Heavy Flavor Measurements in Heavy Ion Collisions with CMS

Jian Sun
Purdue University
for the CMS Collaboration

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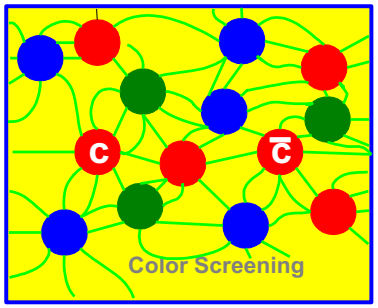
Why study heavy quarks in heavy ion collisions?

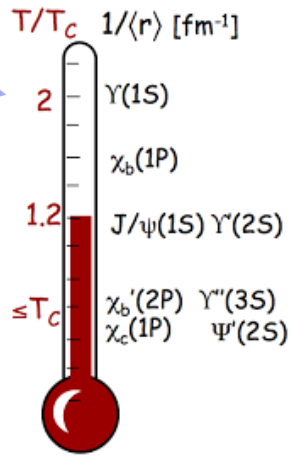
- **Heavy quarks are produced primarily at the early stages of the collisions**

→Experience the full evolution of the medium

→Good probe to properties of the medium



- **Quarkonia:** screening effect in QGP
  - Sequential melting of quarkonia
  - Probe the temperature of the medium

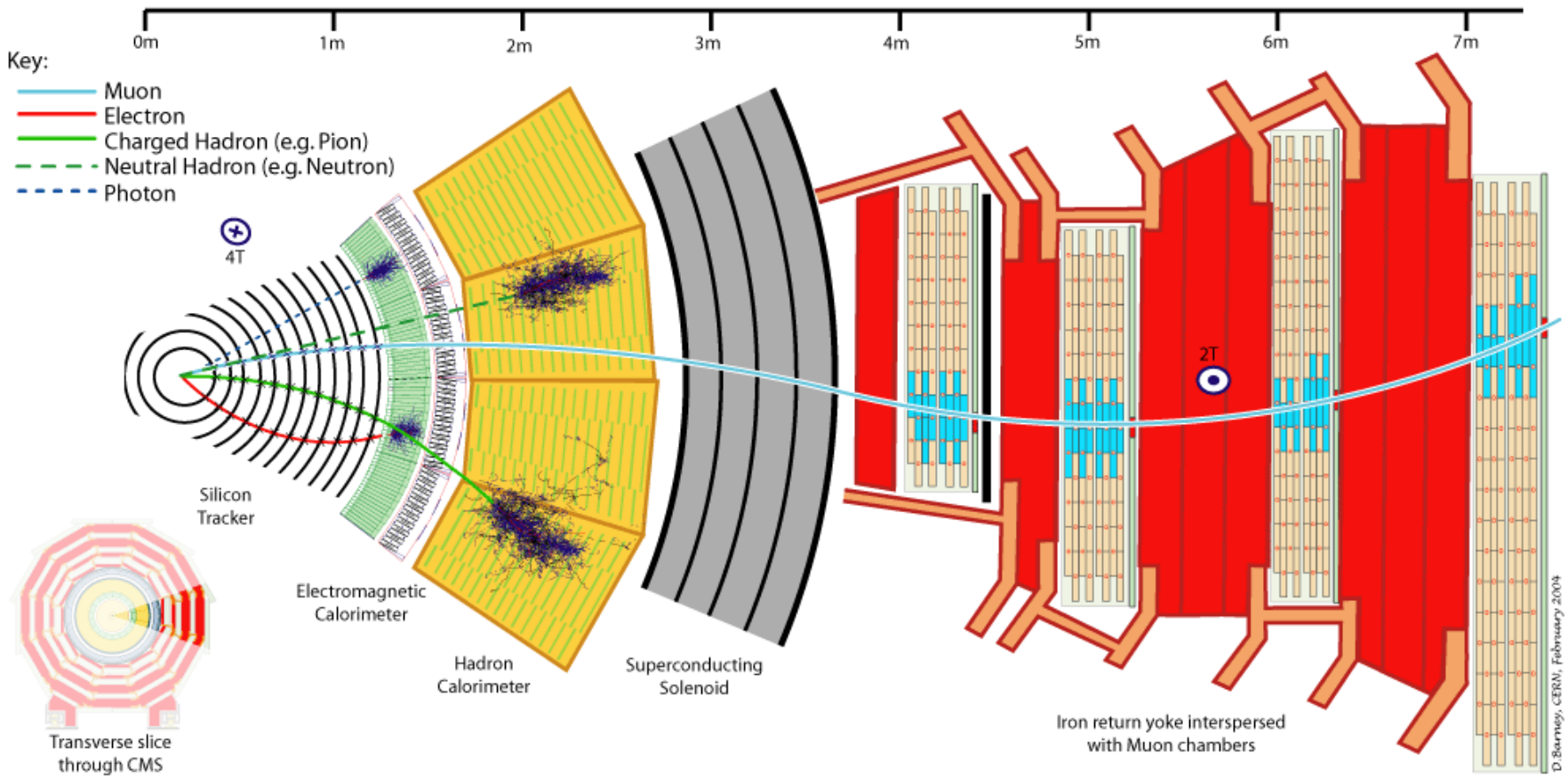


- **Open heavy flavor:** dead cone effect
  - Flavor dependence energy loss

$$\Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

- **Cold nuclear matter effect**

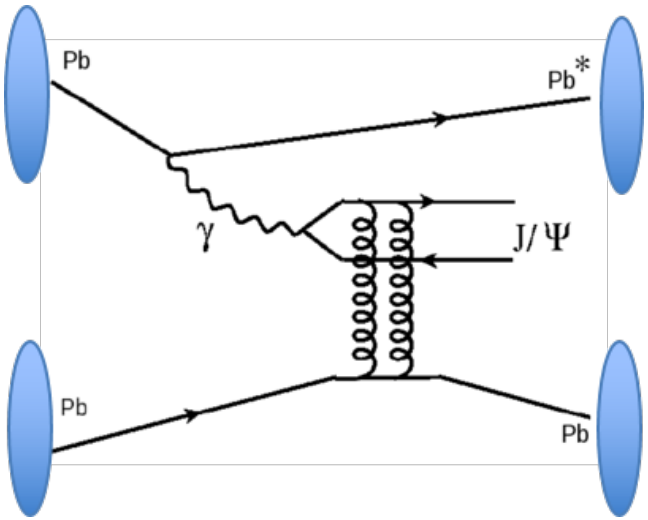
How does CMS measure Quarkonia?

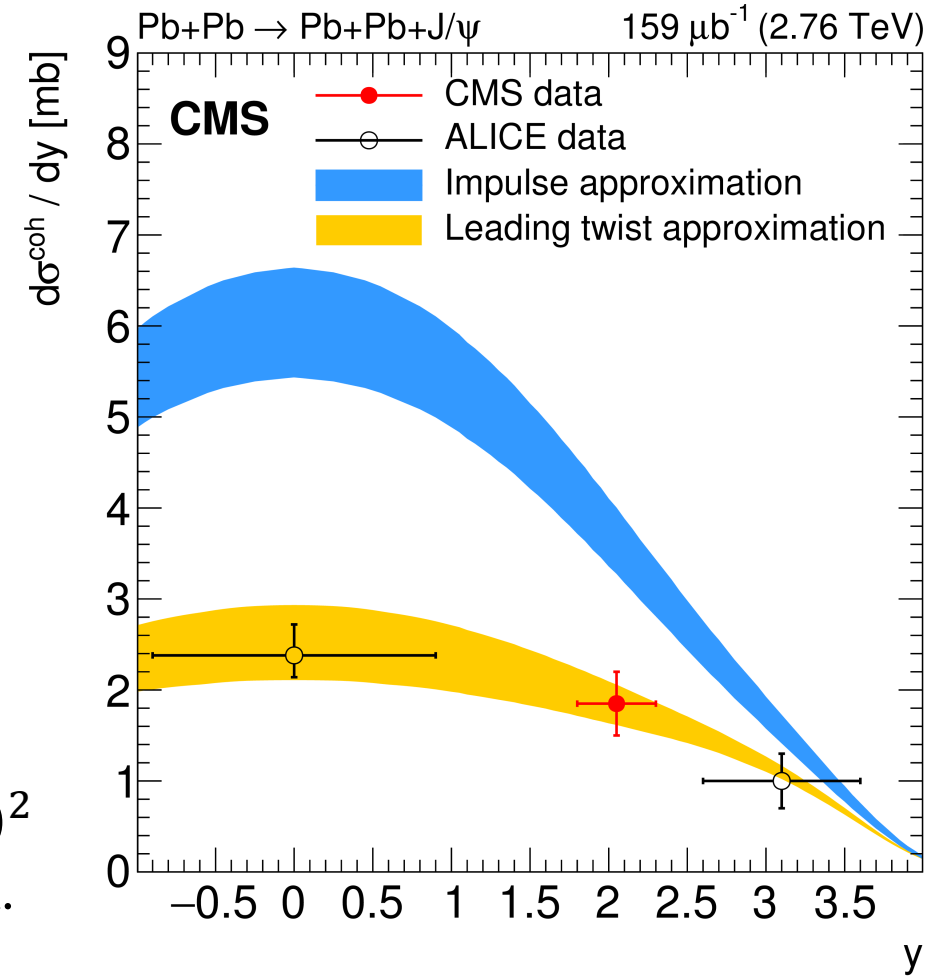


- ❑ Large acceptance
  - Muon & tracker ($|\eta| < 2.4$)
- ❑ Excellent MuID and trigger & track resolution
  - High Mass resolution

⇨ Quarkonia in di-muon channels.

Study cold nuclear matter effects in UPC PbPb collisions

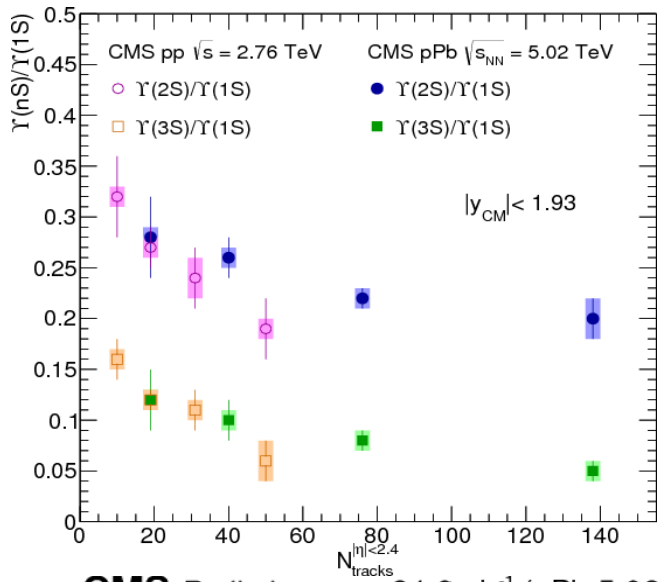


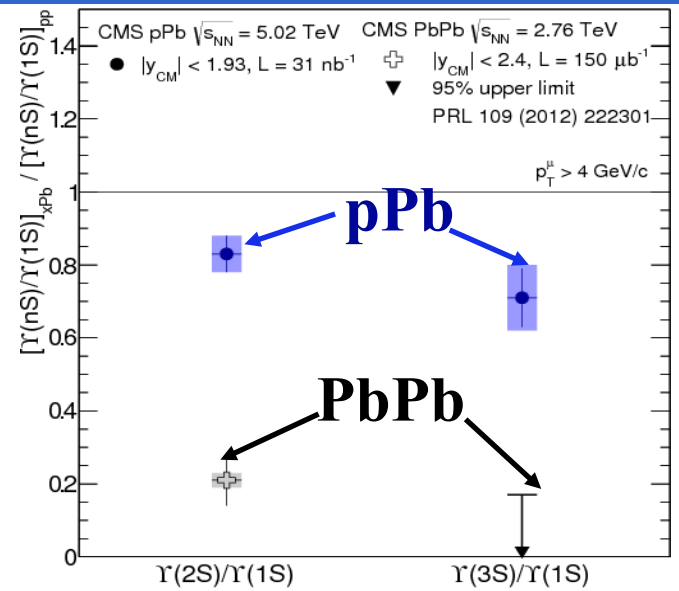


- ❑ Photon induced reaction in UPC
- ❑ Cross section ∝ (gluon density)^2
  - Accessing nPDF information.
- ❑ Measurements favor models with shadowing effects.

arXiv:1605.06966→submitted to PLB

Quarkonia production in pp and pPb collisions

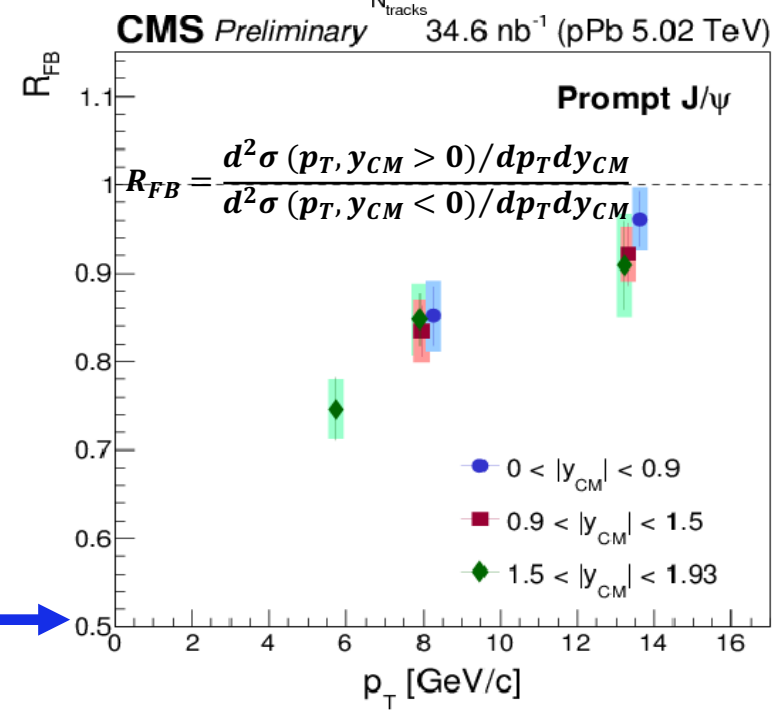




JHEP 04 (2014) 103

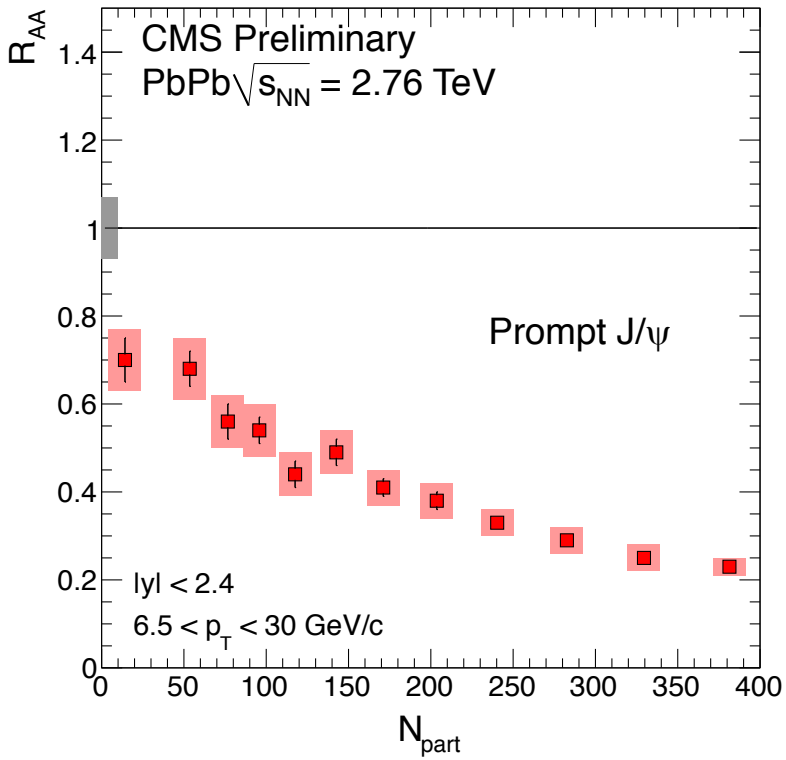
PRL 109 (2012) 222301

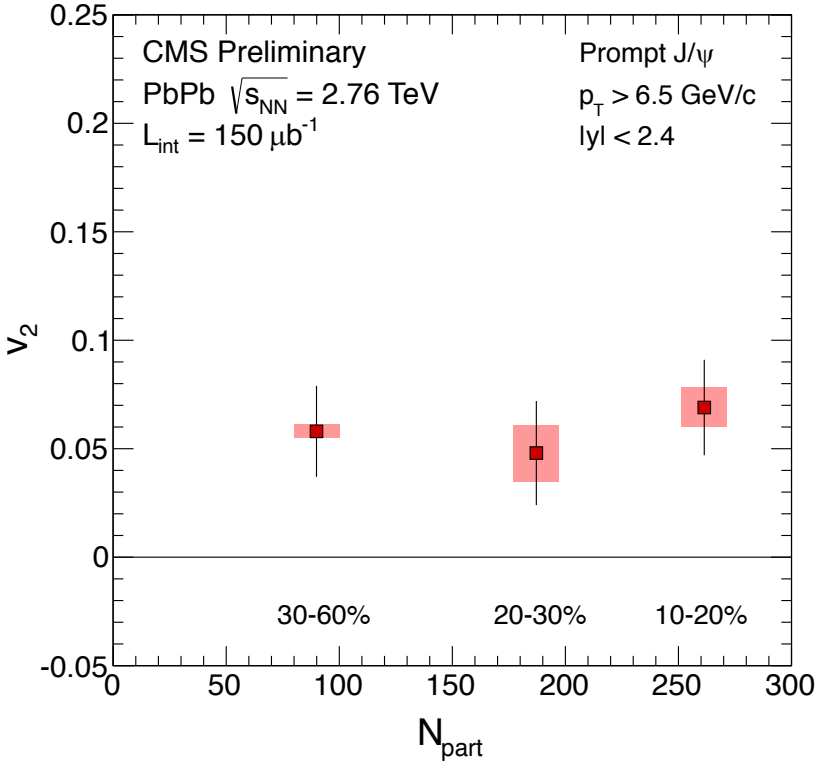
CMS PAS HIN-14-009



- ❑ $\Upsilon(ns)/\Upsilon(1s)$ decrease with multiplicity in pp and pPb collisions.
- ❑ ϒ Double ratio much higher in pPb than PbPb
- ❑ J/ψ production significant suppressed at low p_T in $y_{cms} > 0$
  - ➢ Just cold nuclear matter effect?

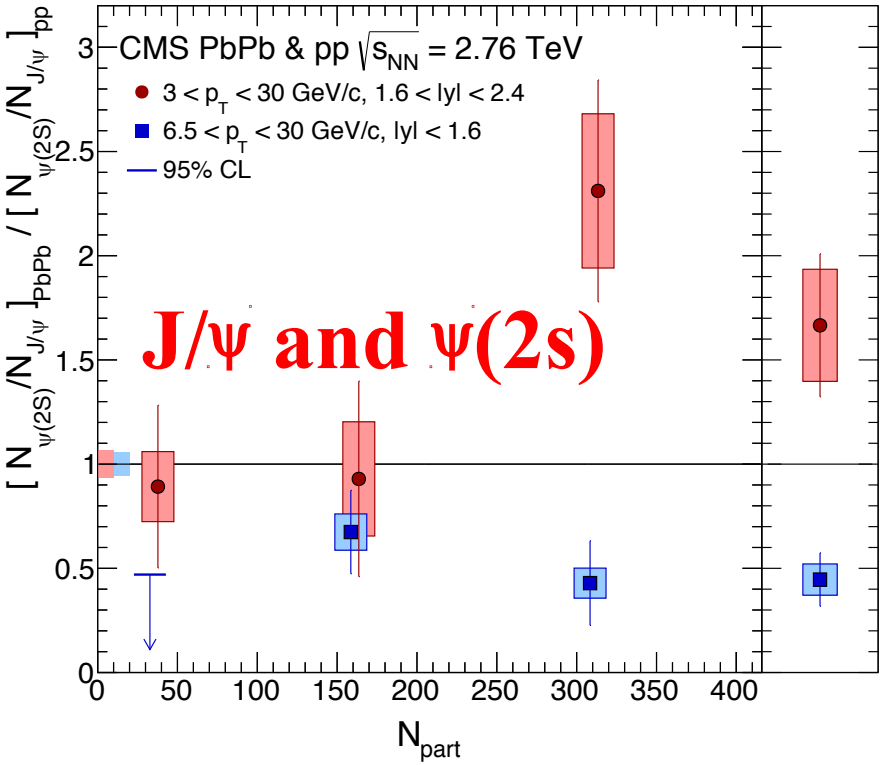
Prompt J/ψ R_{AA} and v_2 in PbPb collisions

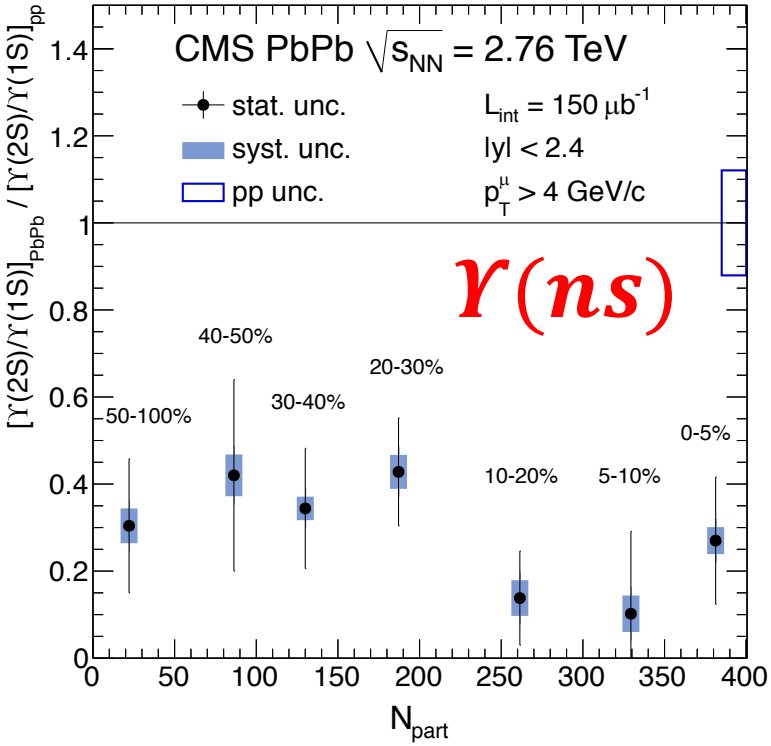




- Clear centrality dependence suppression at high p_T
- Non-zero v_2 observed at high p_T
  - v_2 =0.054±0.013±0.006 in |y|<2.4 for p_T > 6.5 GeV in 10-60% centrality.
  - Indicating path length dependence of energy loss

Quarkonia double ratio in PbPb



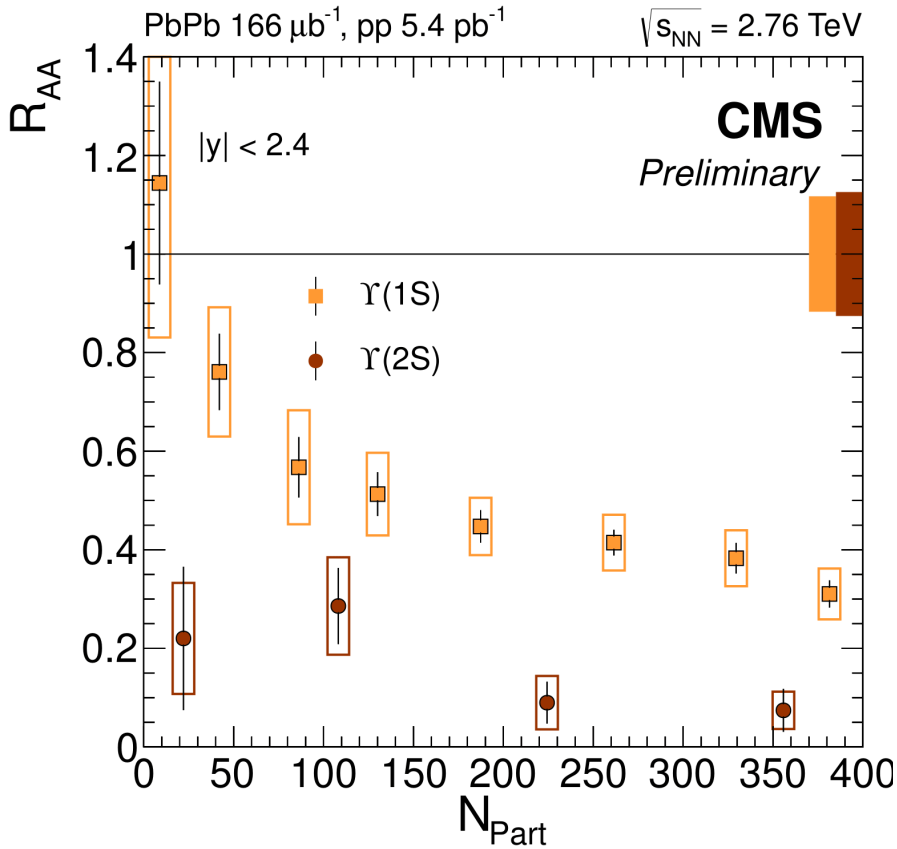


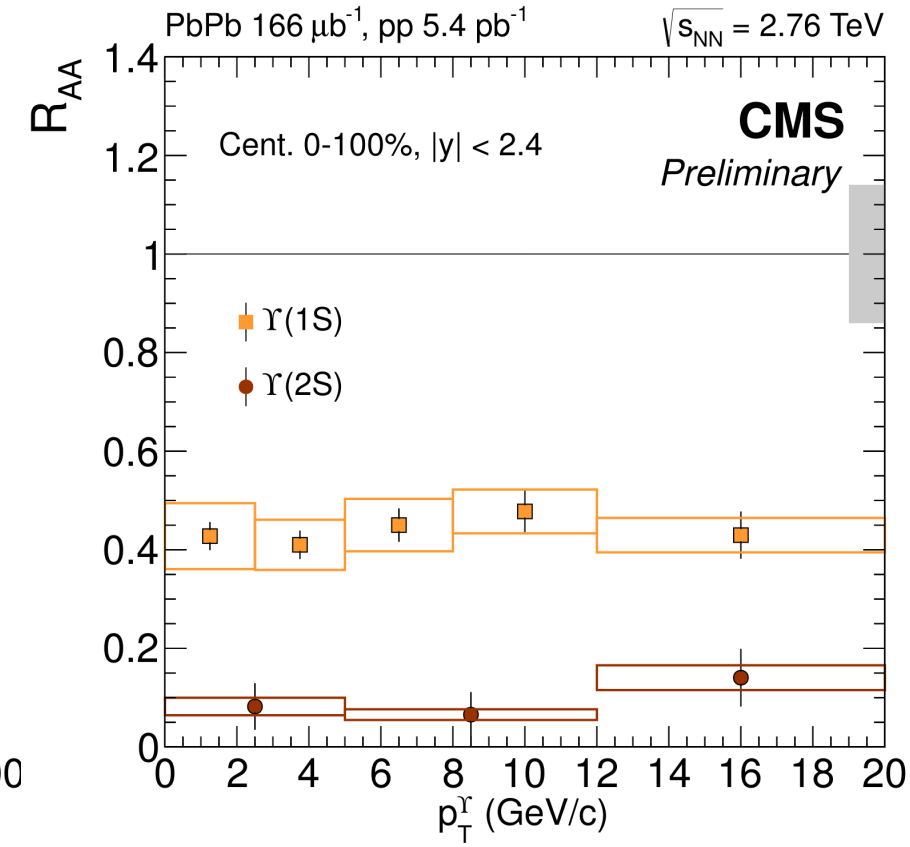
- J/ψ and ψ(2s)
  - At high p_T & mid-rapidity: ψ(2s) more suppressed than J/ψ
  - At low p_T & forward: more impact from regeneration?
- $\Upsilon(ns)$
  - $\Upsilon(2s)$ is more suppressed than $\Upsilon(1s)$

PRL 113 (2014) 262301

PRL 109 (2012) 222301

Υ(ns) R_{AA} in PbPb collisions

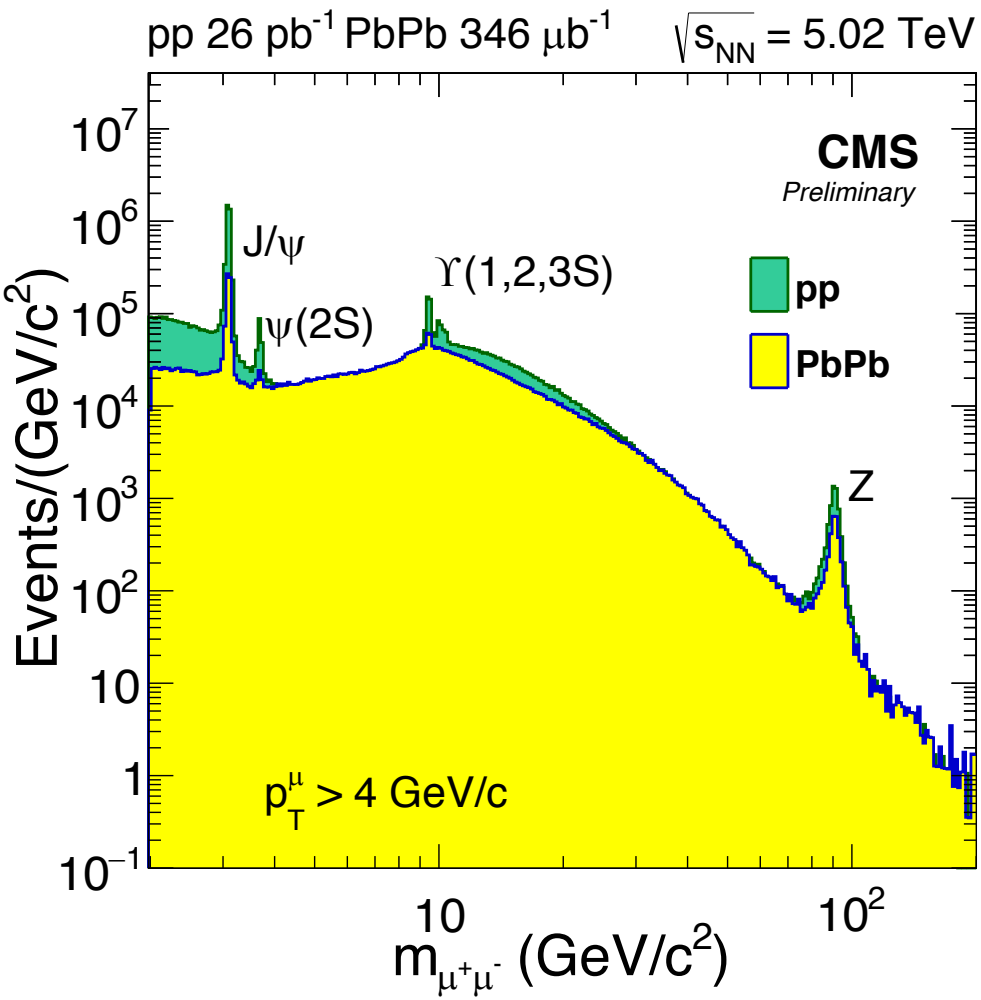




- $R_{AA}(\Upsilon(1s)) > R_{AA}(\Upsilon(2s))$
- Clear centrality dependence: suppression is largest in most central collisions
- No significant dependence on $p_{T.}$

CMS PAS HIN-15-001

New results are on the way!

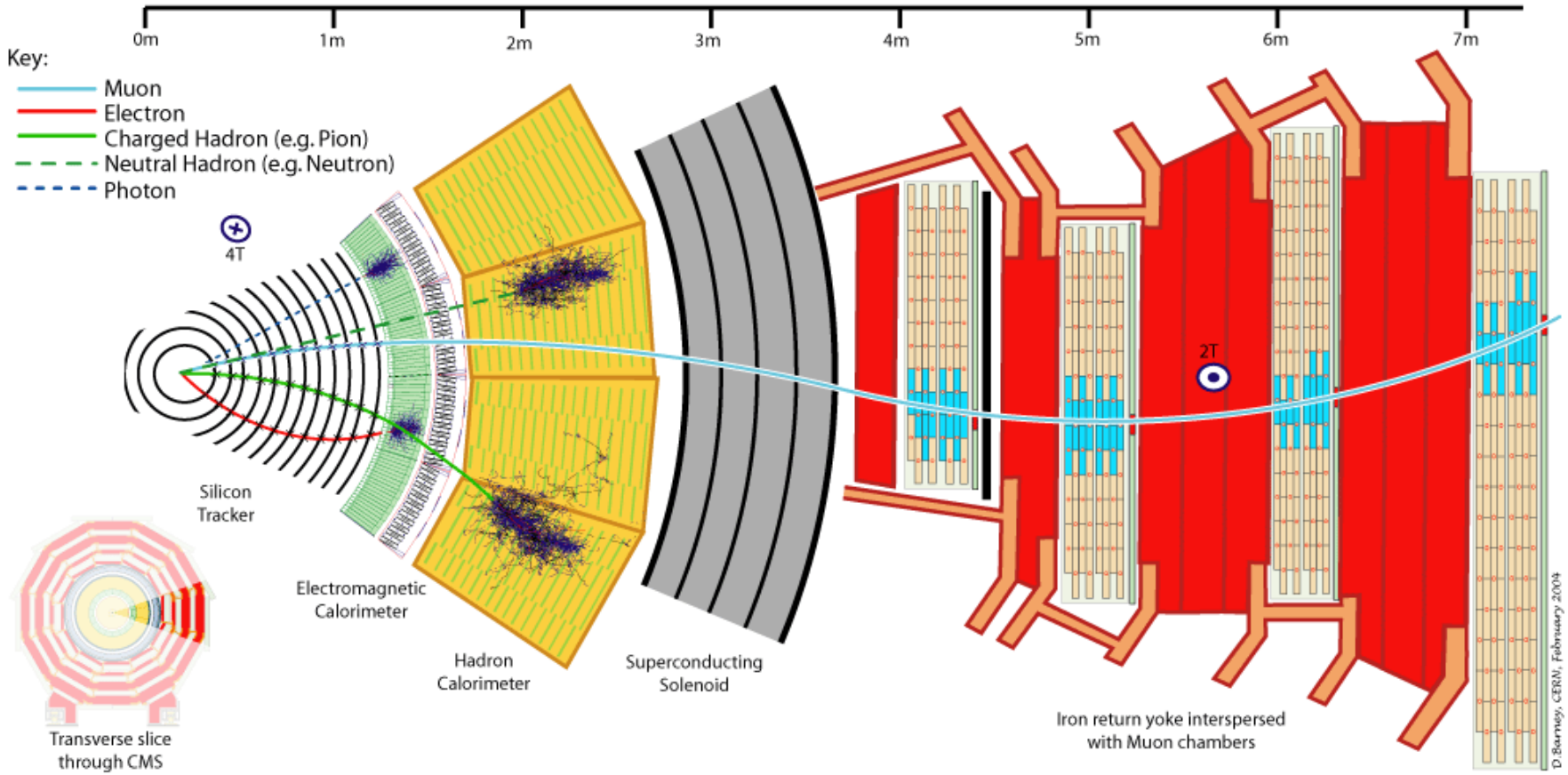


2013 pp data: $L_{int} = 5.4\ pb^{-1}$
2011 PbPb data: $L_{int} = 166\ \mu b^{-1}$

2015 pp data: $L_{int} = 26\ pb^{-1}$
2015 PbPb data: $L_{int} = 346\ \mu b^{-1}$

New results with 2015 data is coming soon!

How does CMS measure Open Heavy Flavor



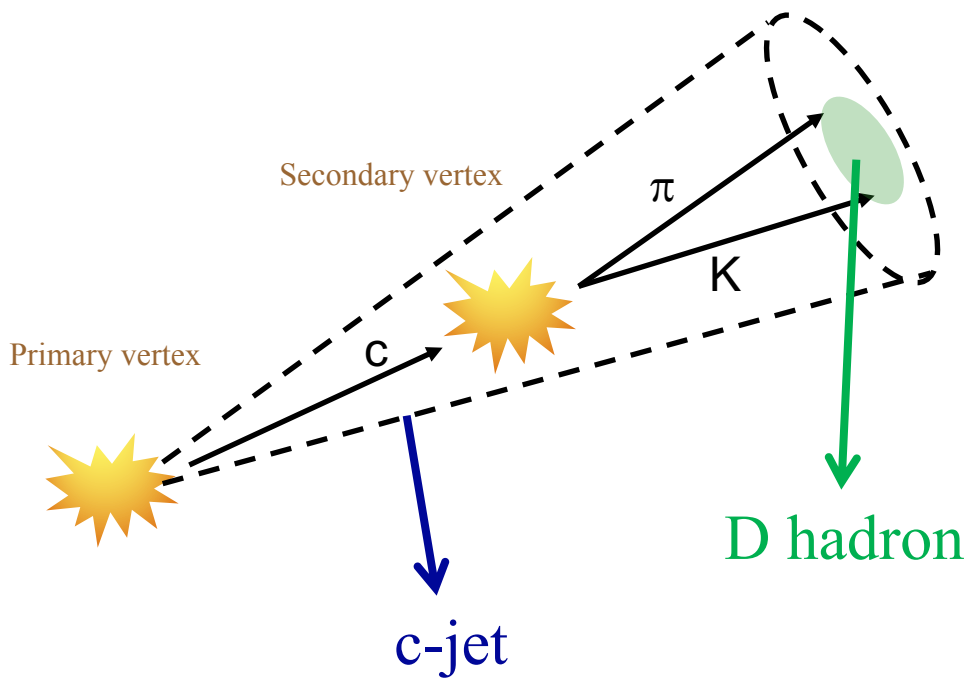
- ❑ Large acceptance
  - tracker ($|\eta| < 2.5$)
  - HCAL ($|\eta| < 5.2$)
  - ECAL ($|\eta| < 3.0$)
- ❑ Excellent track & energy resolution

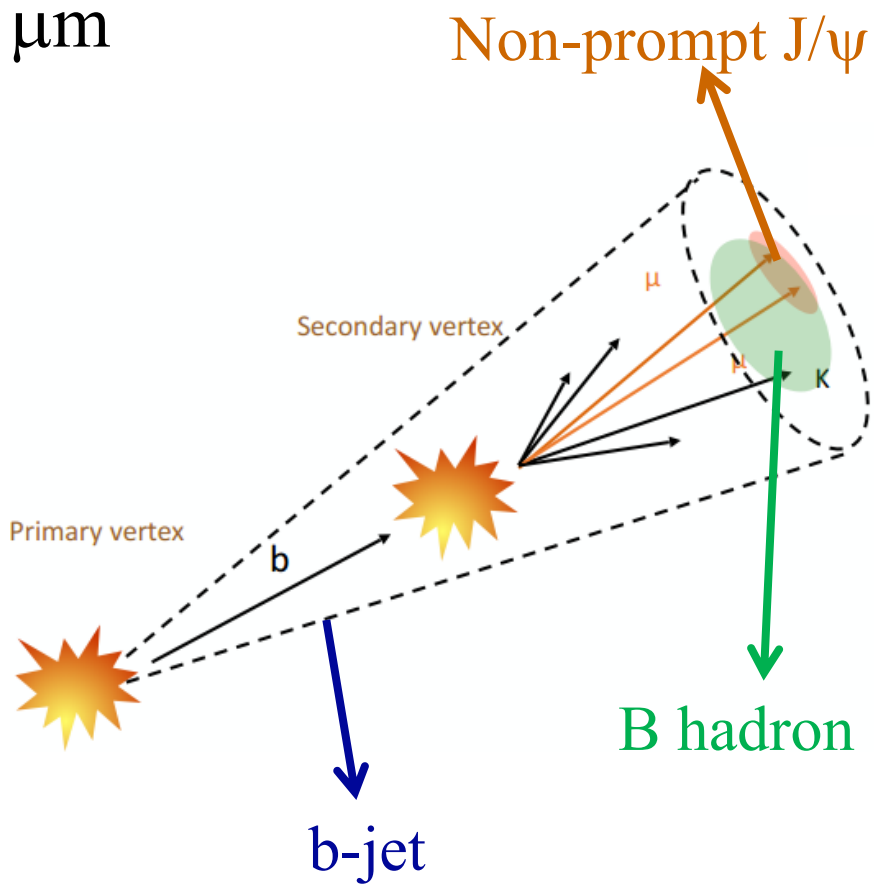
⇒

- ✓ Jet
- ✓ Direct RECO of decay hadrons

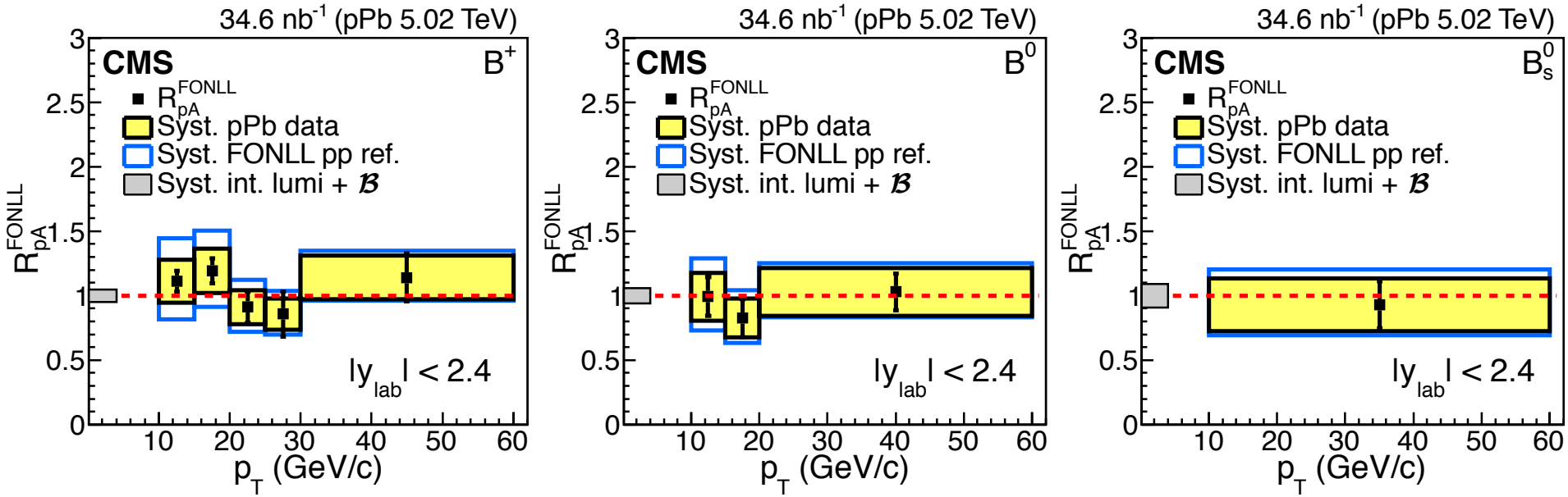
Open heavy flavor measurements with CMS

- c/b-jet, D/B hadron and non-prompt J/ψ
  - cτ (D meson) ~ 100 to 300 μm
  - cτ (B meson) ~ 400 to 500 μm





B mesons in pPb: R_{pA}^{FONLL}



❑Direct reconstruction of B mesons.

$B^+ \rightarrow J/\psi\ K^+ \rightarrow \mu^+\mu^-\ K^+$

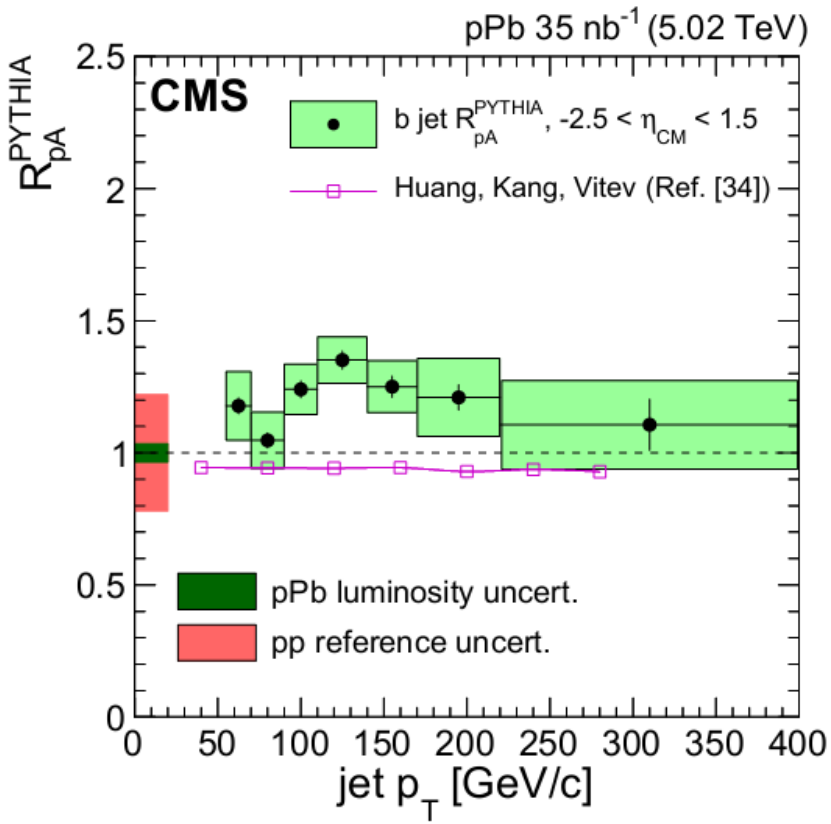
$B^0 \rightarrow J/\psi\ K^{0*} \rightarrow \mu^+\mu^-\ K^+\pi^-$

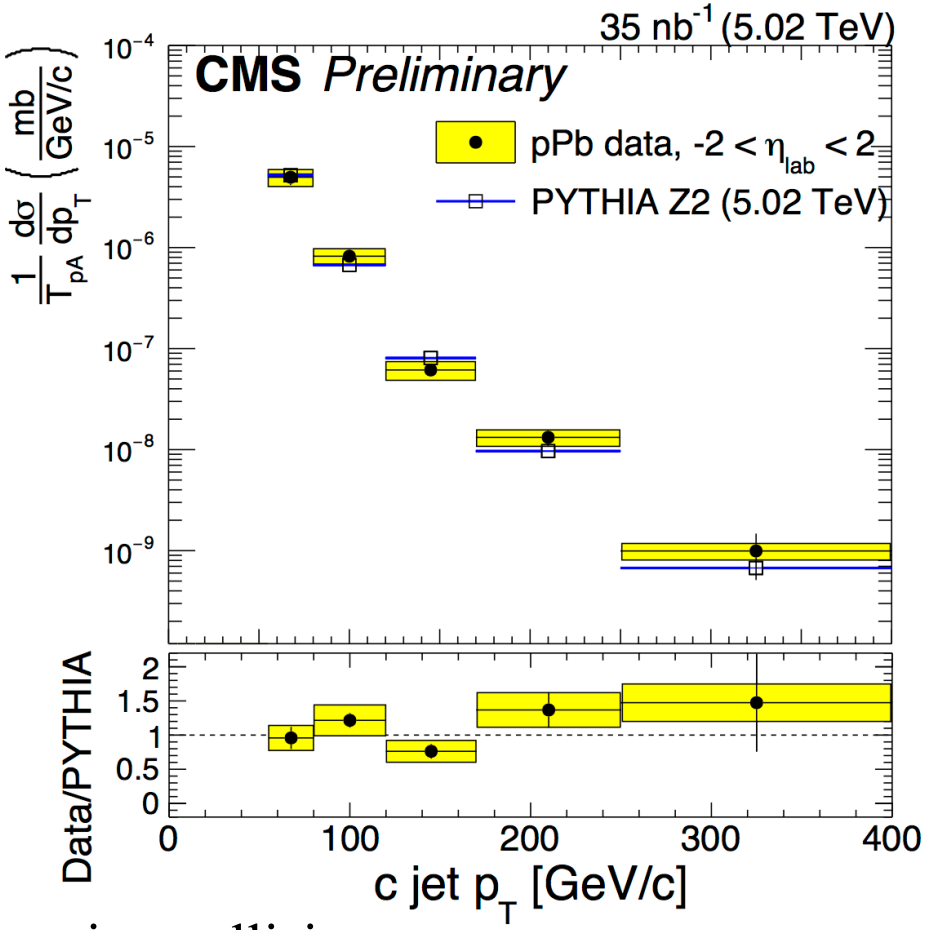
$B_s \rightarrow J/\psi\ \varphi \rightarrow \mu^+\mu^-\ K^+K^-$

- FONLL prediction as pp reference
- R_{pA} is consistent with unity within uncertainties
  - No significant cold nuclear matter effects observed within uncertainties at $p_T > 10$ GeV

PRL 116 (2016) 032301

b-jet and c-jet production in pPb collisions



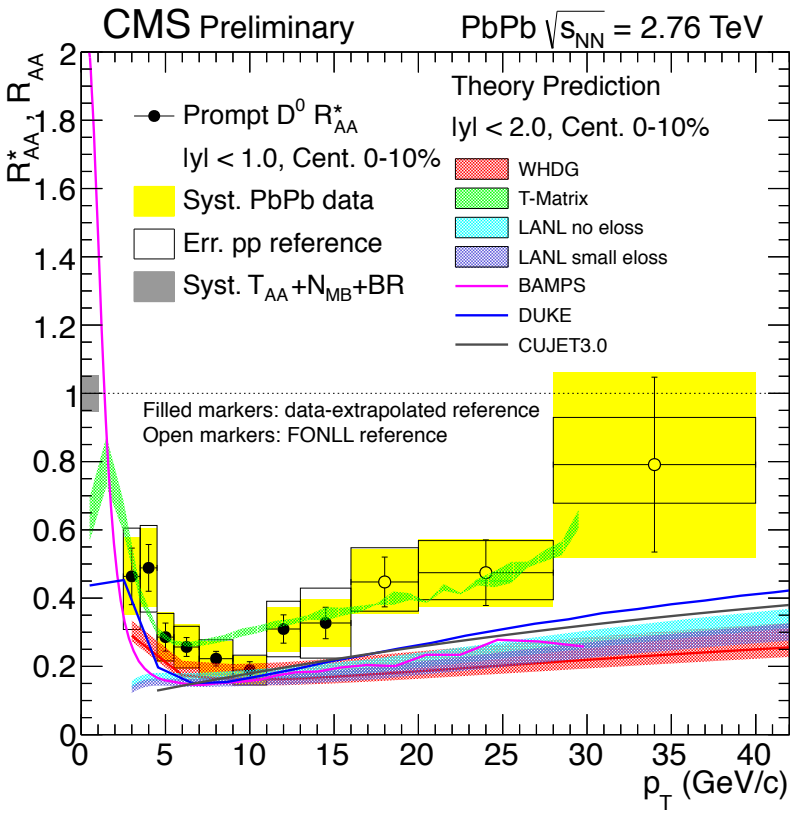


- First c-jet measurements in heavy ion collisions
- pp reference obtained from PYTHIA 6
- No significant cold nuclear matter effect at $p_T > 50$ GeV within uncertainties

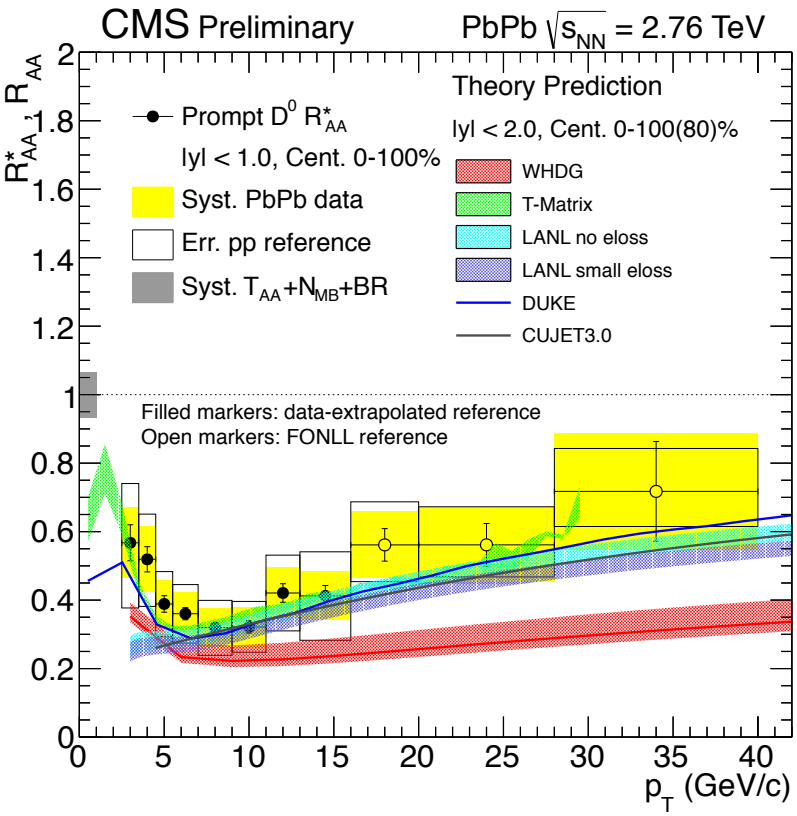
PLB 754 (2016) 59

CMS PAS HIN-15-012

D^0 productions in PbPb collisions at 2.76 TeV



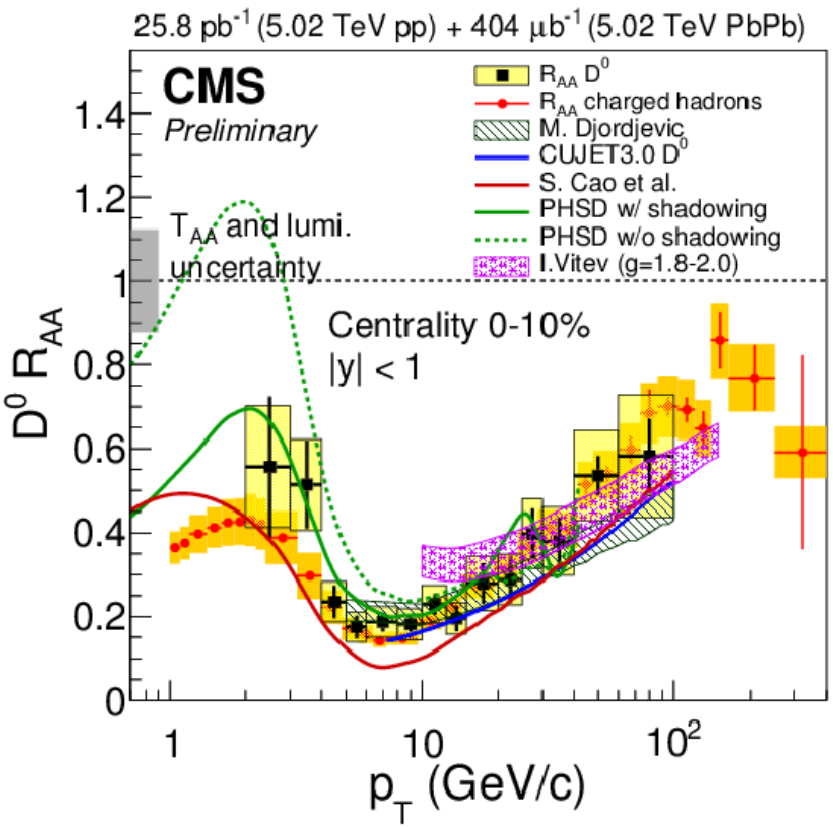
Cent. 0-10%



Cent. 0-100%

- **pp reference @ 2.76 TeV ➔ ALICE 7 TeV pp measurement + FONLL**
- R_{AA} going down for p_T < 10 GeV/c and going up at higher p_T
- The centrality dependence in some models is inconsistent with data

D^0 productions in PbPb collisions at 5.02 TeV



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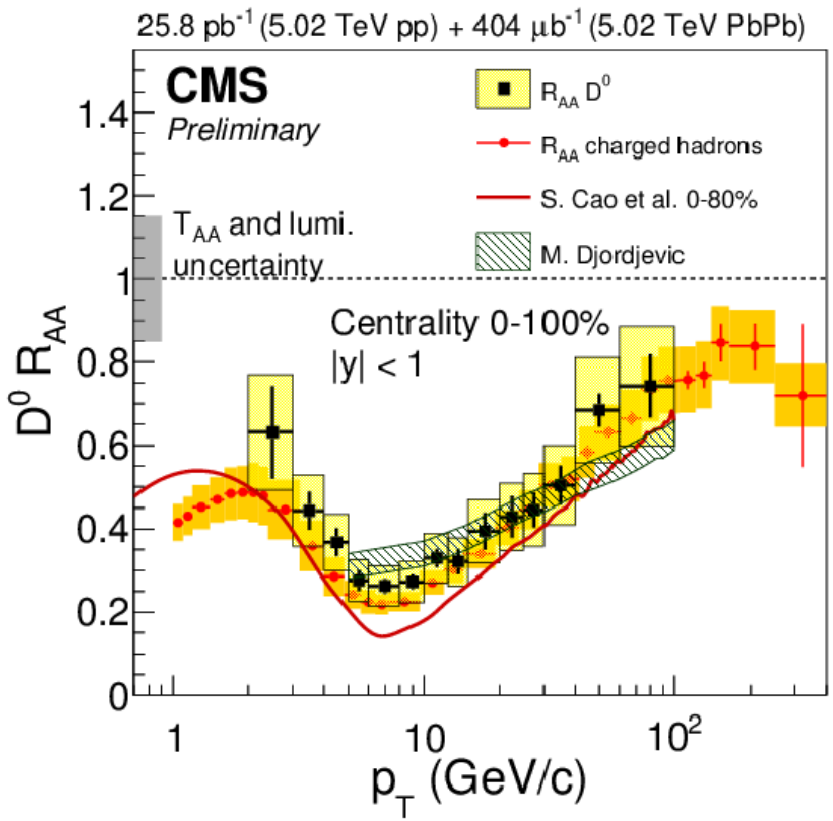
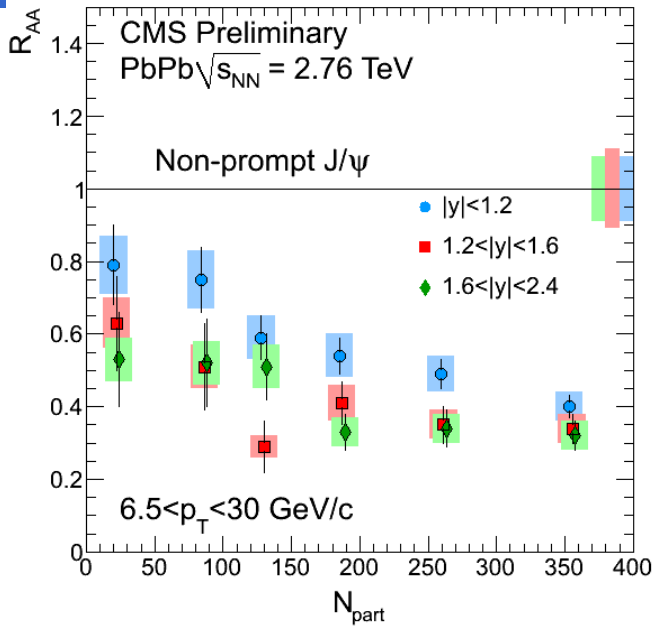
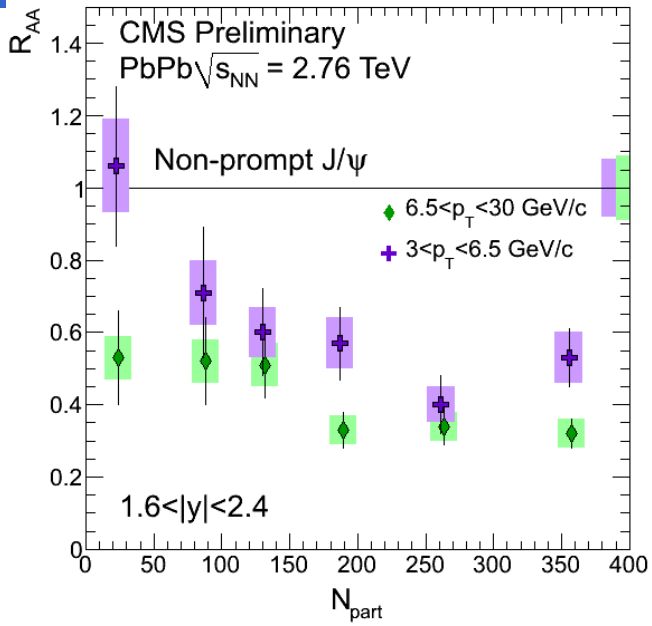


Cent. 0-100%

- **New measurements for D^0 and charged hadron from 5.02 TeV PbPb and pp**
  - D^0 up to 100 GeV/c, charged hadron up to 400 GeV/c
- R_{AA} dependence on p_T similar as at 2.76 TeV
  - Measured pp reference @ 5.02 TeV
- Consistent with charged particle R_{AA} within uncertainties

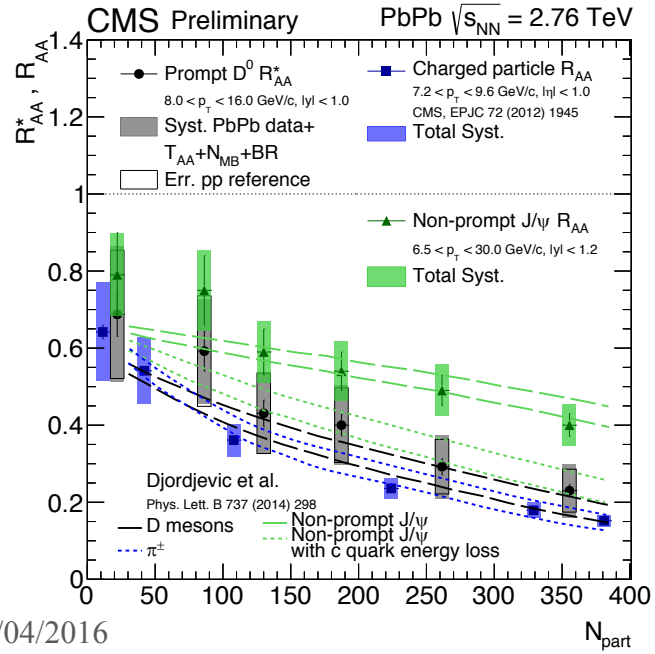
B→J/ψ production in PbPb collisions at 2.76 TeV





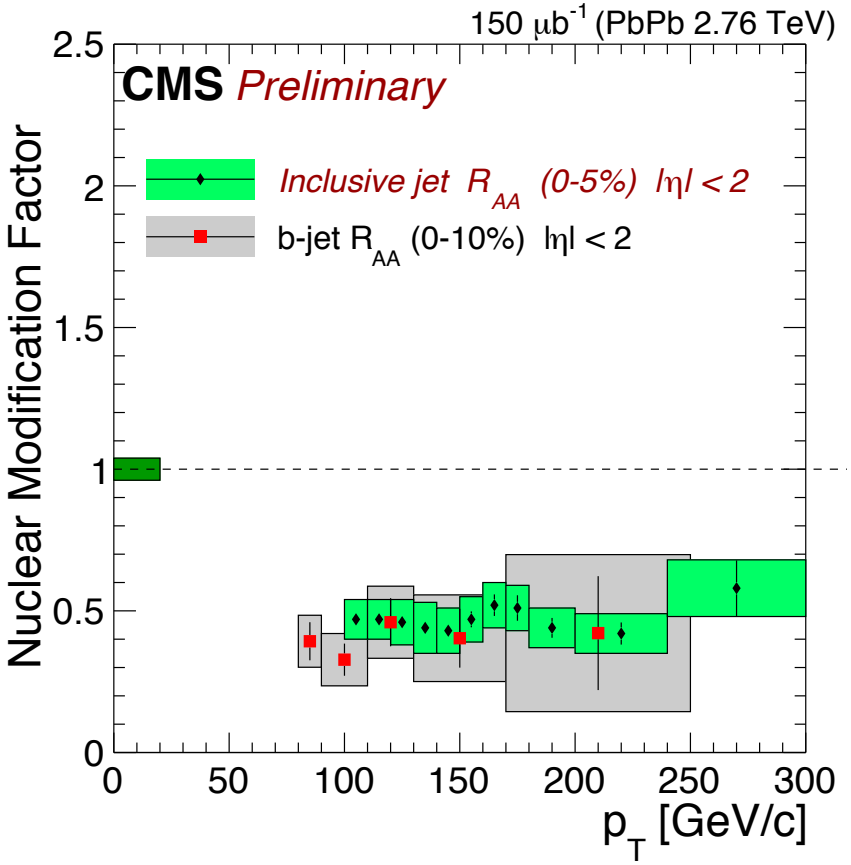
CMS PAS HIN-12-014

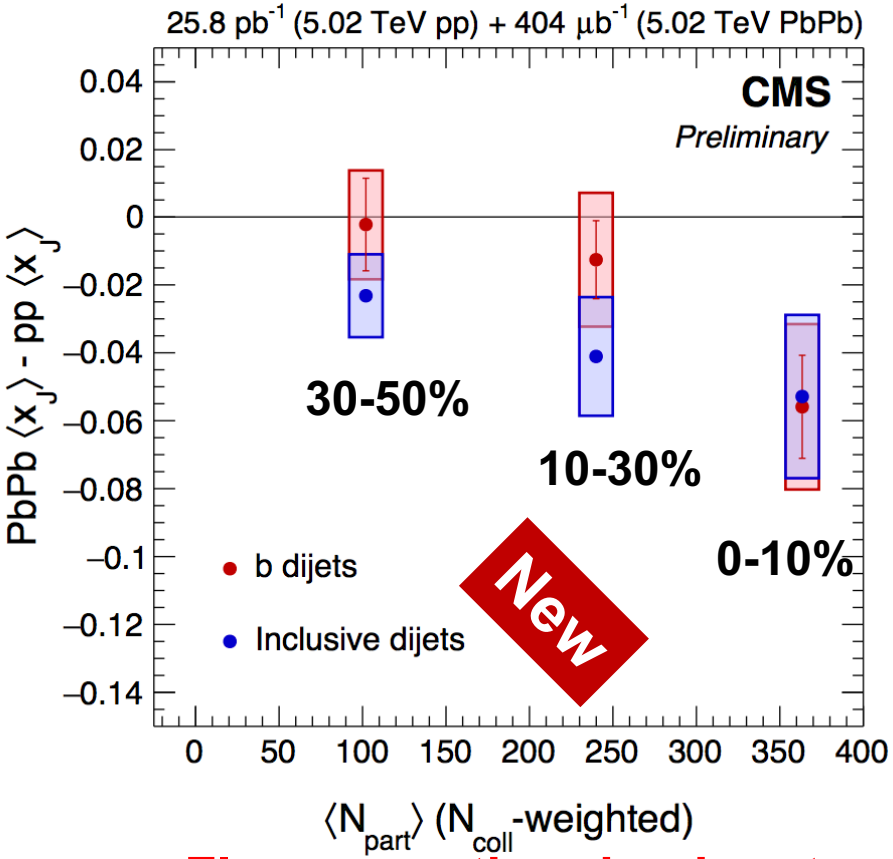
CMS PAS HIN-15-005



- ❑ Significant B suppression observed.
  - even at most peripheral bin, shadowing?
- ❑ Indicating larger suppression in more forward rapidity region.
- ❑ Less suppression in lower p_T
- ❑ Indication of R_{AA} (D^0) > R_{AA}(B→J/ψ)

B-Jet measurements in PbPb collisions





Flavor creation not dominant **Flavor creation dominant**

- B-Jet suppression is consistent with inclusive jet suppression within uncertainties
- **For the first time, the imbalance of b dijets is measured**
  - **Similar level with inclusive jets**

Summary

Quarkonia

- Υ suppression in PbPb collisions ordered:
  $R_{AA}(\Upsilon(1s)) > R_{AA}(\Upsilon(2s)) > R_{AA}(\Upsilon(3s))$
- $\psi(2s)$ more suppressed than J/ψ at high p_T but less suppressed at low p_T
- Significant J/ψ v_2 observed at high p_T in PbPb collisions

Open heavy flavor

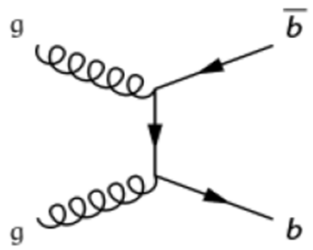
- No significant cold nuclear matter effects observed
- Prompt D^0 R_{AA} consistent with charged particle R_{AA} within uncertainties
- Bottom measurements
  - At intermediate p_T, indication of $R_{AA}(B \rightarrow J/\psi) > R_{AA}(D^0)$
  - At high p_T, R_{AA} (b-jet) $\approx$ R_{AA} (inclusive jet)
  - Imbalance of b dijets is measured and at the similar level with inclusive jet

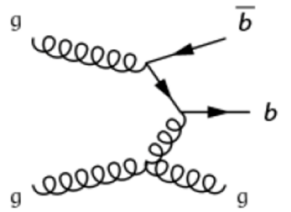
More new resutls are coming!

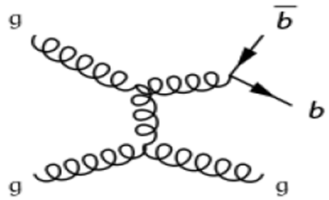
- **Quarkonia double ratio in PbPb collisions at 5.02 TeV**
  - Better precision than previous measurements
- **D meson v_n**
  - charm collective behavior
- **B meson in PbPb via direct reconstruction**
  - more direct access to bottom-medium interaction
- **B→D+X and B→J/ψ +X in PbPb**
  - complementary to direct B reconstruction but with higher precision
- Story continues

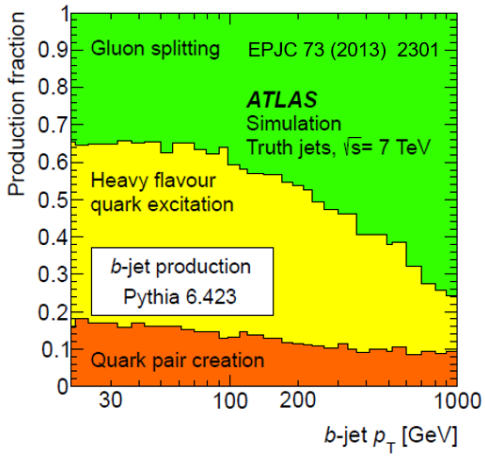
Backup

HF production









LO process: Flavour Creation (FCR)

→ gluon fusion or light qq annihilation

→ bb produced back-to-back in azimuthal plane and symmetric in p_T

NLO process: Flavour Excitation (FEX)

→ excitation of b/b̄ sea quark by gluon or light quark/anti-quark

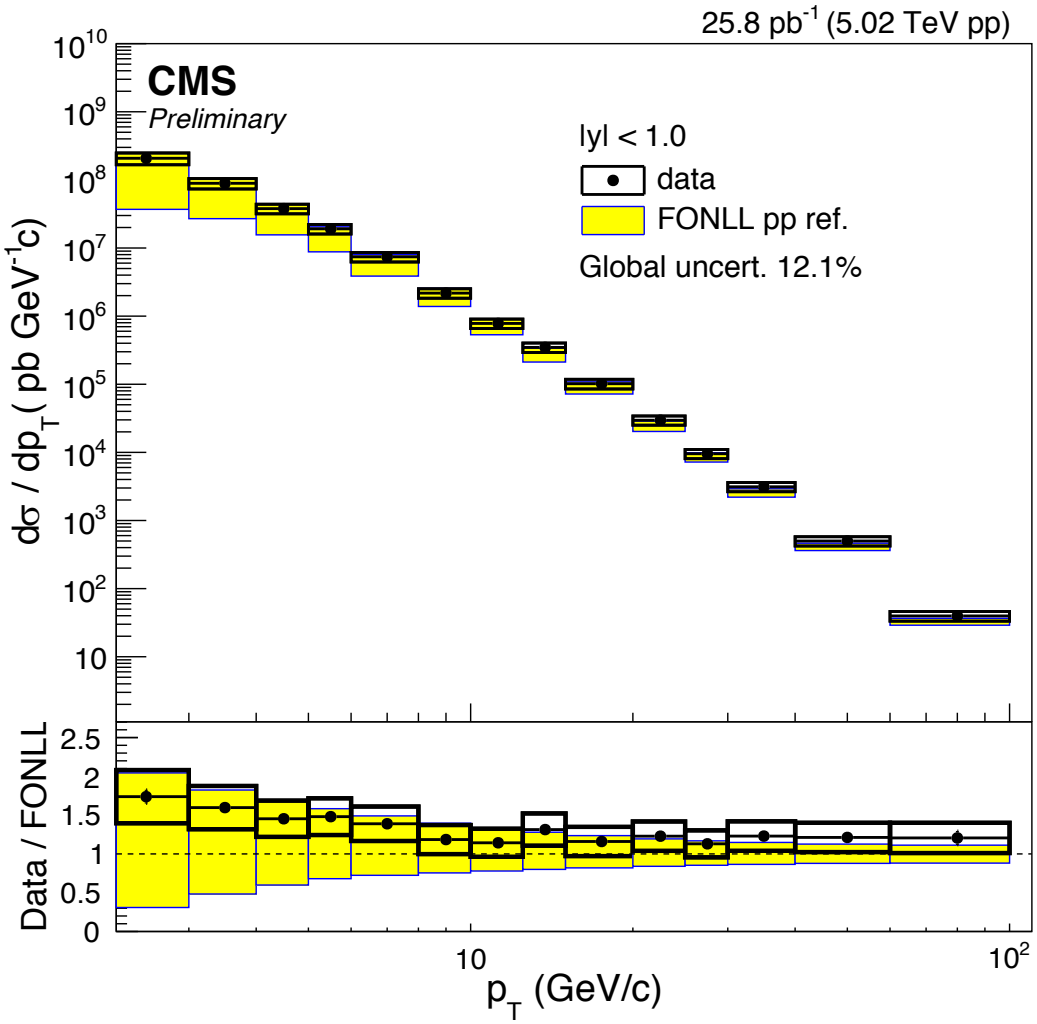
→ bb pairs produced asymmetric in p_T and with a broad opening angle

NLO process: Gluon splitting (GSP)

- gluon splits in a bb pair

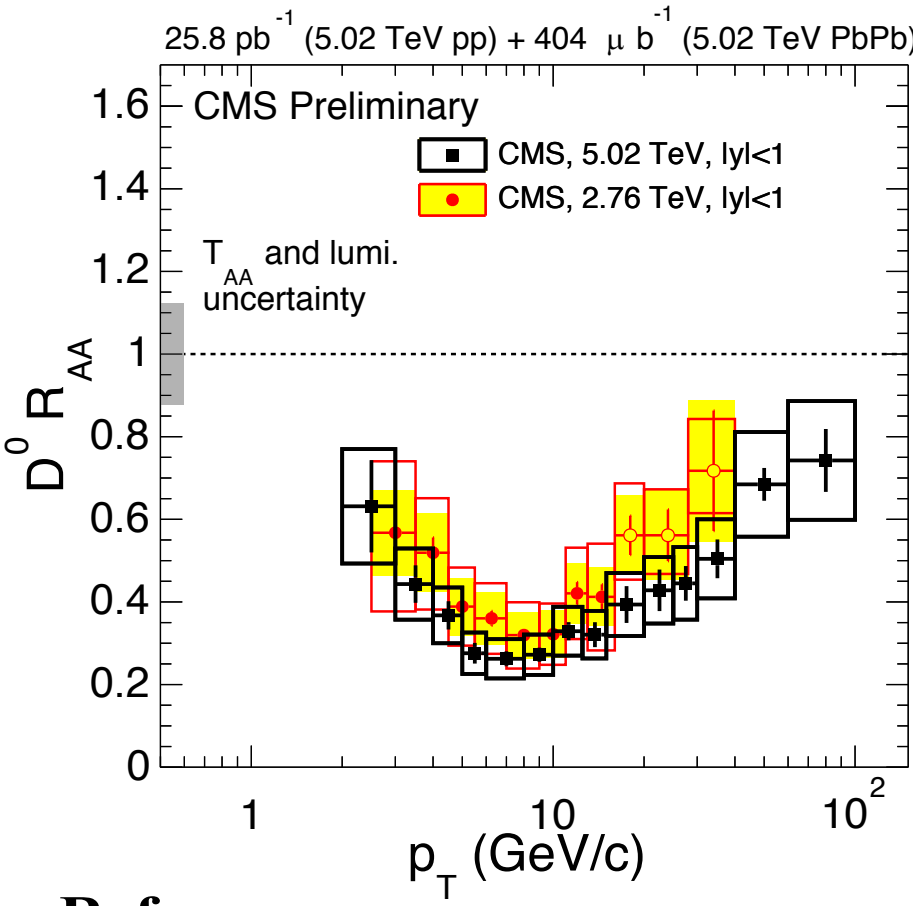
→ produced with small opening angles and asymmetric in p_T

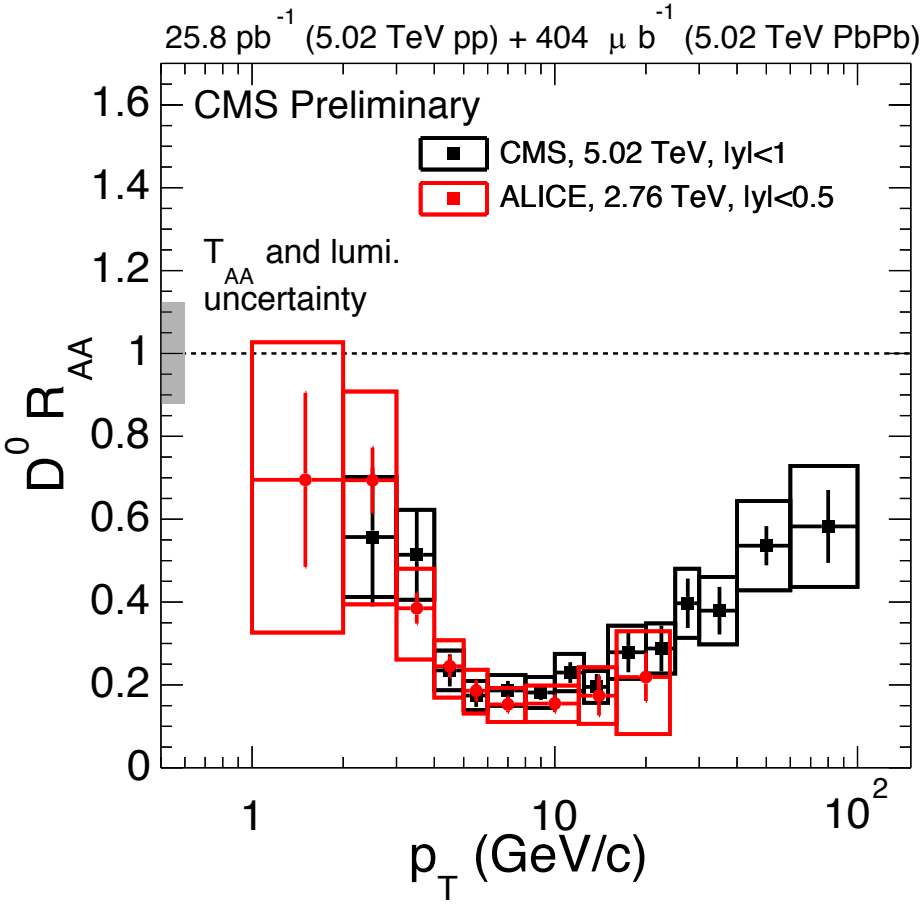
Prompt D^0 cross section in pp collisions at 5.02 TeV



- The first measurement of D^0 cross-section in pp collisions at 5.02 TeV
- p_T range covers from 2 to 100 GeV/c in |y| <1
- Consistent with the upper bound of FONLL predictions

Comparison of D^0 R_{AA}





Reference:

CMS 2.76 TeV: scaled Alice 7 TeV pp measurement + FONLL

Alice 2.76 TeV: scaled Alice 7 TeV pp measurement

CMS 5.02 TeV: 5 TeV pp measurement