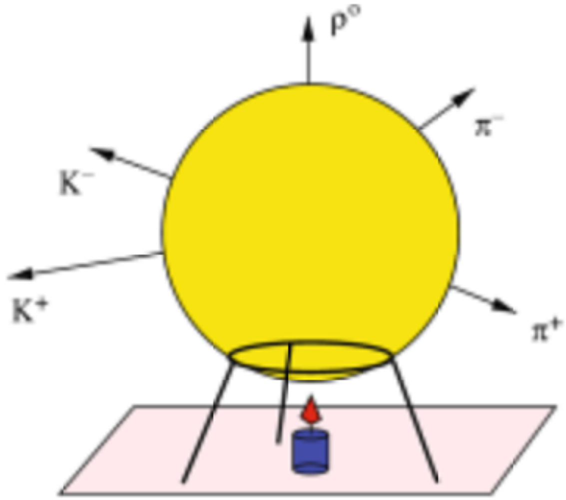
LHC Heavy Ion Physics
Lecture 6: Quarkonia and Heavy Quarks

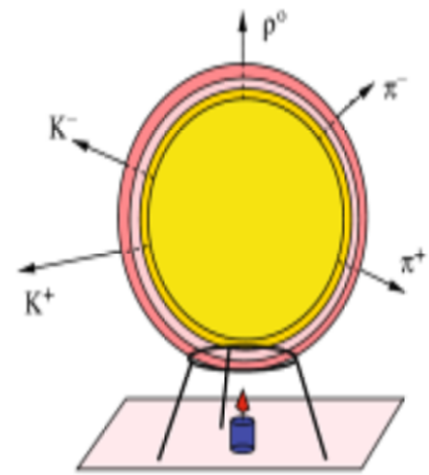
HUGS 2015

Bolek Wyslouch

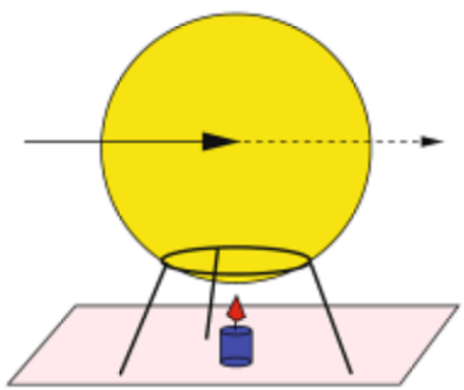
Techniques to study the plasma



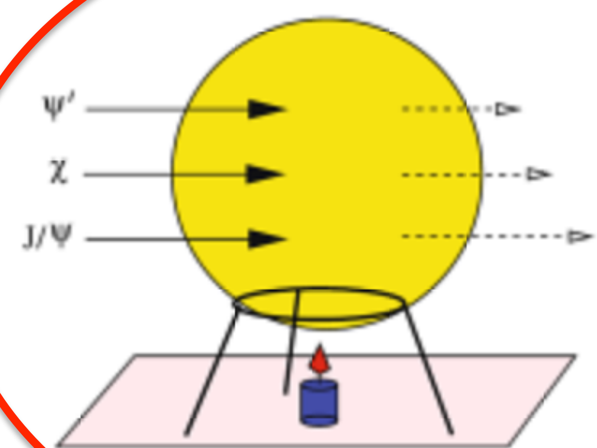
Radiation of hadrons



Azimuthal asymmetry and radial expansion



Energy loss by quarks, gluons and other particles

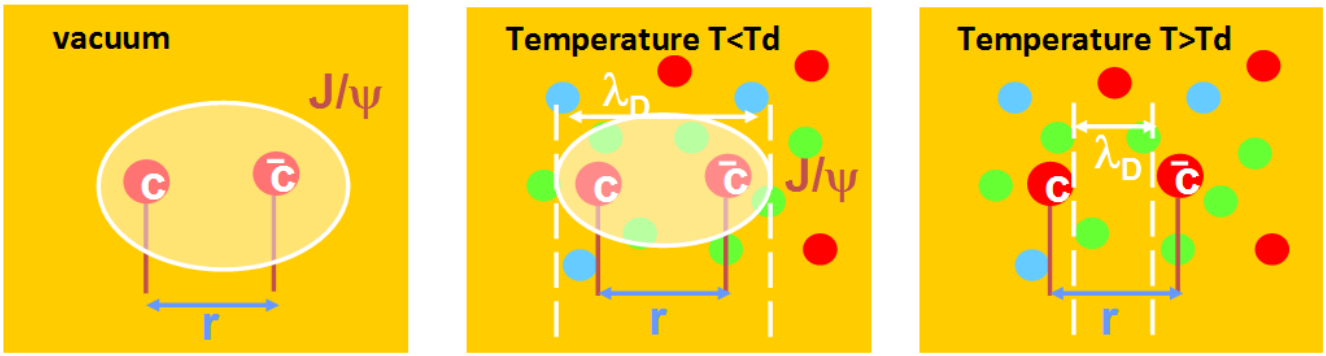


Suppression of quarkonia

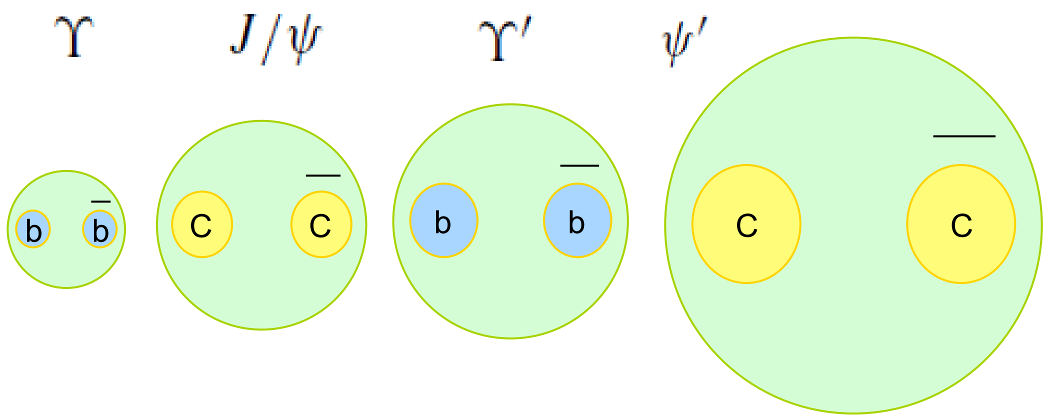
Production and suppression of quarkonia

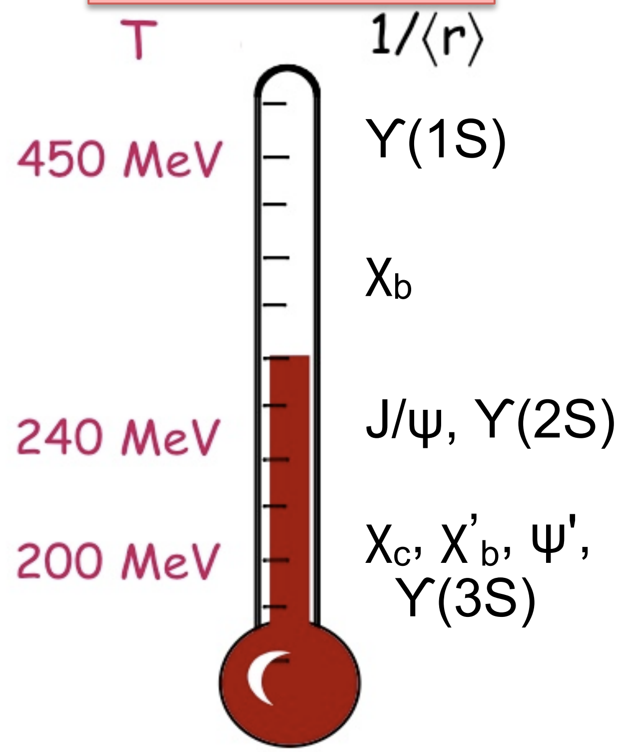
- Bound states of heavy quarks produced inside plasma are being used as an indicator of plasma temperature and density
- Comparison of production of quarkonia between ion-ion, proton-ion and proton-proton collisions show several interesting effects that can be interpreted in terms of plasma properties
  - J/ψ, ψ' suppression and recombination
  - Properties of Υ family

Quarkonia as a tool to probe the QGP



Matsui & Satz, PLB168 (1986) 415





Different states have different binding energies
Loosely bound states "melt" first!

Successive suppression of individual states provides a "thermometer" of the QGP

Mocsy, EPJC61 (2009) 705
BNL workshop in June

Flavor dependence of parton energy loss

- From QCD:
  - Color charge:

    E_{loss} in gluons > E_{loss} in quarks
  - Kinematics: "Dead cone effect":

    E_{loss} in quarks > E_{loss} in heavy quarks

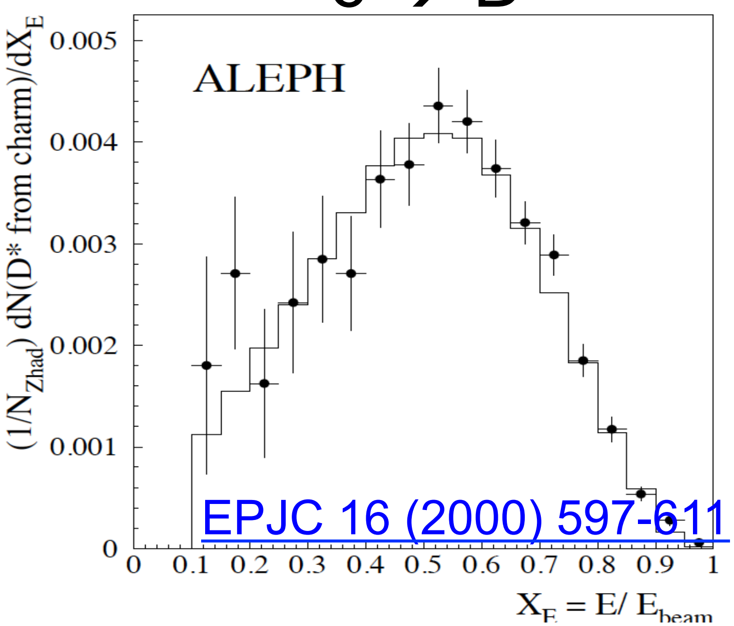
Flavor dependence of parton energy loss

- From QCD:
  - Color charge:

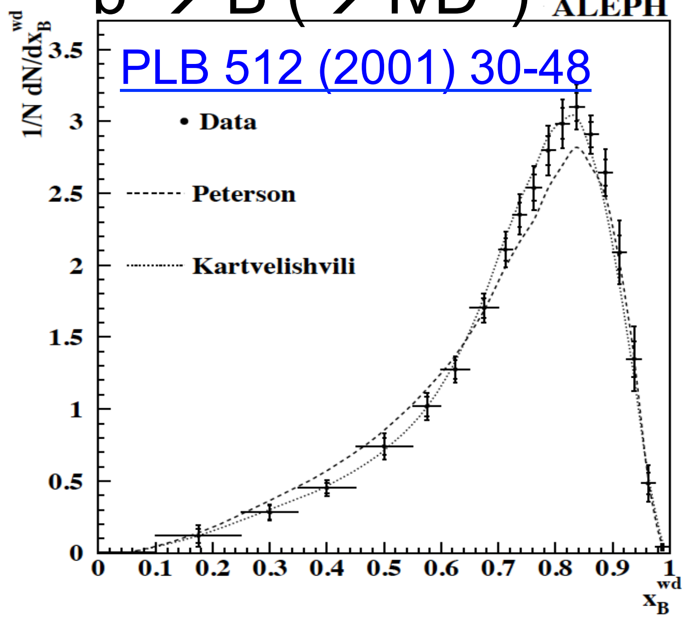
    E_{loss} in gluons > E_{loss} in quarks
  - Kinematics: "Dead cone effect":

    E_{loss} in quarks > E_{loss} in heavy quarks

c → D*



b → B (→ lνD*)



$\langle X_E(\mathrm{D}^*)\rangle_{c\bar{c}} = 0.4878 \pm 0.0046 \pm 0.0061$ $\quad \langle x_B^{\mathrm{wd}}\rangle = 0.7163 \pm 0.0061\,(\mathrm{stat}) \pm 0.0056\,(\mathrm{syst})$

b → B harder than c → D harder than q/g → h

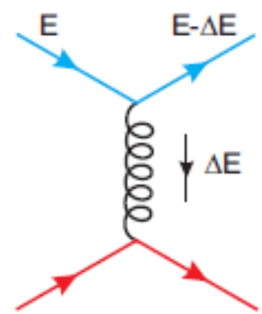
Heavy Quark Physics In Heavy-Ion Collisions 6

Flavor dependence of parton energy loss

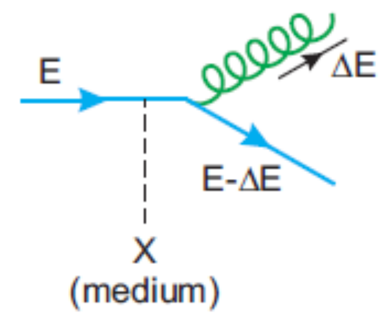
- From QCD
  - Color charge:
    E_{loss} in gluons > E_{loss} in quarks
  - Kinematics: "Dead cone effect":
    E_{loss} in quarks > E_{loss} in heavy quarks

Heavy Quark vs. Light Quark:
Changing the ratio of
collisional and radiative energy loss
→ Determination of the
elastic energy loss coefficient ($\hat{e}$)

Collisional energy loss



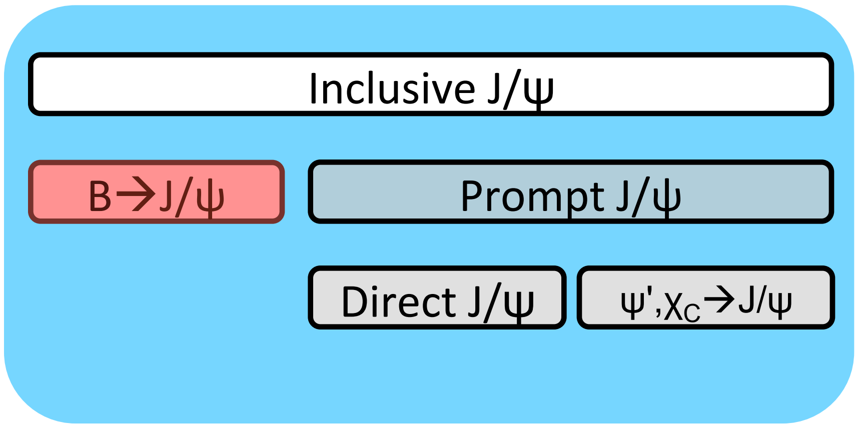
Radiative energy loss

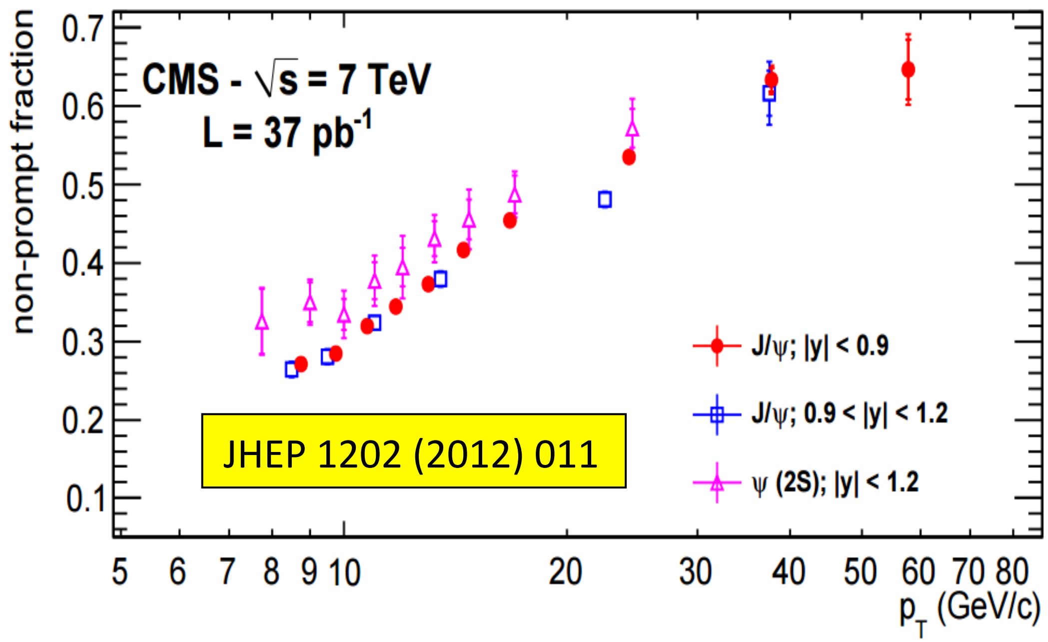


Heavy flavor jet and hadron analyses cover a wide kinematics range
→ Suppression of induced radiation at low p_T and the disappearance of this effect at high p_T

Quarkonia production at LHC

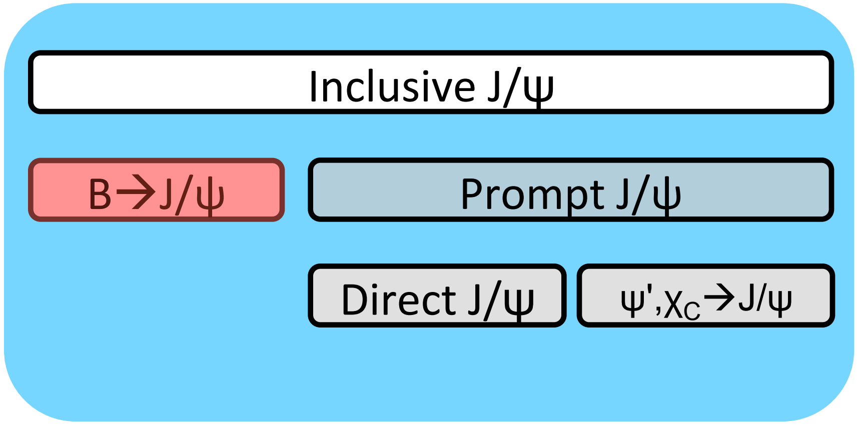
Charmonium production

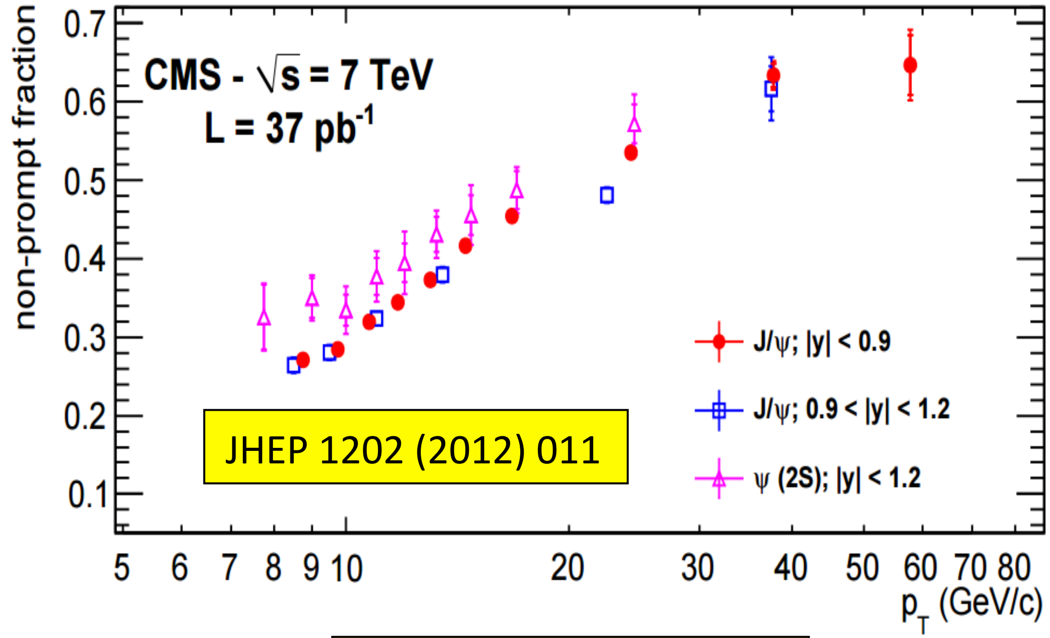




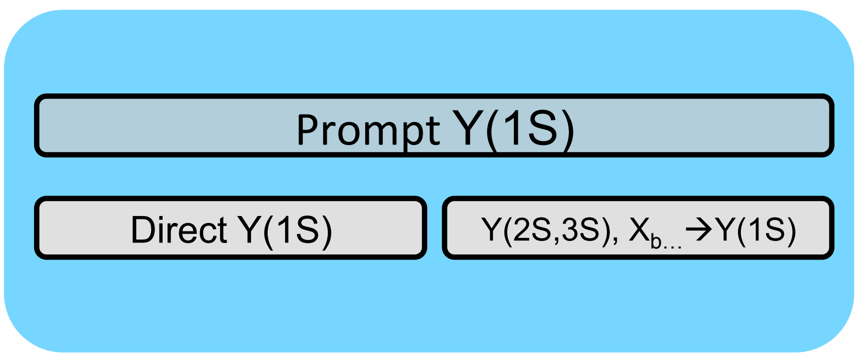
Quarkonia production at LHC

Charmonium production

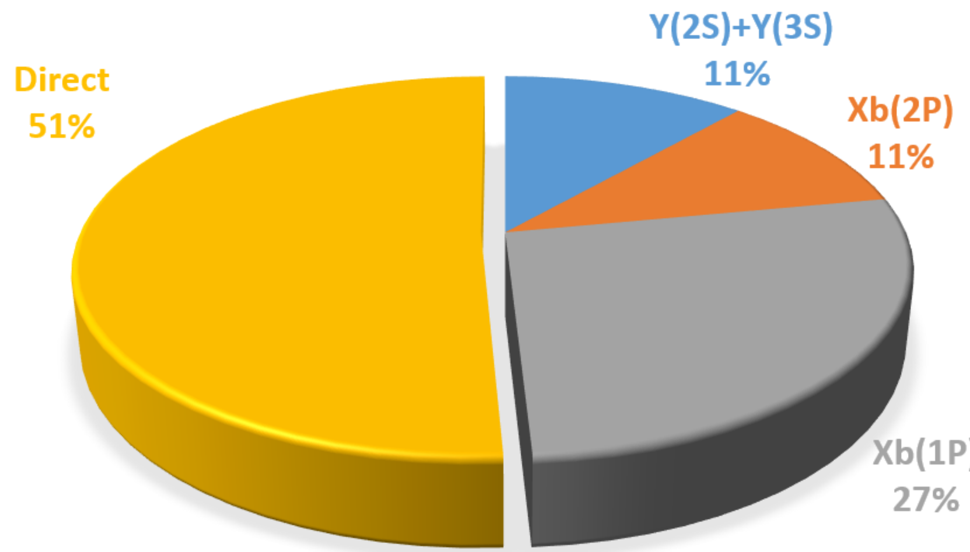




Bottomium production

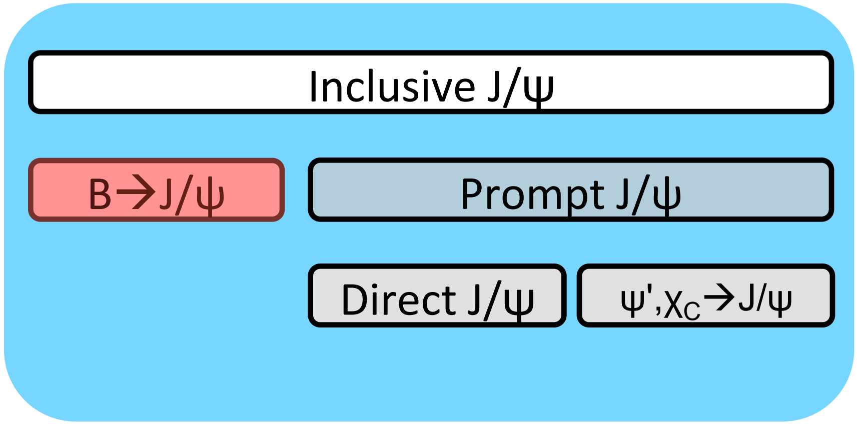


CDF, PRL 84 (2000) 2094



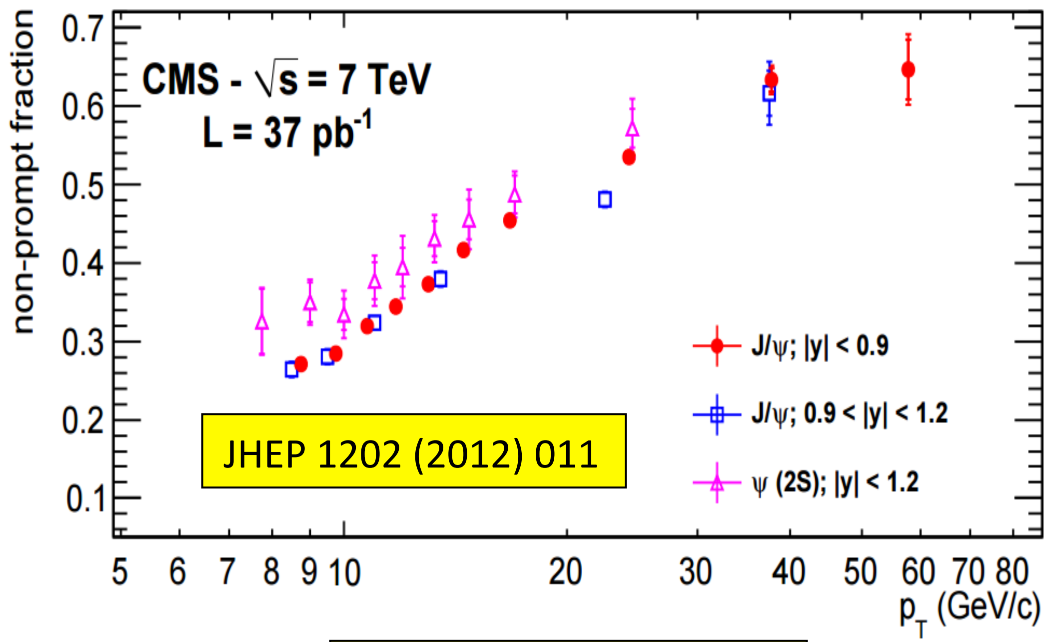
Quarkonia production at LHC

Charmonium production

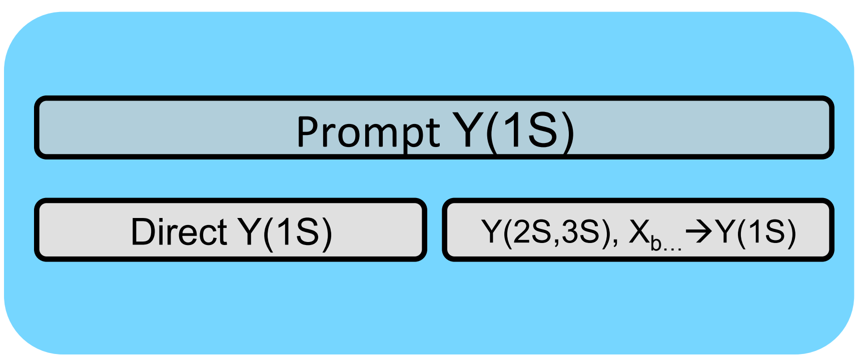


Stopping / scattering power of QGP

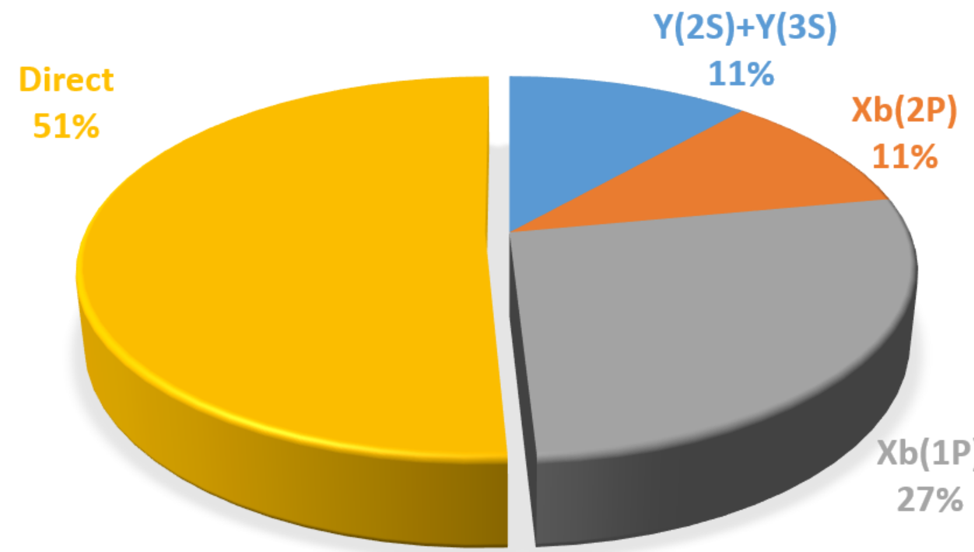
Temperature / Screening length



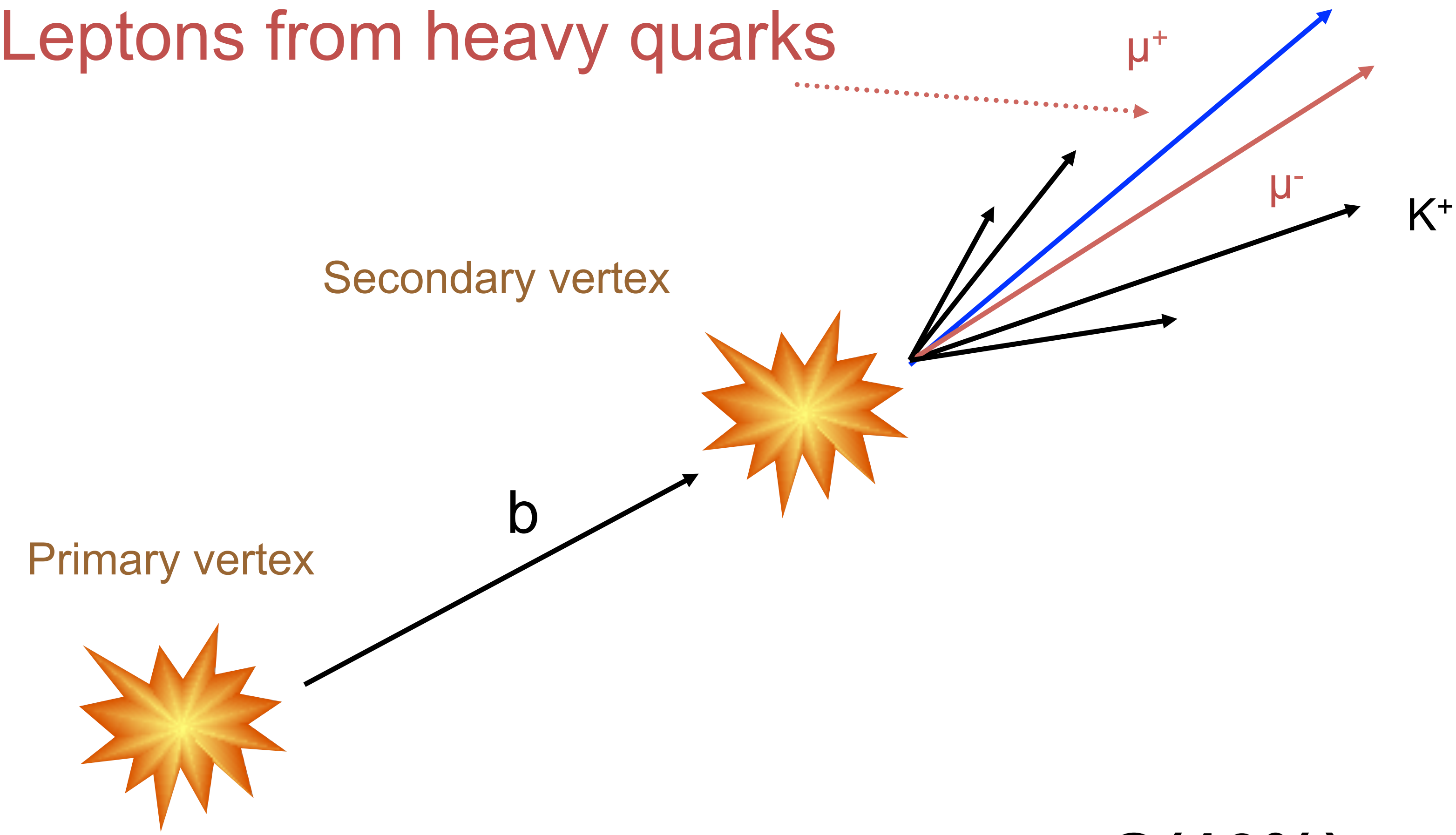
Bottomium production



CDF, PRL 84 (2000) 2094



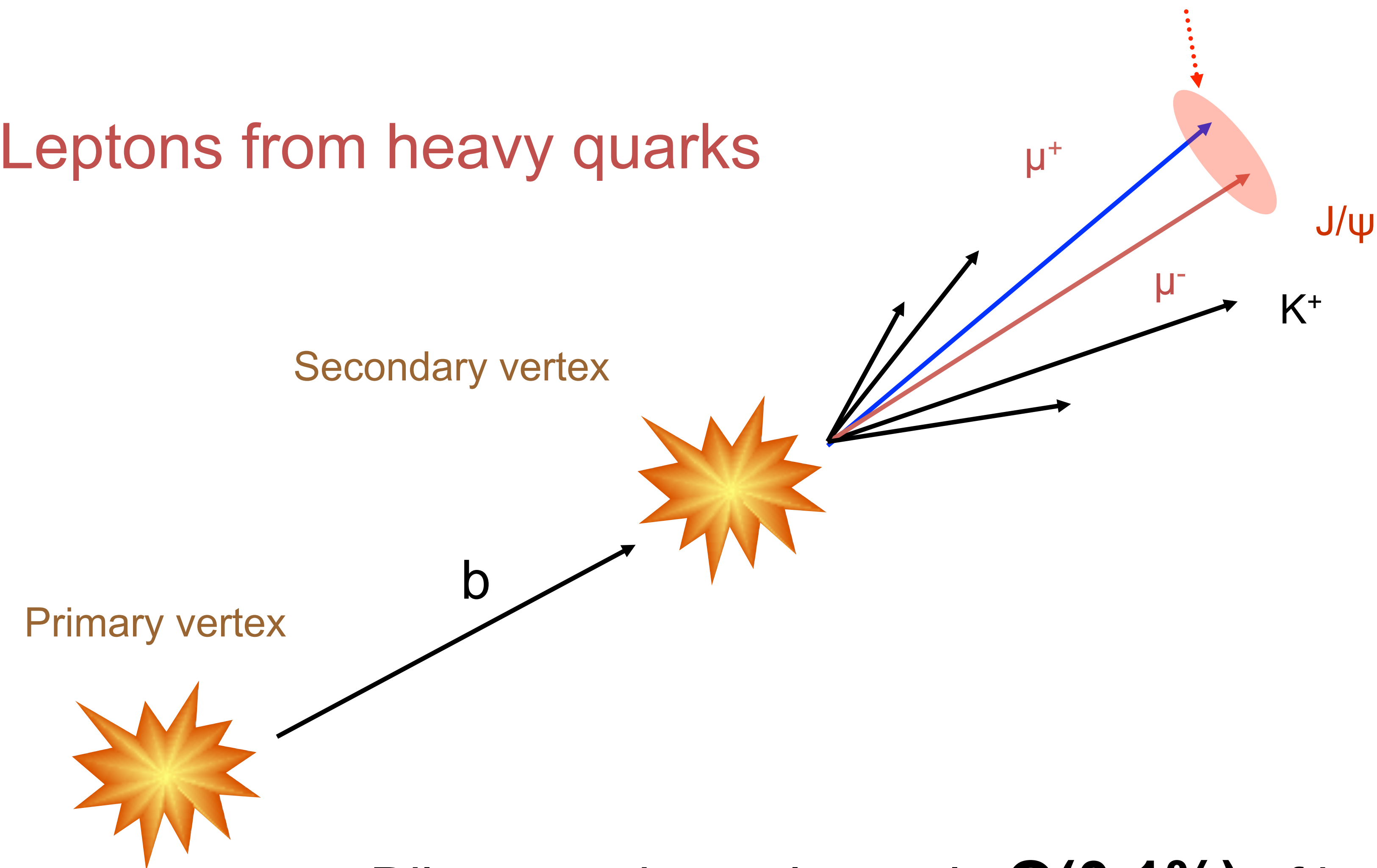
Leptons from heavy quarks



Sample **O(10%)** of b cross-section

Non-prompt J/ψ

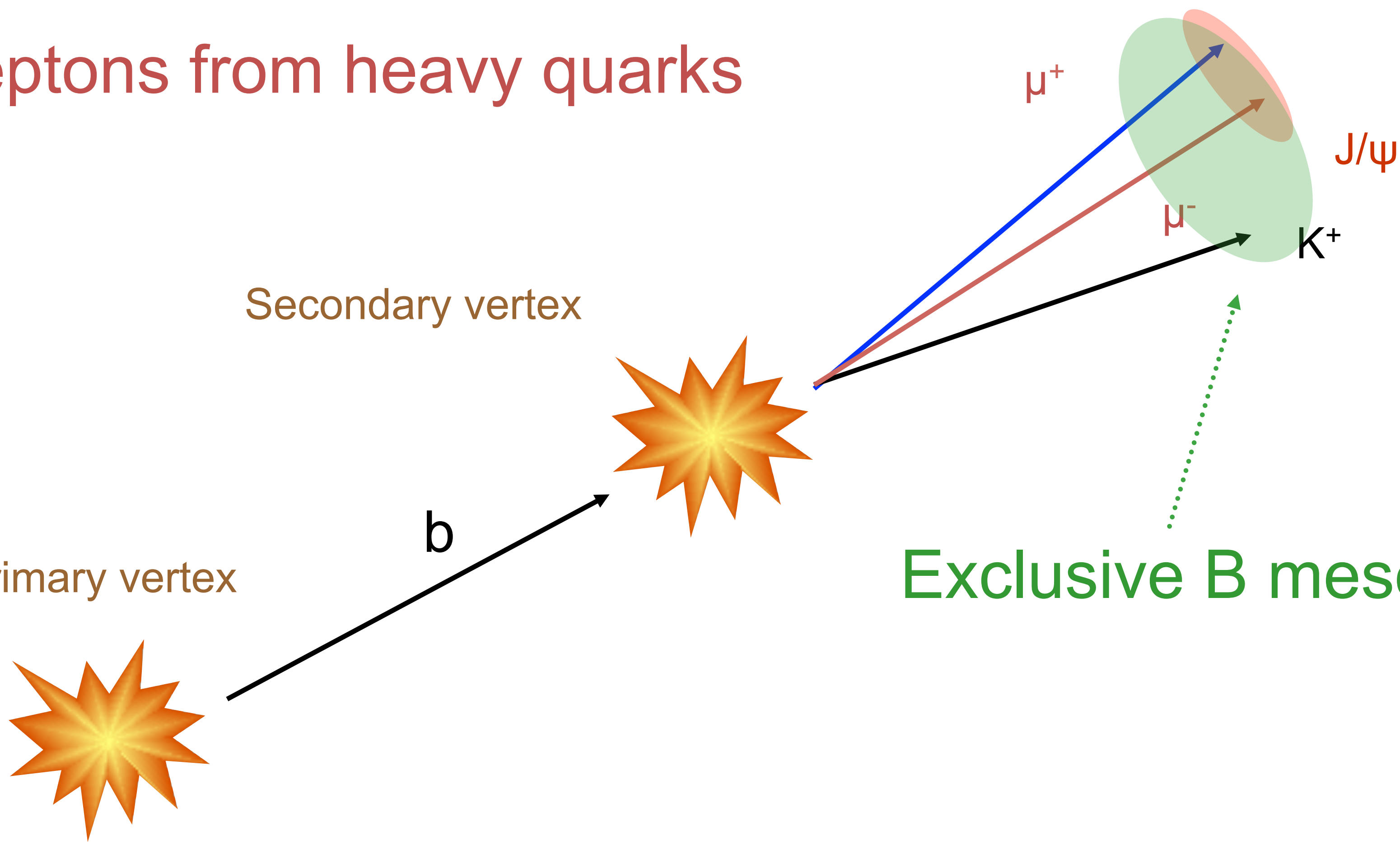
Leptons from heavy quarks



Dileptons channel sample **O(0.1%)** of b cross-section

Non-prompt J/ψ

Leptons from heavy quarks

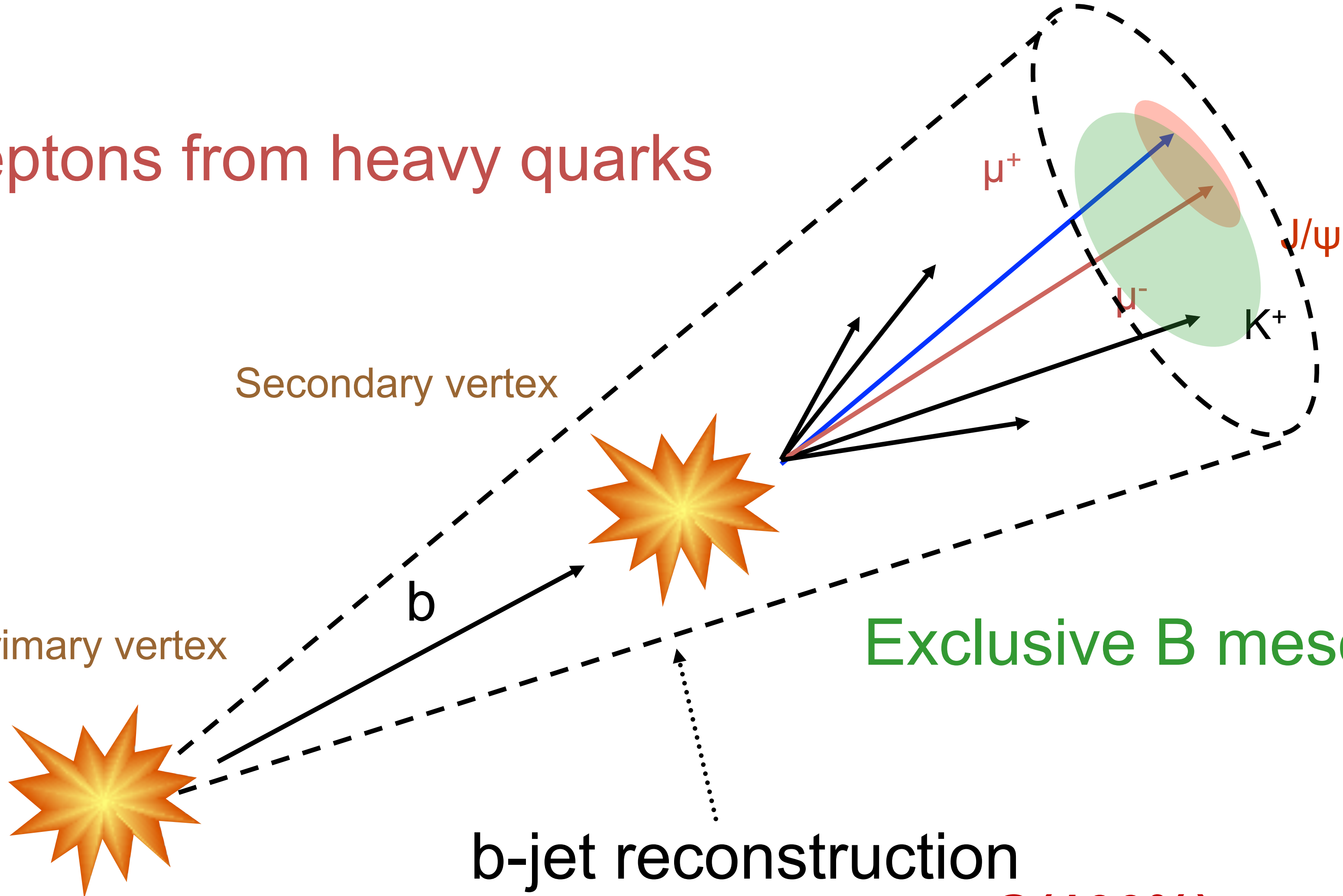


Exclusive B meson decays

J/ψ+1(2) tracks decay channels sample **O(0.01%)** of b cross-section

Non-prompt J/ψ

Leptons from heavy quarks



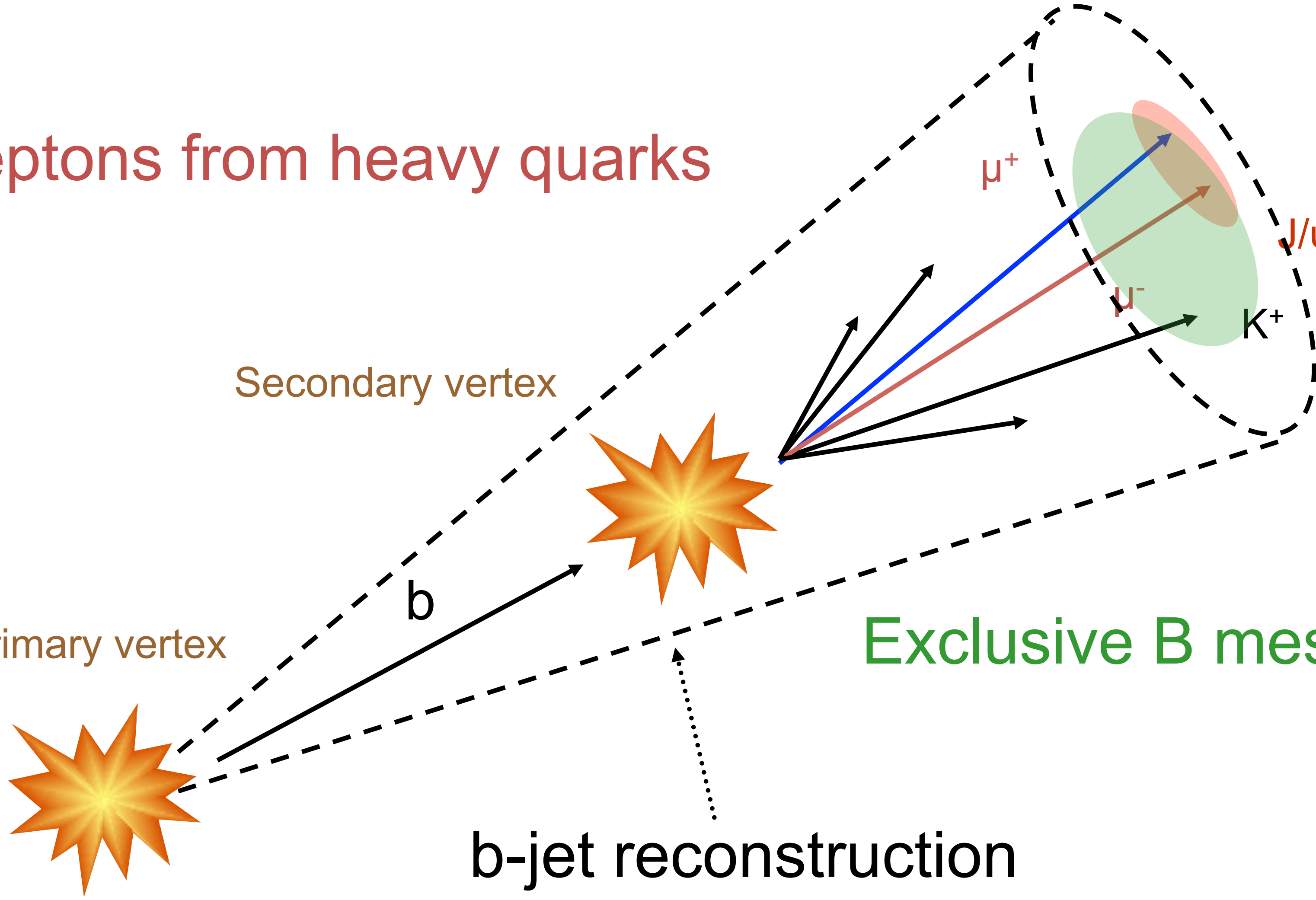
Exclusive B meson decays

b-jet reconstruction

b-tagged jet sample **O(100%)** of b cross-section
and ~70-90% of the b quark energy

Non-prompt J/ψ

Leptons from heavy quarks



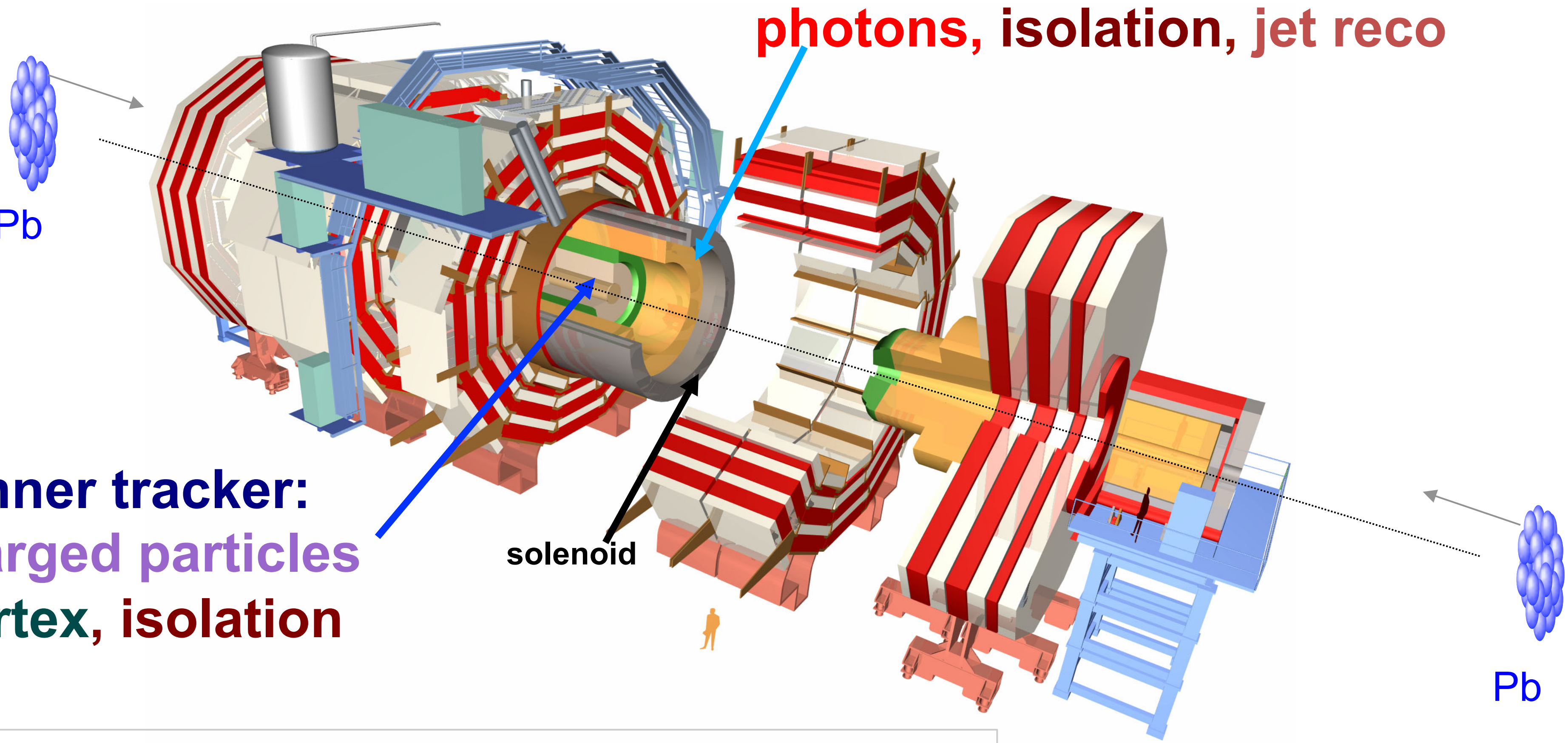
Exclusive B meson decays

b-jet reconstruction

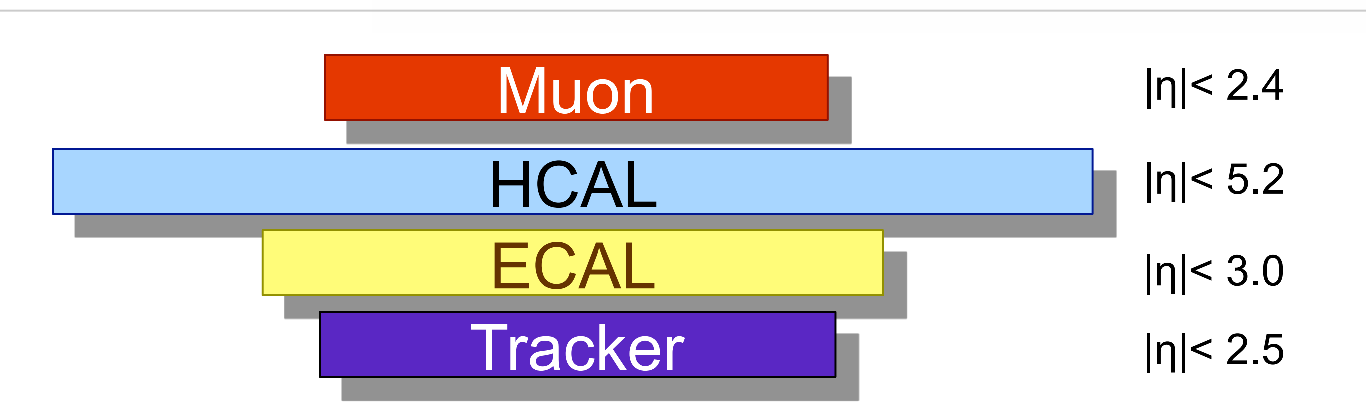
Requirement: flexible trigger system, muon / electron detection, secondary vertex reconstruction, jet reconstruction

CMS Detector

EM and Hadron calorimeters
photons, isolation, jet reco



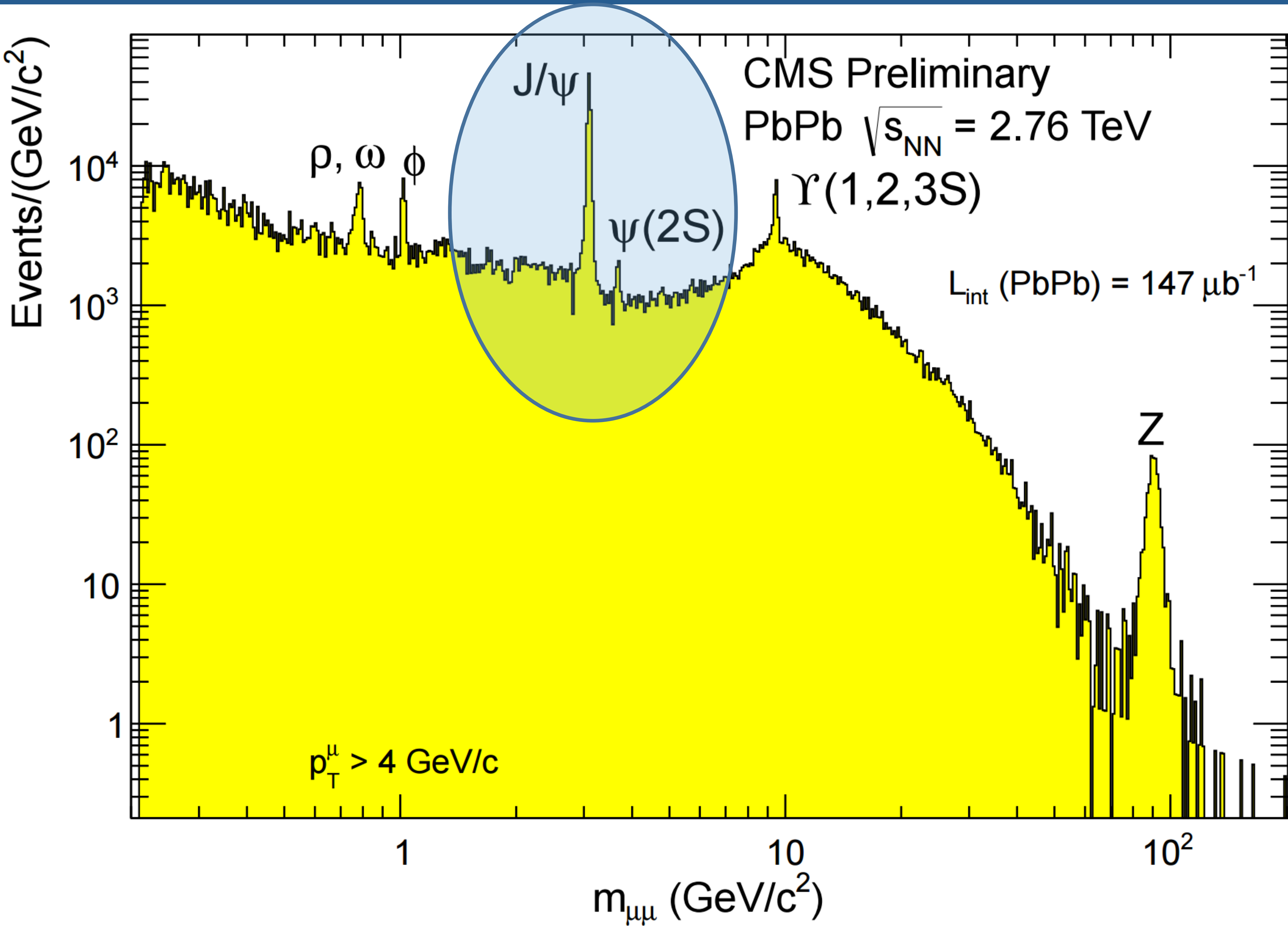
Inner tracker:
charged particles
vertex, isolation



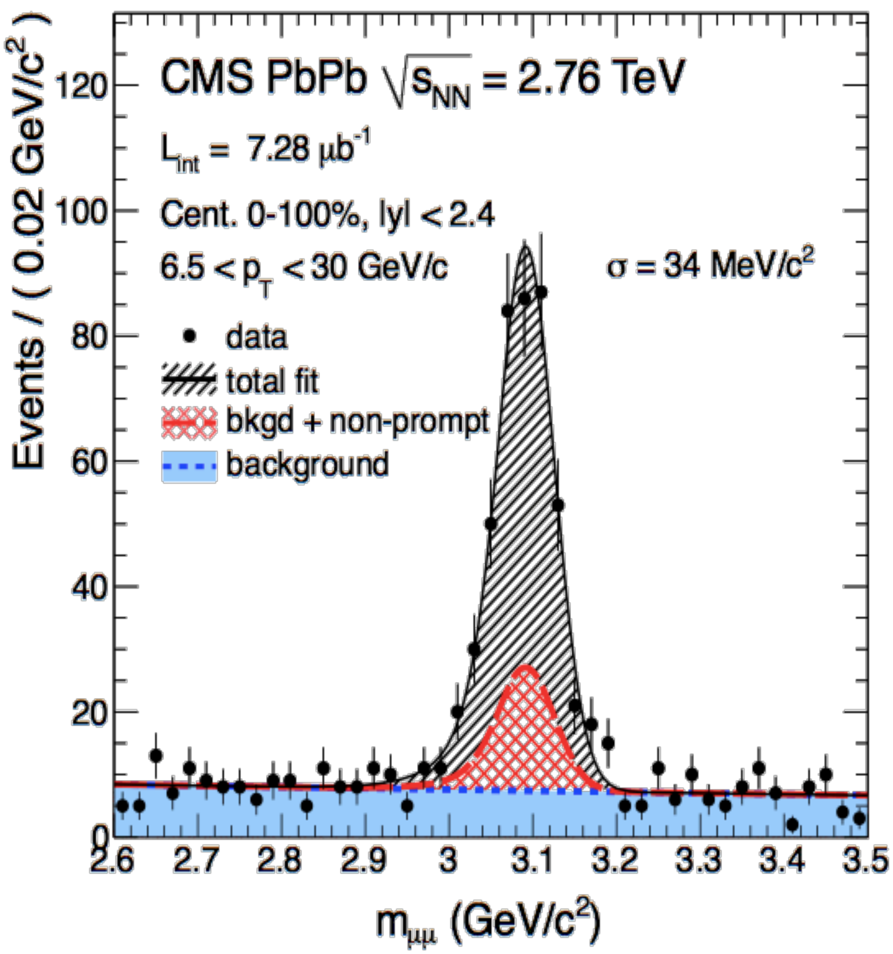
Track impact parameter resolution

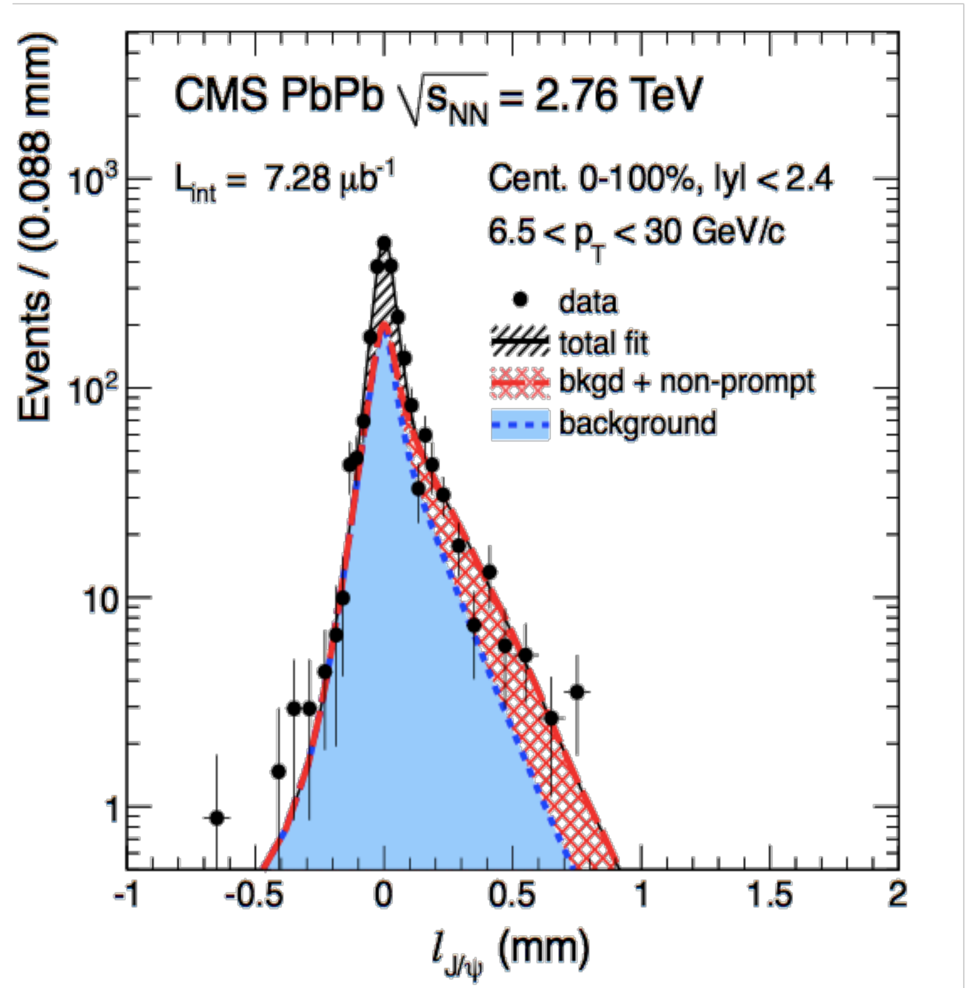
- 100 μm @ 1 GeV/c
- 20 μm @ 20 GeV/c

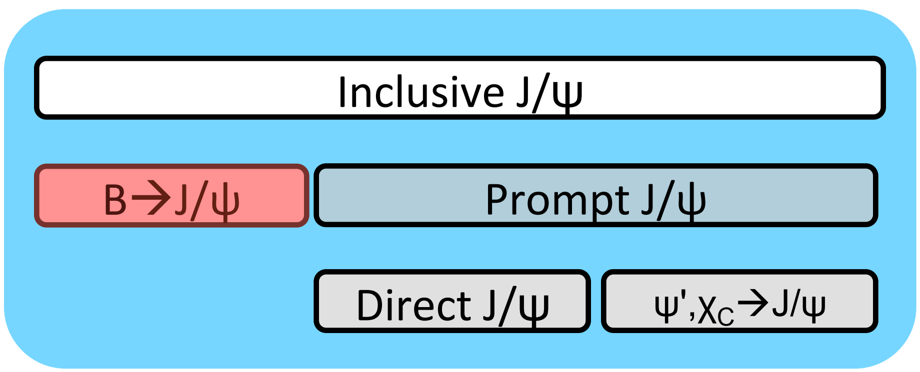
Quarkonia production: Dimuons

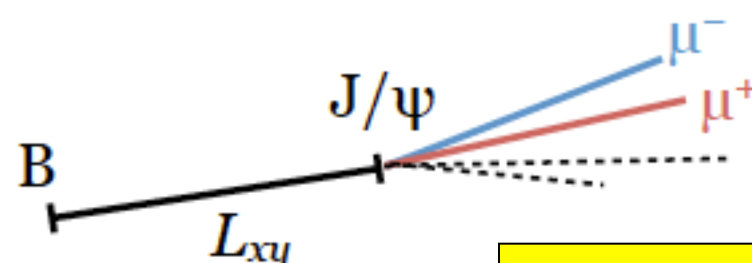


Prompt and non-prompt J/ ψ





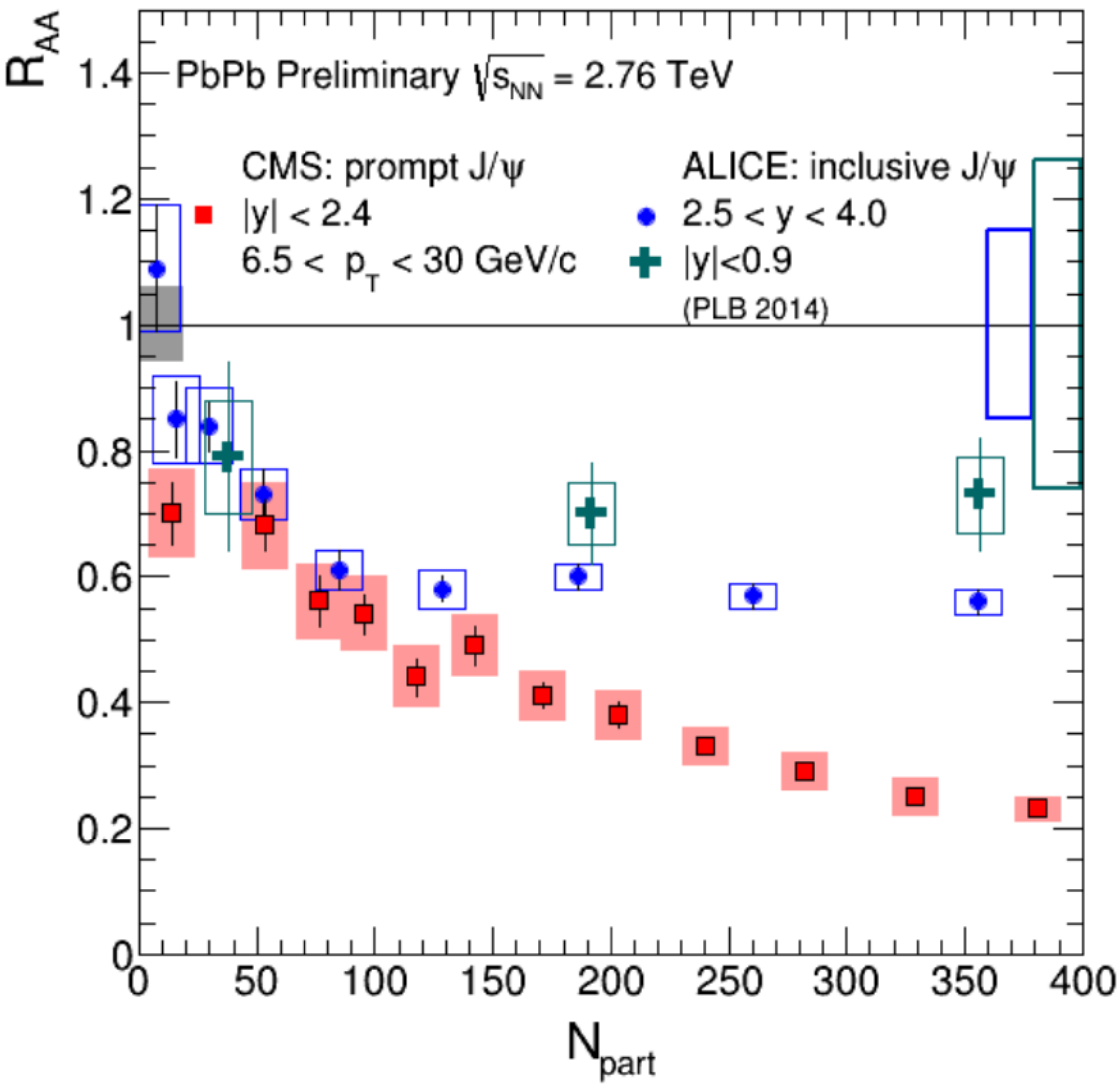




CMS PAS HIN-12-014

J/ψ R_{AA} vs. centrality in PbPb collisions

CMS PAS HIN-12-014

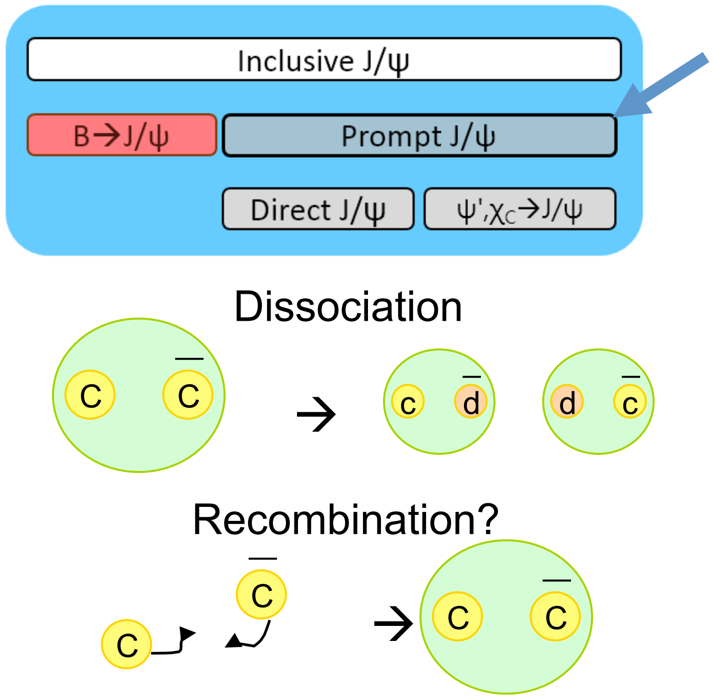


CMS: Prompt J/ψ

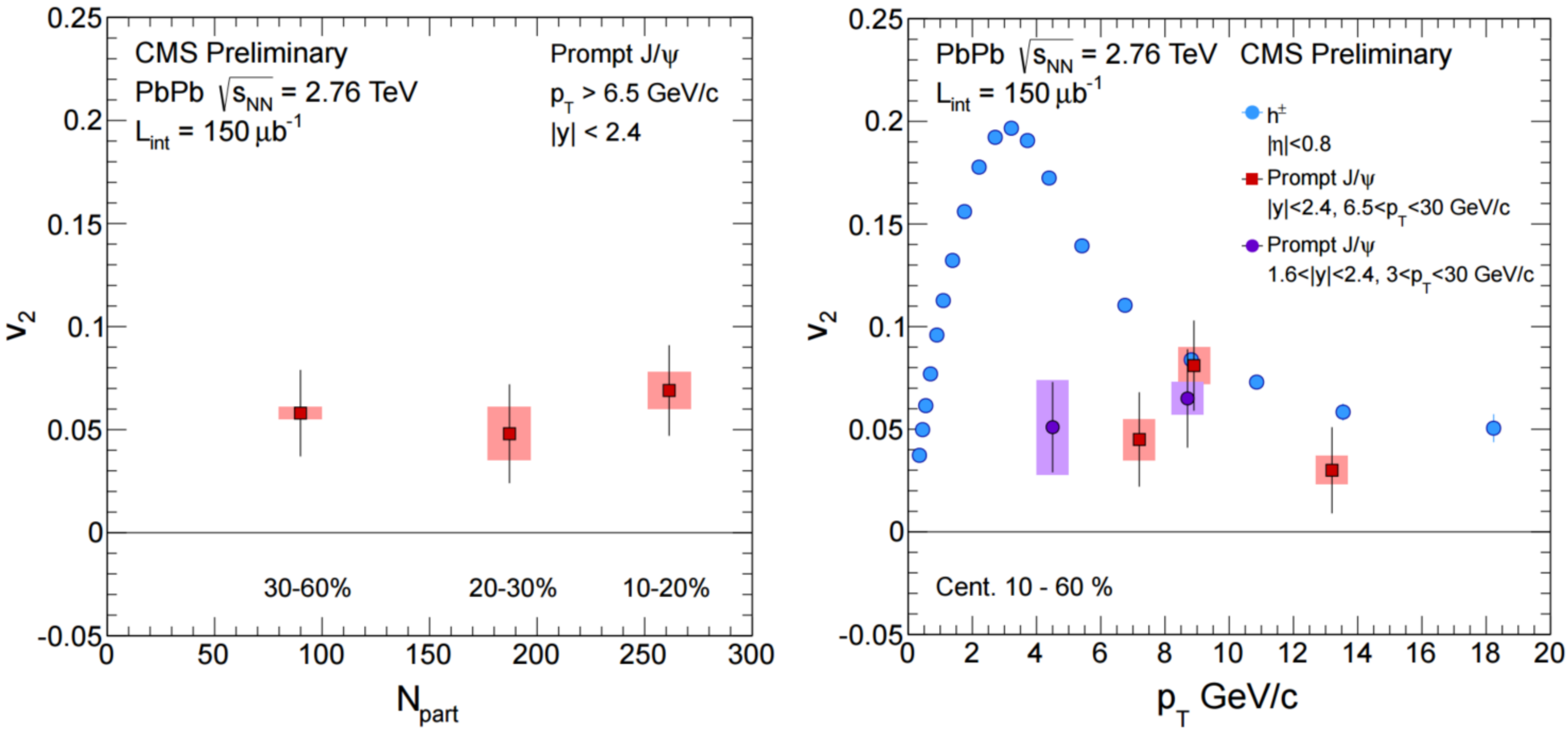
- |y|<2.4 and p_T > 6.5 GeV/c

ALICE: inclusive J/ψ

- |y|<0.9 and p_T> 0
- 2.5<|y|<4.0 and p_T> 0
- Includes ~10% non-prompt J/ψ from b decays



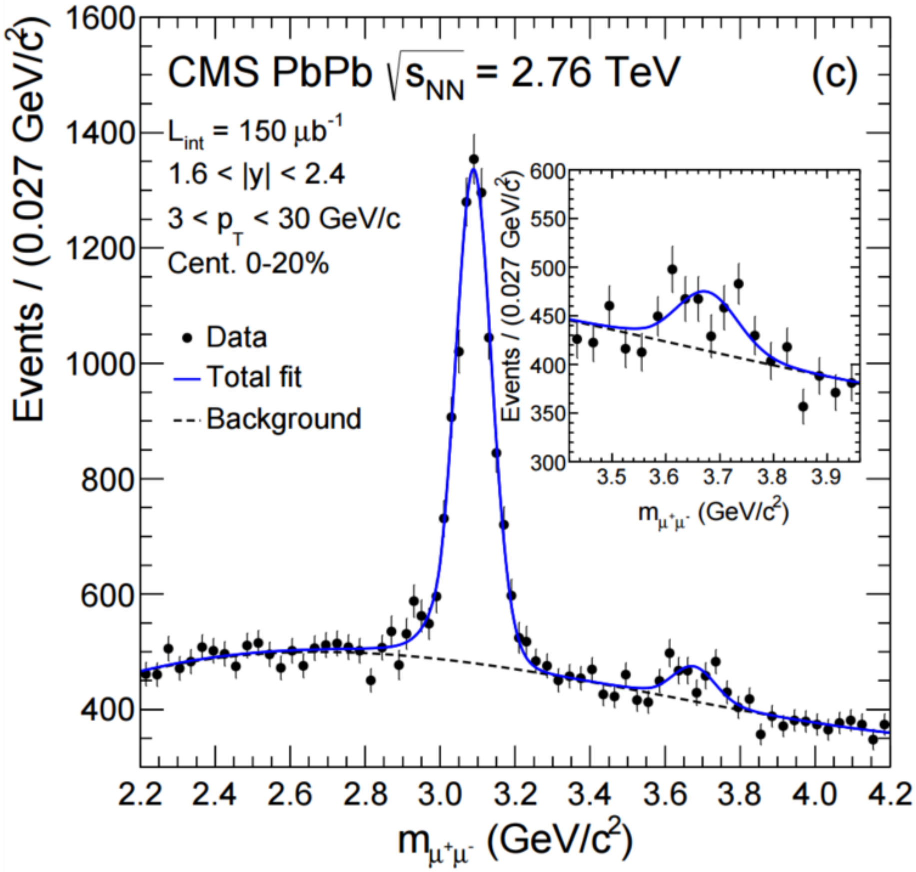
J/ψ v_2 vs. transverse momentum

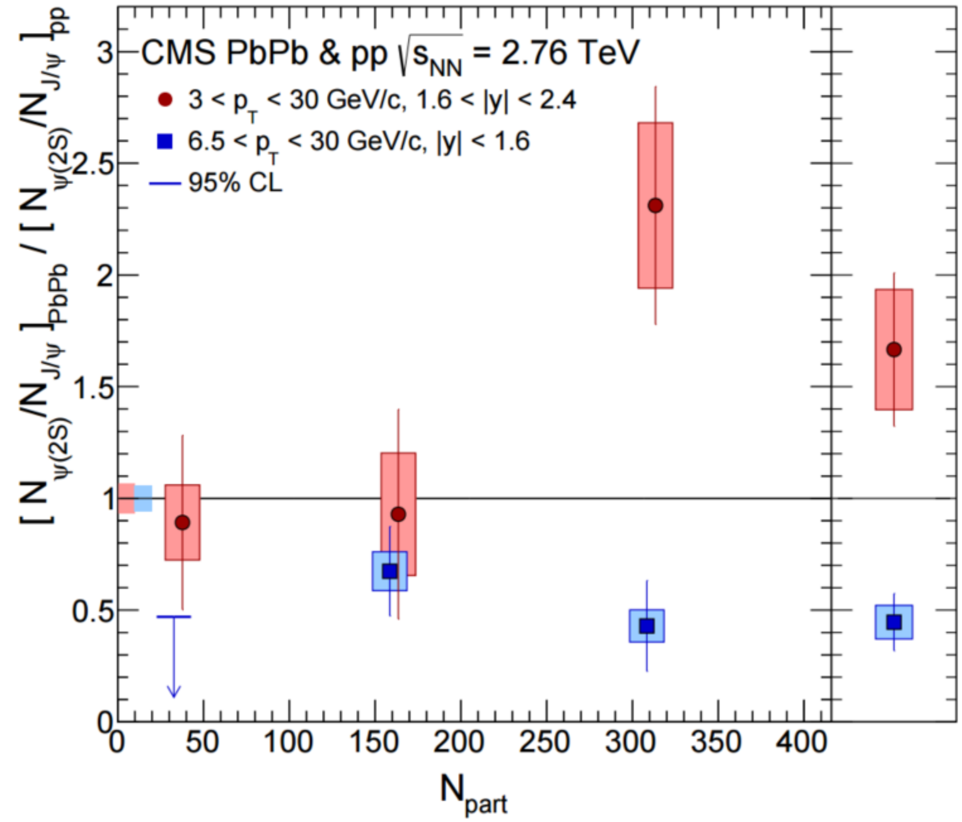


CMS observed non-zero prompt J/ψ v_2 in PbPb collisions
At high p_T: related to path length dependent energy loss
Smaller than inclusive hadron v_2

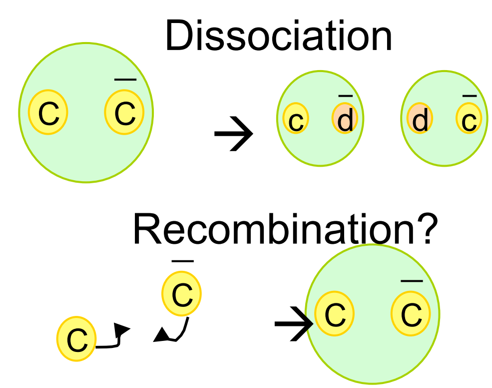
CMS PAS HIN-12-001

Ψ(2S) / J/Ψ Double Ratio





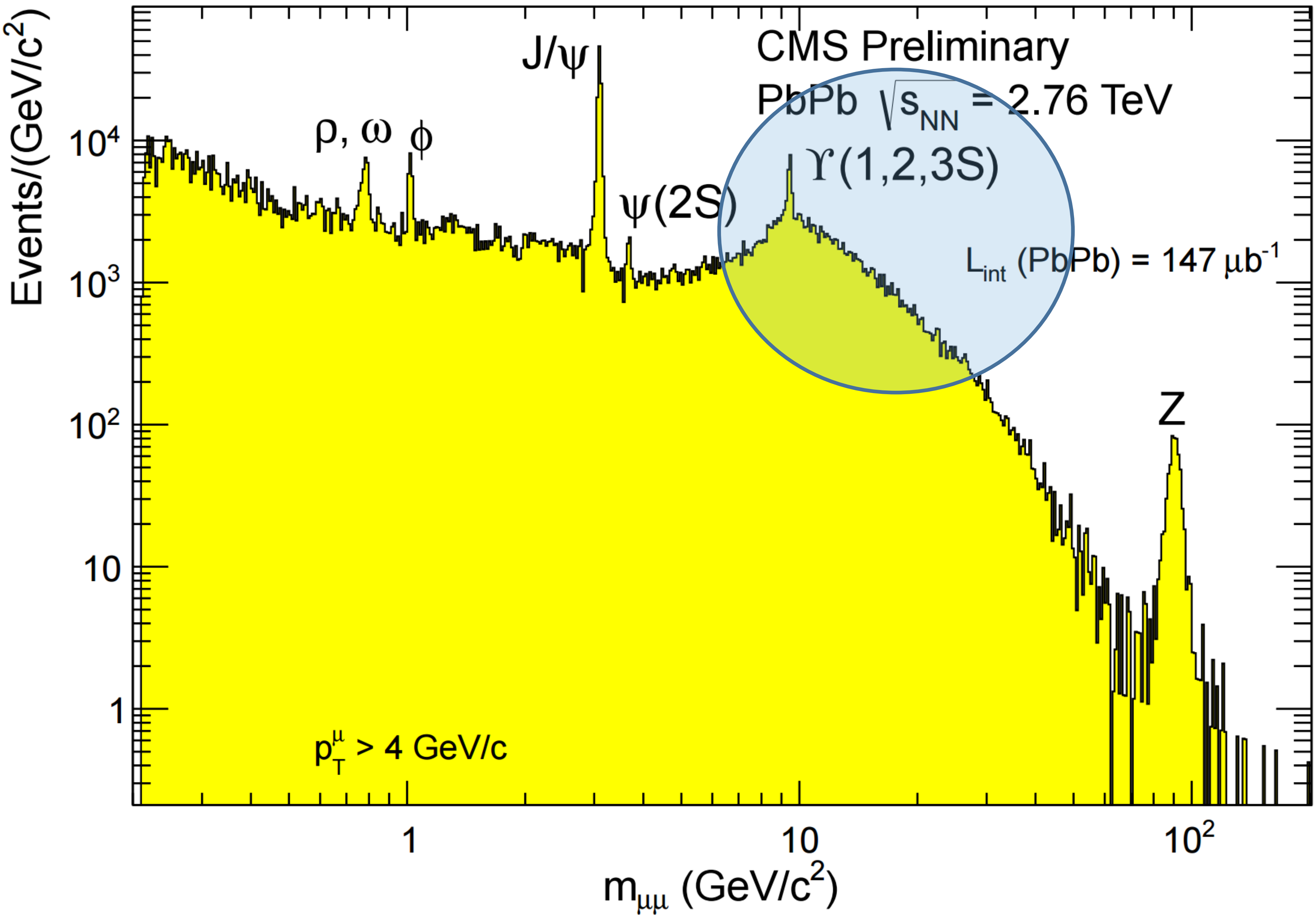
Double ratio $\frac{\left(\frac{\psi(2S)}{J/\psi}\right)_{PbPb}}{\left(\frac{\psi(2S)}{J/\psi}\right)_{pp}}$ >1



→ ψ(2S) is less suppressed compared to J/ψ in central PbPb collisions

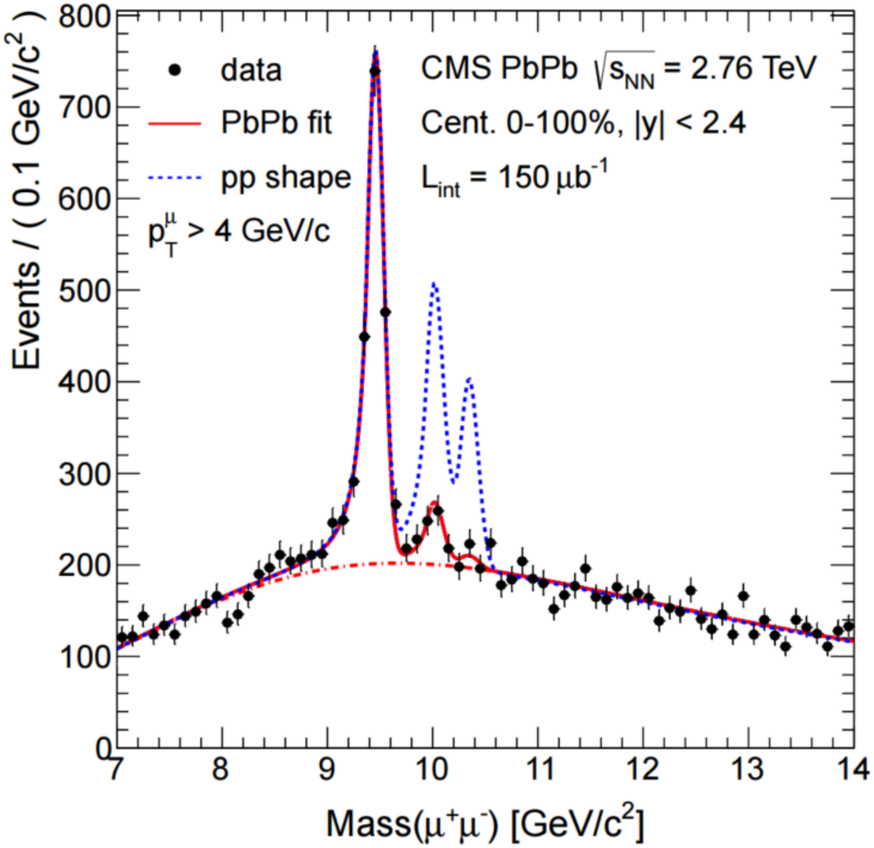
PRL 113 (2014) 262301

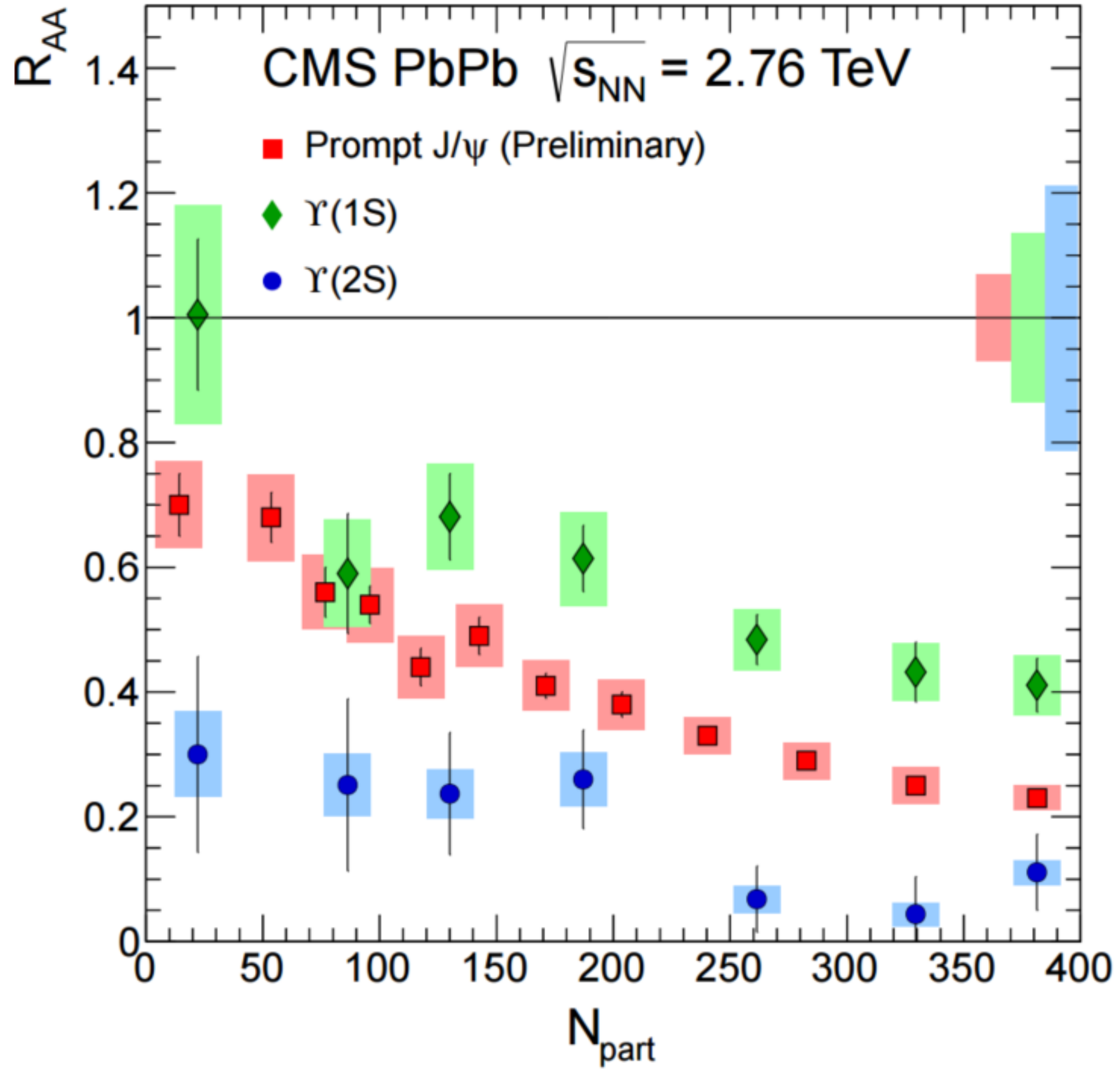
Quarkonia production: Dimuons

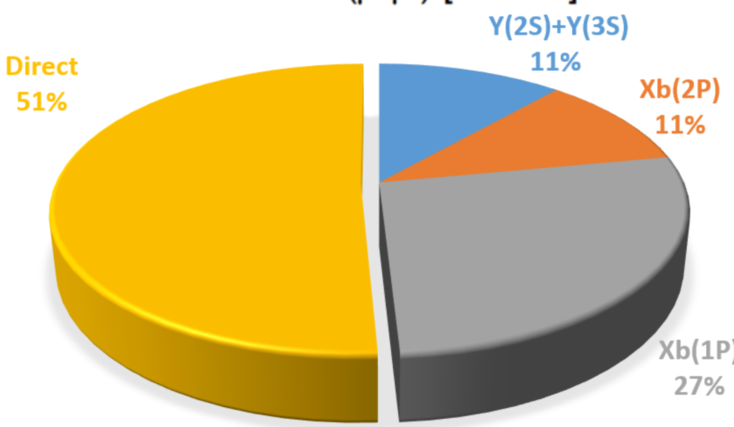


Upsilons in PbPb collisions

PRL 109 (2012) 222301



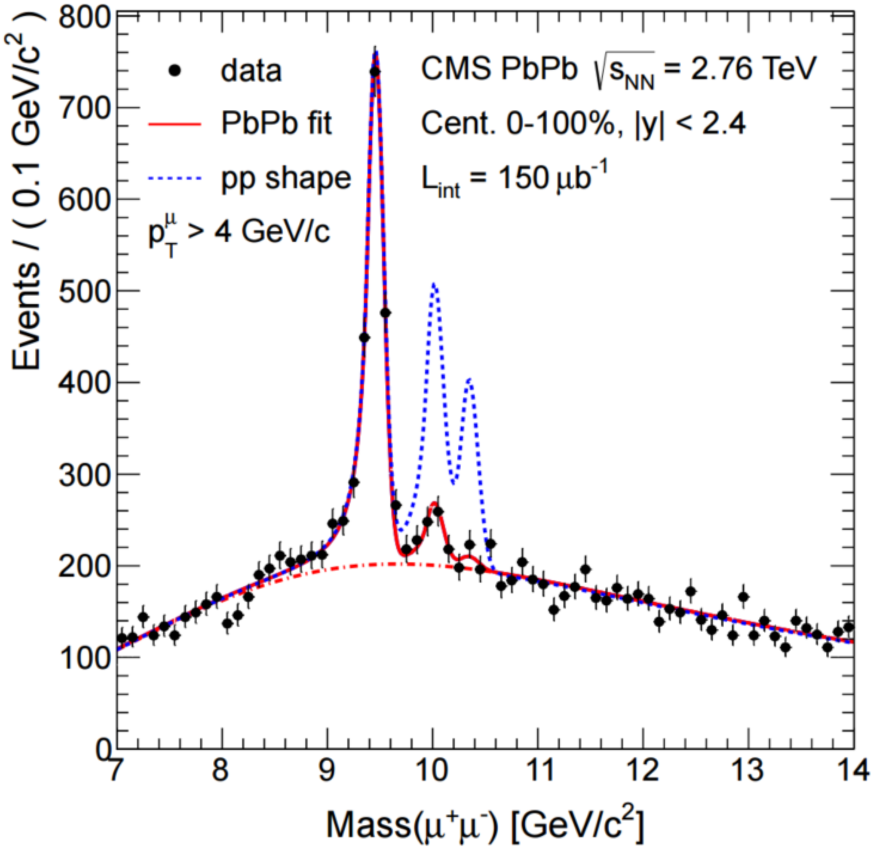


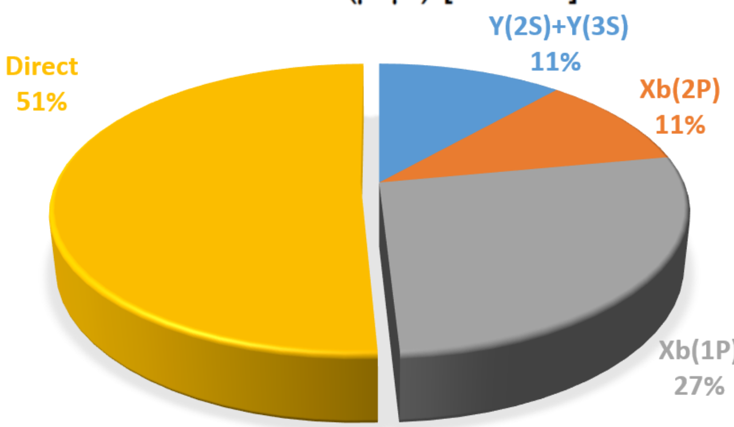


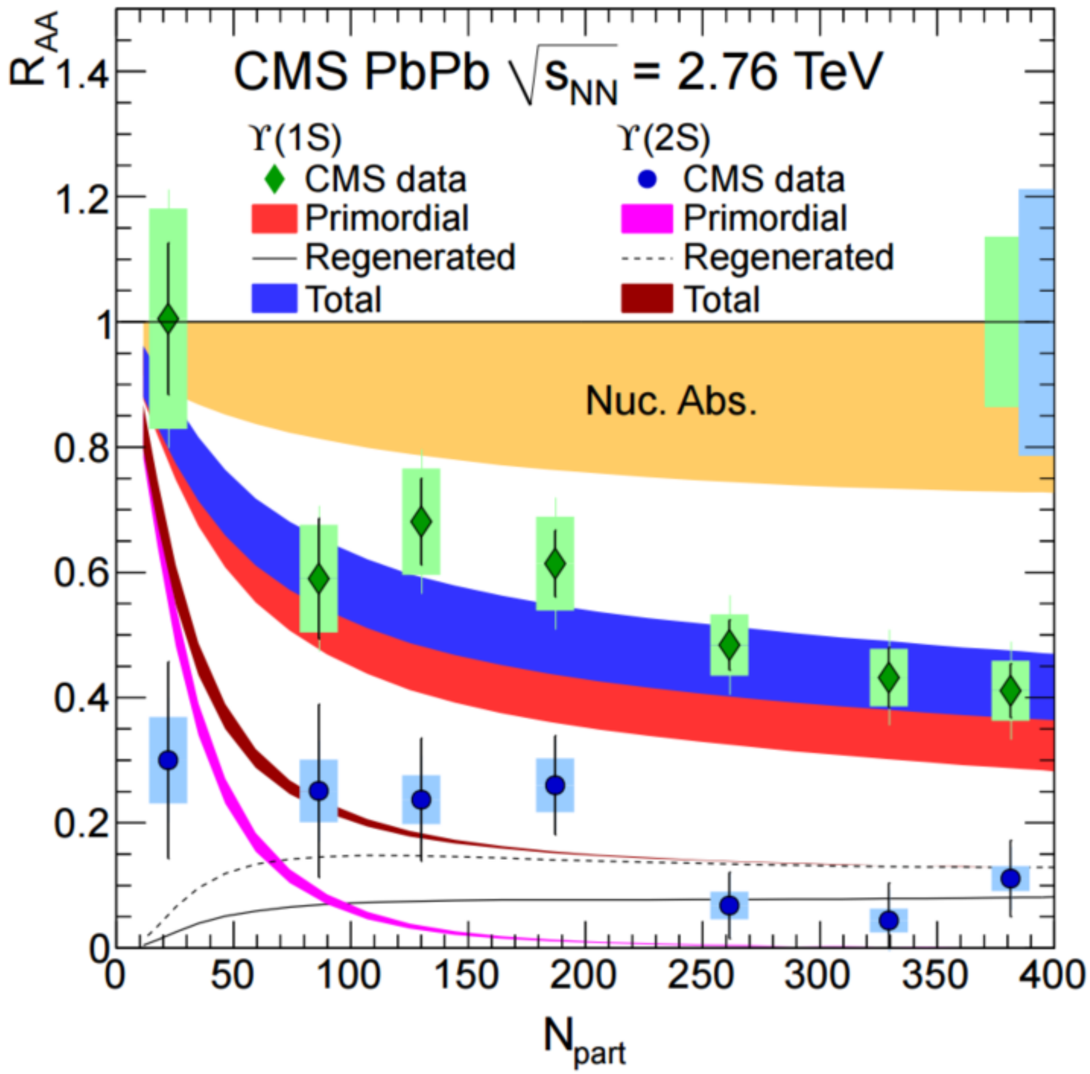
0-100% R_{AA} (Y(3S)) <0.1 (at 95% C.L)
Sequential suppression of the three states in order of their binding energy

Upsilons in PbPb collisions

PRL 109 (2012) 222301

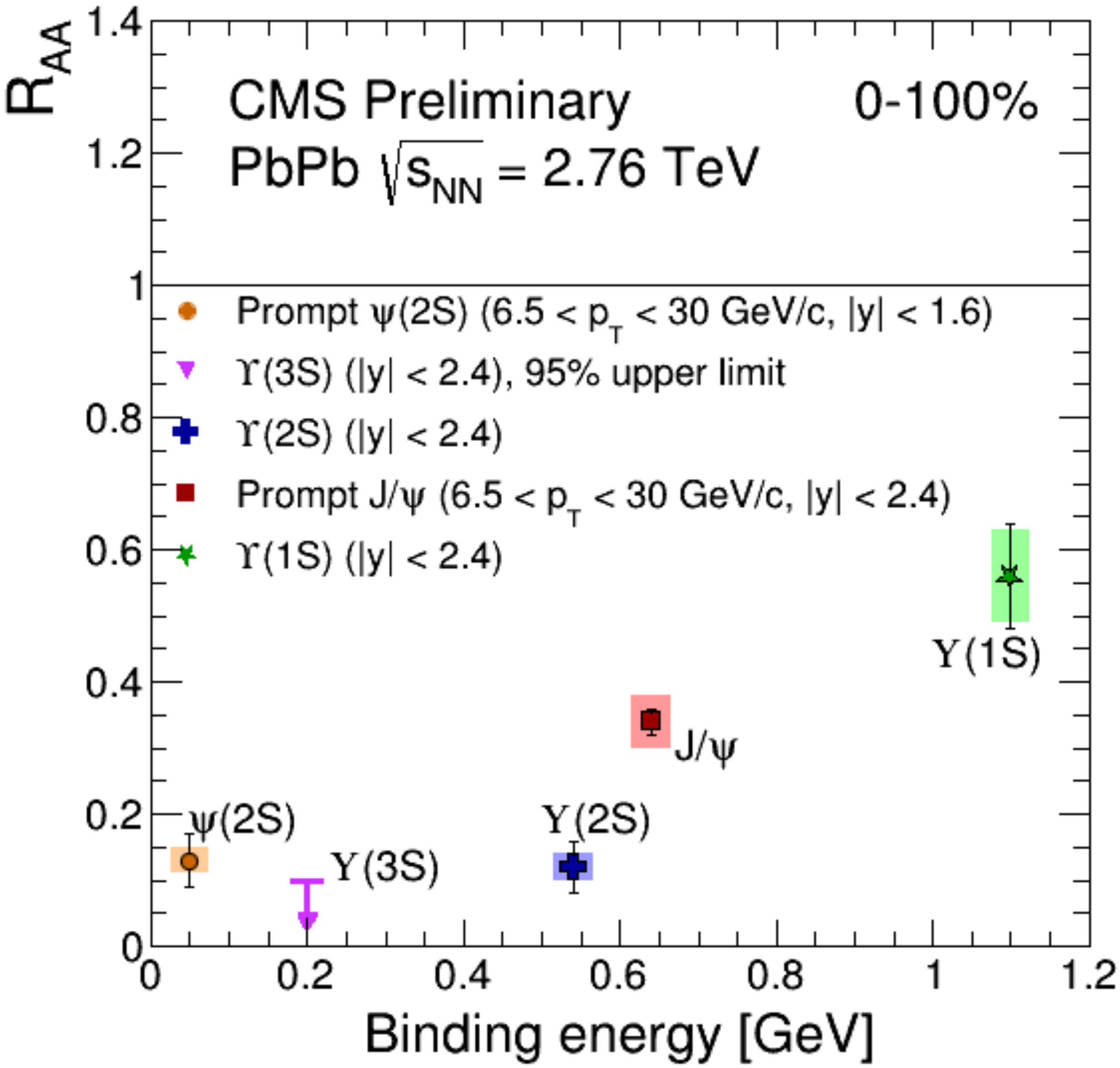




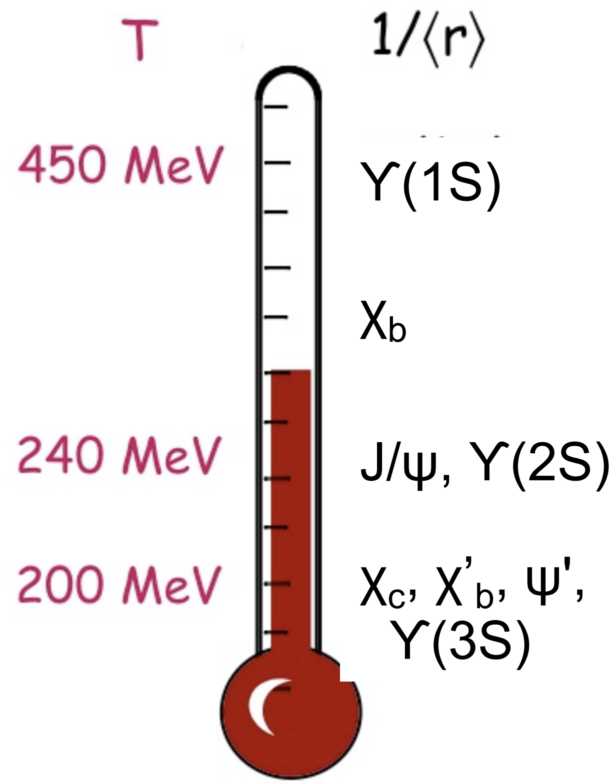


0-100% R_{AA} (Y(3S)) <0.1 (at 95% C.L)
Sequential suppression of the three states in order of their binding energy

Suppression of the five quarkonia in PbPb collisions



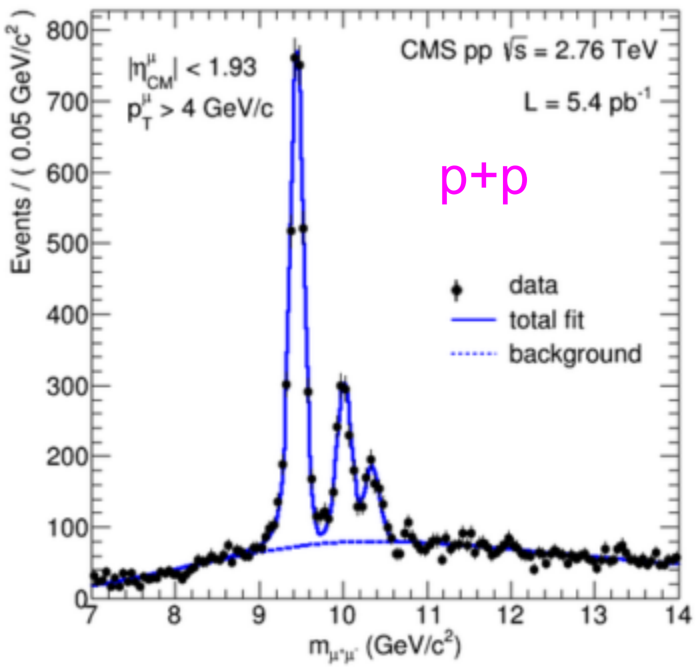
Matsui & Satz,
PLB168 (1986) 415

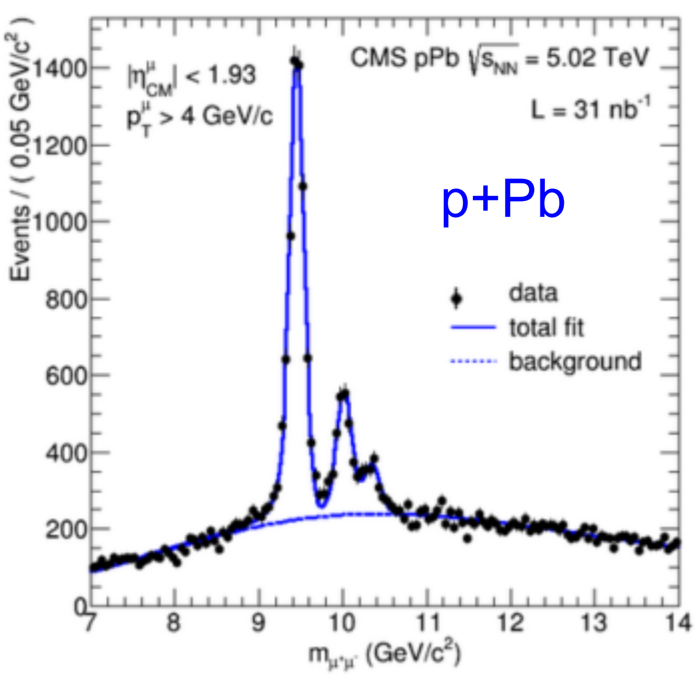


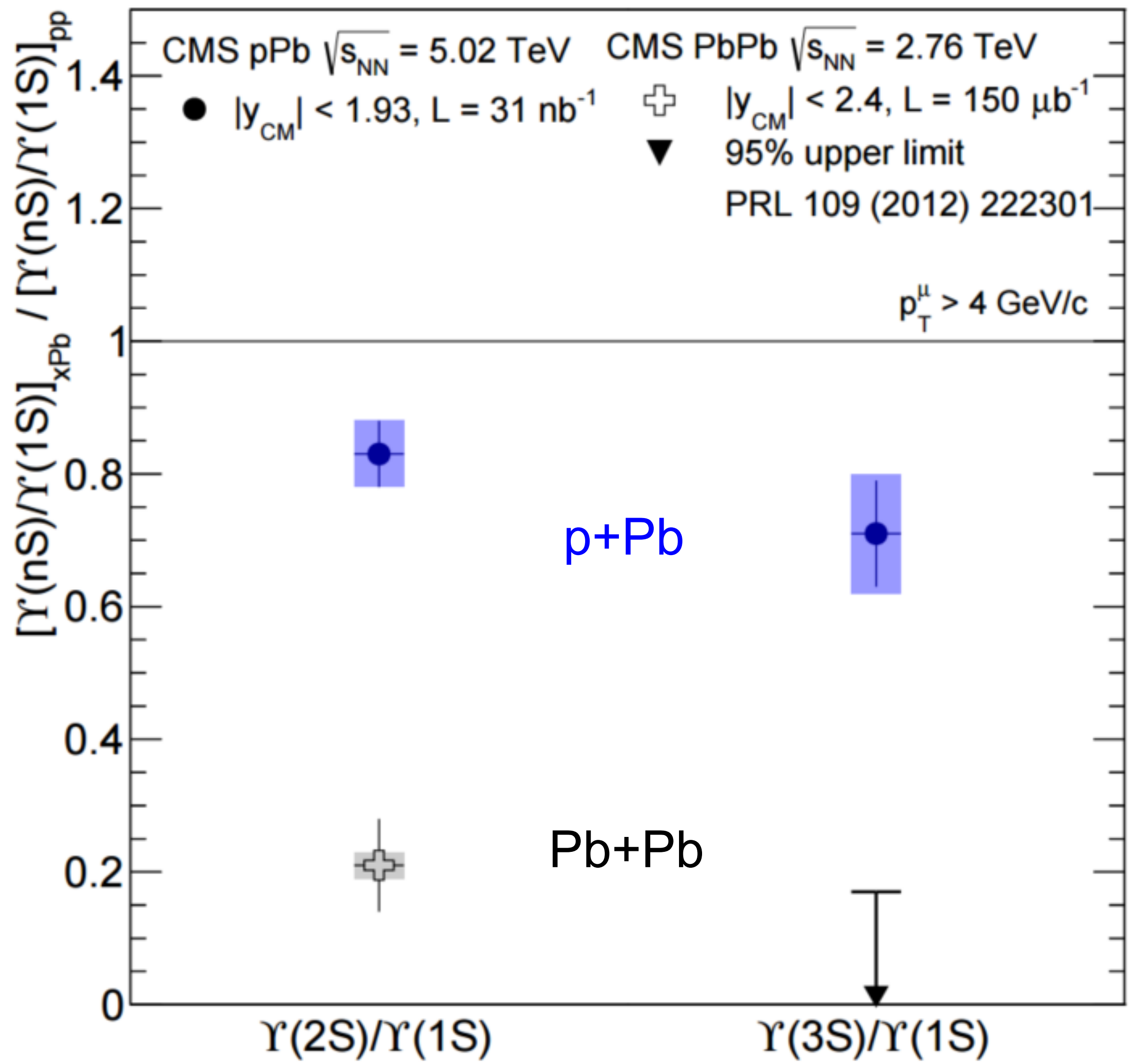
Mocsy, EPJC61 (2009) 705
BNL workshop in June

- The suppression of 5 quarkonia was observed in PbPb
  - Well-ordered with binding energy: Quarkonia melt in quark matter
  - Caveat: Including feed-down, recombination …

Upsilons in pp, pPb, and PbPb







Double ratios in pPb larger than in PbPb

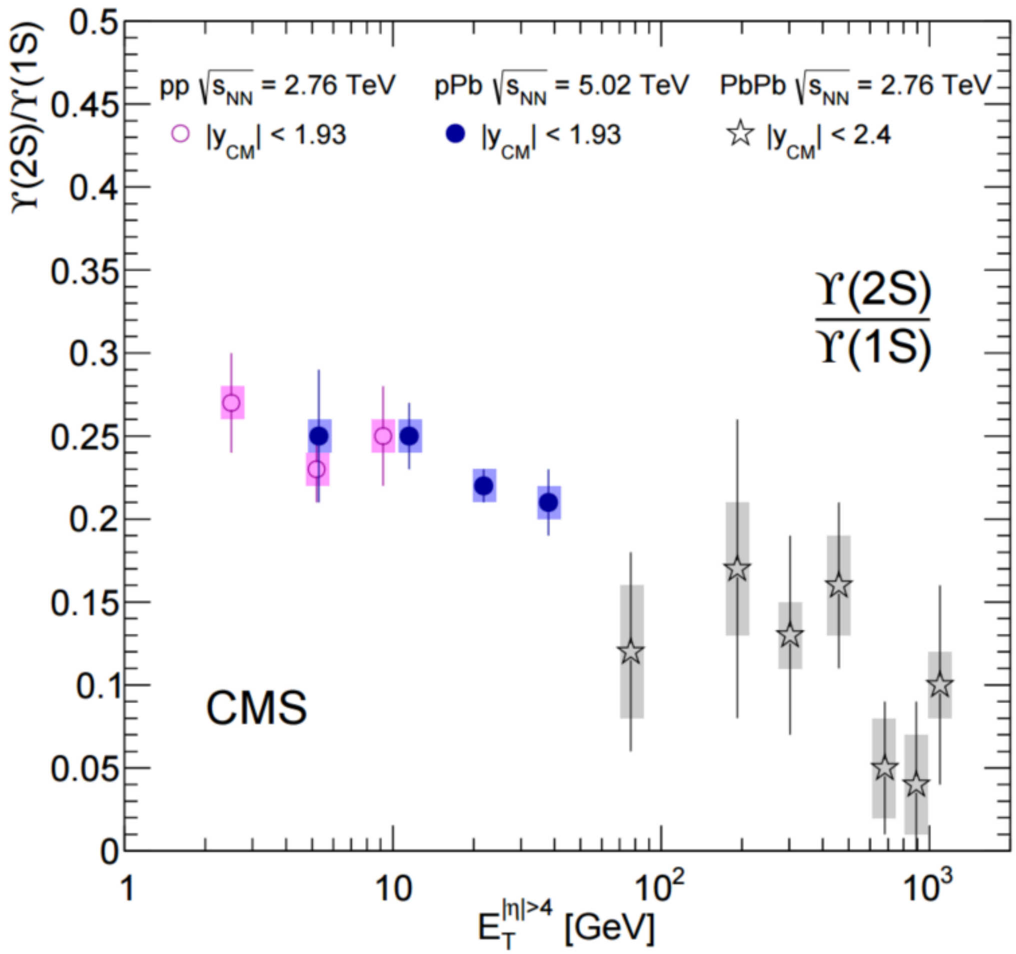
→ Final state effects in PbPb

JHEP 04 (2014) 103

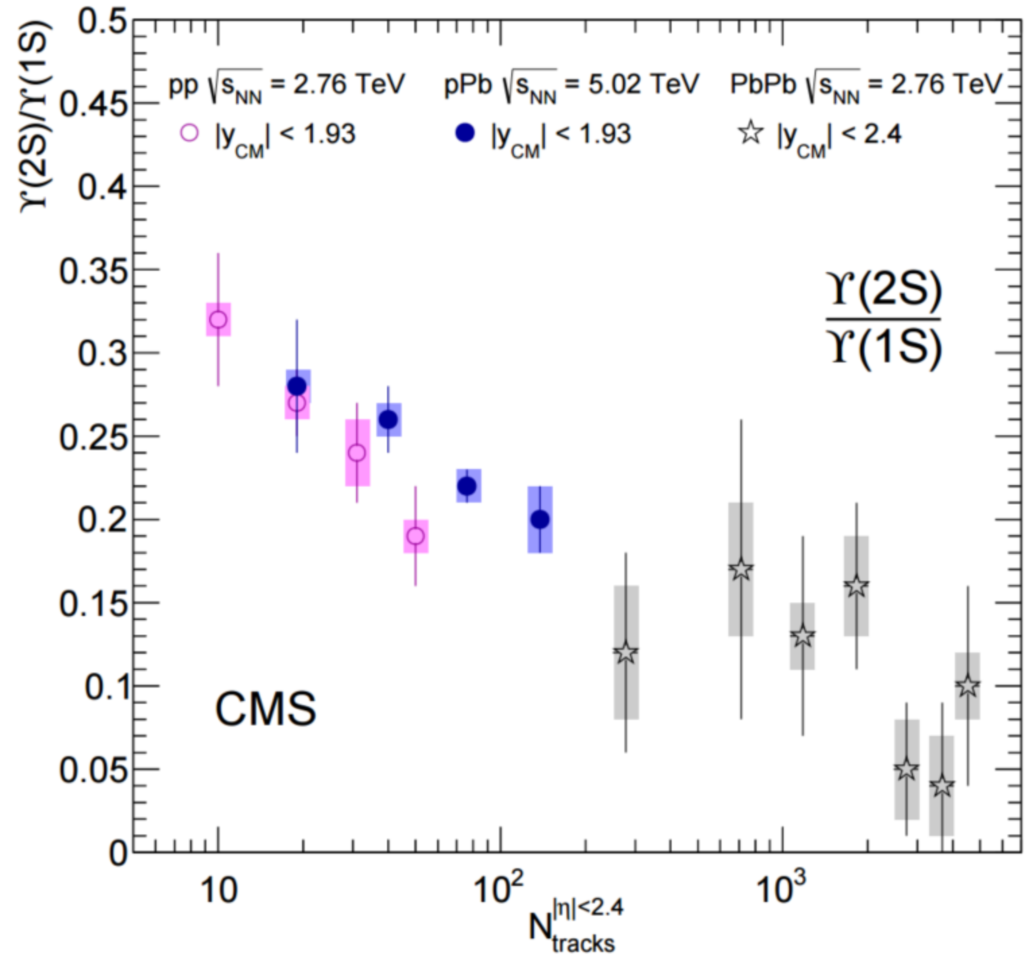
Υ(2S)/Υ(1S) ratios as a function of event activities

p+p p+Pb Pb+Pb

Vs. forward calorimeter transverse energy



Vs. mid-rapidity track multiplicity



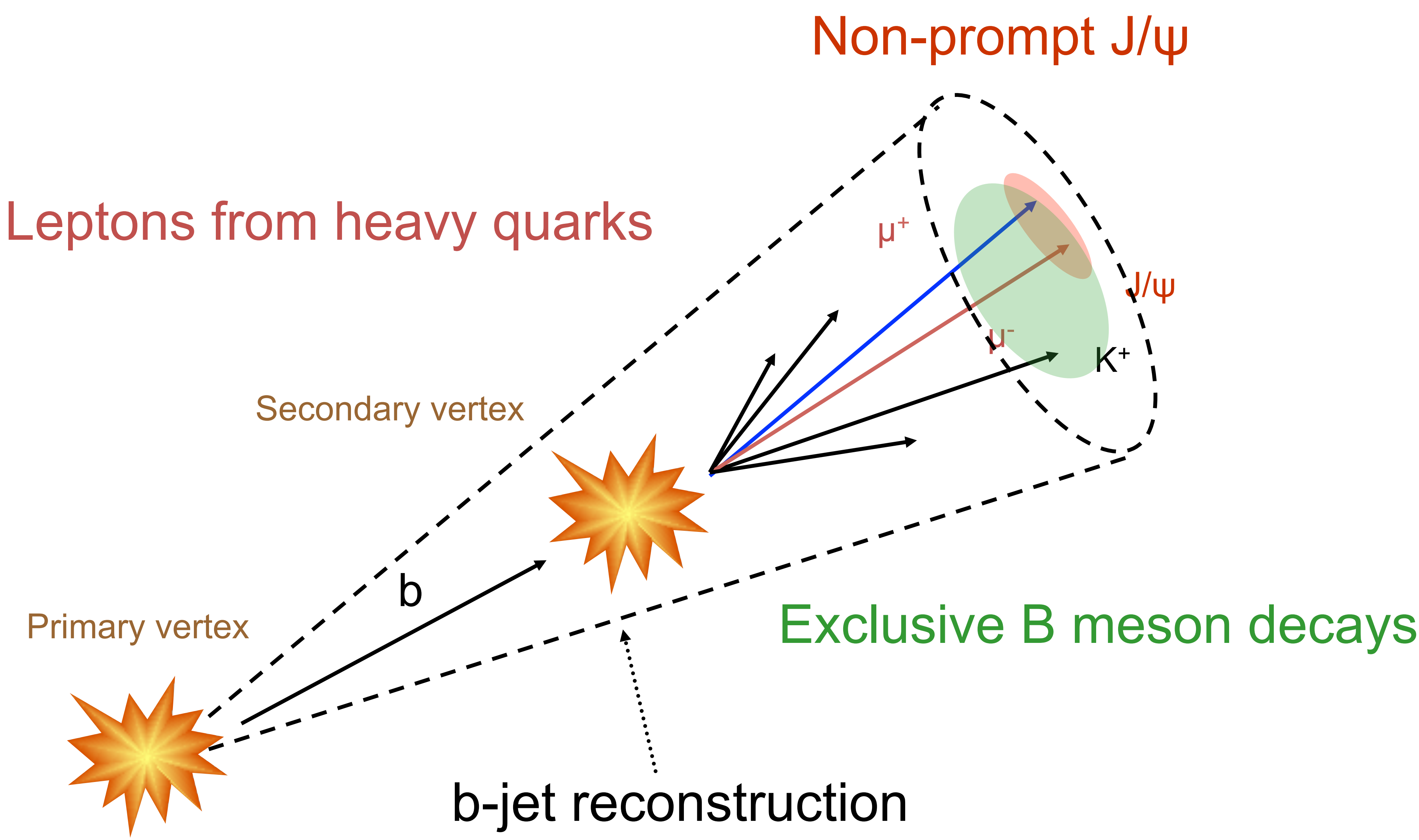
Υ(2S)/Υ(1S) ratio decreases as a function of event activity!

(1) More associated yield with Υ(1S)?

(2) Large event size (multiplicity) affects Υ states?

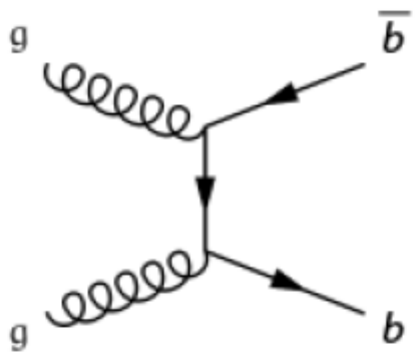
JHEP 04 (2014) 103

(b)-jet Quenching

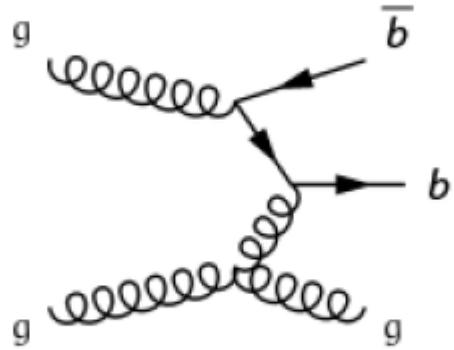


b-jet Production Mechanisms

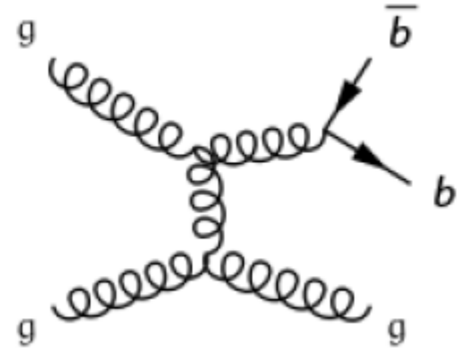
Flavor Creation (FCR)



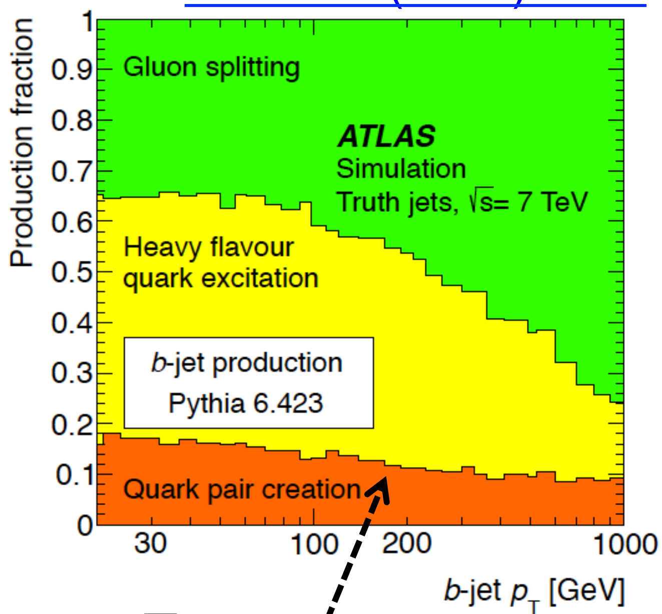
Flavor Excitation (FEX)



Gluon Splitting (GSP)



EPJC 73 (2013) 2301



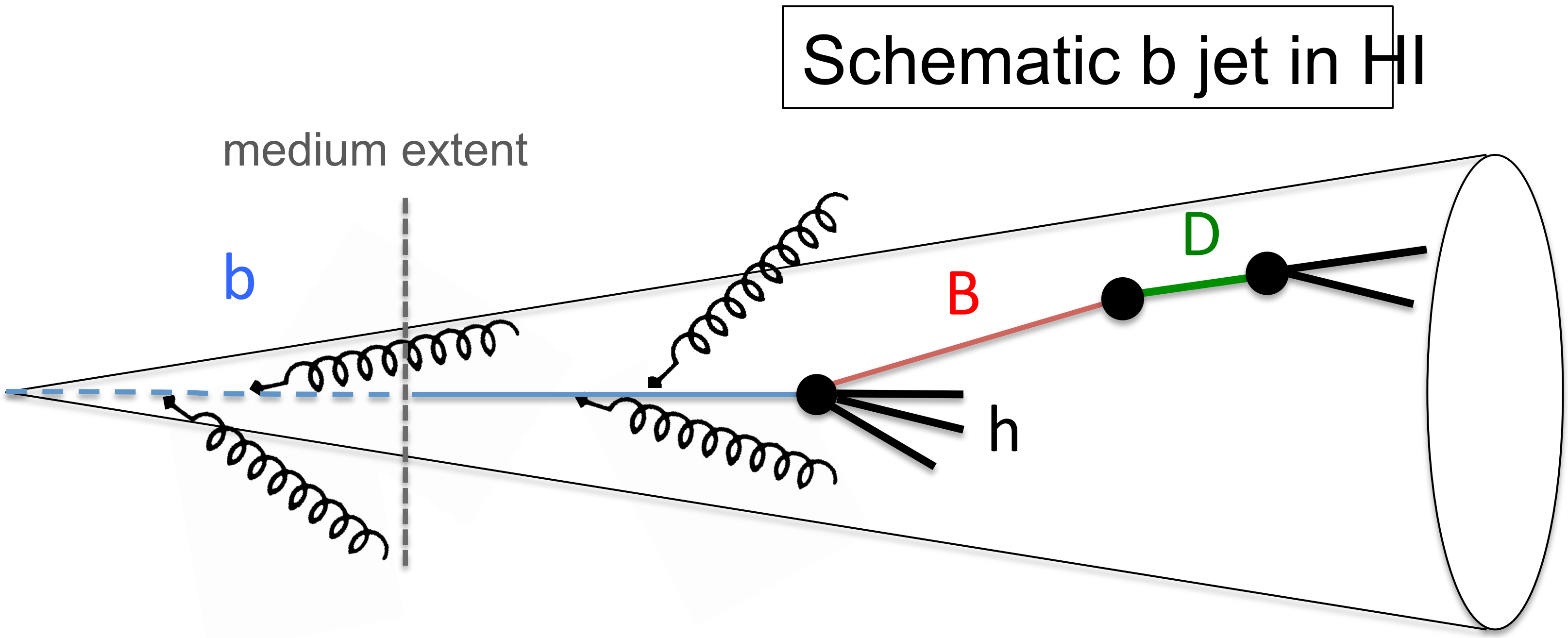
LO b-$\bar{b}$ production (FCR) sub-dominant at the LHC

At NLO:

- Excitation of sea quarks → $\bar{b}$(b) + light dijet, w/ b($\bar{b}$) at beam rapidity
- Gluon splitting into b and $\bar{b}$ which can be reconstructed as a single jet

E-loss of split gluons can be different from primary b quarks

Heavy Flavor Jets



- Standard flavor definition used in CMS:
  - If there is a b quark within ΔR<0.3 from jet axis, then it's a b jet
  - Same for c jets, except b quarks take priority
- HF jet = HF hadron + energy in cone
  - HF hadron need not be fully reconstructed
  - b quark need not be primary (for instance g→$b\bar{b}$), although typically assumed for e-loss calculations!

Tagging and Counting b-quark Jets

Select b-tagged jets using "Secondary Vertex Tagger"

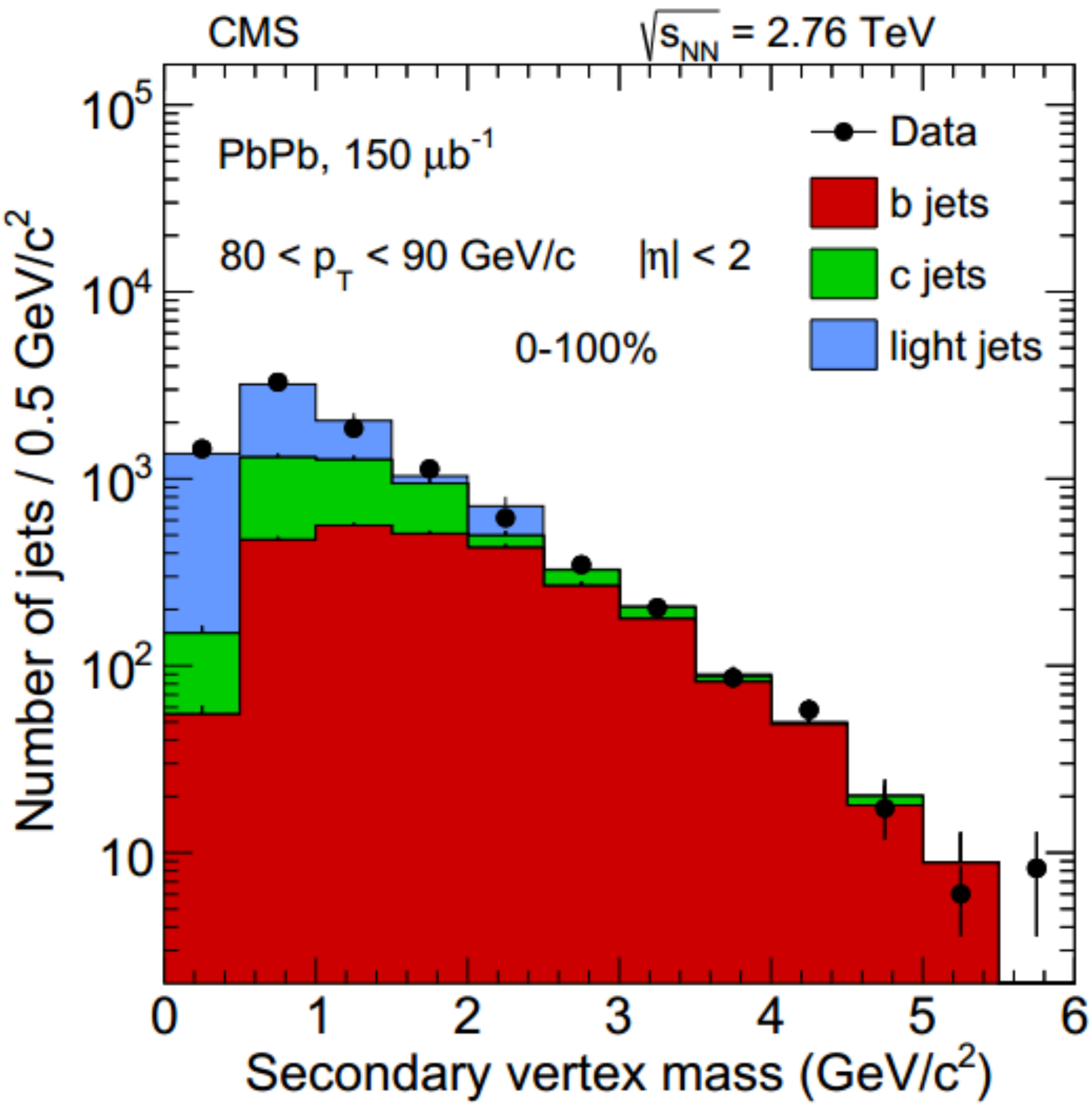
b-jet purity:

From **template fits** to secondary vertex mass distributions using templates from PYTHIA+(HI background)

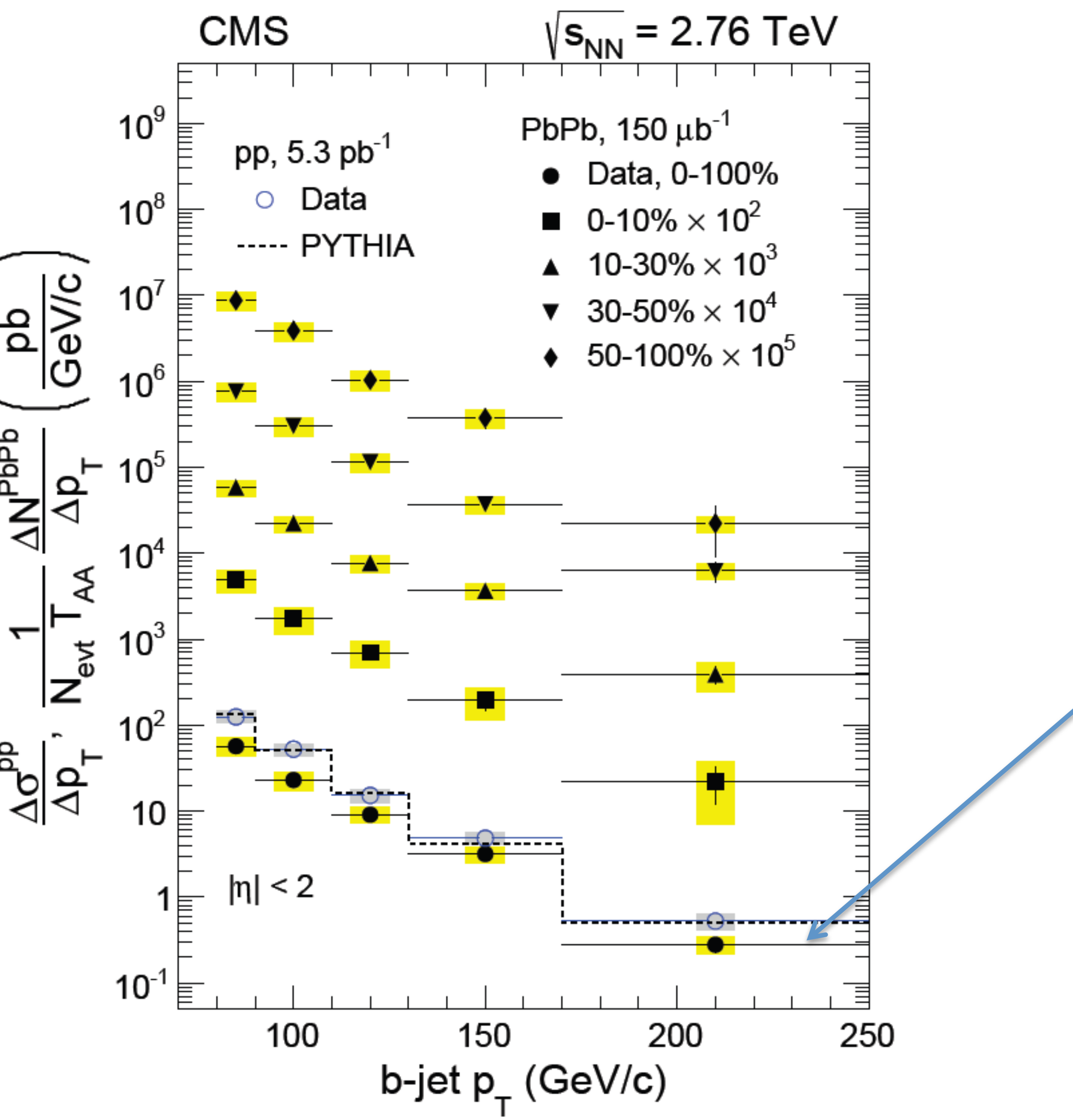
Monte Carlo simulation

CMS HIN-12-003
PRL 113, 132301 (2014)

CMS PAS HIN-14-007



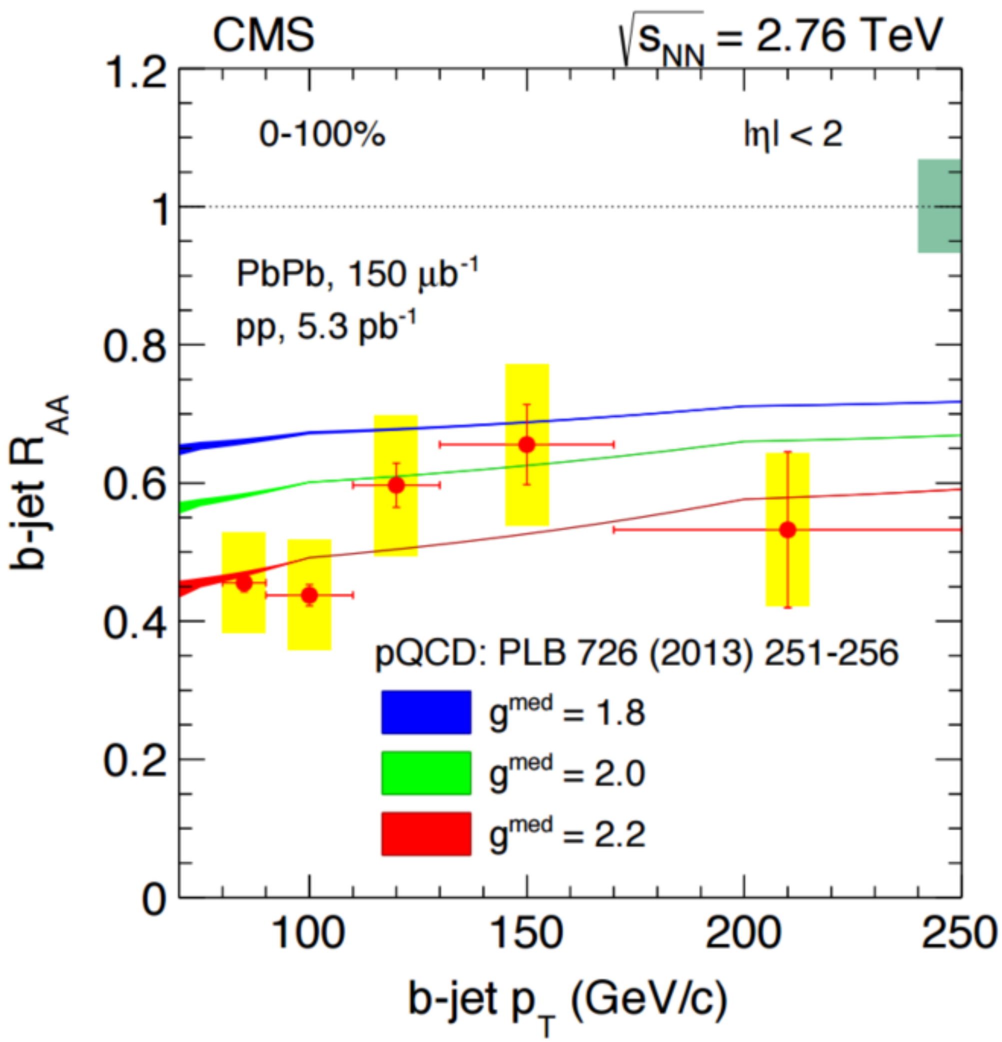
PbPb b-Jet Spectra

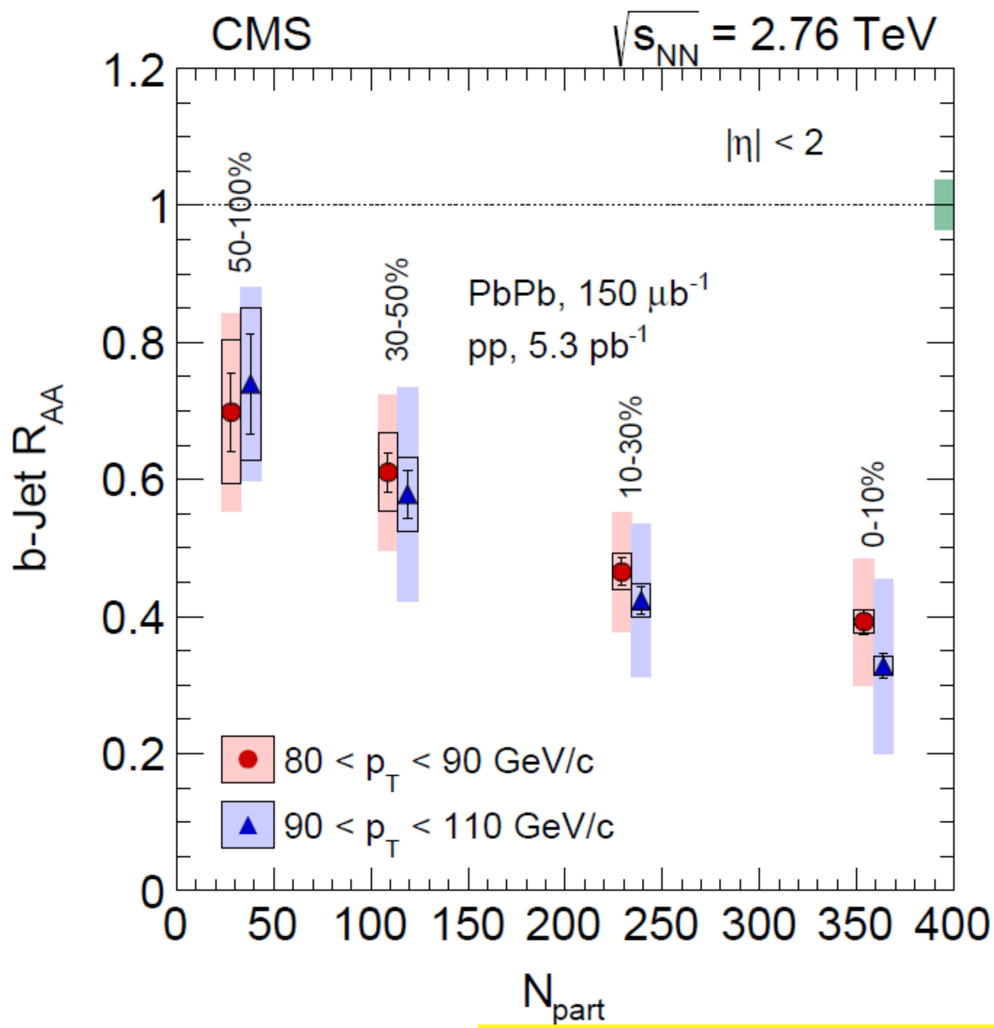


- Efficiency *corrected* and resolution *unfolded* spectra plotted for both PbPb and pp
- b jets in PbPb is scaled by T_{AA}
- Clear indication of b-jet suppression seen

CMS HIN-12-003
PRL 113, 132301 (2014)

b-Jet R_{AA}

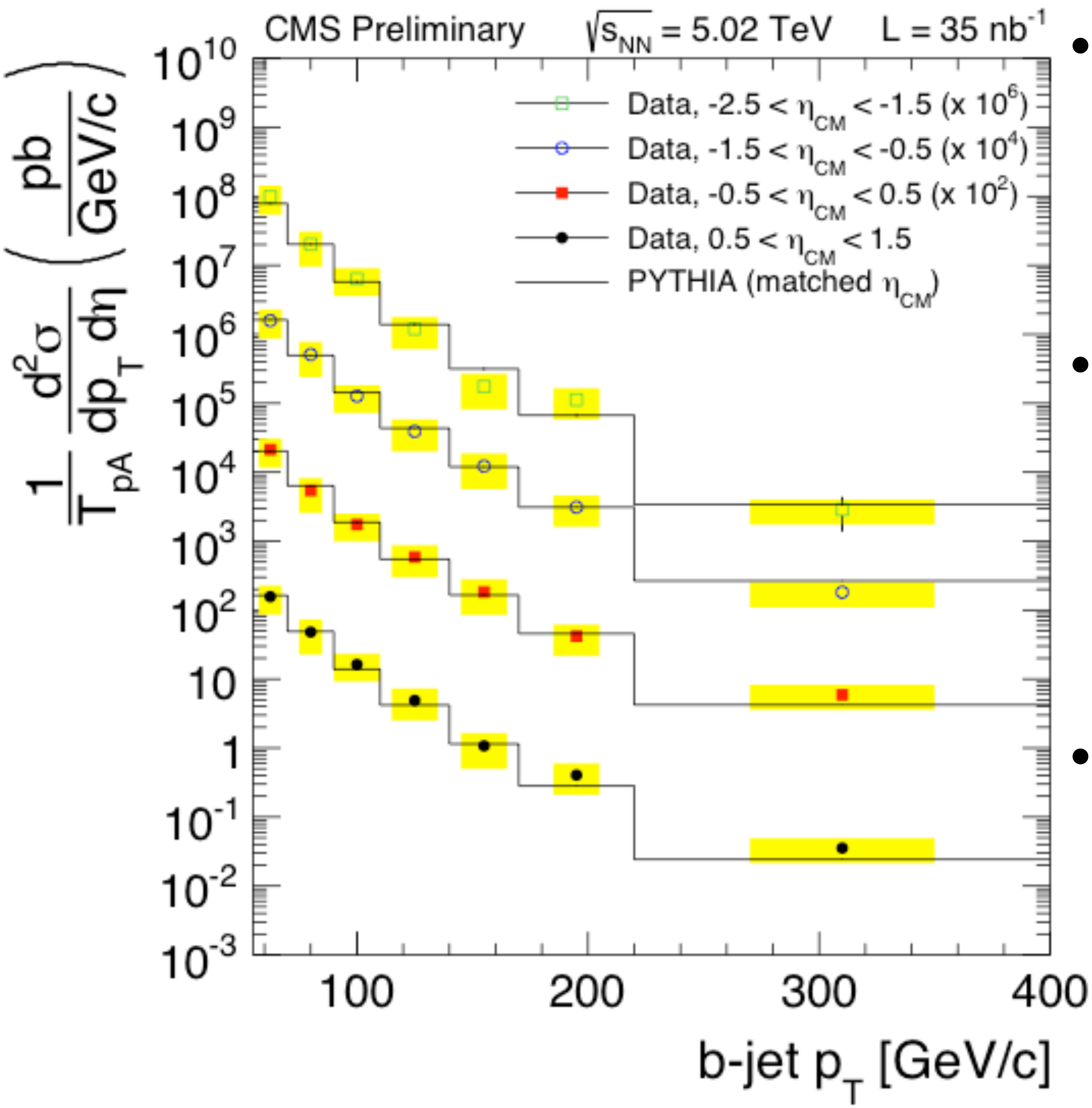




CMS HIN-12-003
PRL 113, 132301 (2014)

- **Evidence of b-jet suppression in PbPb collisions**
- Suppression favors pQCD model with stronger jet-medium coupling
- Are there cold nuclear effects contributing to the observed suppression?

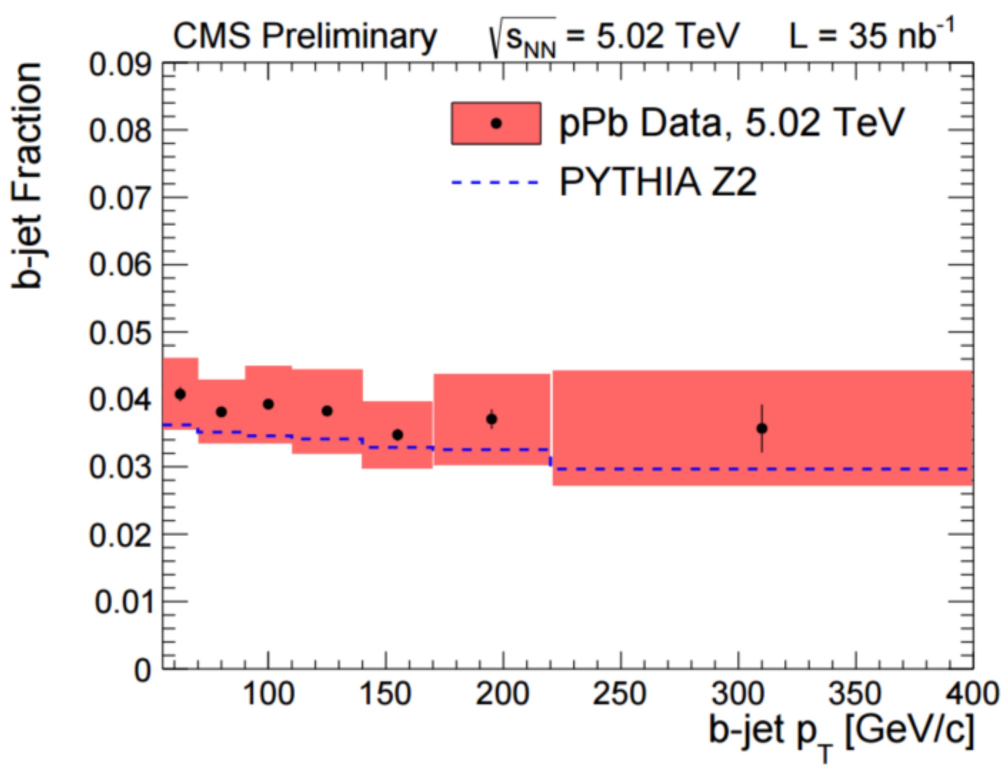
pPb b-jet Spectra

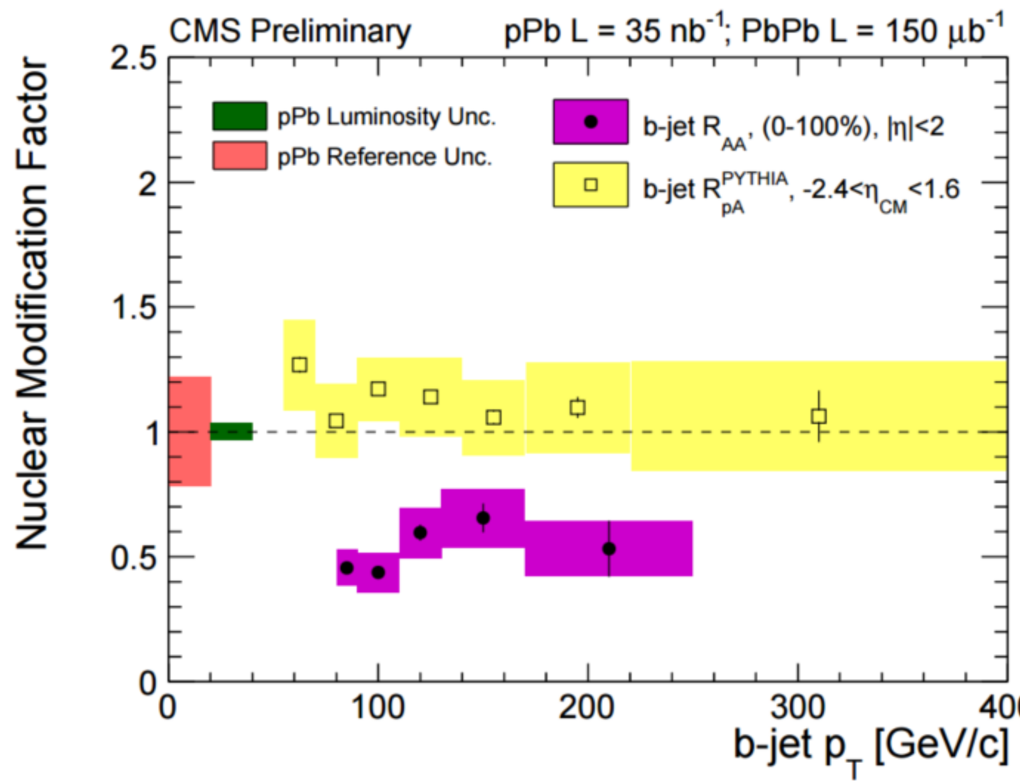


- b-jet spectra shown for various selections in η_{CM}
- pPb Spectra scaled by T_{pPb} to be compared to PYTHIA reference
- Minimal suppression or enhancement is observed

CMS PAS HIN-14-007

b-jet Fraction and R_{pPb} in pPb Collisions





- Measured b-jet fraction is consistent with PYTHIA prediction
- b-jet R_{PA} is consistent with unity within the quoted systematical uncertainty
- Suppression of b-jet in PbPb collisions is not from initial / cold nuclear effects

CMS PAS HIN-14-004

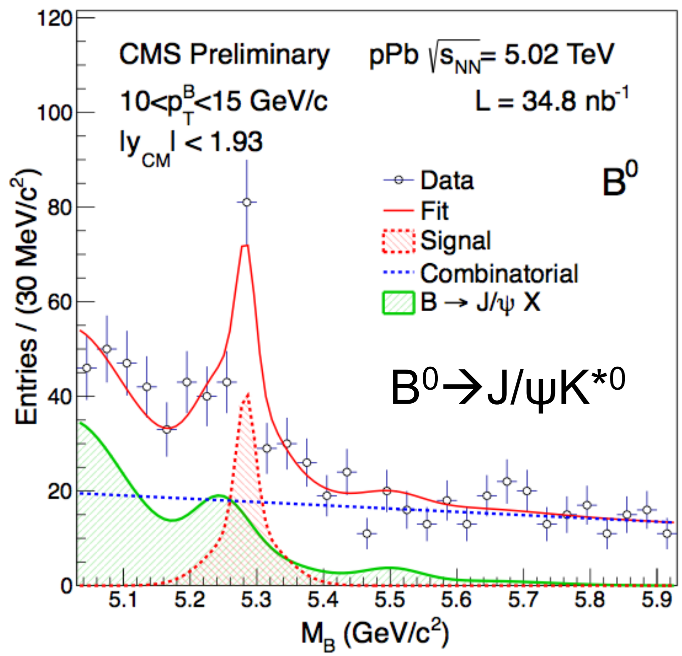
B Meson Production in pPb Collisions at 5.02 TeV

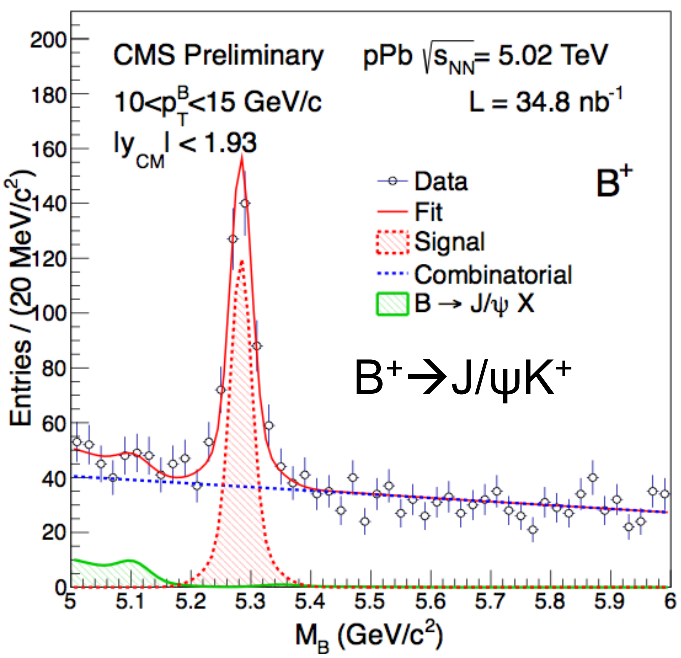
CMS PAS HIN-14-004

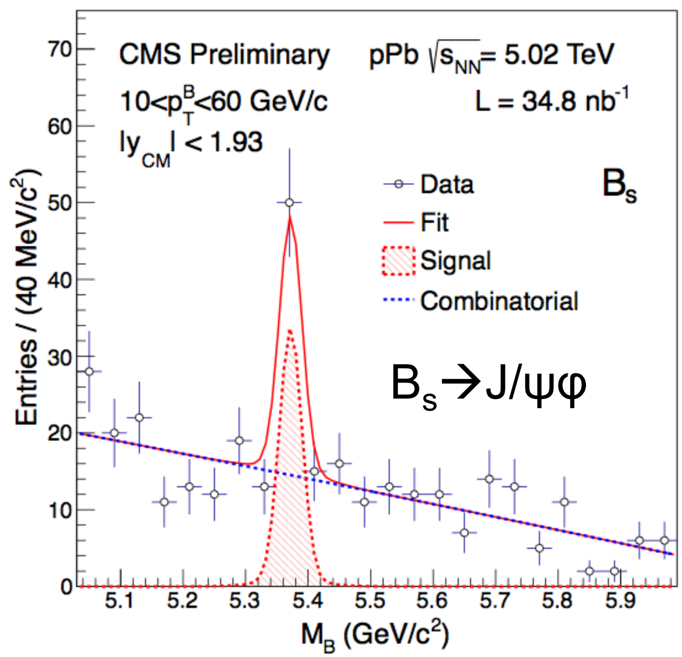
Three component fit for signal extraction:

- Signal
- Combinatorial background from J/ψ-track(s)
- Non-prompt component from other B-meson decays that form peaking structures (e.g. in B^+ analysis, bkg from $B^0 \rightarrow J/\psi K^{0*}$)

Fully reconstructed B meson signal in heavy ion collisions!

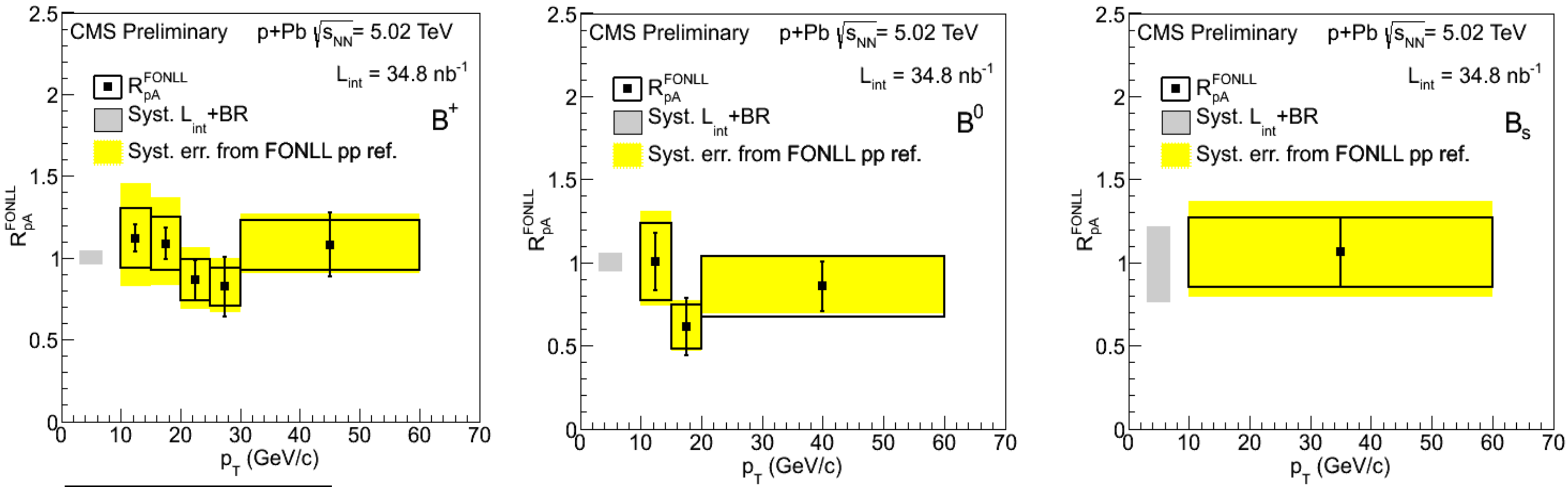






Nuclear Modification Factors: R_{pA}^{FONLL}

$$R_{pA}^{FONLL}(p_T) = \frac{\left(\frac{d\sigma}{dp_T}\right)_{pPb}}{A \times \left(\frac{d\sigma^{FONLL}}{dp_T}\right)_{pp}}$$

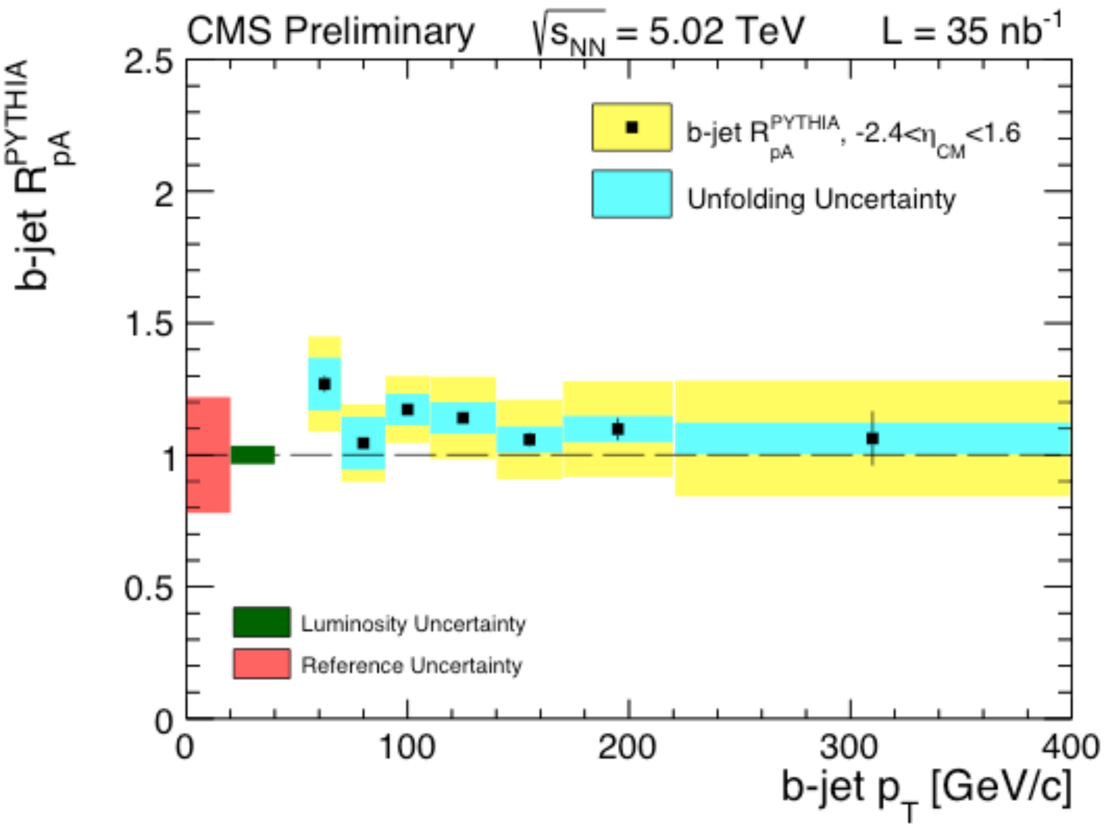


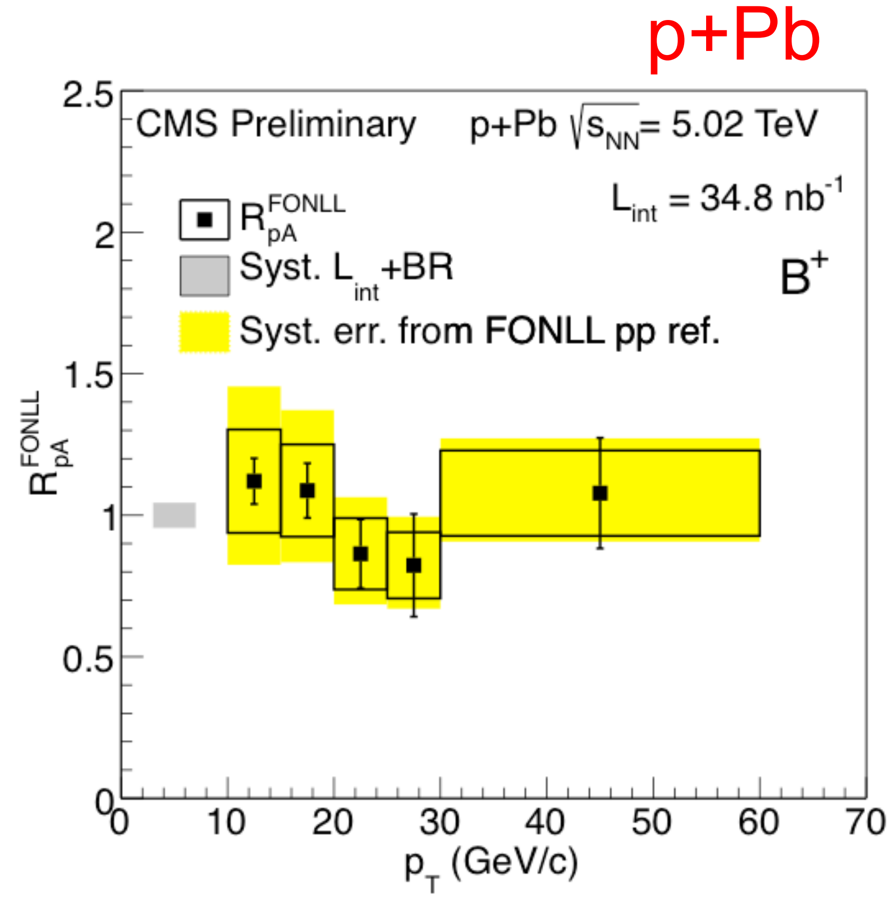
$|y_{CM}|<1.93$

R_{pA}^{FONLL} is compatible with unity within given uncertainties for the three B-mesons

CMS PAS HIN-14-004

b-jets vs. Fully Reconstructed B Mesons





- Measurements of nuclear modification factors of b-jet and B mesons are consistent with unity over a wide p_T range

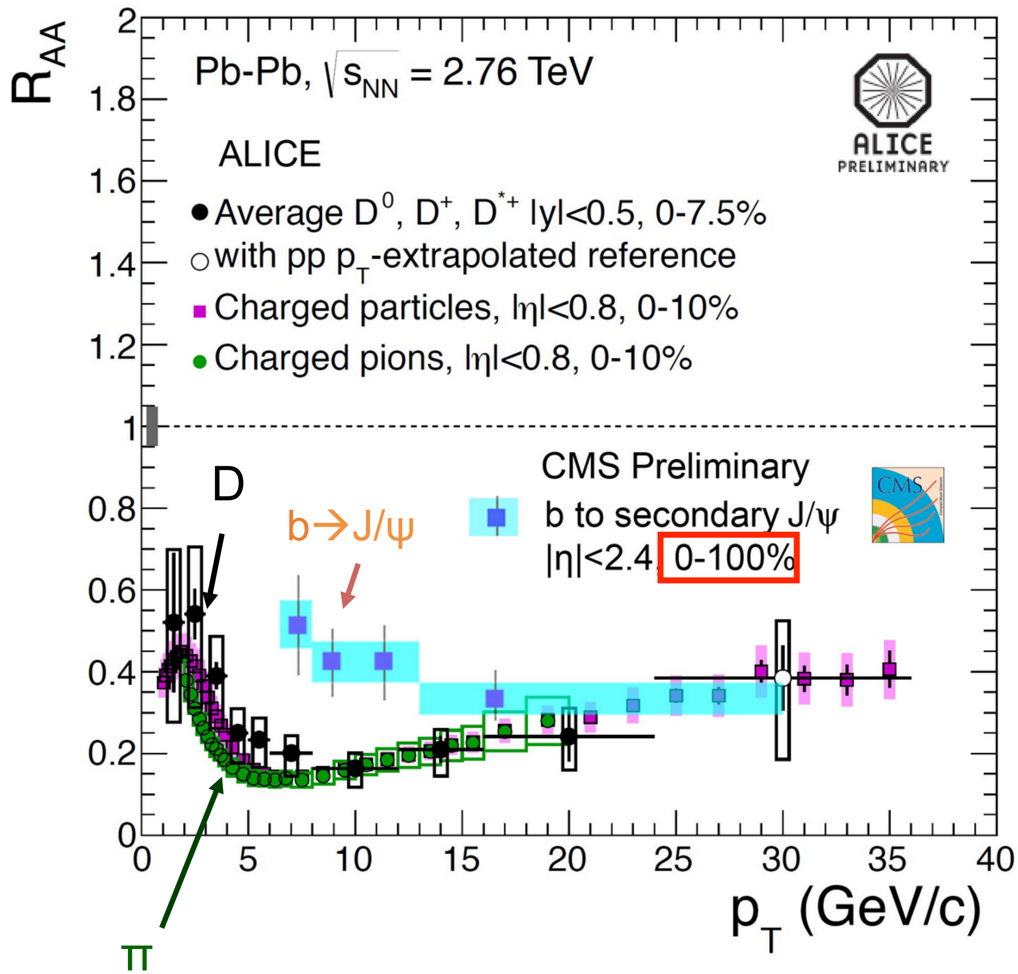
CMS PAS HIN-14-004

CMS PAS HIN-14-007

Flavor Dependence of Jet Quenching

Indication of $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$ at low p_T
(However, spectra slope are different)

Pb+Pb

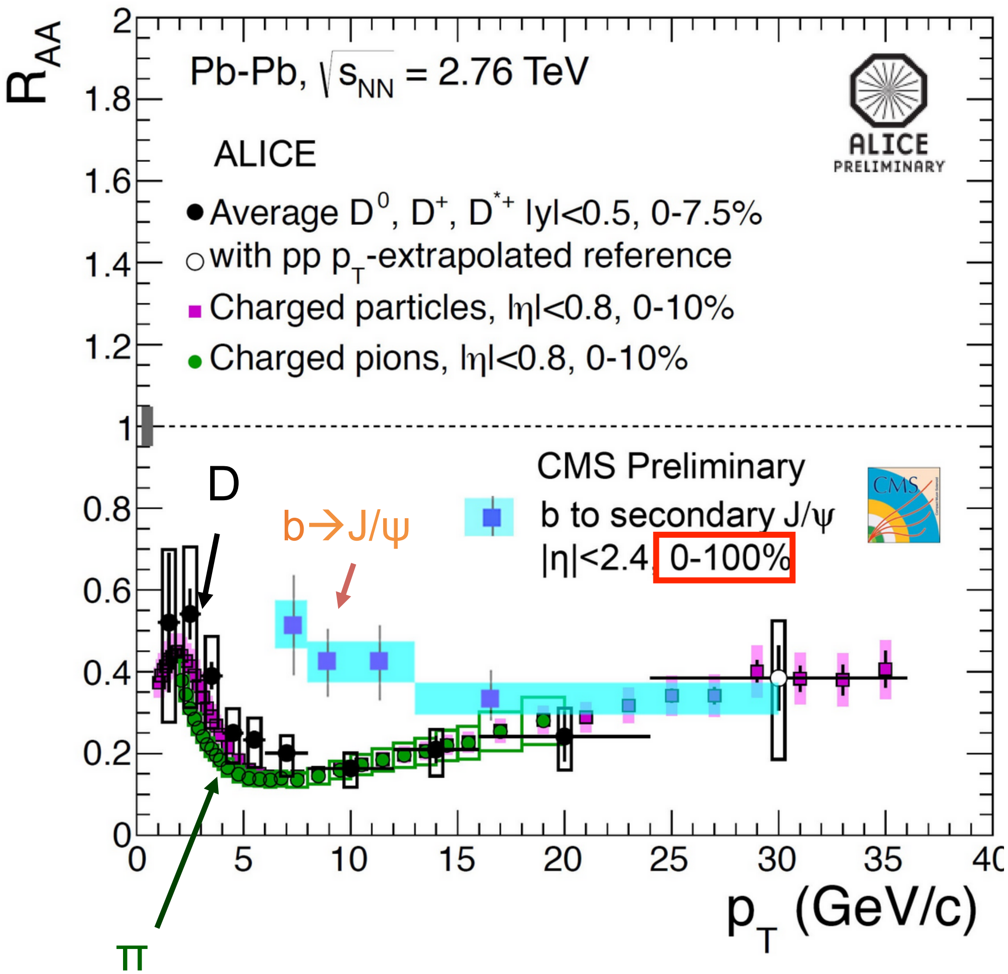


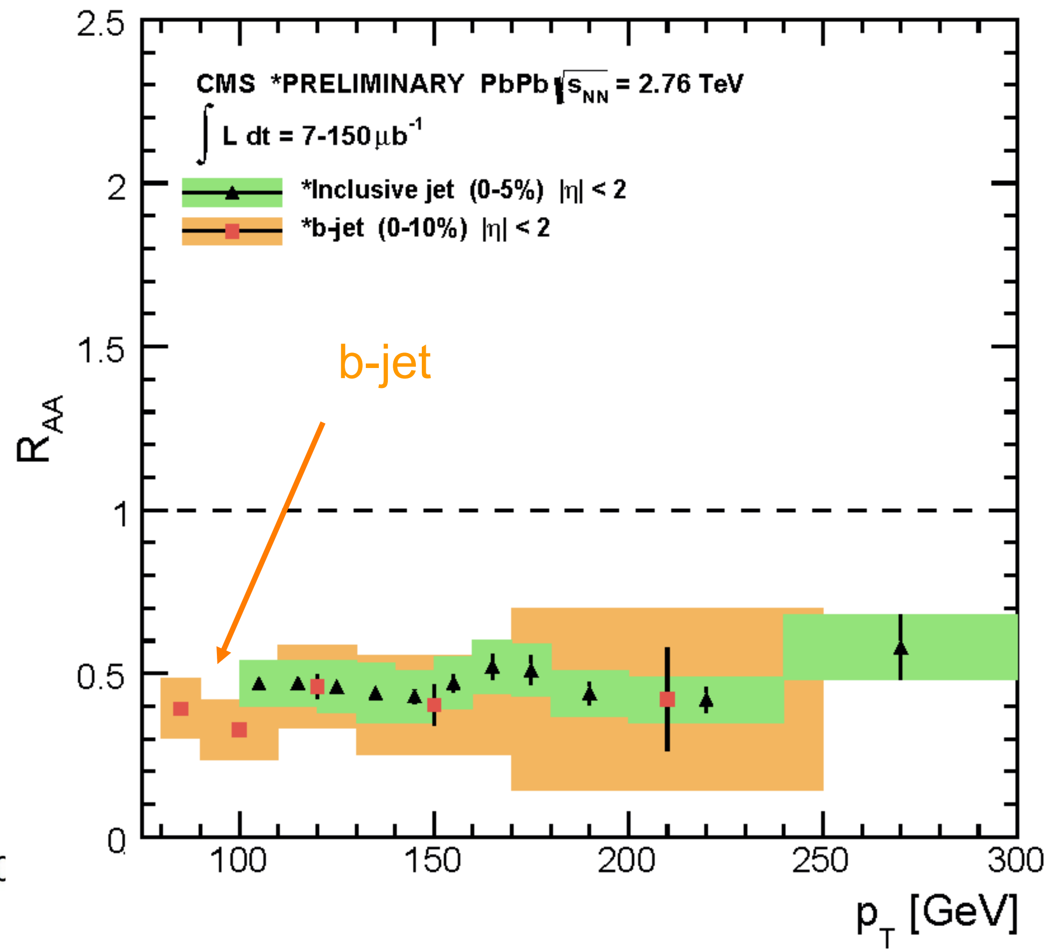
Flavor Dependence of Jet Quenching

Indication of $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$ at low p_T
(However, spectra slope are different)

Indication of R_{AA}(b-jet) ~ R_{AA}(all jets) at high jet p_T

Pb+Pb





b quark jet (quark jet) ~ inclusive jet (dominated by gluon jets)?

Contribution from gluon splitting?

Summary

- Quarkonia production is strongly affected by the hot plasma. The pattern of suppression depends on the strength of bonding. Work to interpret it as a measure of plasma properties is in progress
- Jets containing heavy quarks can be clearly identified in collider detectors. The pattern of suppression provides important handle to energy loss calculations

Summary of the lecture series

- We discussed general ideas behind the goals of the heavy ion physics field: study of hot nuclear matter that existed about 1 microsecond after the Big Bang
- We discussed several different ways in which we try to experimentally characterize the properties of such matter
- We discussed some of the conclusions from the measurements and pointed "things to do"
- We expect new understand coming from the upcoming runs at LHC and RHIC, I hope that these lectures will help you understand the context of the results to come