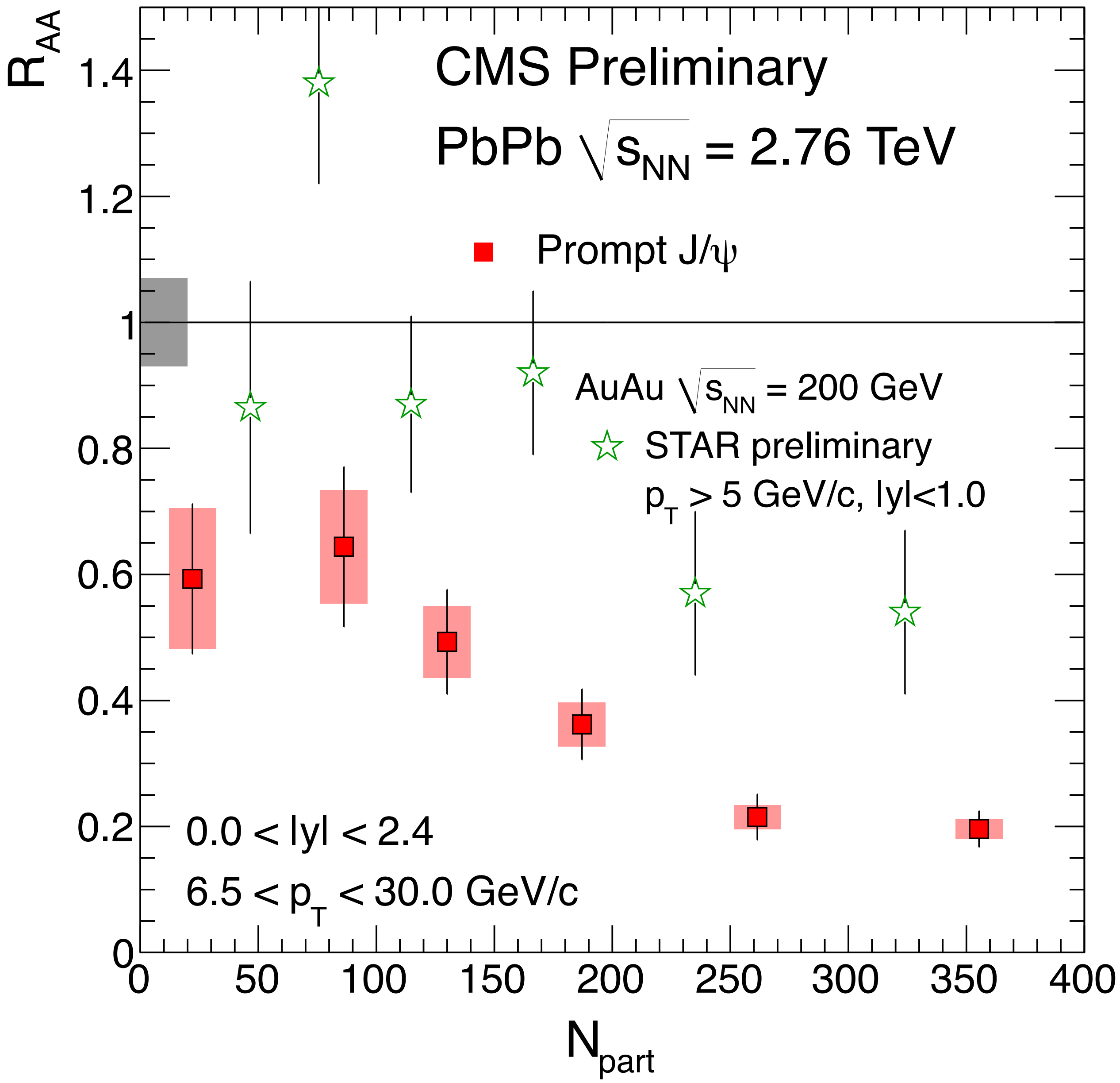
Prompt J/ψ R_{AA} vs. centrality



CMS PAS
HIN-10-006

- Prompt J/ψ:
  - 0-10% suppressed by factor 5 with respect to pp
  - 50-100% suppressed by factor ~1.6
- Similar suppression seen at RHIC
  - though at lower p_T

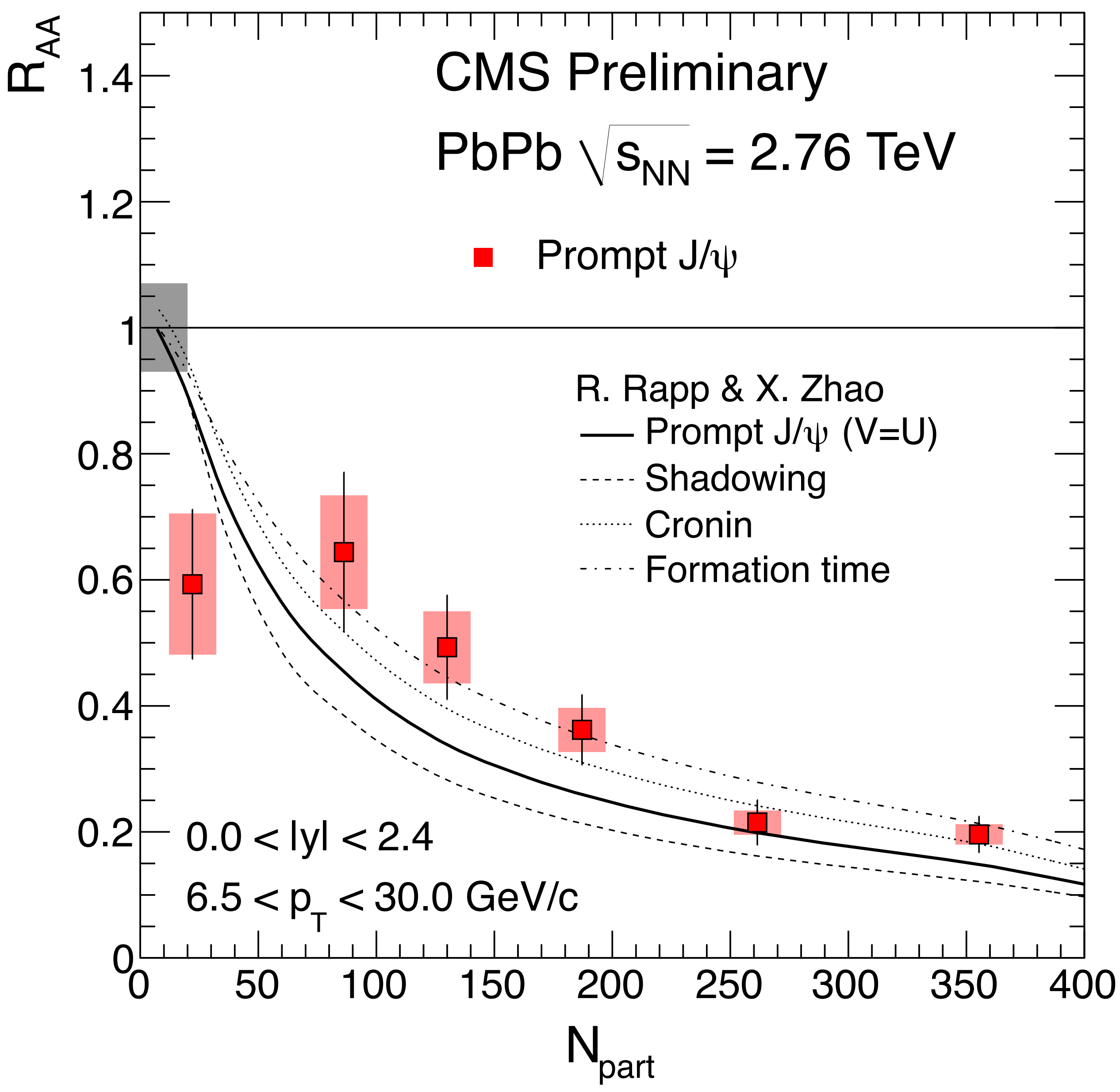
Prompt J/ψ R_{AA} vs. centrality



CMS PAS
HIN-10-006

- Prompt J/ψ:
  - 0-10% suppressed by factor 5 with respect to pp
  - 50-100% suppressed by factor ~1.6
- Similar suppression seen at RHIC
  - though at lower p_T
  - Suppression at high p_T much smaller at RHIC

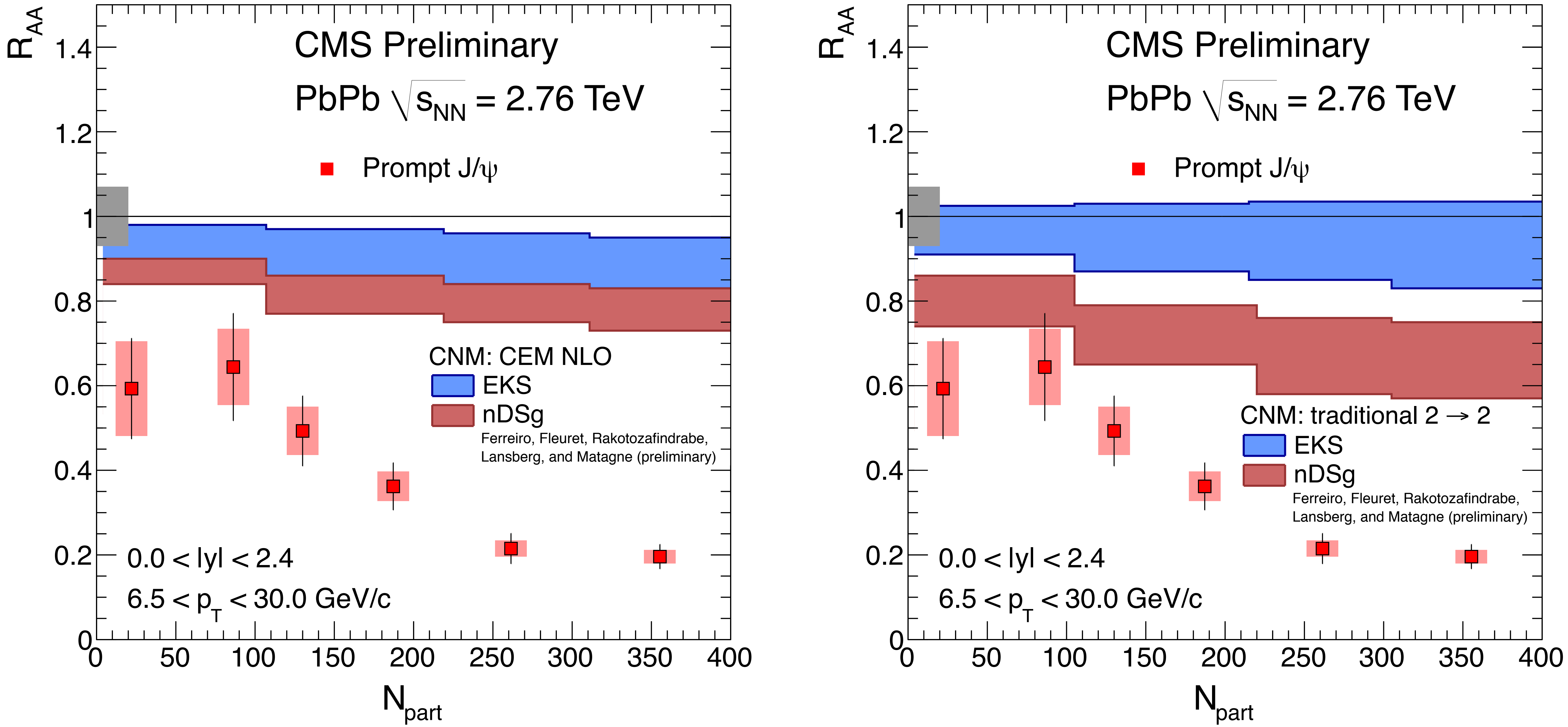
Prompt J/ψ R_{AA} vs. centrality



- Prompt J/ψ:
  - 0-10% suppressed by factor 5 with respect to pp
  - 50-100% suppressed by factor ~1.6
- Recombination negligible for p_T>6.5 GeV/c

Zhao & Rapp, NPA 859 (2011) 114
+ private communication

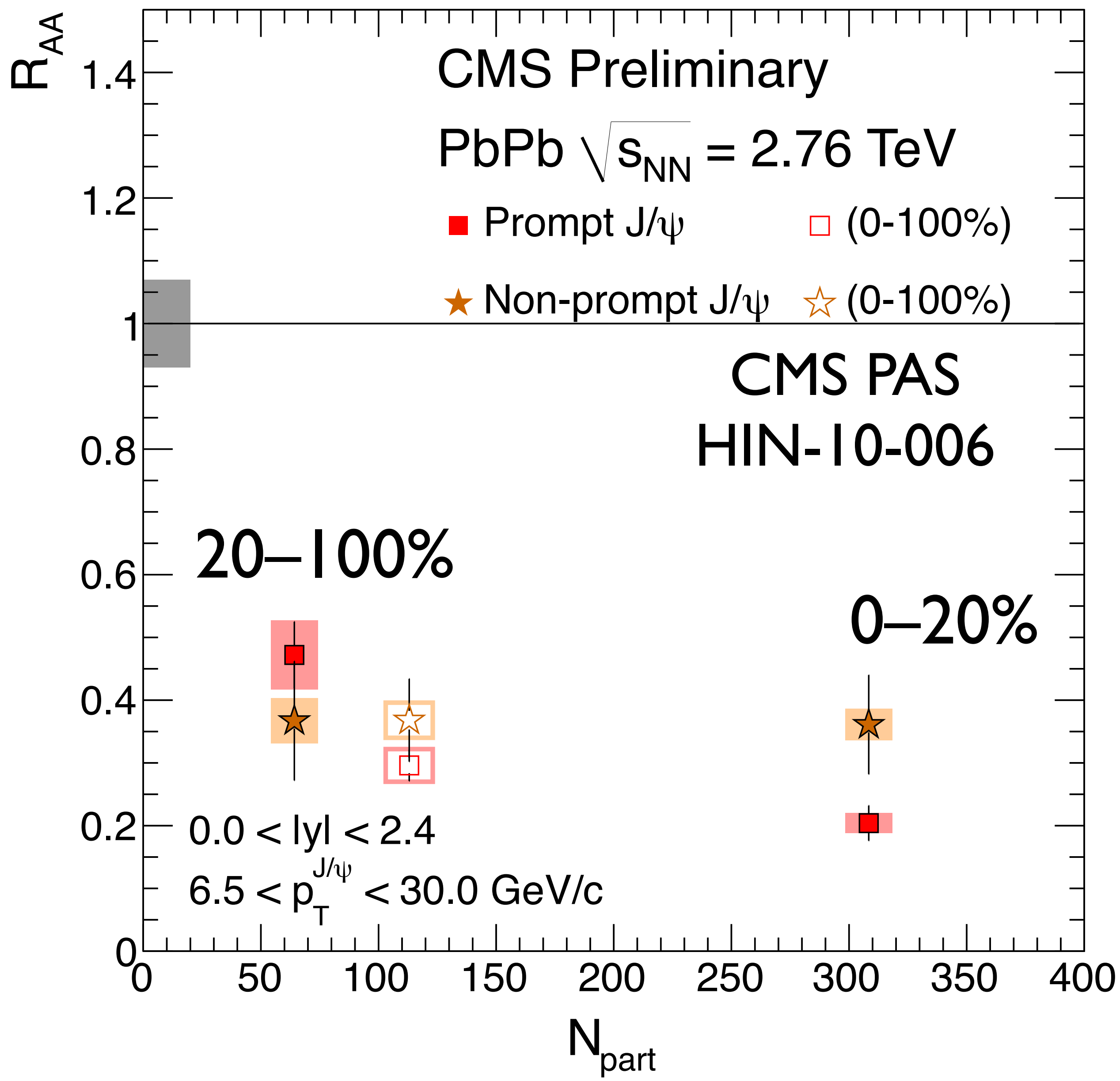
Prompt J/ψ: Cold Nuclear Matter effects?

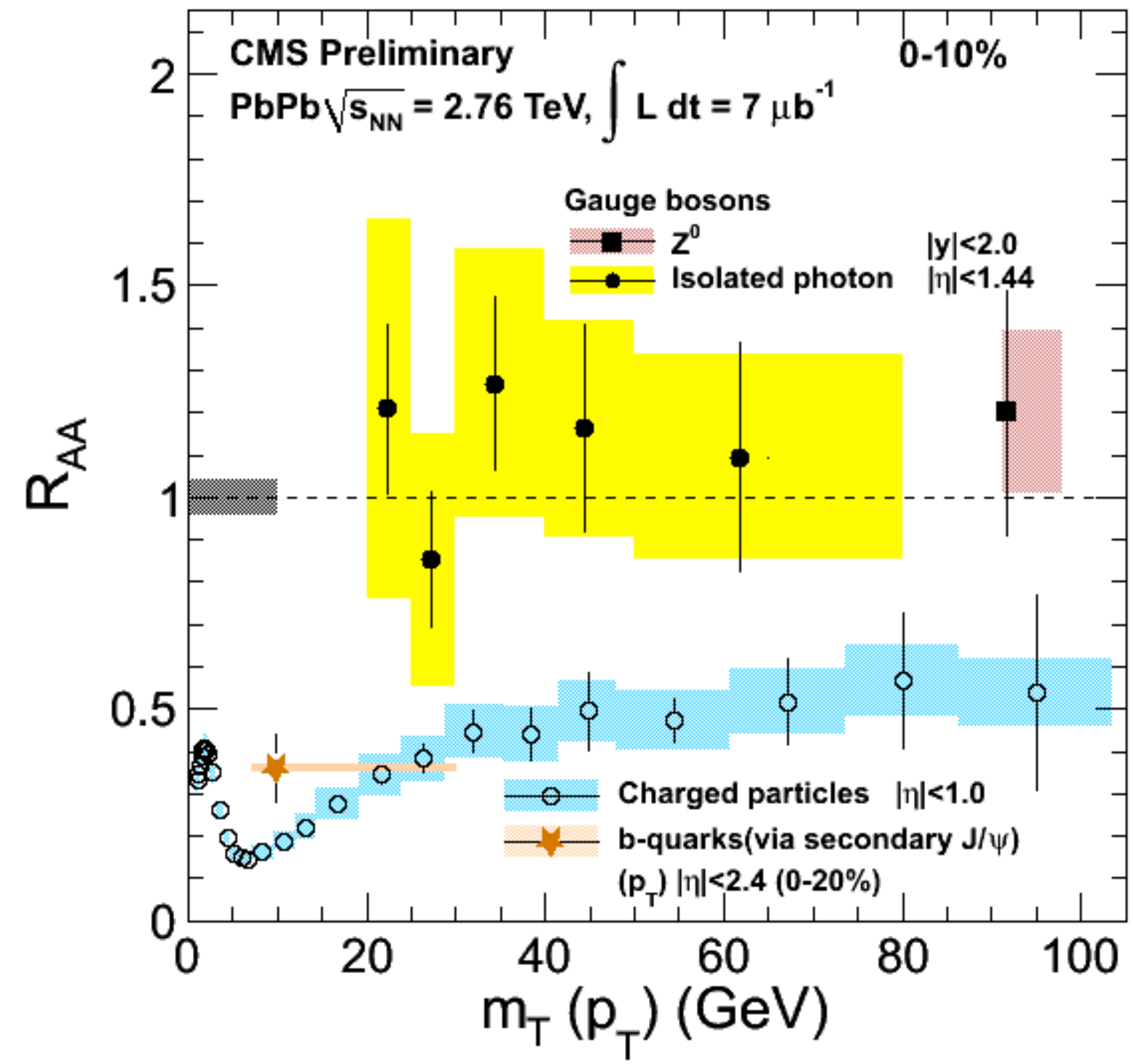


- Work in progress to estimate (anti)shadowing contributions

Ferreiro et al.
(preliminary)

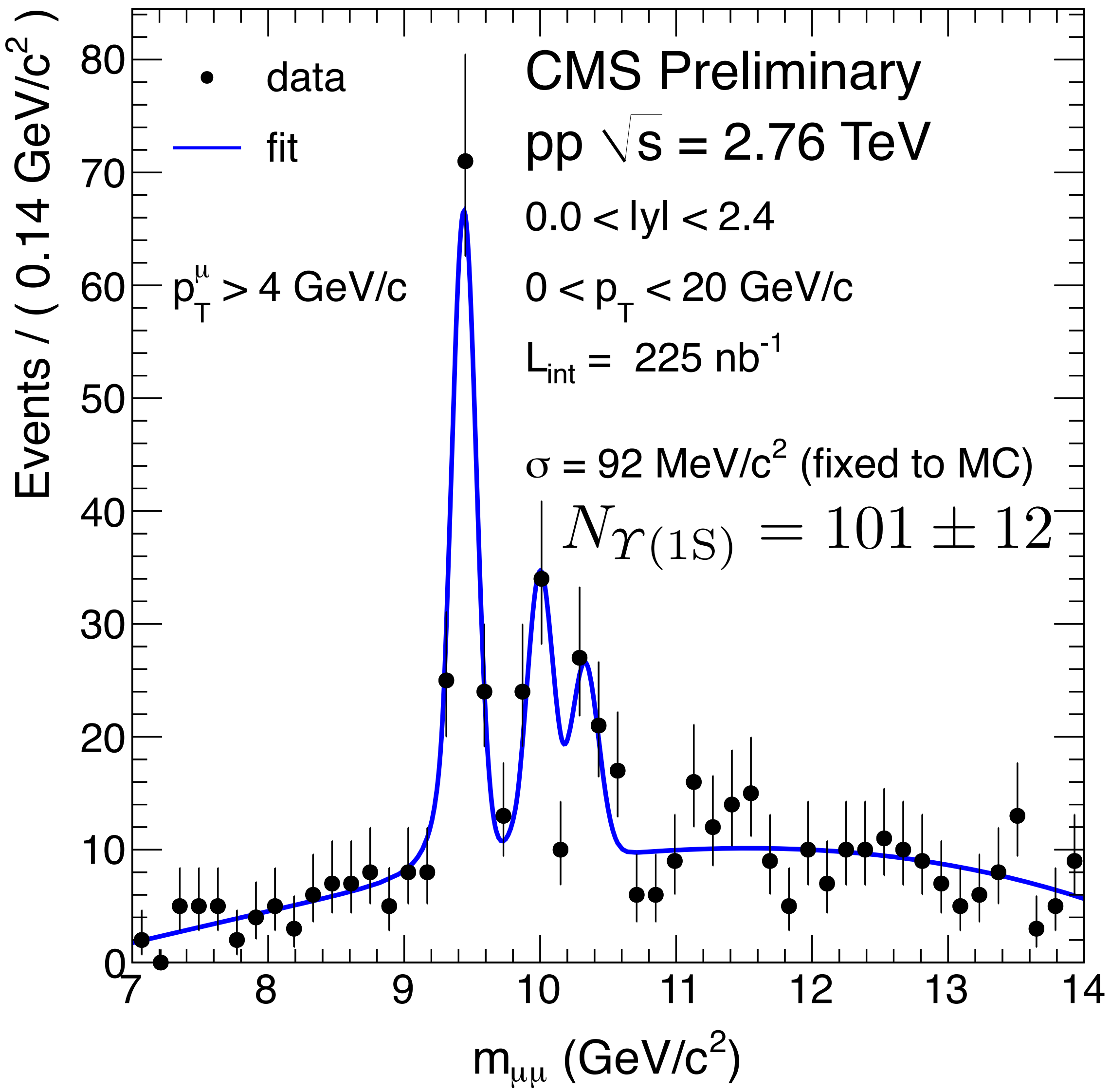
Open heavy-flavour: Non-Prompt J/ψ R_{AA}



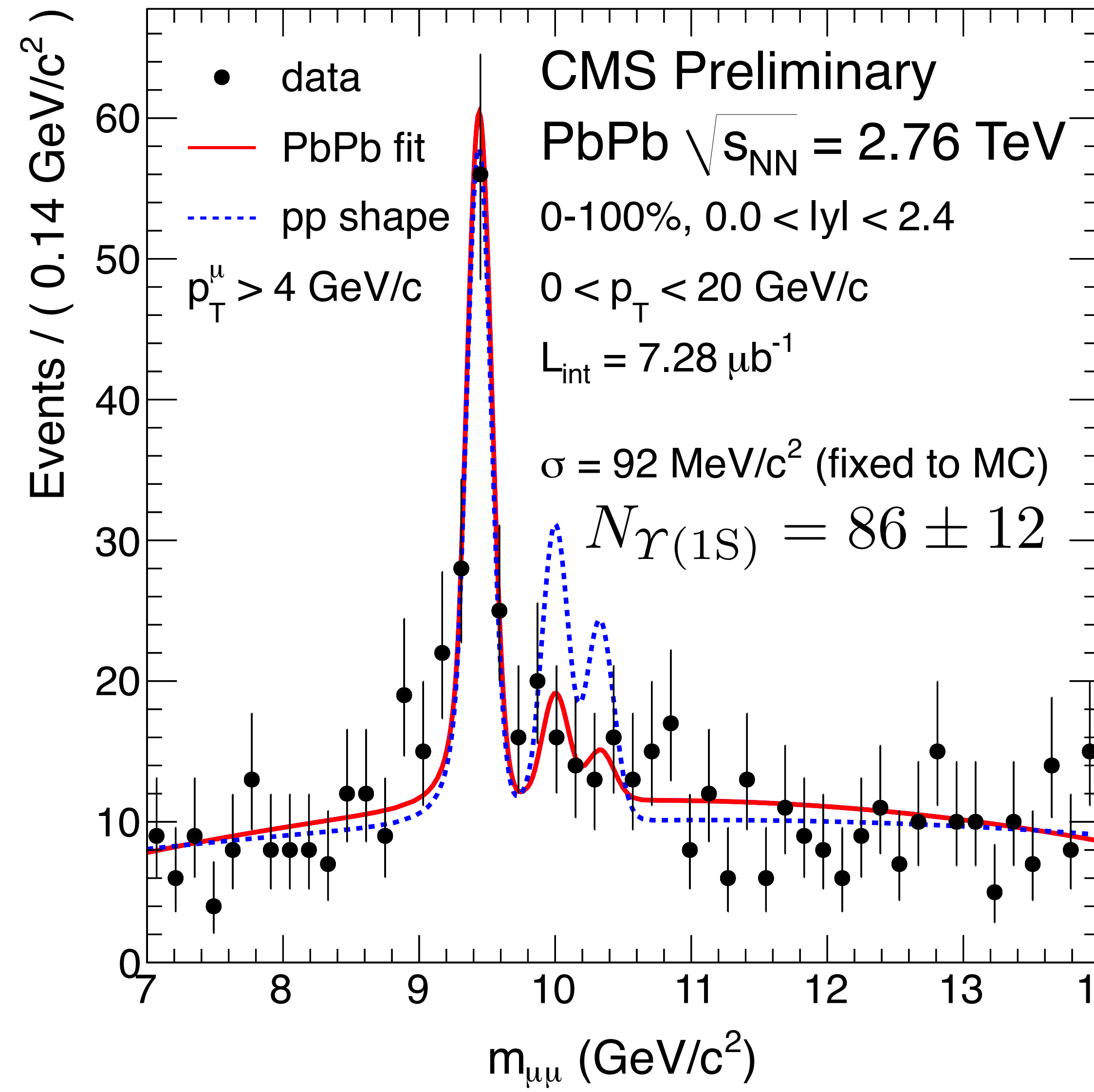


- Suppression of non-prompt J/ψ observed in min. bias and central PbPb collisions
  - First indications of high-p_T b-quark quenching!

Υ(2S+3S) Suppression



$\Upsilon(2S+3S)/\Upsilon(1S)|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$



$\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

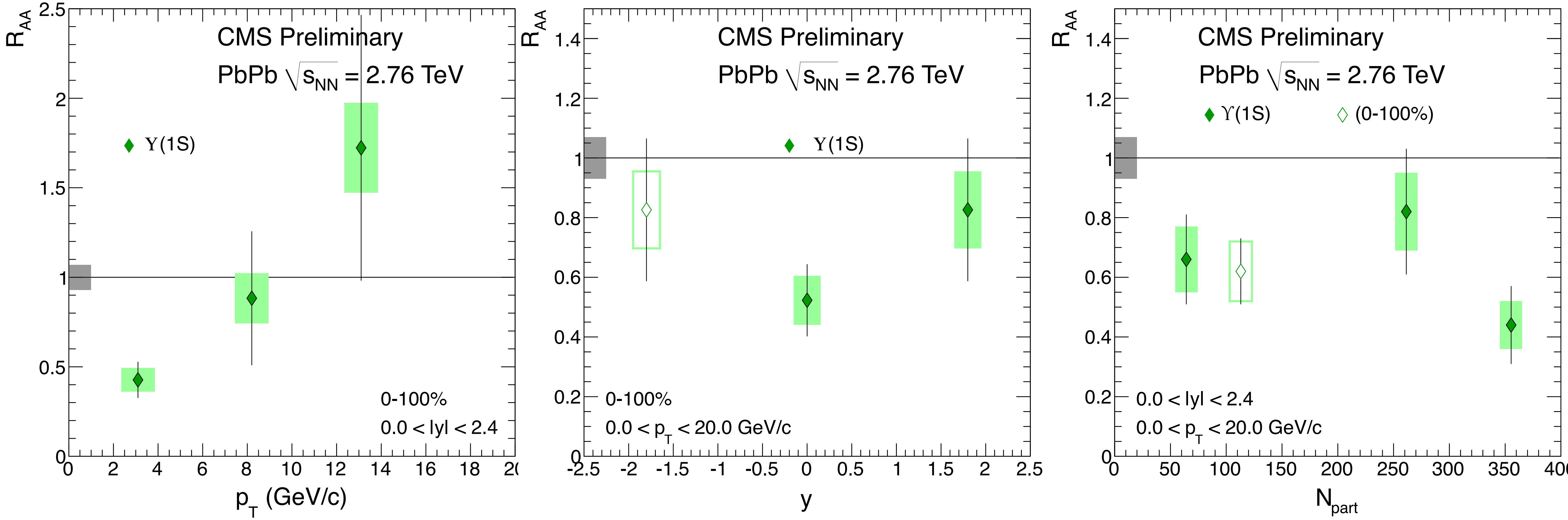
- Measure Υ(2S+3S) production relative to Υ(1S) production
- Simultaneous fit to pp and PbPb data at 2.76 TeV

PRL 107 (2011) 052302

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Probability to obtain measured value, or lower, if the real double ratio is unity, has been calculated to be less than 1%

$\Upsilon(1S)$ R_{AA}

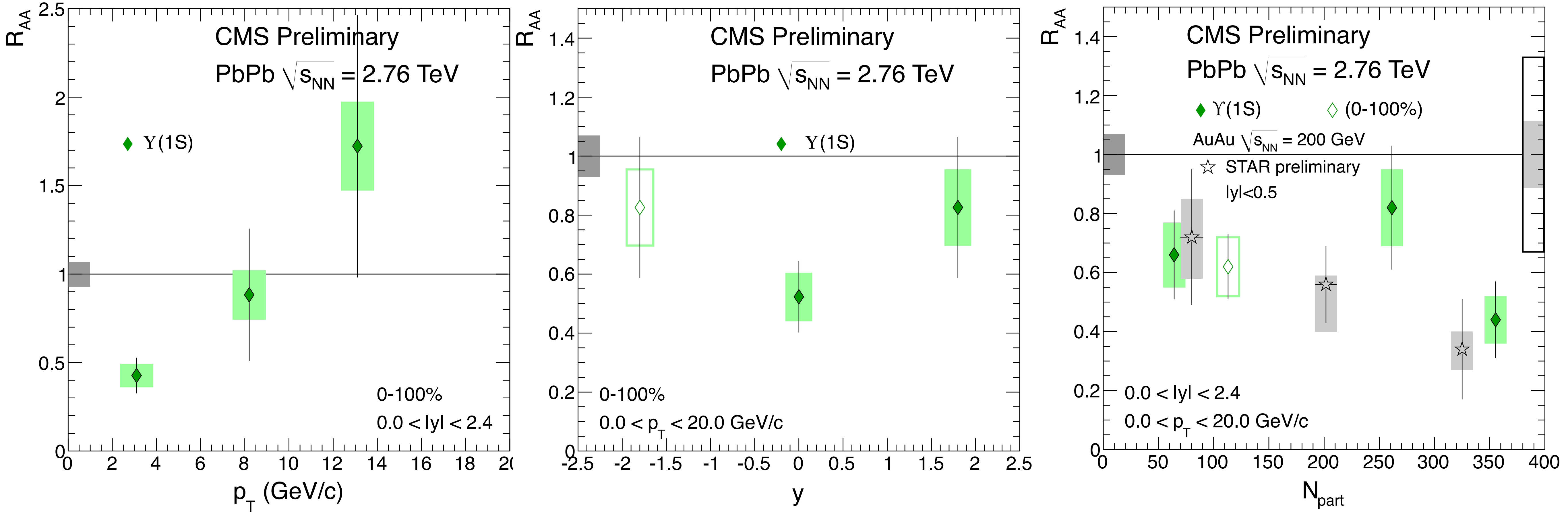


- $\Upsilon(1S)$ suppressed at low p_T
- No obvious rapidity dependence
- CMS: $\Upsilon(1S)$
  - suppressed by factor ~2.3 in 0–10%
- Large feed down contribution from excited states (χ_b, $\Upsilon(2S)$, $\Upsilon(3S)$)
  - Observed $\Upsilon(1S)$ suppression consistent with melting of excited states only

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\mathrm{MB}}} \frac{N_{\mathrm{PbPb}}(\Upsilon(1S))}{N_{pp}(\Upsilon(1S))} \frac{\varepsilon_{pp}}{\varepsilon_{\mathrm{PbPb(cent)}}}$$

CMS PAS HIN-10-006

Υ(1S) R_{AA}



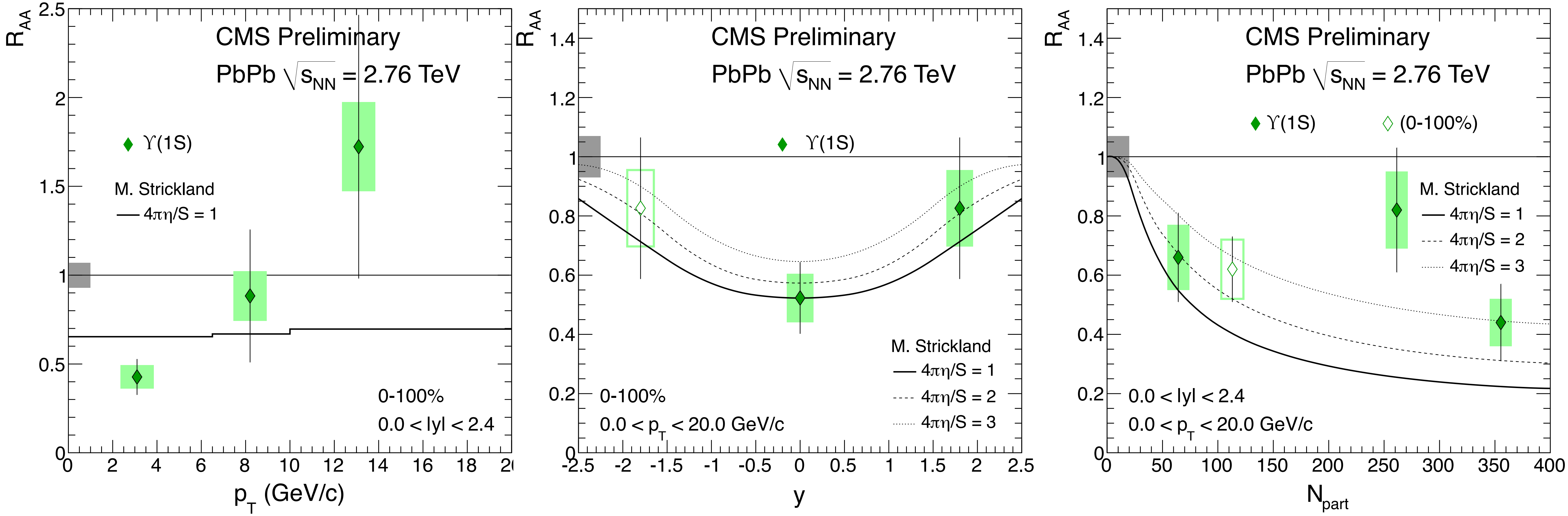
- Υ(1S) suppressed at low p_T
- No obvious rapidity dependence
- CMS: Υ(1S)
  - suppressed by factor ~2.3 in 0–10%

CMS PAS HIN-10-006

- STAR measures $R_{AA}(\Upsilon(1S+2S+3S)) = 0.56 \pm 0.21^{+0.08}_{-0.16}$ (arXiv:1109.3891)
  - for CMS (0–100%): $R_{AA}(\Upsilon(1S+2S+3S)) = R_{AA}(\Upsilon(1S)) \times \frac{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{\rm PbPb}}{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{\rm pp}}$

$$= 0.62 \times \frac{1+0.24}{1+0.78} \approx 0.43$$

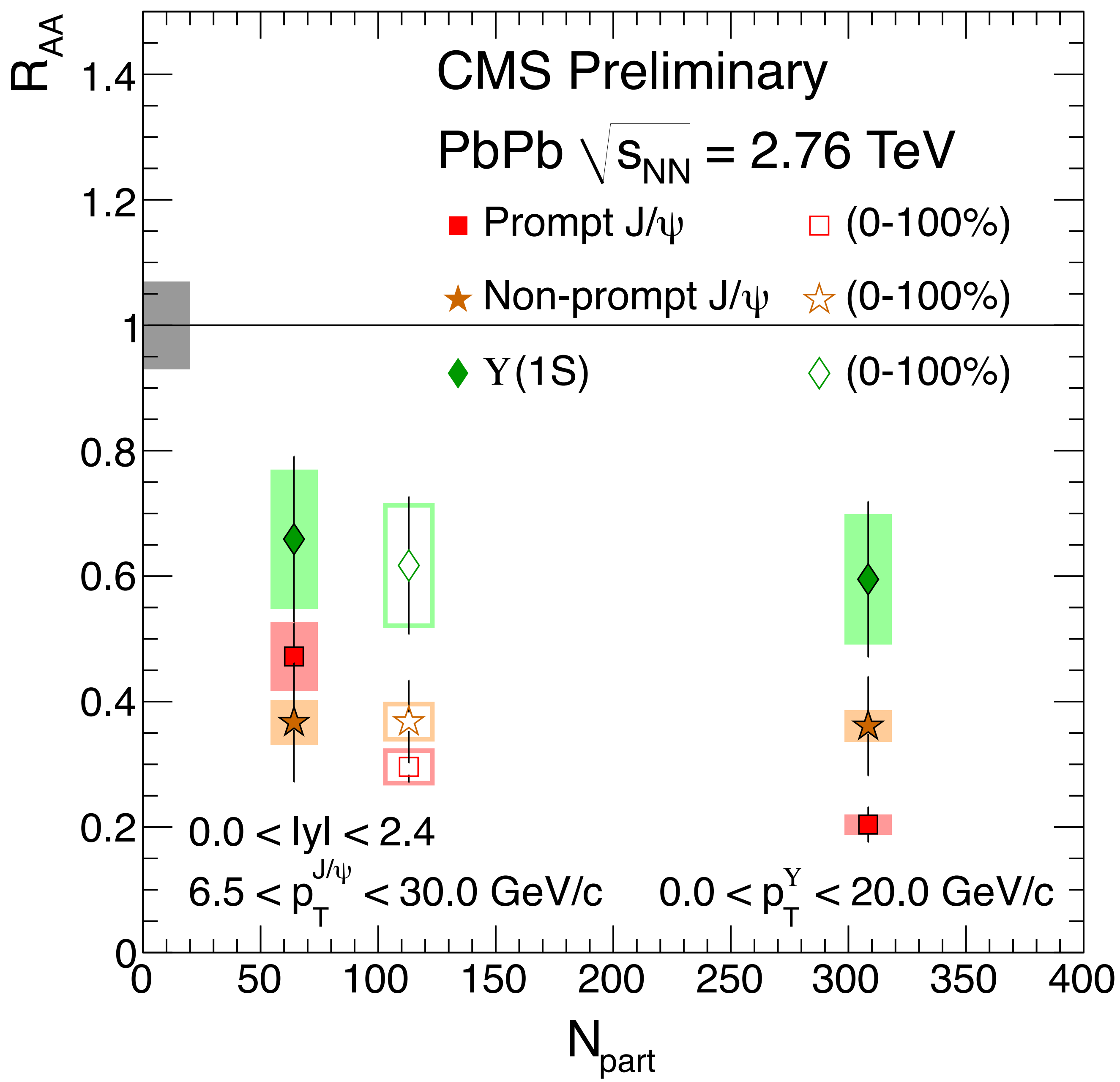
Υ(1S) R_{AA}



- Υ(1S) suppressed at low p_T
- No obvious rapidity dependence
- CMS: Υ(1S)
  - suppressed by factor ~2.3 in 0–10%
- M. Strickland calculates Υ(1S) and χ_b R_{AA} (arXiv:1106.2571)
  - For feed down: no explicit calculation of Υ(nS) R_{AA}: assume all states as suppressed as the χ_b
  - Rapidity and centrality dependence in good agreement, but misses suppression at low p_T

CMS PAS HIN-10-006

Summary



In PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

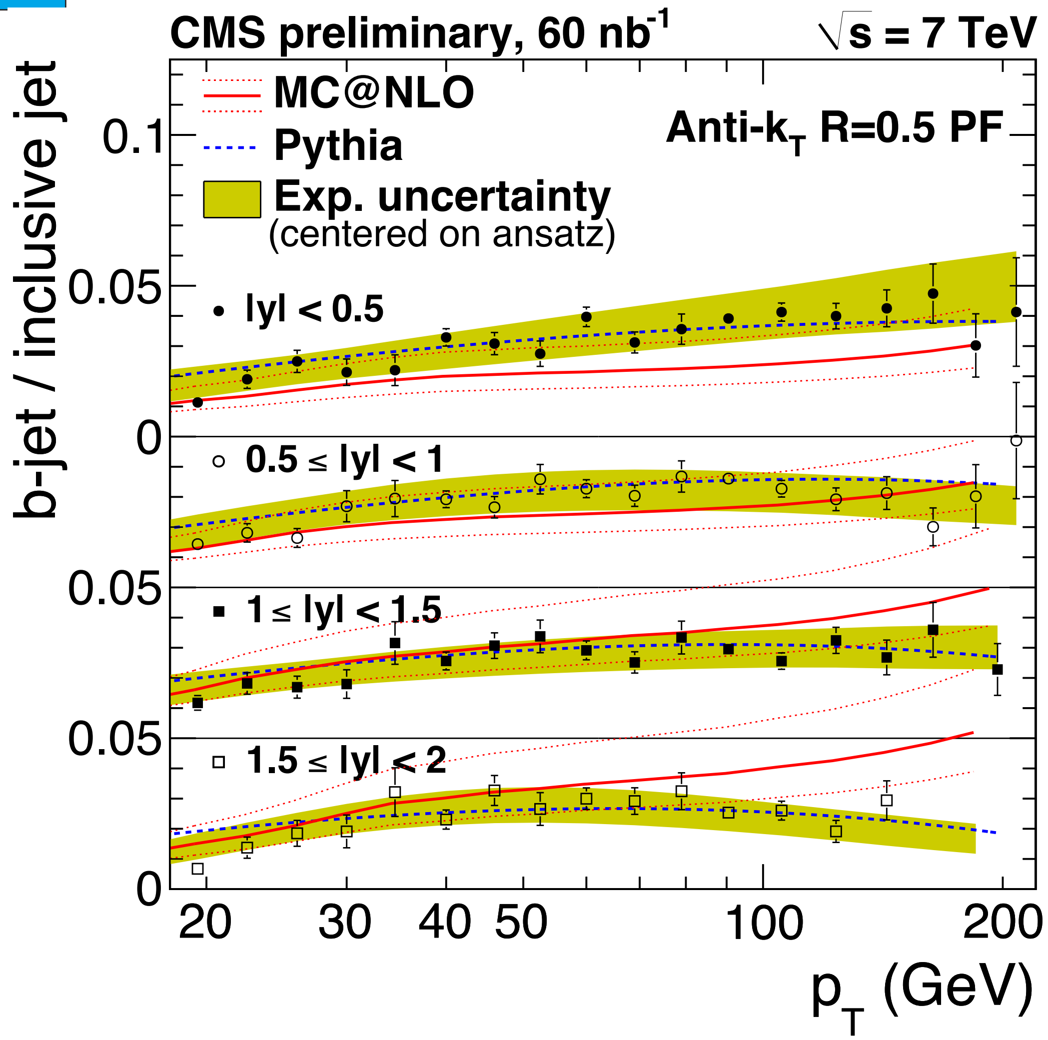
- Prompt J/ψ suppressed
- Υ(2S+3S) suppressed relative to Υ(1S)
  - Observed Υ(1S) suppression consistent with melting of excited states only
- J/ψ from B decays suppressed

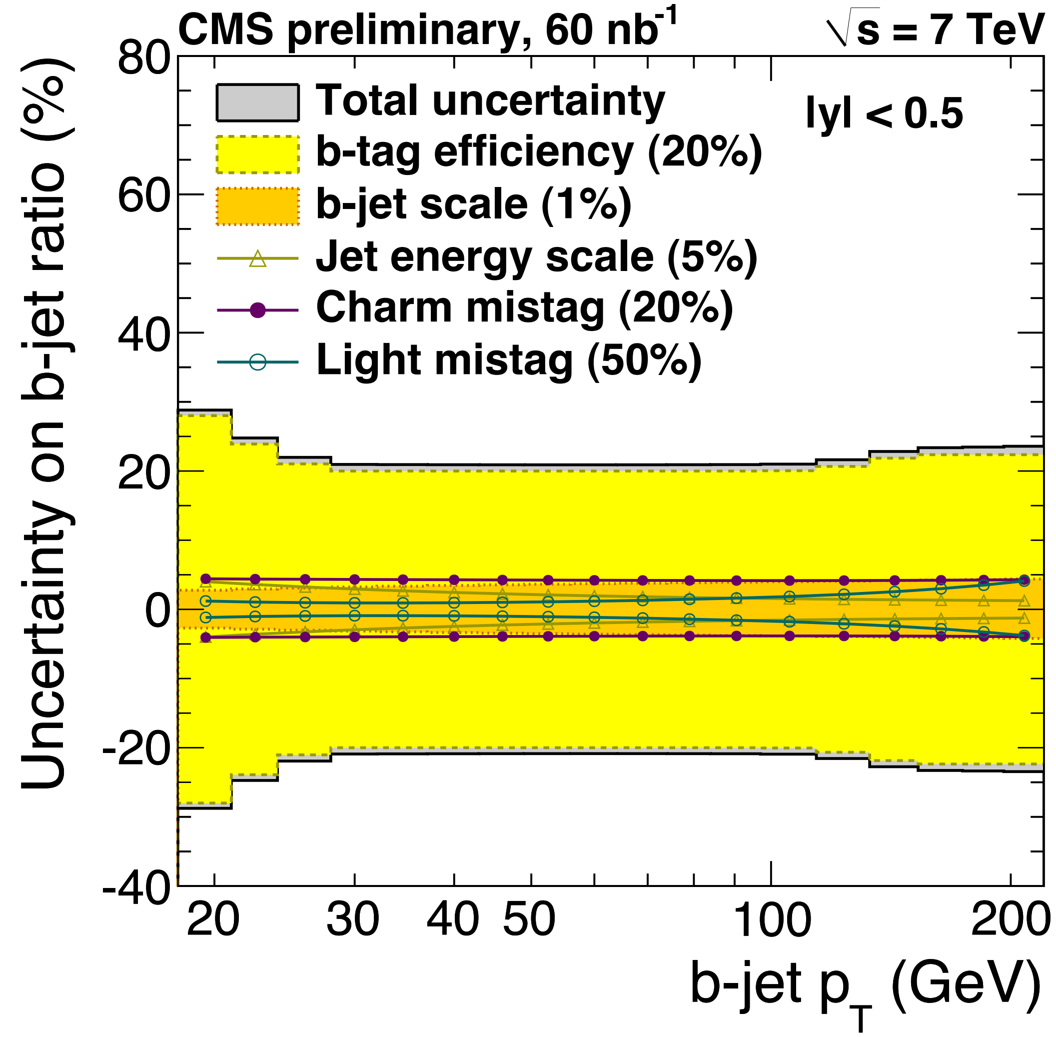
In pp collisions at $\sqrt{s}$ = 7 TeV

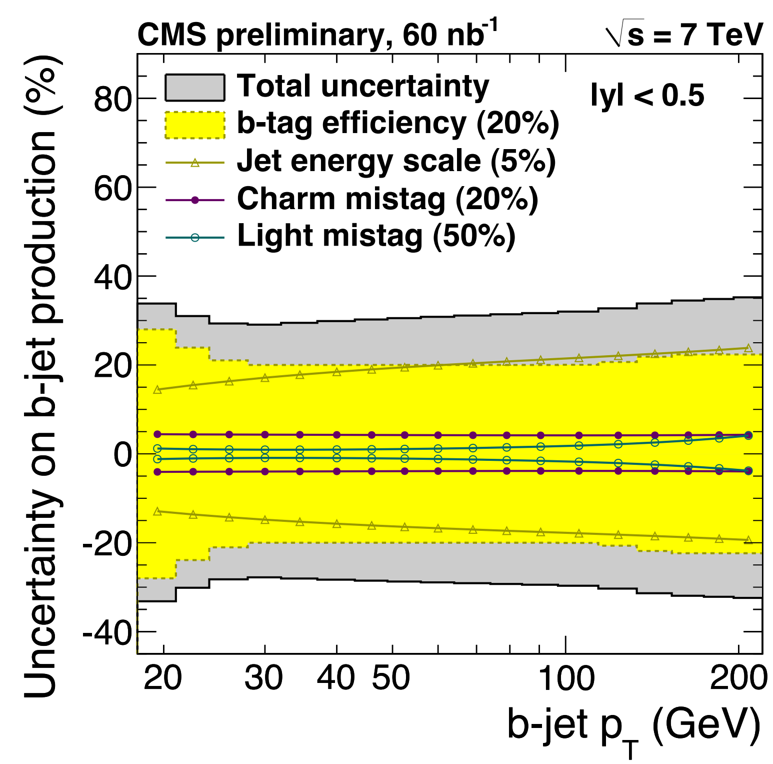
- B production measured in a variety of channels
- Differential cross sections described by models within theoretical and experimental uncertainties
- Angular BB(bar) correlations at small ΔR challenges models

Backup

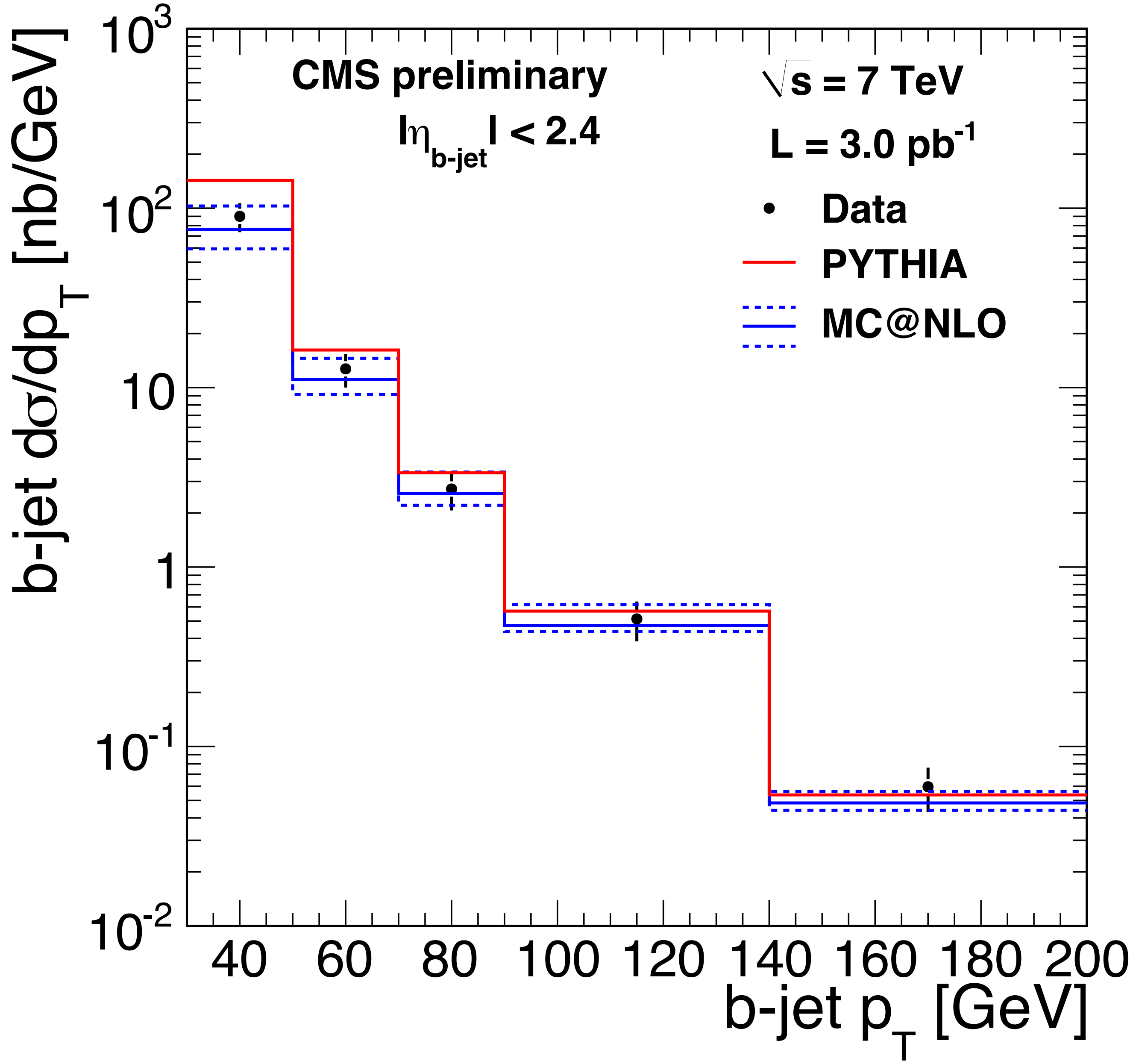
b-jet/inclusive jet ratio

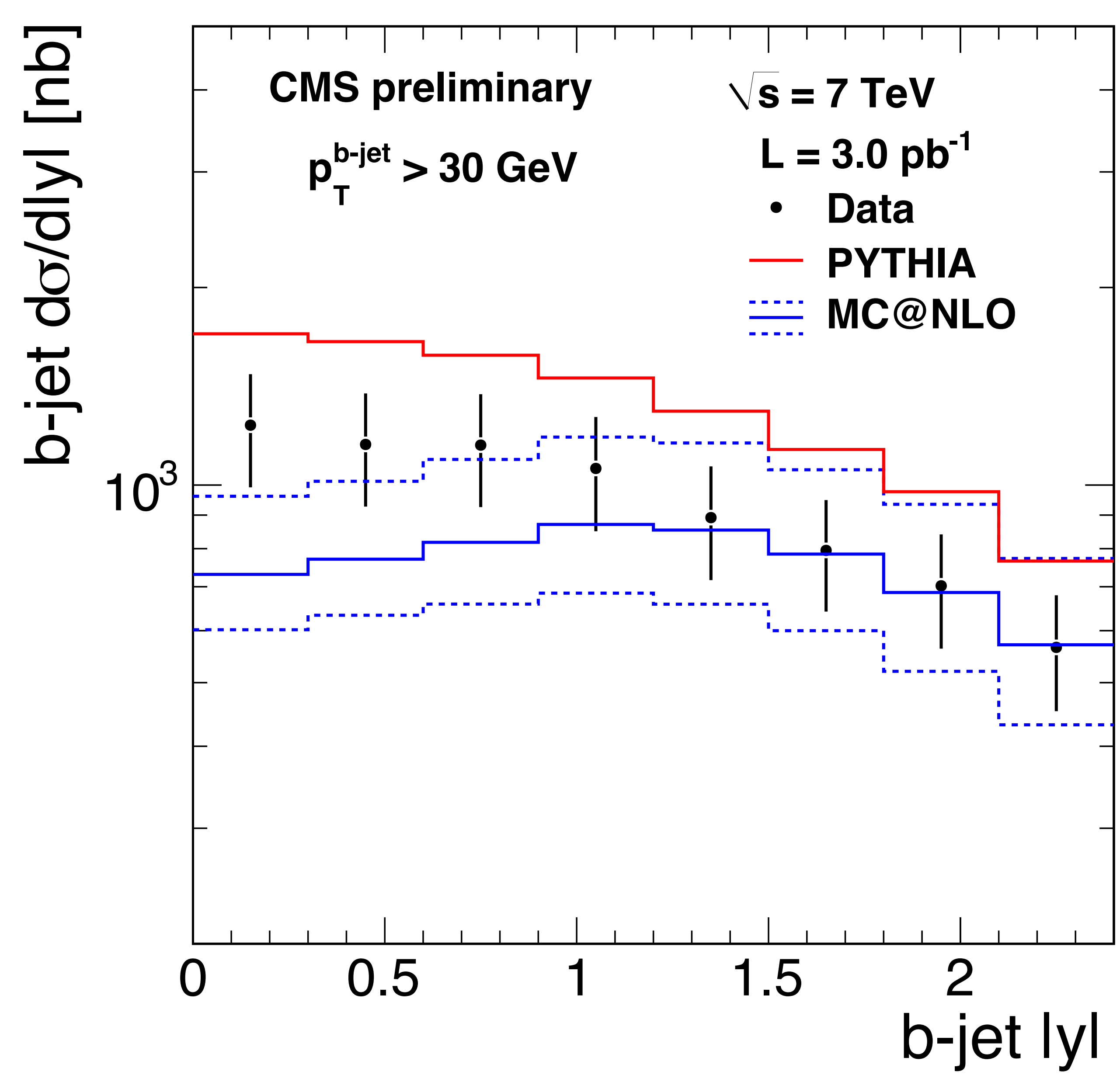






Inclusive b-jets





use secondary vertex to tag b-jets and then p_T^{rel} as further discriminator

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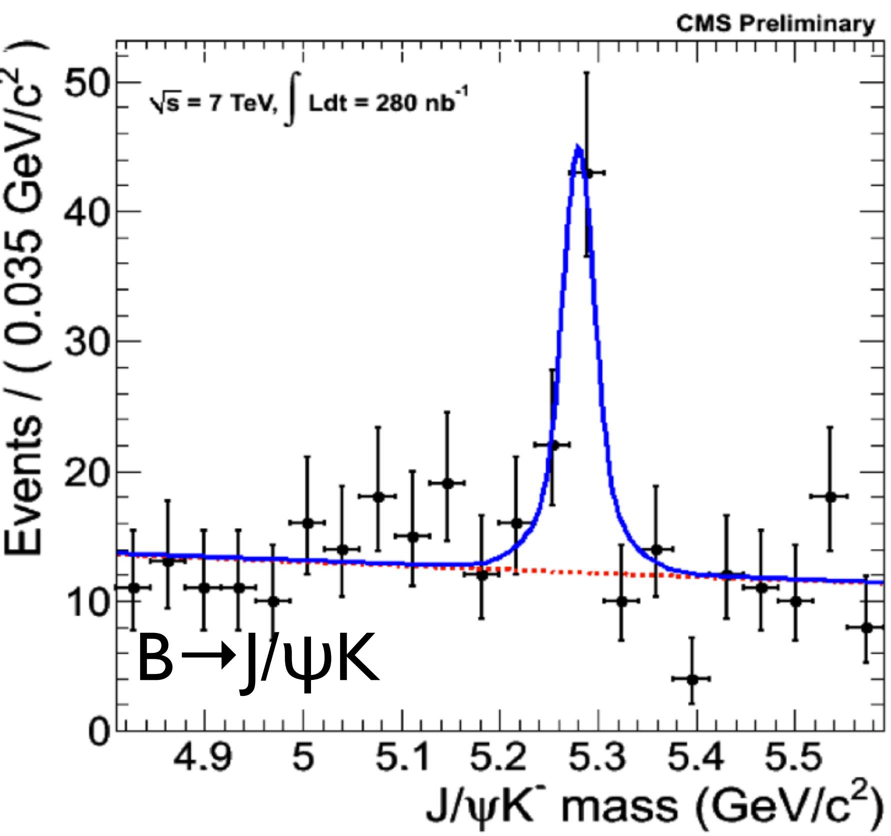
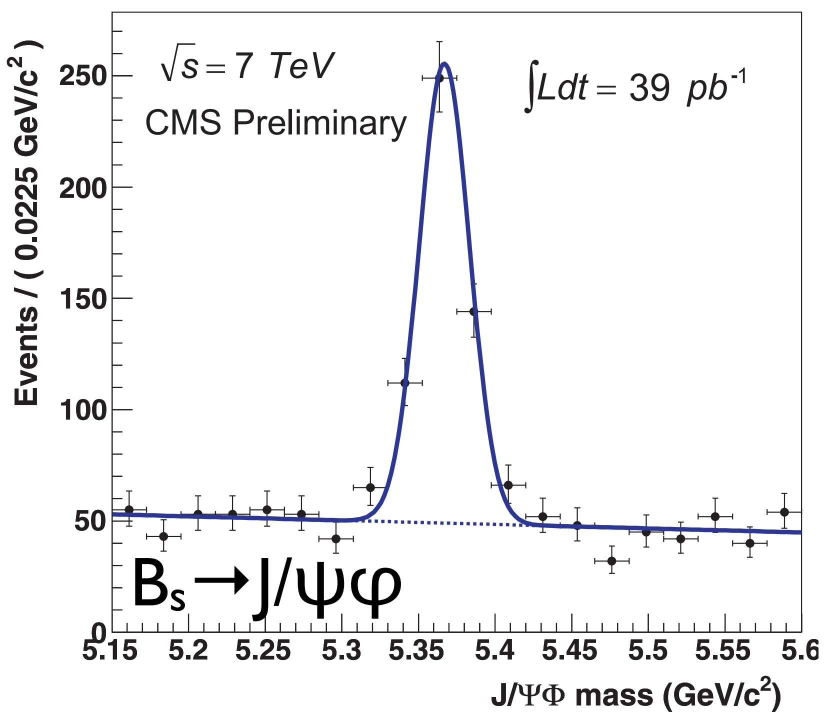
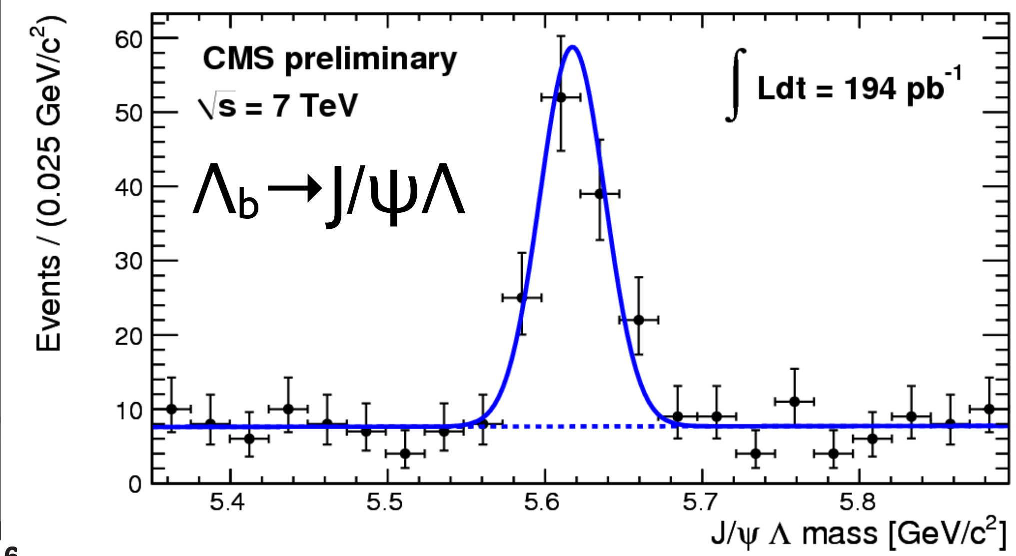
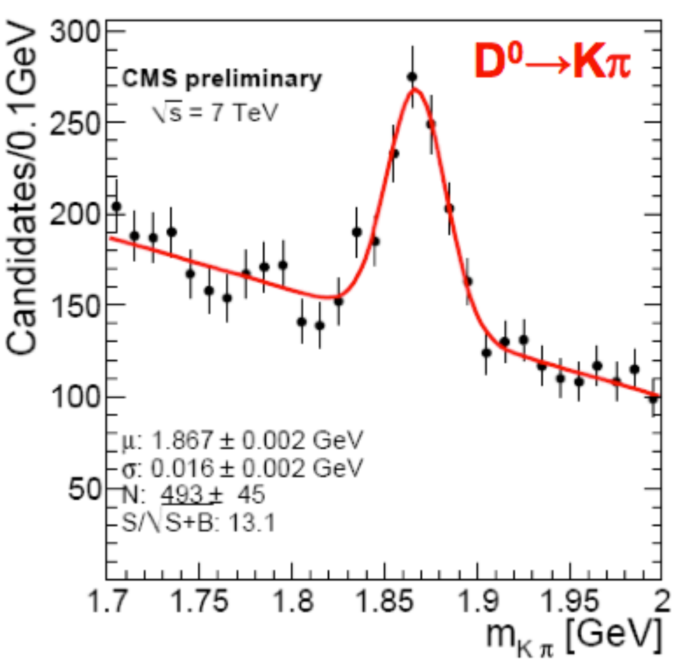
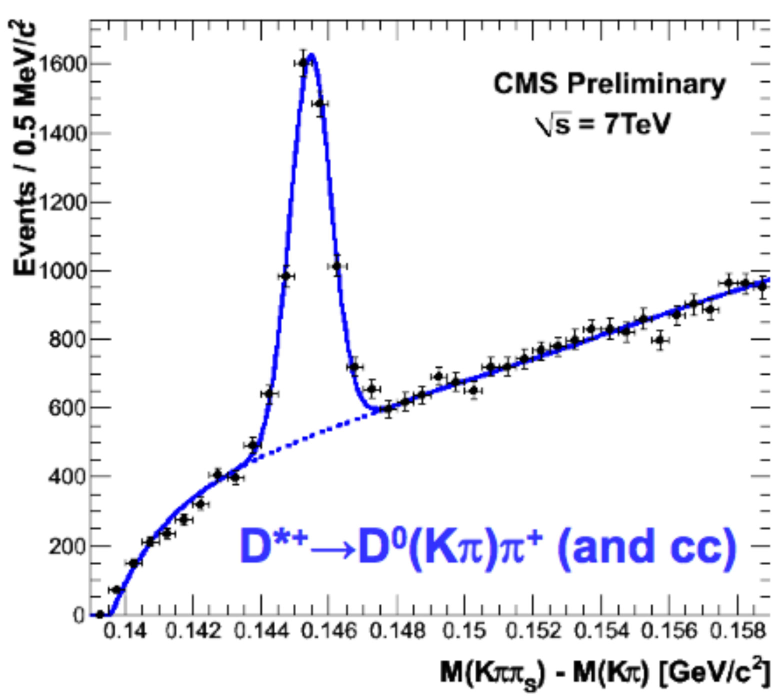
Full B and D hadron reconstruction

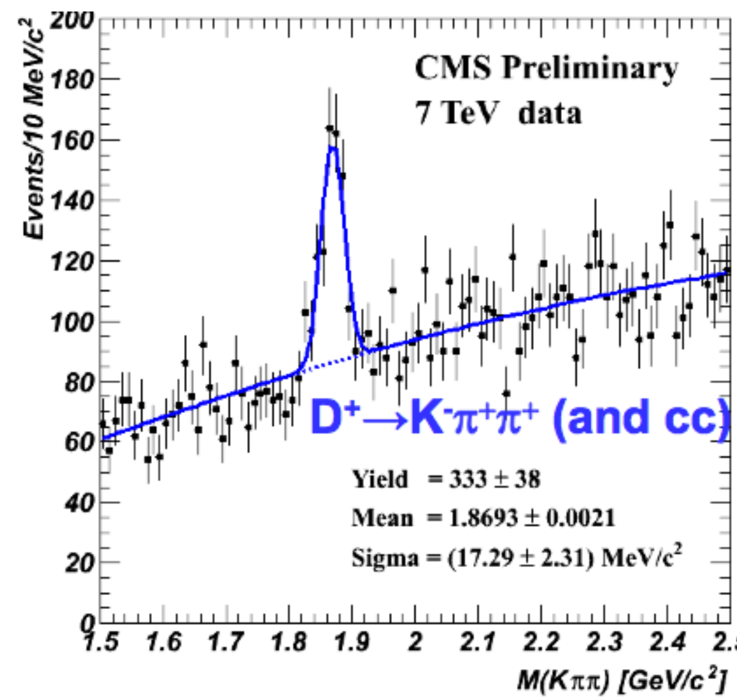




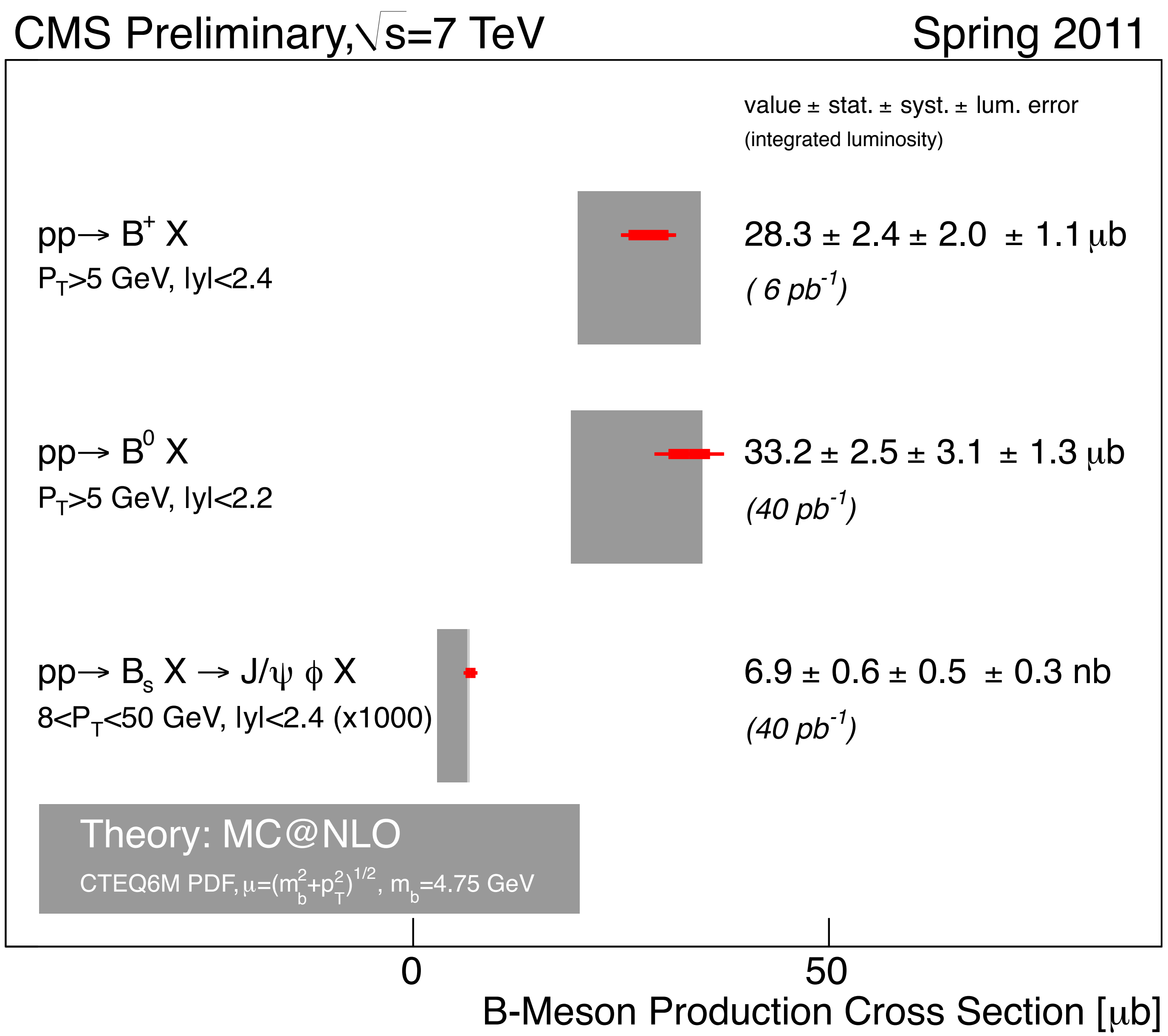








Exclusive B cross sections



$\Upsilon(2S+3S)$ Suppression

- Systematic uncertainty: 9.1%
- Statistical uncertainty: 55%
- Null-hypothesis testing:
  - p-value = 1%
  - Significance of suppression is 2.4 σ
- Relative suppression of $\Upsilon(2S+3S)$ vs. $\Upsilon(1S)$
  - Observation consistent with melting of the excited states only?
- What about cold nuclear matter effects?
  - Shadowing cancelling in the $\Upsilon(2S+3S)/\Upsilon(1S)$ ratio
  - pA run?

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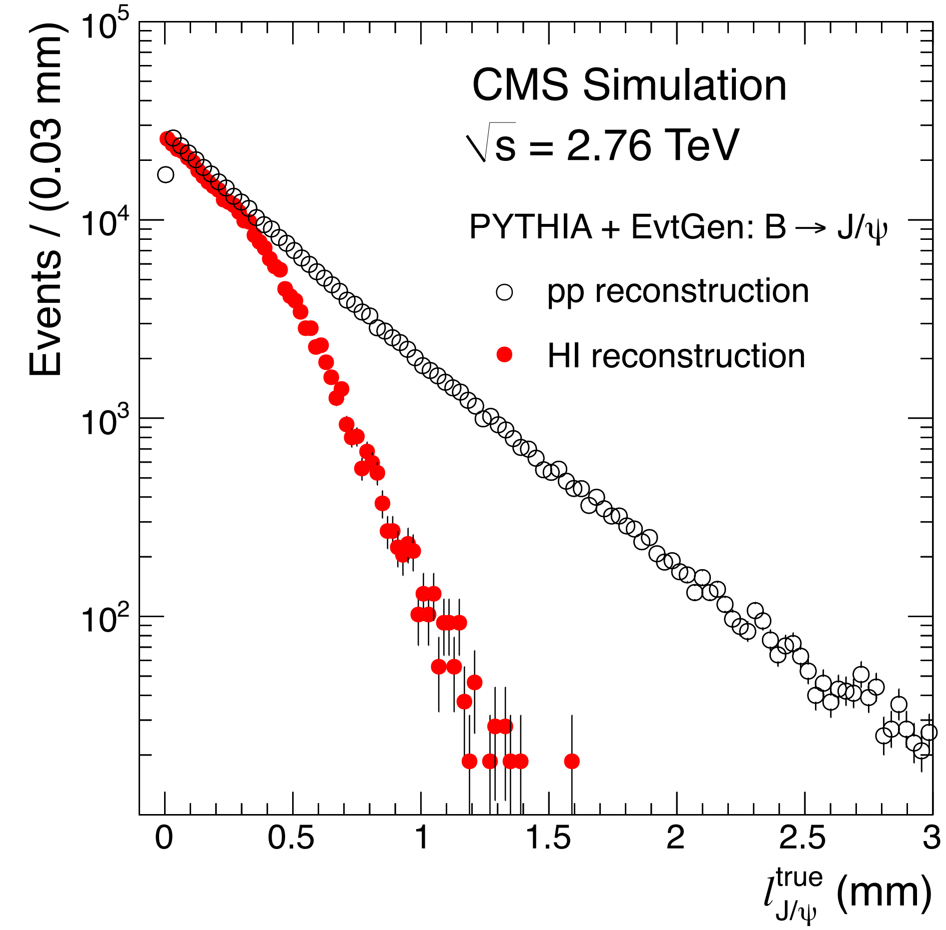
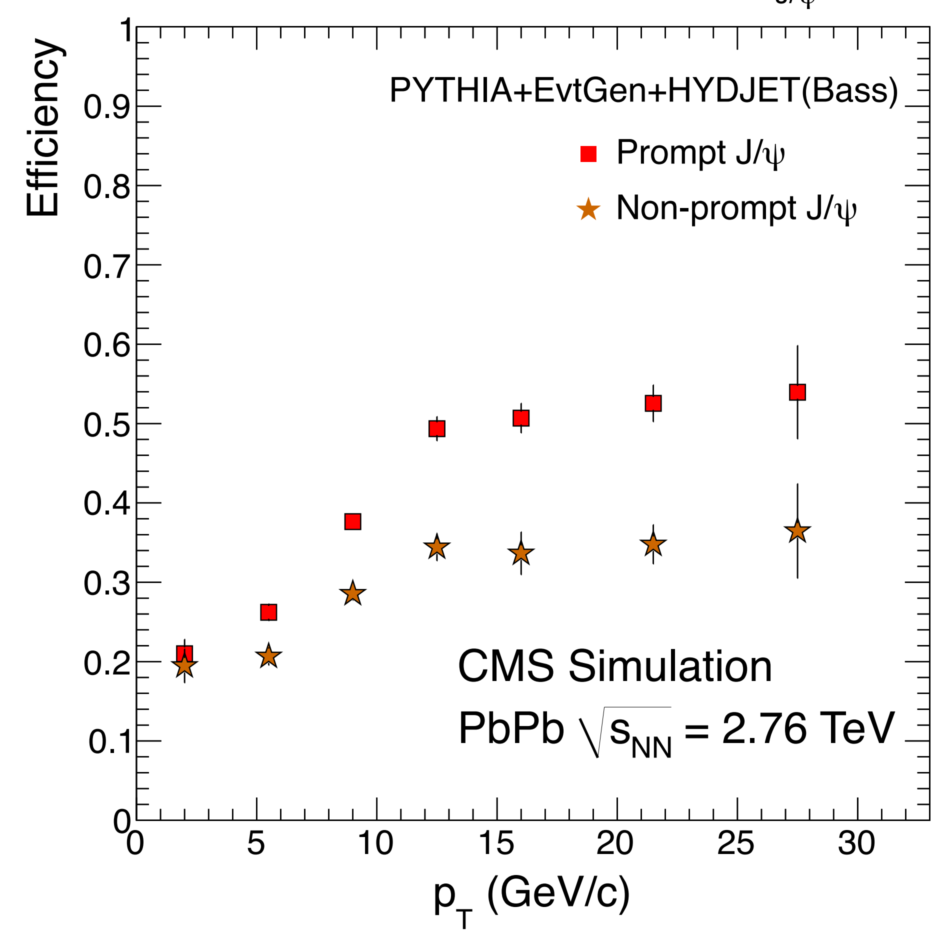
J/ψ in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

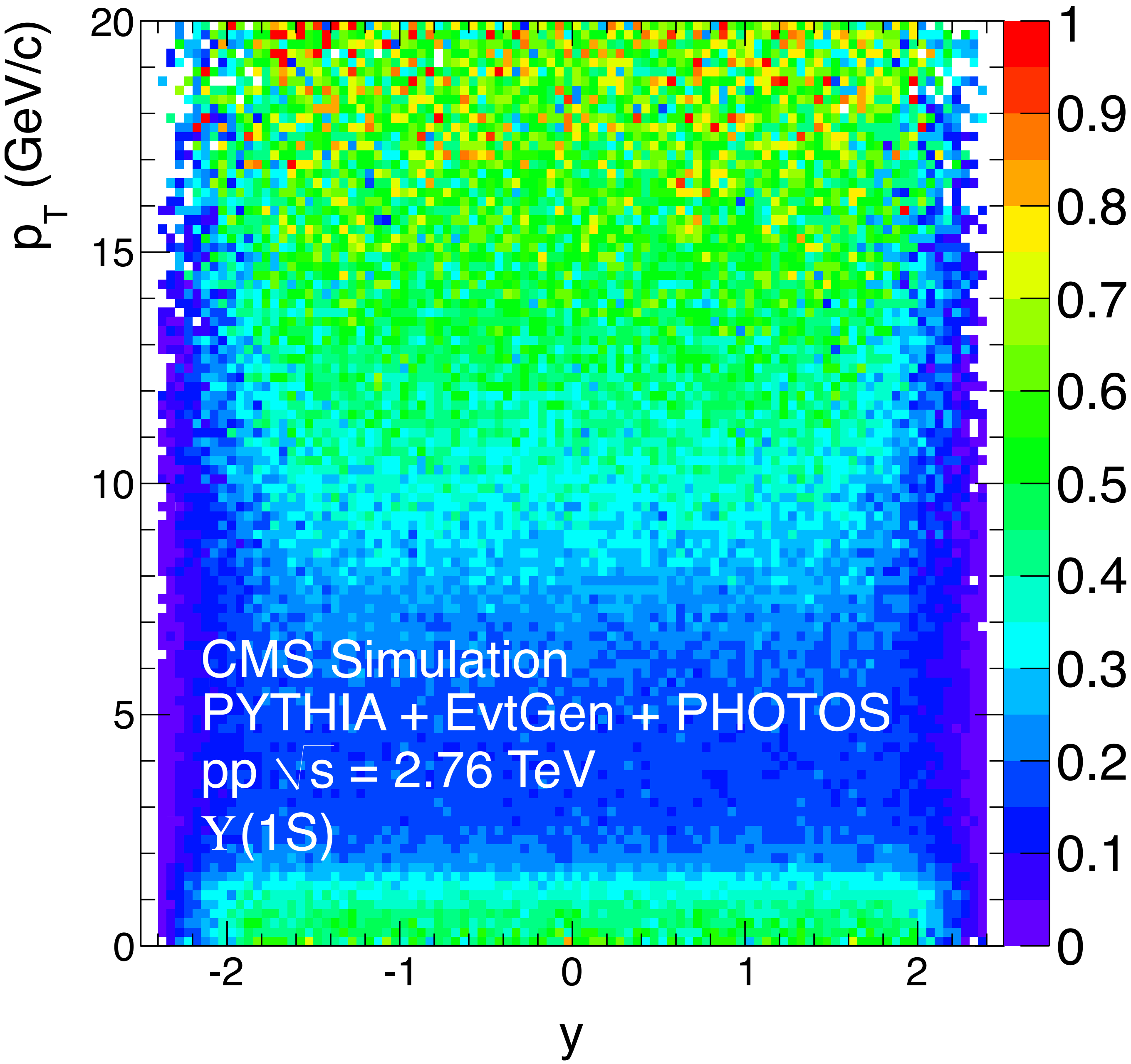
- Separate prompt & non-prompt J/ψ
- HI tracking algorithm uses vertex constraint
  - Smaller efficiency for non-prompt than for prompt J/ψ
  - Effect increases with p_T
- Efficiencies from Monte Carlo
  - Simulate signal with "realistic" PYTHIA
  - Embed signal in min. bias event simulated with HYDJET (also in data)
  - Validated MC by comparing efficiencies measured with "Tag & Probe" in MC and data



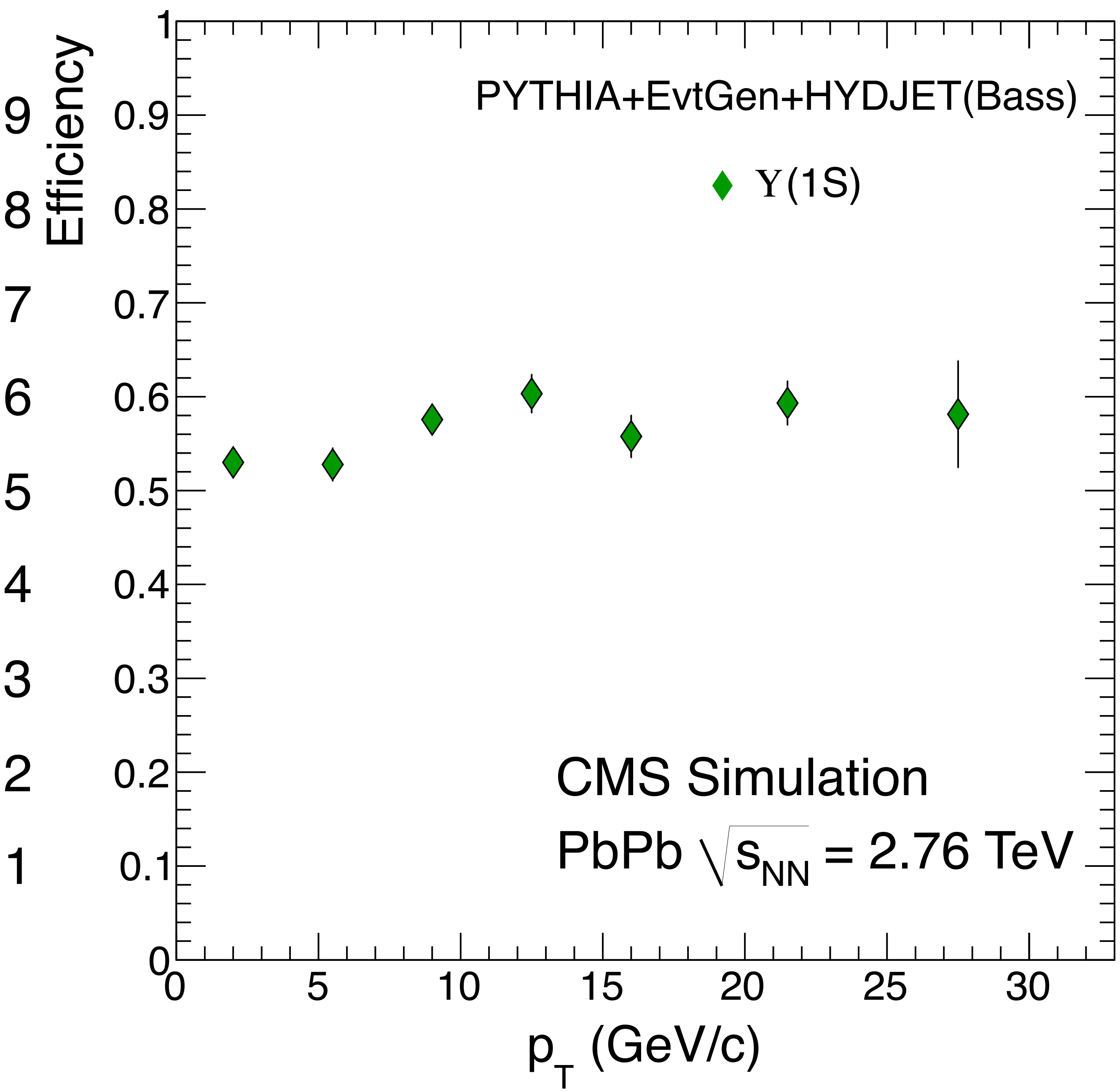


Υ(1S) Acceptance and Efficiency

Acceptance

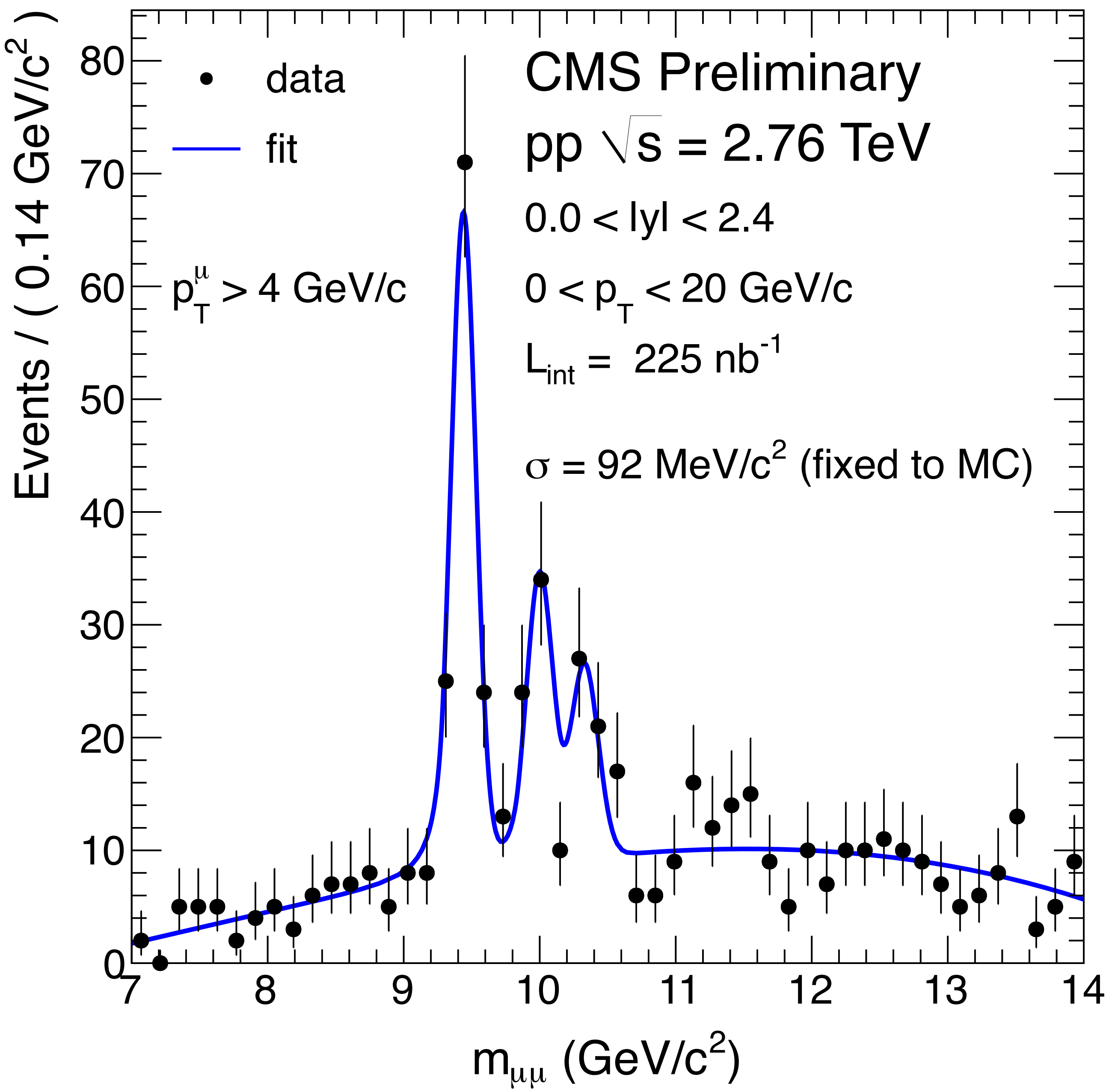


Efficiency



- Efficiencies from Monte Carlo
  - Validated with data driven method (Tag & Probe)
- Acceptance to $p_T = 0$ GeV/c

$\Upsilon(nS)$ in pp at $\sqrt{s}$ = 2.76 TeV

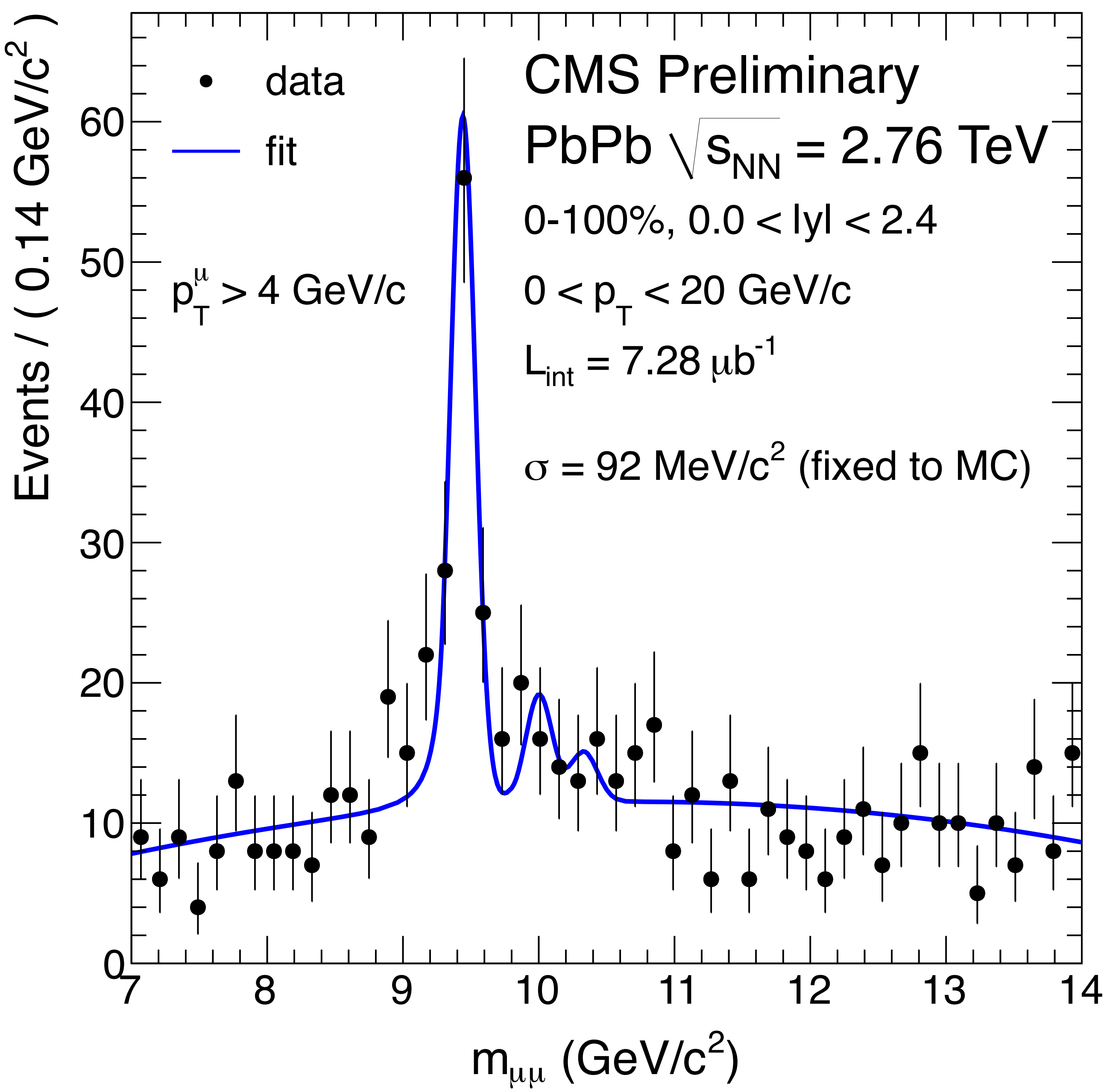


$$N_{\Upsilon(1S)} = 101 \pm 12$$

$$\Upsilon(2S+3S)/\Upsilon(1S)|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$$

- Signal shape: sum of three Crystal Ball functions
- Background: 2nd order polynomial
- Free parameters:
  - Υ(1S) mass
  - Υ(1S) yield
  - Υ(2S+3S)/Υ(1S) yield ratio
  - Υ(3S)/Υ(2S) yield ratio
  - background shape
- Mass ratios of higher states fixed to PDG
- Υ(1S) resolution fixed from MC: 92 MeV/c^2
  - Consistent with fits when leaving resolution free (both in pp and PbPb)
- Resolution of higher states fixed to scale with mass ratio $\sigma_{2S} = m_{2S}/m_{1S}\ \sigma_{1S}$
  - Crystal Ball radiative tail fixed to MC

Υ(nS) in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

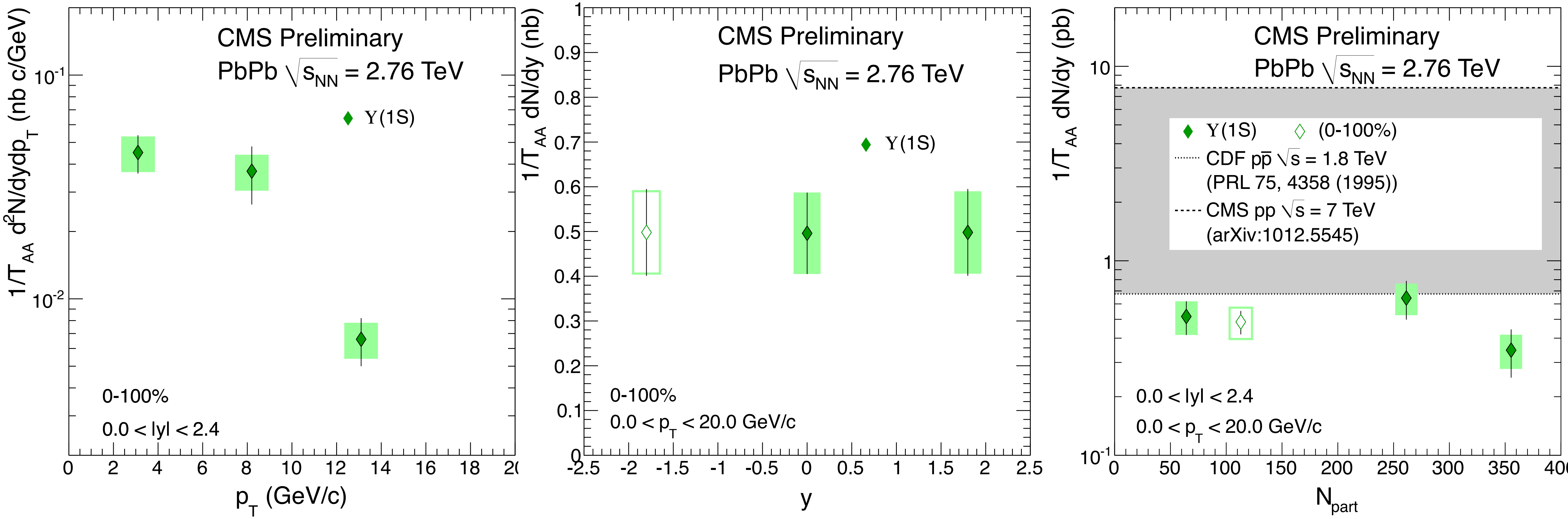


$$N_{\Upsilon(1S)} = 86 \pm 12$$

$$\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{PbPb}} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

- Signal shape: sum of three Crystal Ball functions
- Background: 2^{nd} order polynomial
- Free parameters:
  - Υ(1S) mass
  - Υ(1S) yield
  - Υ(2S+3S)/Υ(1S) yield ratio
  - Υ(3S)/Υ(2S) yield ratio
  - background shape
- Mass ratios of higher states fixed to PDG
- Υ(1S) resolution fixed from MC: 92 MeV/c^2
  - Consistent with fits when leaving resolution free (both in pp and PbPb)
- Resolution of higher states fixed to scale with mass ratio $\sigma_{2S} = m_{2S}/m_{1S}\,\sigma_{1S}$
  - Crystal Ball radiative tail fixed to MC

Υ(1S) Yield in PbPb



- Υ(1S) in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV below cross section measured in $p\bar{p}$ at 1.8 TeV by CDF
    - No strong centrality or rapidity dependence

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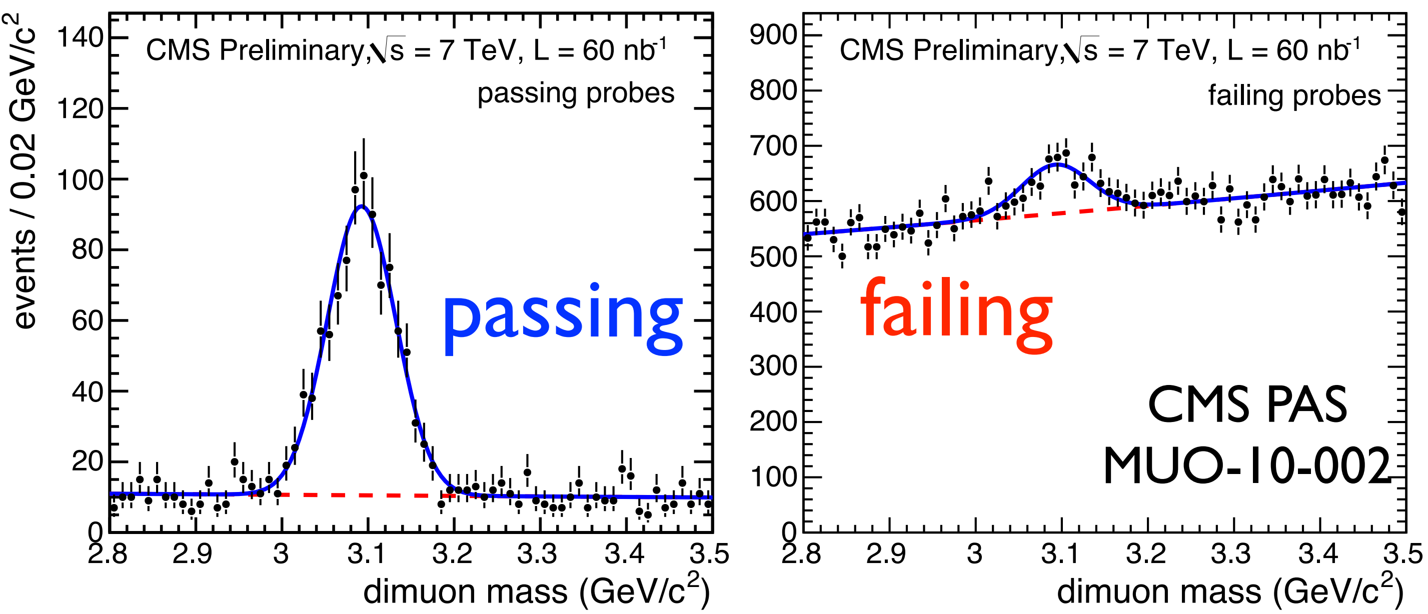
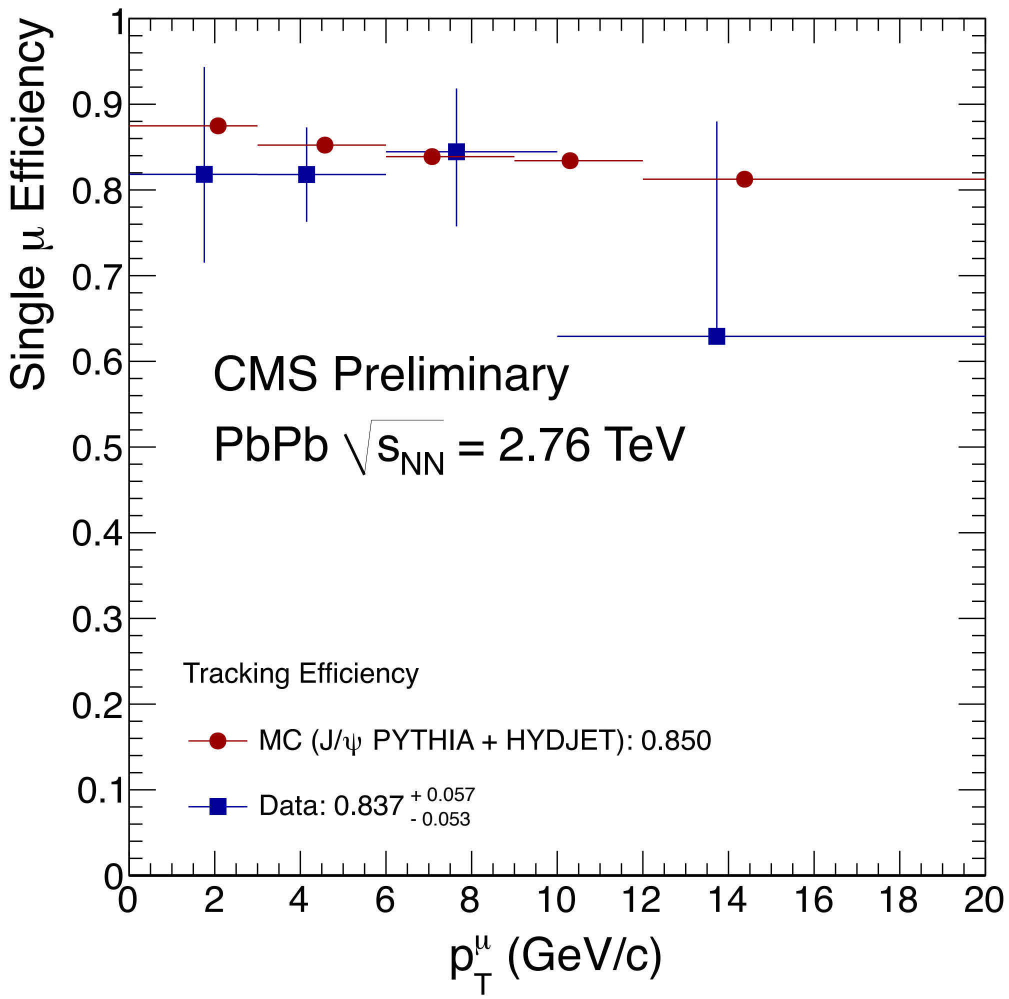
Tag & Probe





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Tracking efficiency:

- Tag: high quality muon
- Probe: track in the muon station
- Passing Probe:
  - Probe that is also reconstructed as global muon (i.e. with a track in the Si-tracker)
- Reconstruct J/ψ peak in passing probe-tag pairs and in failing probe-tag pairs
- Simultaneous fit to passing and failing probes allows us to measure the efficiency of the inner track reconstruction
- Agreement within stat. uncertainty of data → 14% systematic uncertainty on data/MC agreement
  - dominant systematic uncertainties on cross section results in PbPb