Quarkonia and Open Heavy Flavor Results from CMS

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For the CMS collaboration

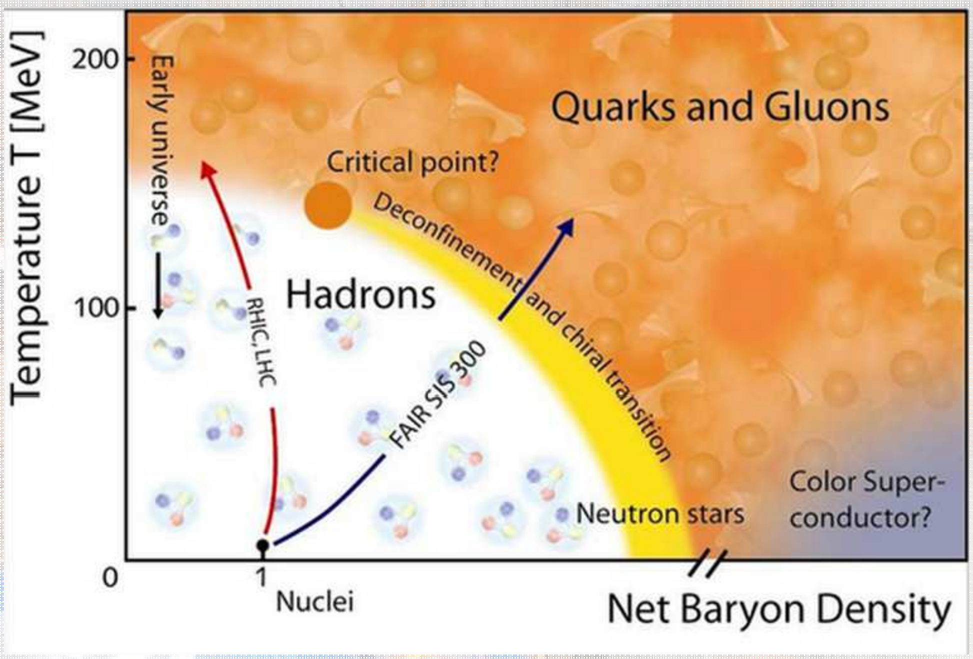
Heavy Quark Physics in Heavy-Ion Collisions

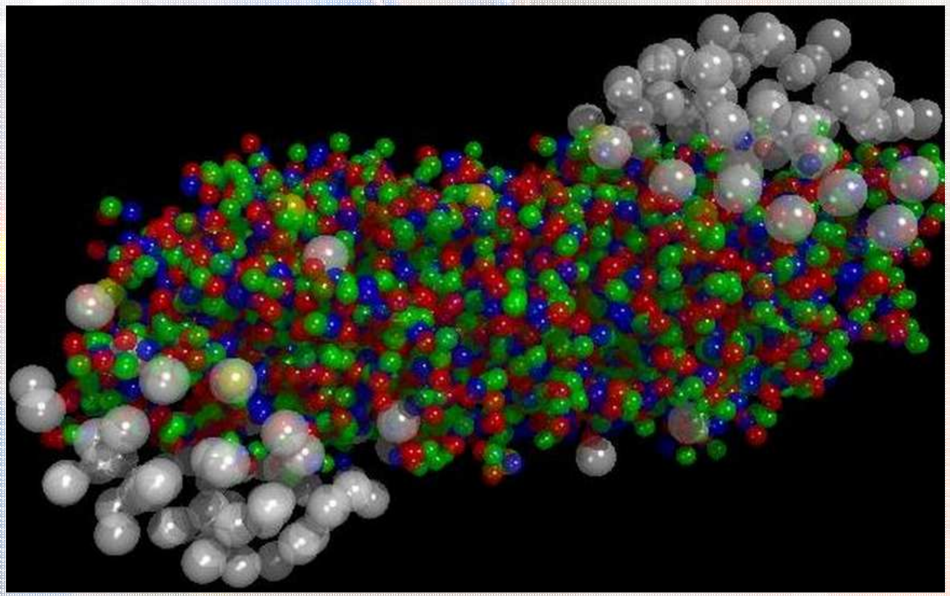
ECT*, Trento, Italy

16-20 March, 2015

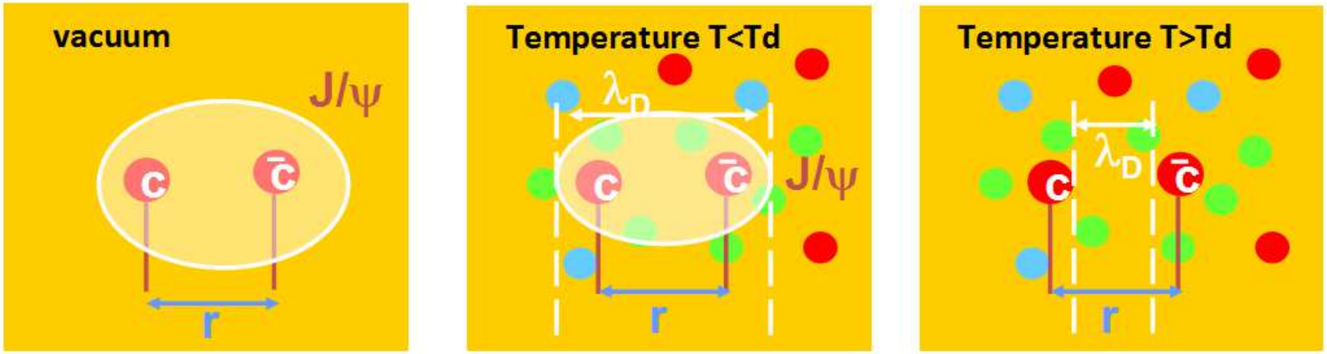
Relativistic Heavy Ion Collisions

- Trying to answer two fundamental questions in the high density QCD:
  - **Where is the critical point of the QCD phase diagram?**
  - **What are the properties of Quark Gluon Plasma?**

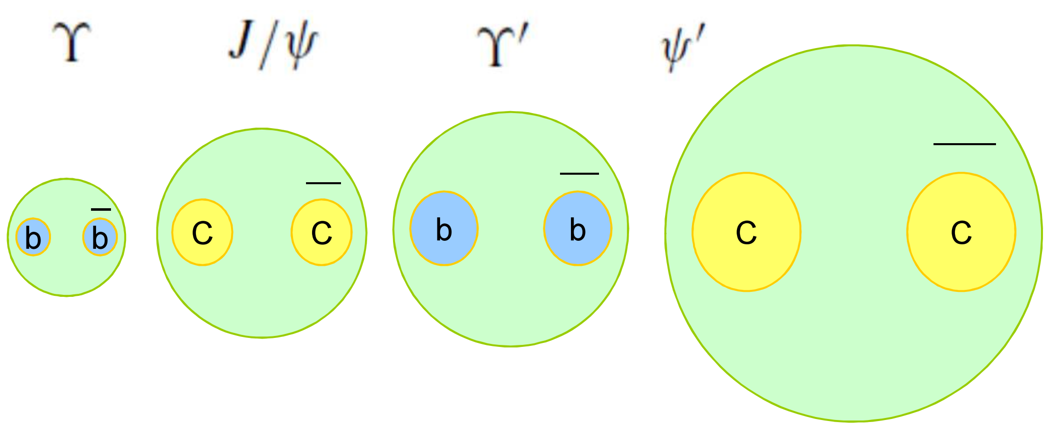


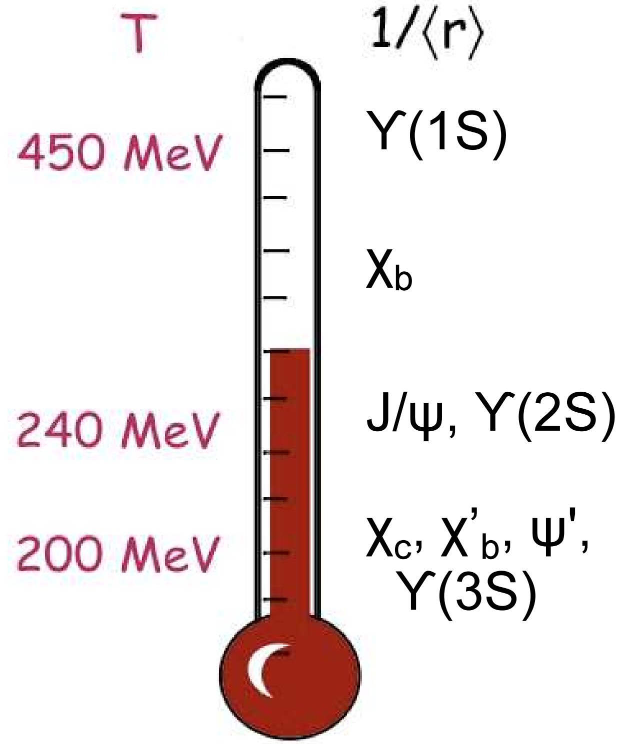


Quarkonia as a tool to probe the QGP



Matsui & Satz, PLB168 (1986) 415





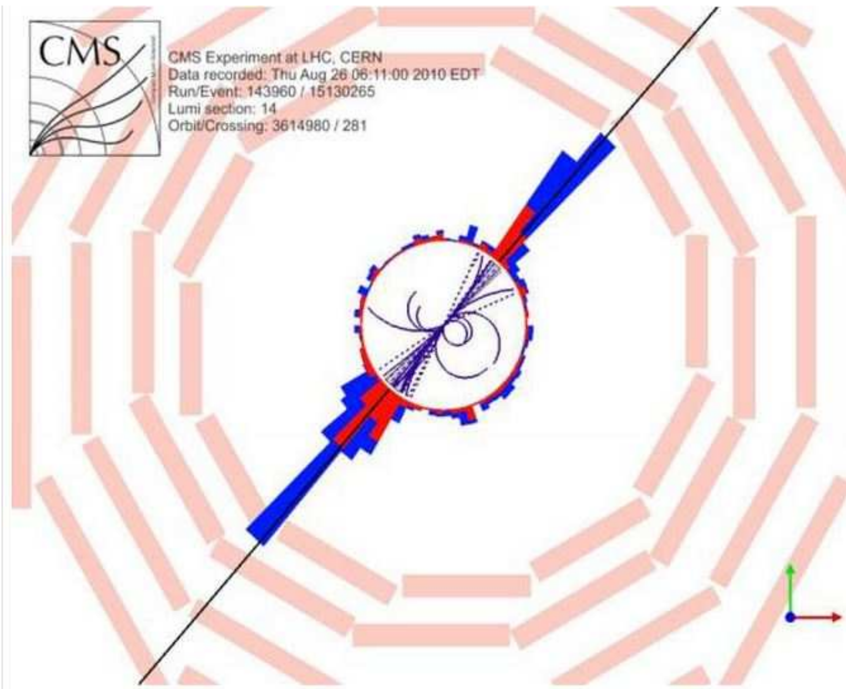
Different states have different binding energies
Loosely bound states "melt" first!

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

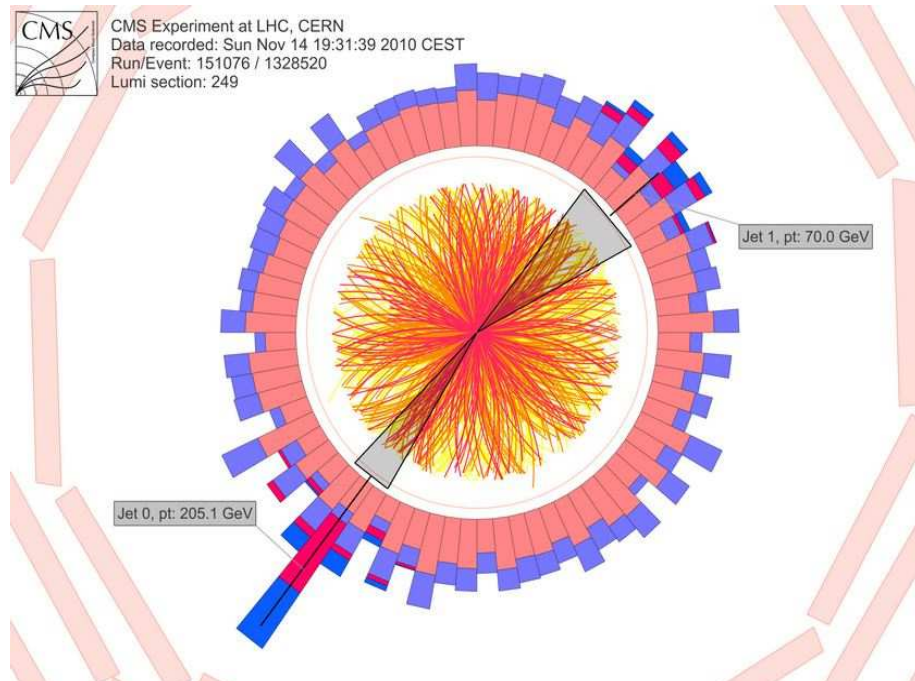
Mocsy, EPJC61 (2009) 705
BNL workshop in June

Probe the QGP with high energy quarks and gluons

Quark-gluon plasma is incredibly strongly interacting – It even stops very high energy quarks and gluons passing through it



P + P



Pb + Pb

PRC 84 (2011) 024906

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

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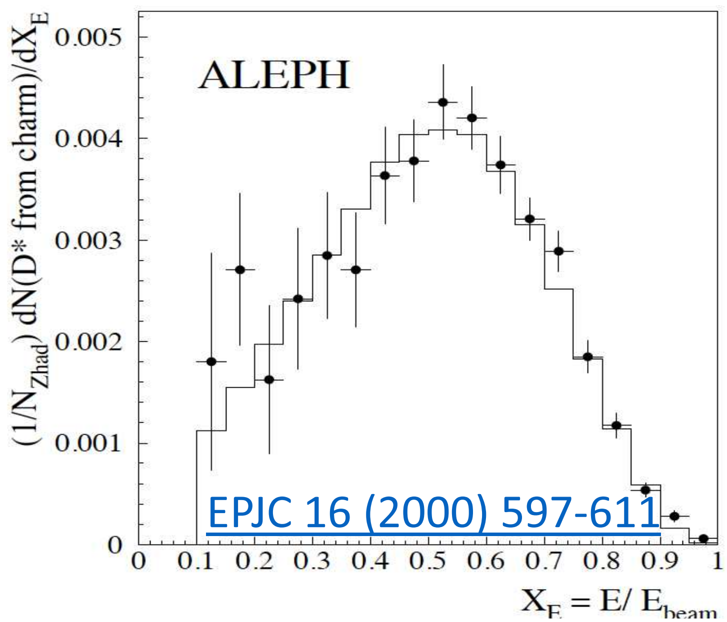
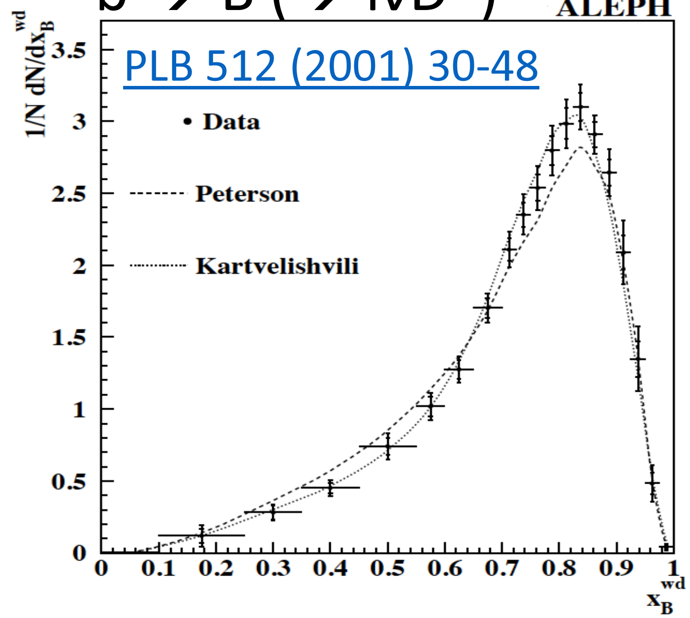
c → D*



b → B (→ lνD*)



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

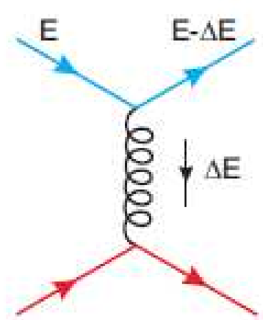
b → B harder than c → D harder than q/g → h

Flavor dependence of parton energy loss

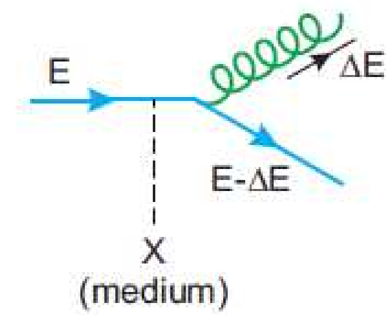
- From QCD
  - Color charge:
    E_{loss} in gluons > E_{loss} in quarks
  - Kinematics: "Dead cone effect":
    E_{loss} in quarks > E_{loss} in heavy quarks

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



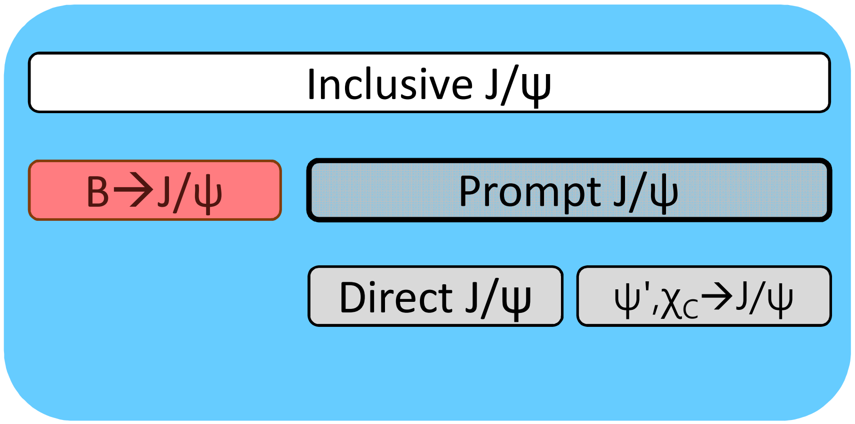
Radiative energy loss

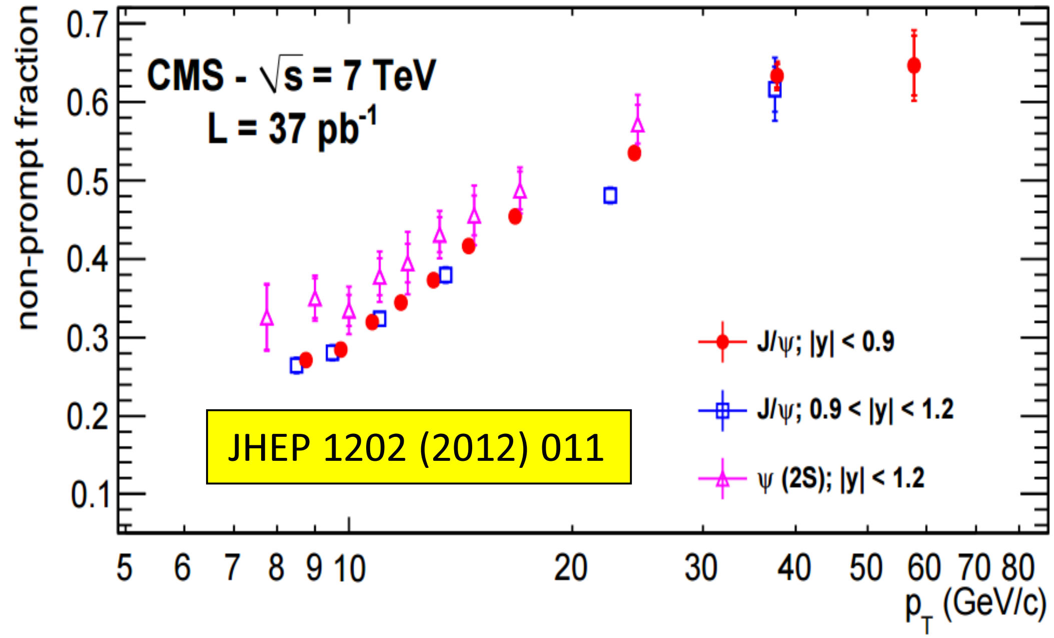


Heavy flavor jet and hadron analyses cover a wide kinematics range
→ Suppression of induced radiation at low p_T and the disappearance of this effect at high p_T

Quarkonia production at LHC

Charmonium production

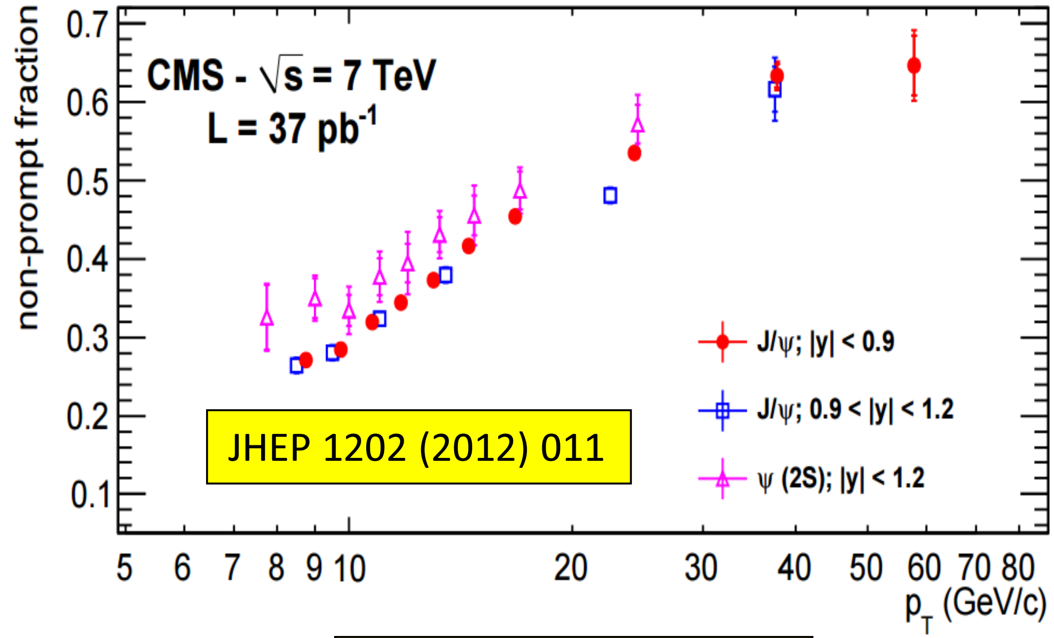




Quarkonia production at LHC

Charmonium production

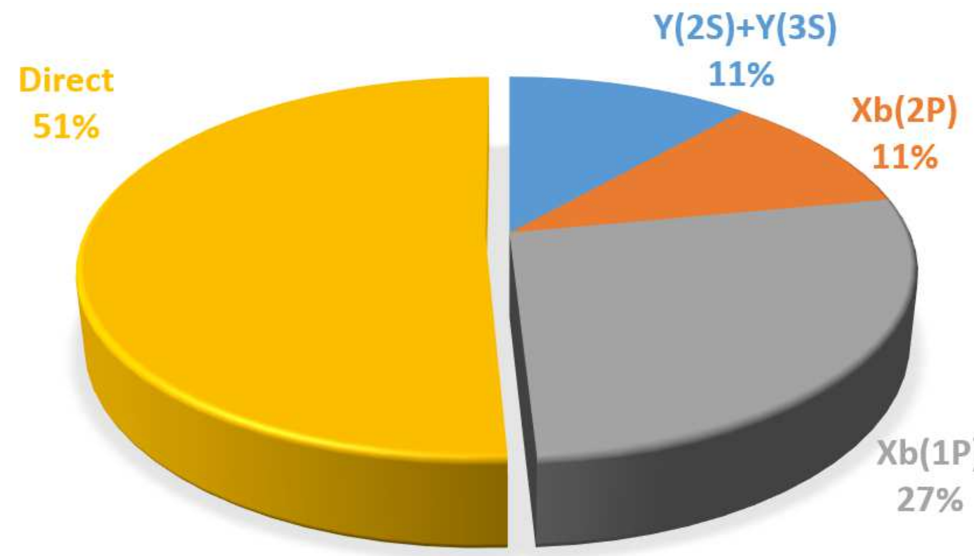
- Inclusive J/ψ
  - B→J/ψ
  - Prompt J/ψ
    - Direct J/ψ
    - ψ',χ$_C$→J/ψ



CDF, PRL 84 (2000) 2094

Bottomium production

- Prompt Υ(1S)
  - Direct Υ(1S)
  - Υ(2S,3S), $X_{b...}$→Υ(1S)



Quarkonia production at LHC

Charmonium production

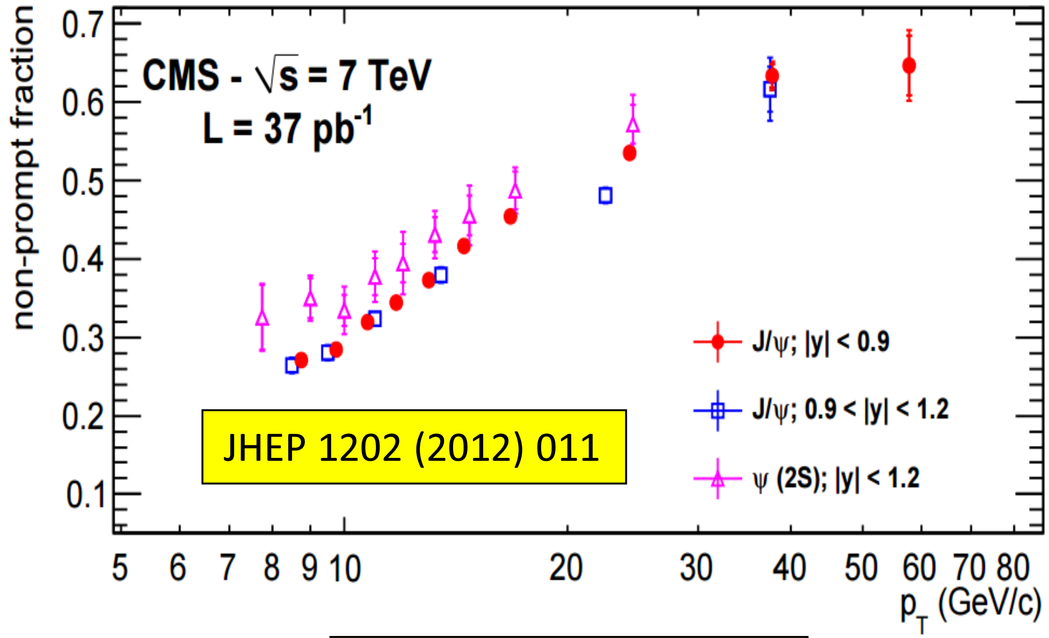
- Inclusive J/ψ
  - B→J/ψ
  - Prompt J/ψ
    - Direct J/ψ
    - ψ',χ_C→J/ψ

Stopping / scattering power of QGP

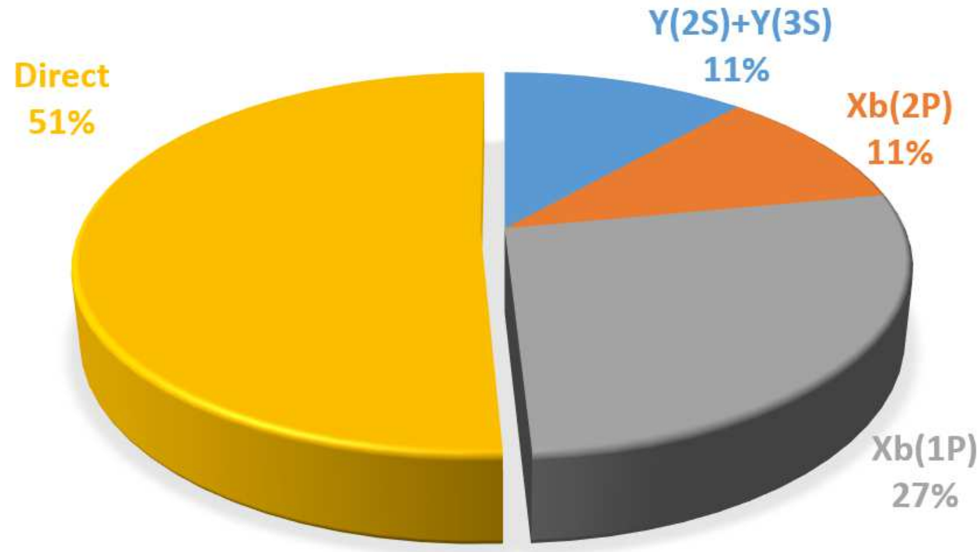
Temperature / Screening length

Bottomium production

- Prompt Υ(1S)
  - Direct Υ(1S)
  - Υ(2S,3S), $X_{b...}$→Υ(1S)

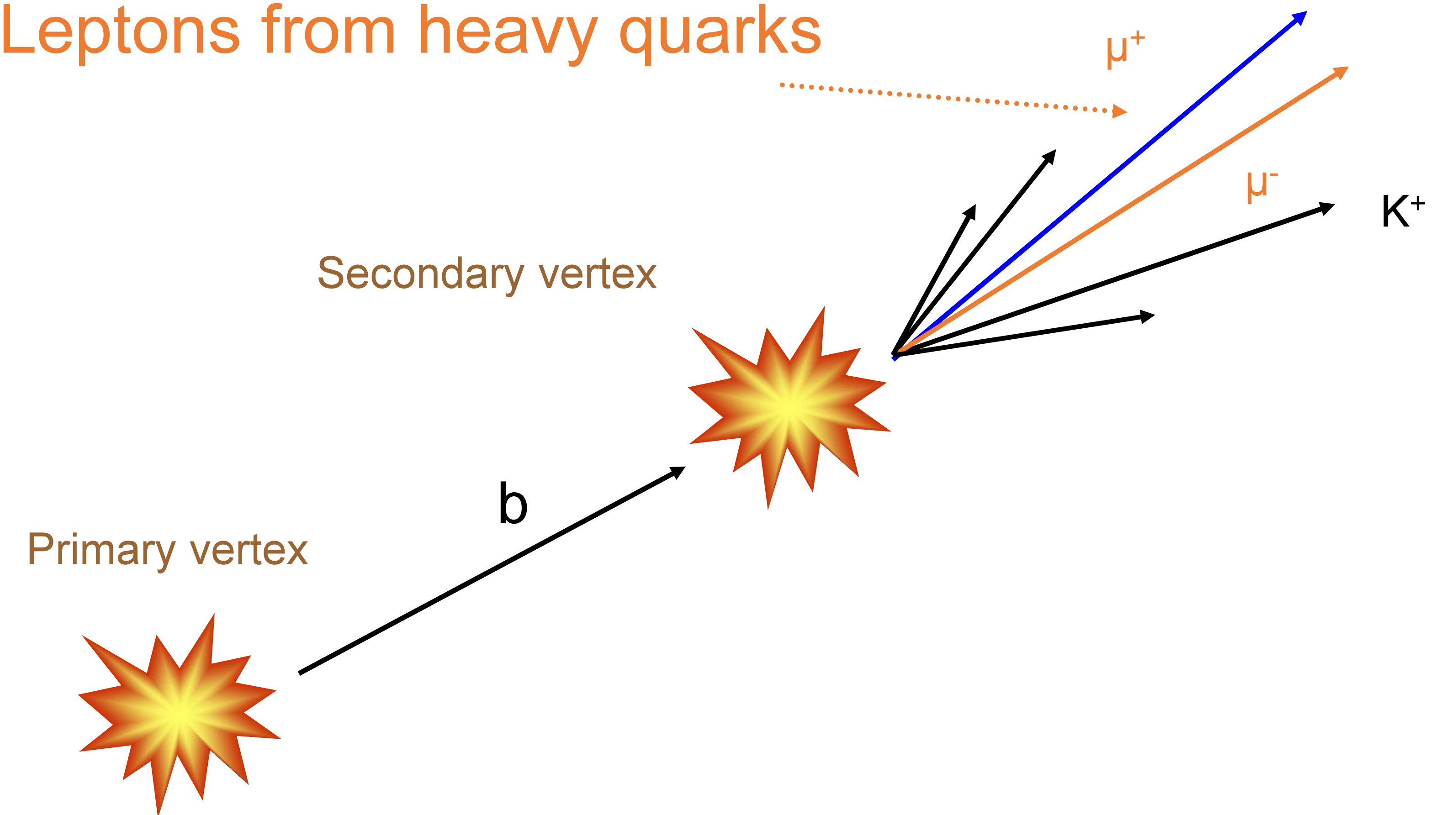


CDF, PRL 84 (2000) 2094



Open Heavy Flavor Production (1/4)

Leptons from heavy quarks

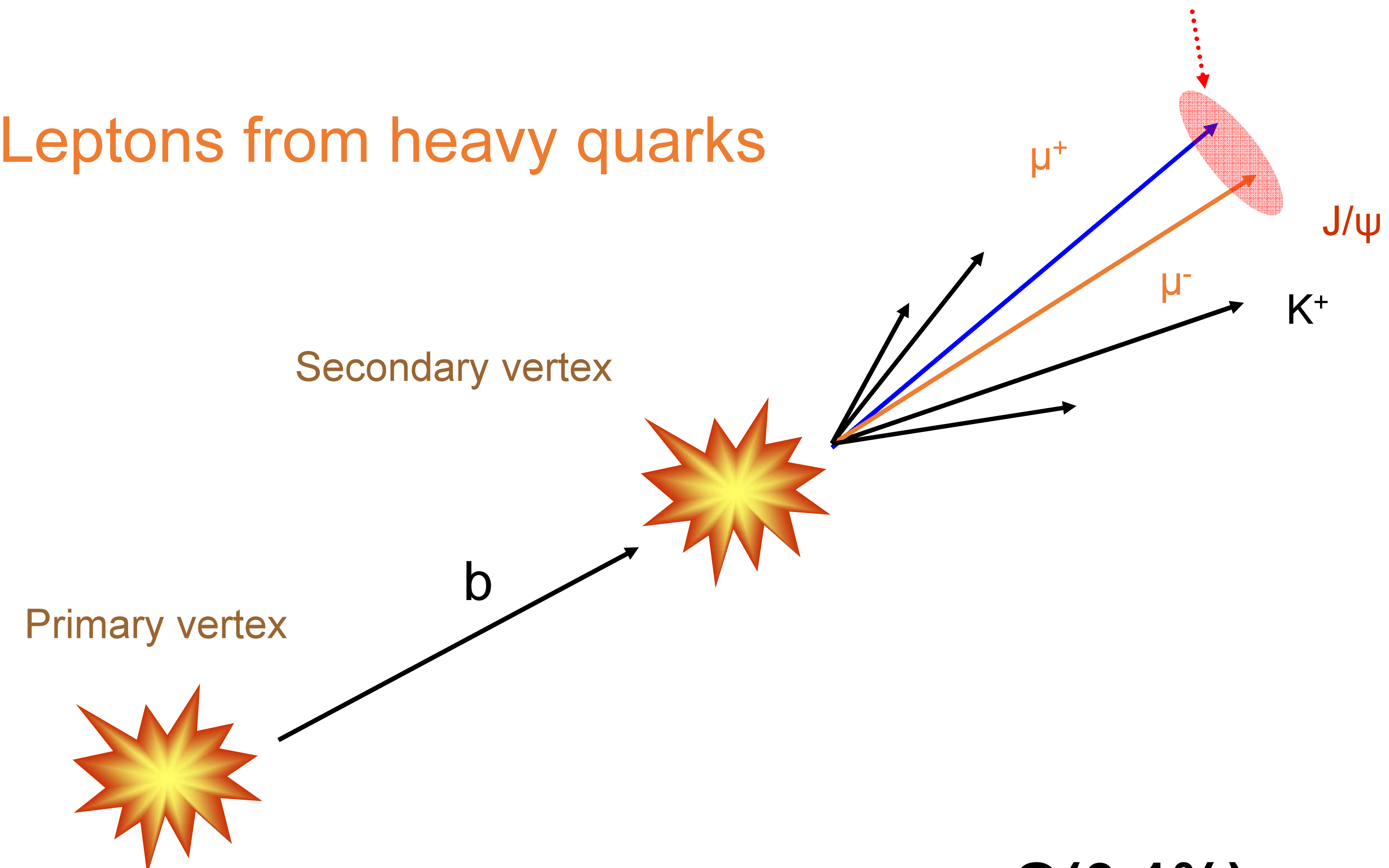


Sample **O(10%)** of b cross-section

Open Heavy Flavor Production (2/4)

Non-prompt J/ψ

Leptons from heavy quarks

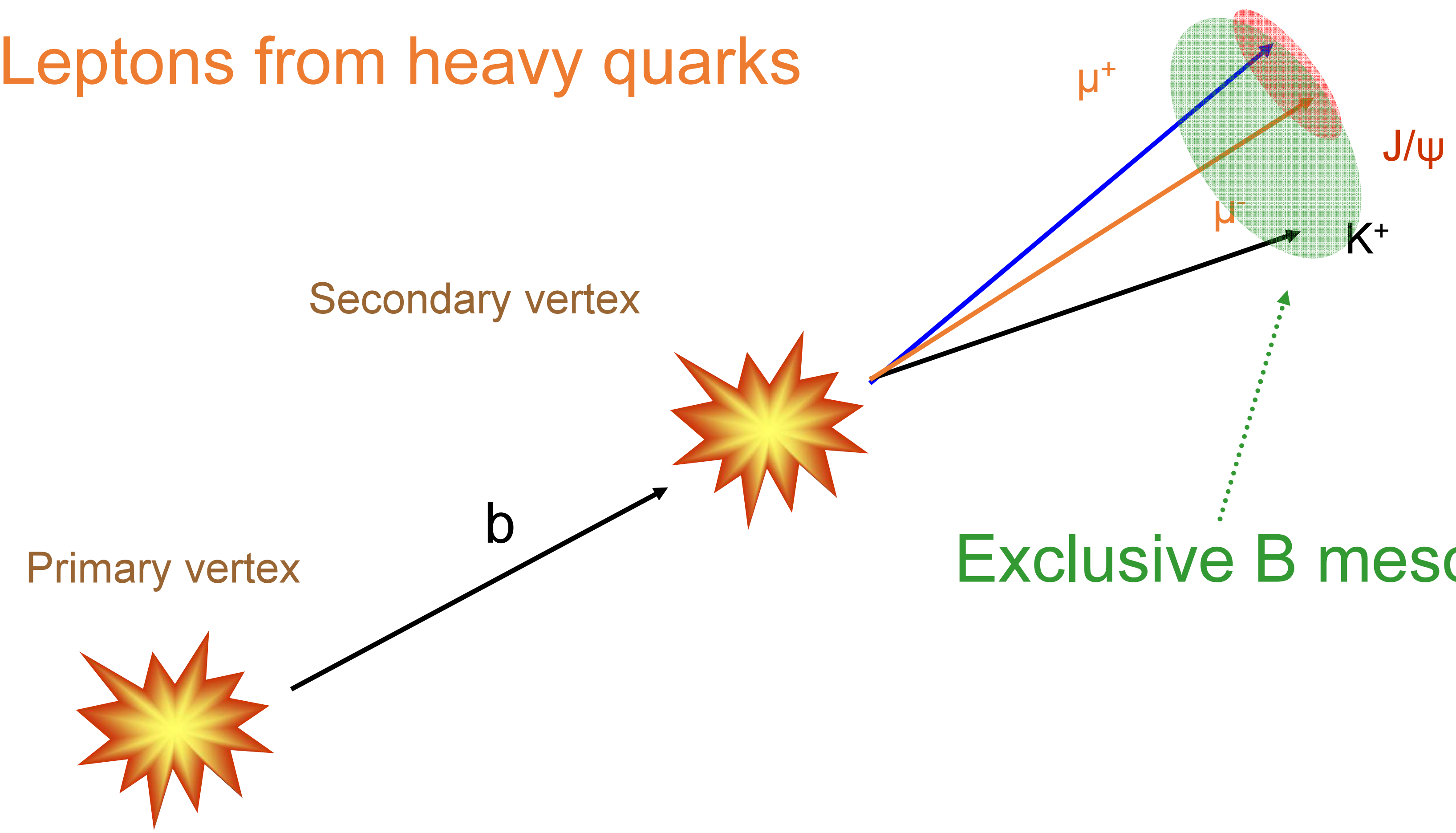


Dileptons channel sample **O(0.1%)** of b cross-section

Open Heavy Flavor Production (3/4)

Non-prompt J/ψ

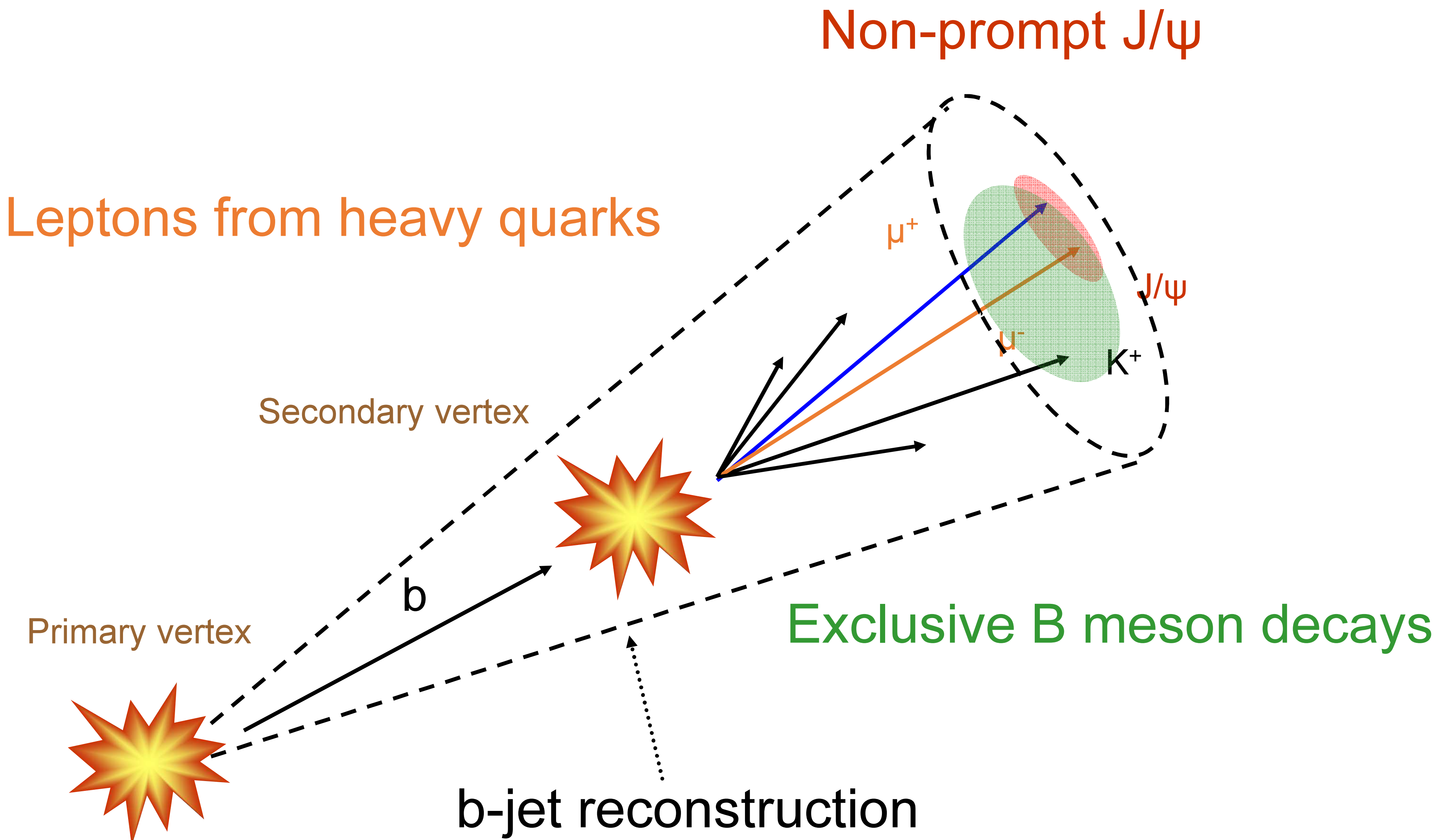
Leptons from heavy quarks



Exclusive B meson decays

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

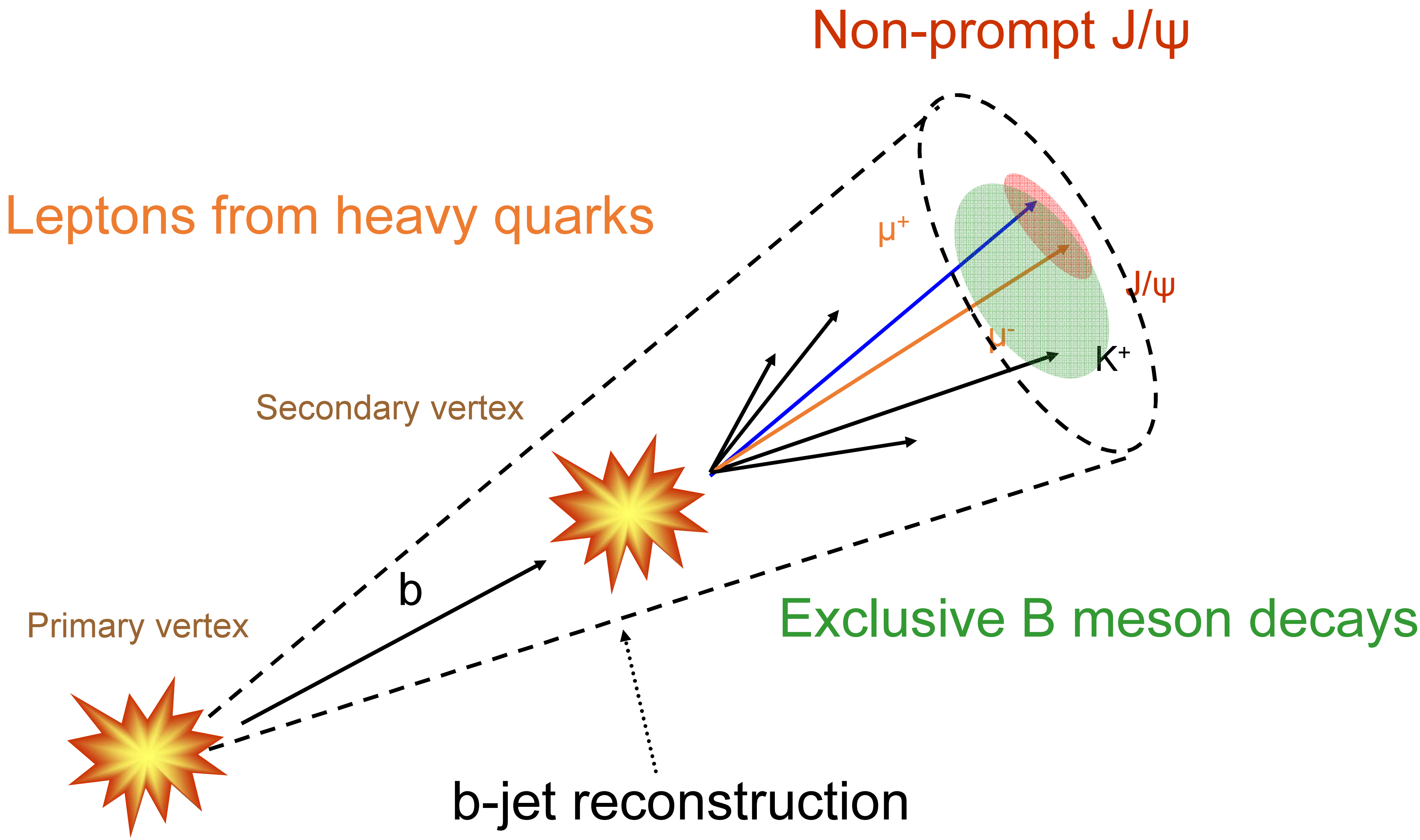
Open Heavy Flavor Production (4/4)



b-jet reconstruction

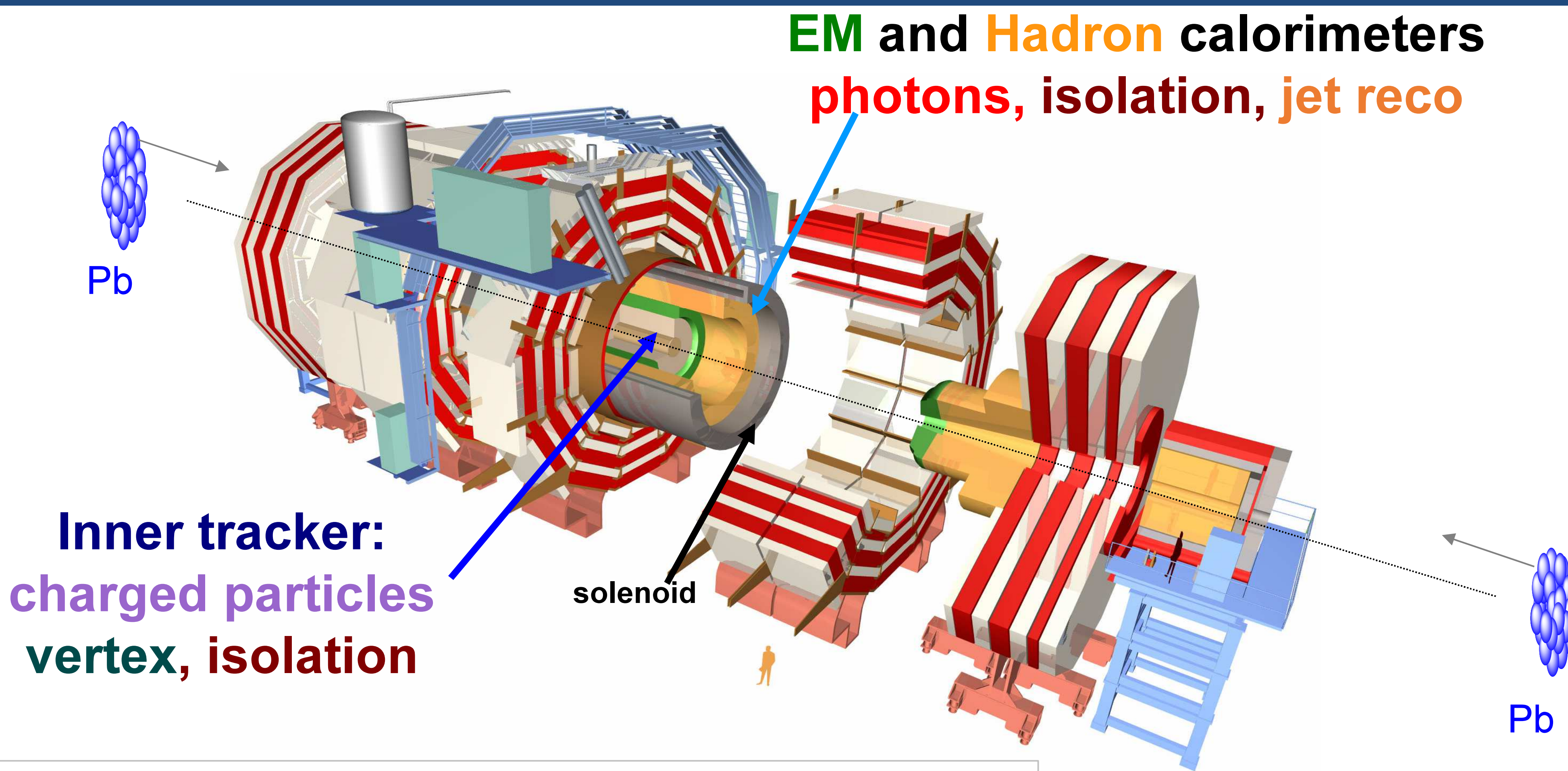
b-tagged jet sample **O(100%)** of b cross-section and ~70-90% of the b quark energy

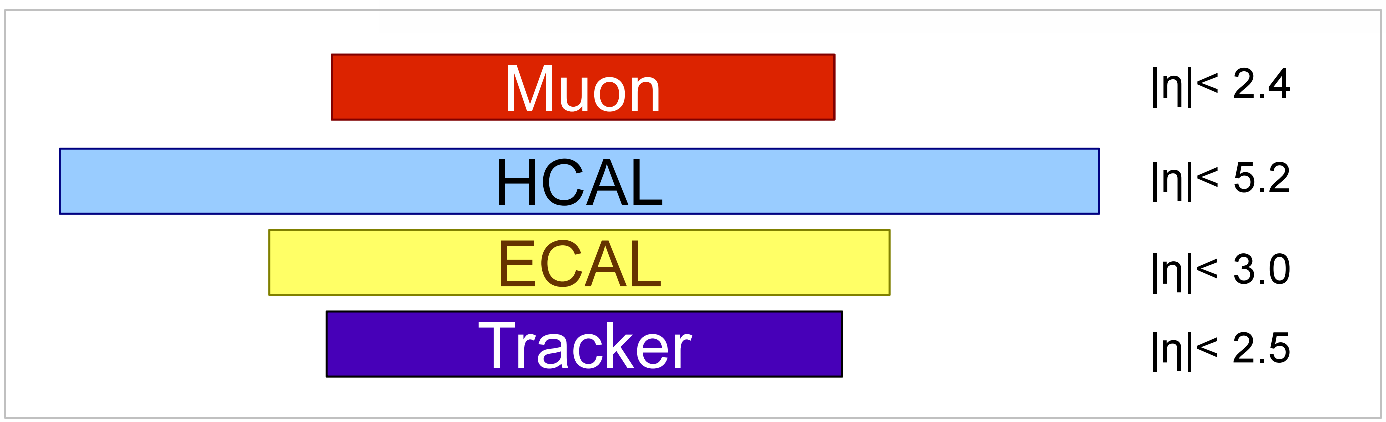
Requirements



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

CMS Detector

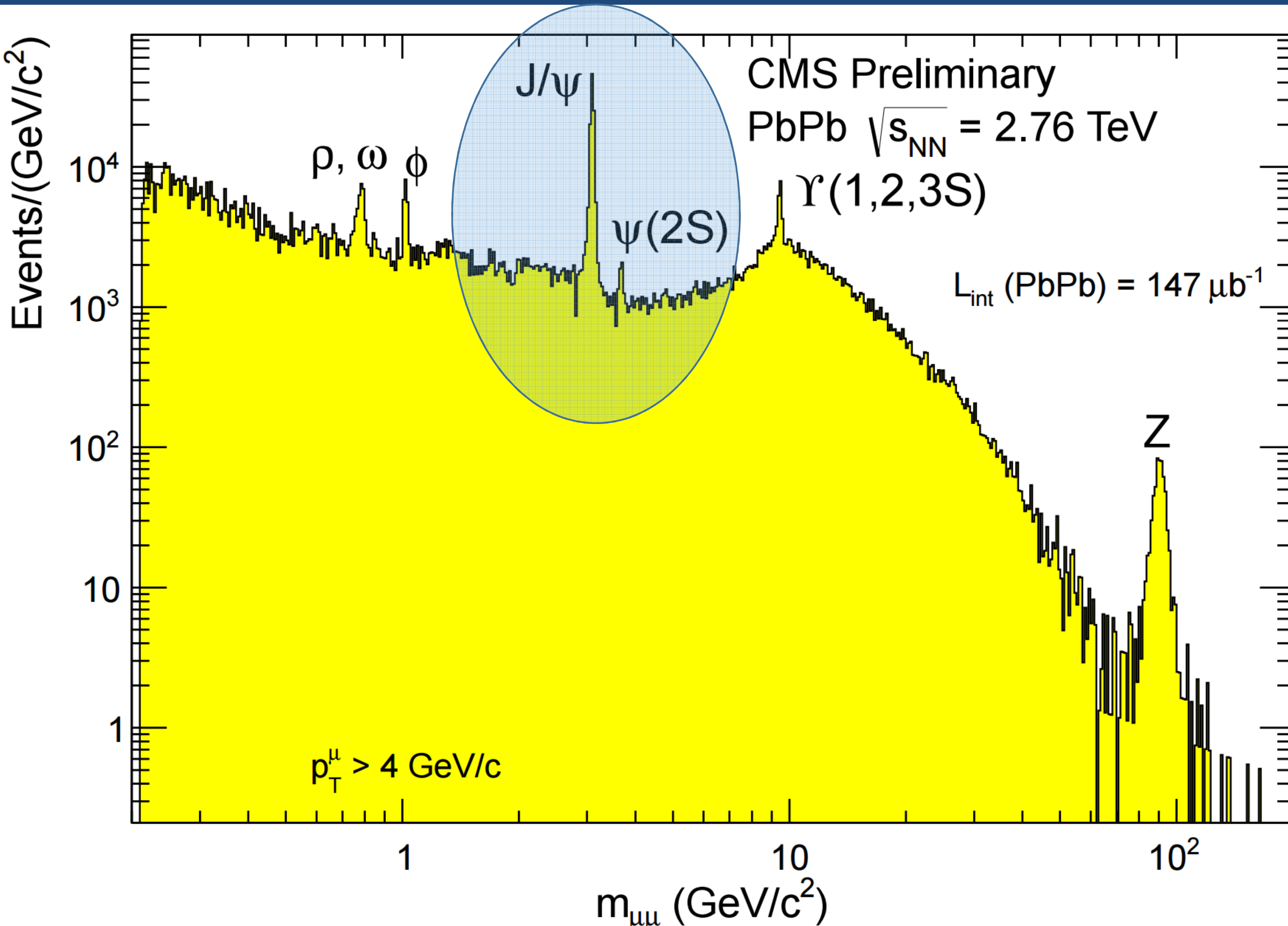




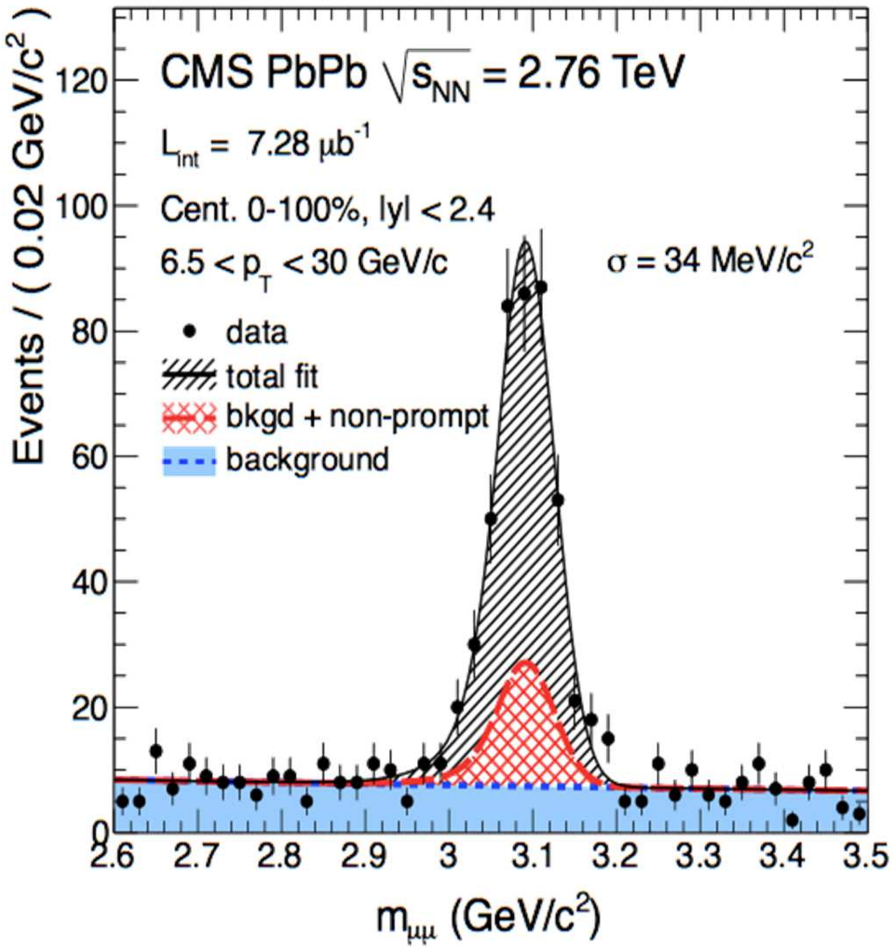
Track impact parameter resolution

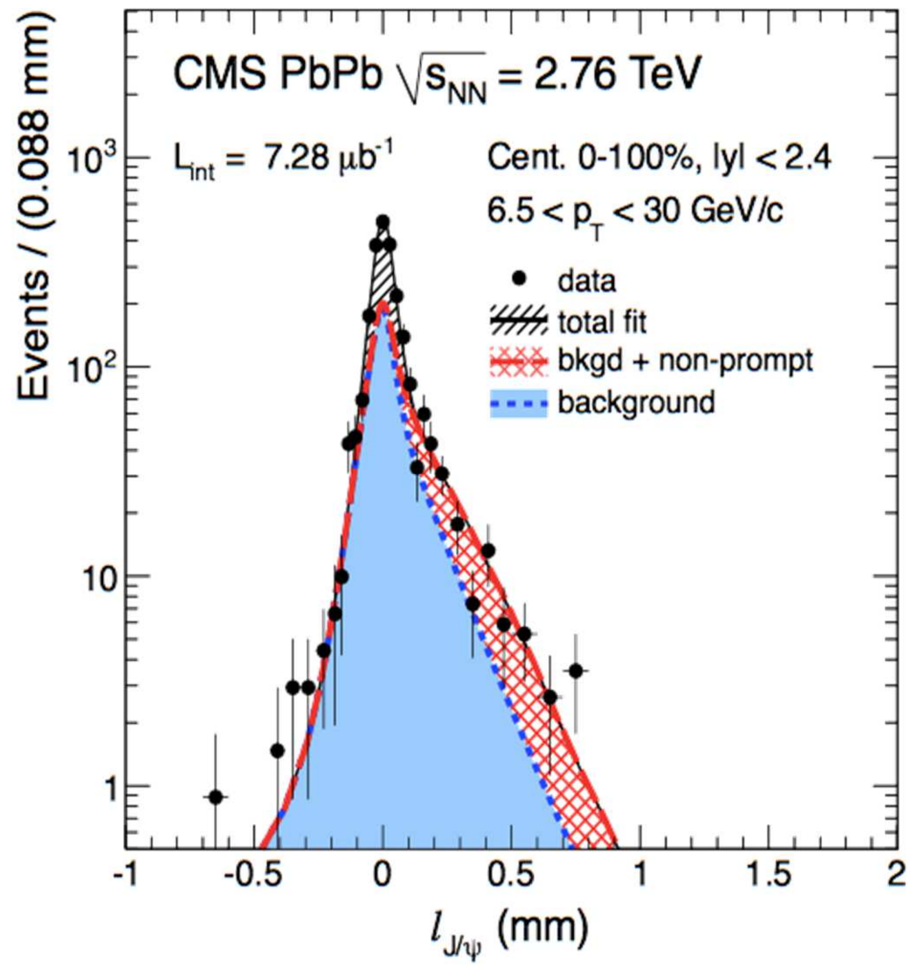
- 100 μm @ 1 GeV/c
- 20 μm @ 20 GeV/c

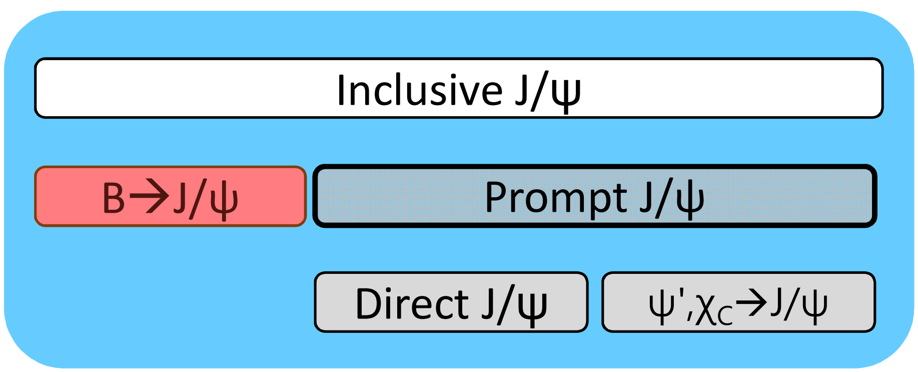
Quarkonia production: Dimuons

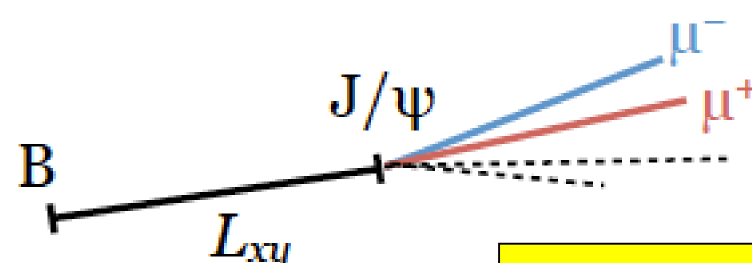


Prompt and non-prompt J/ ψ





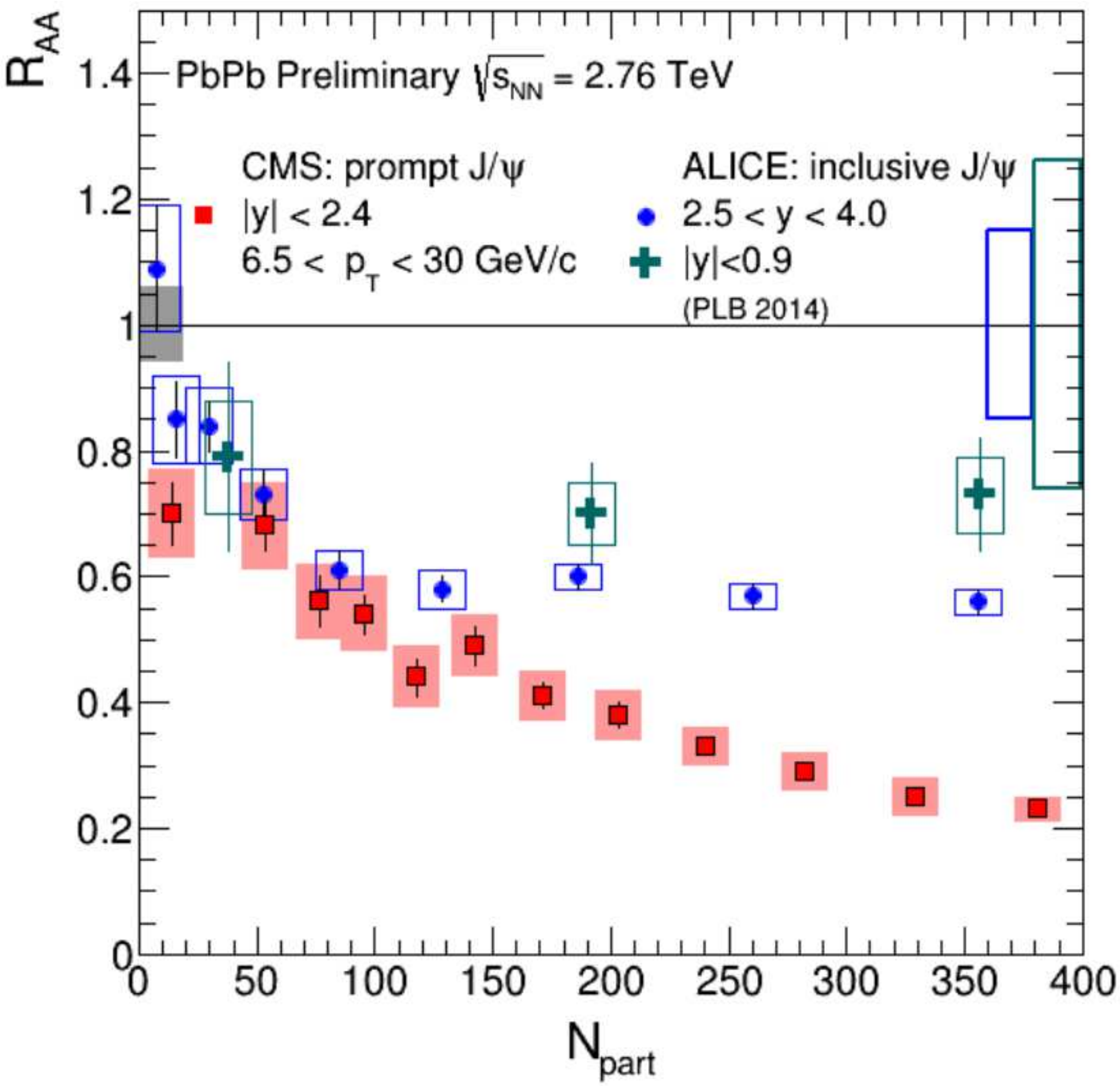




CMS PAS HIN-12-014

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

CMS PAS HIN-12-014

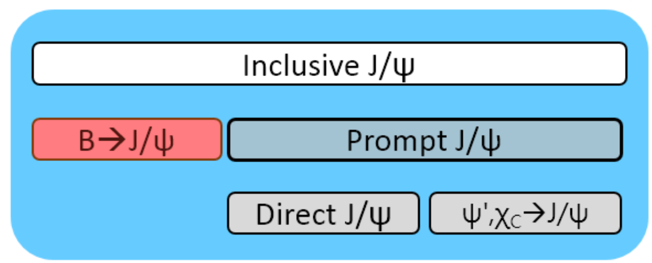


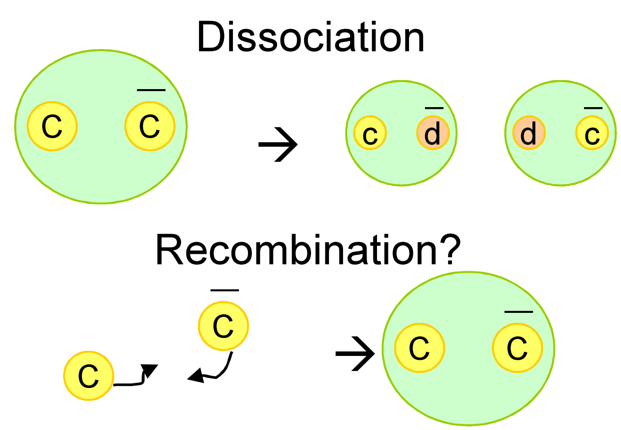
CMS: Prompt J/ψ

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

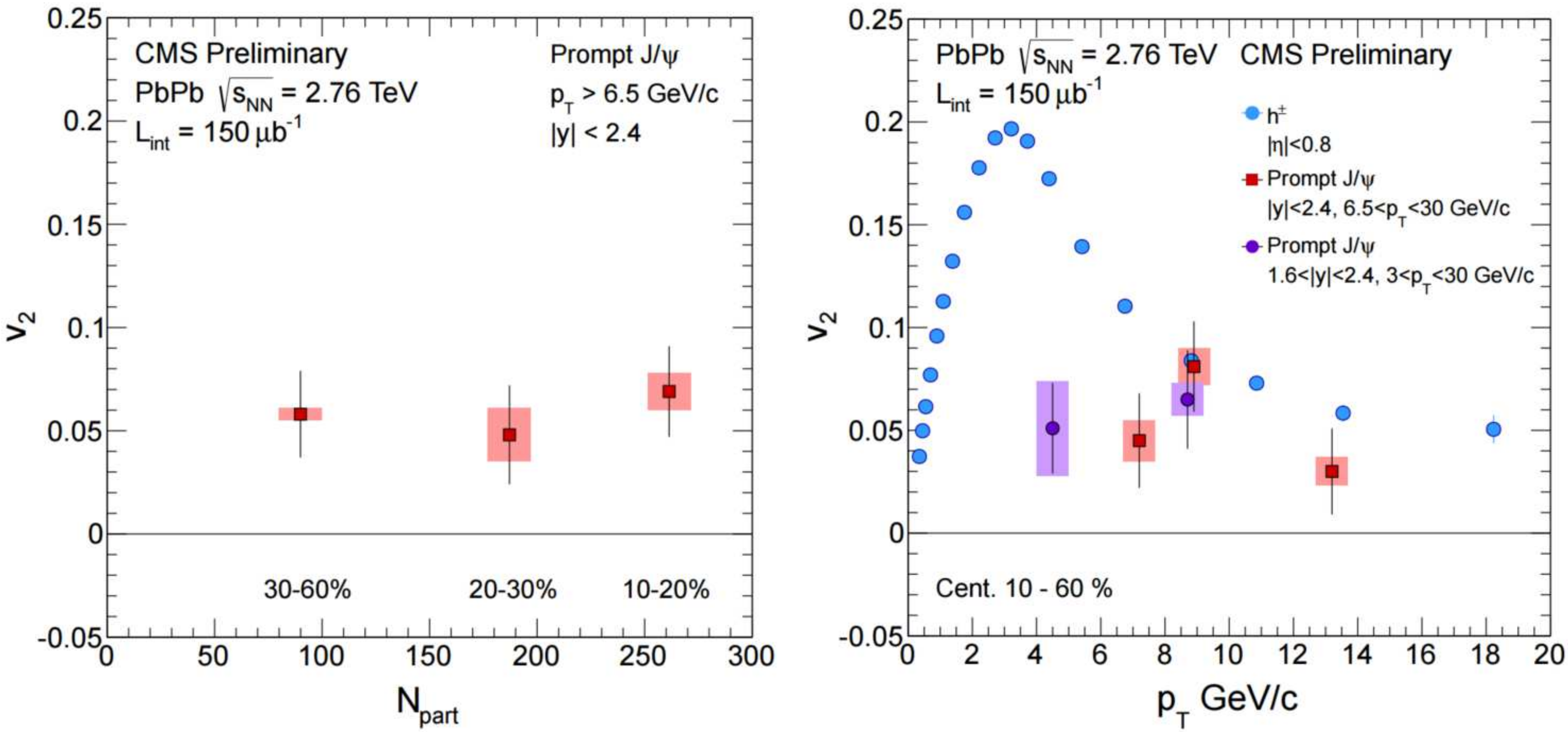
ALICE: inclusive J/ψ

- |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





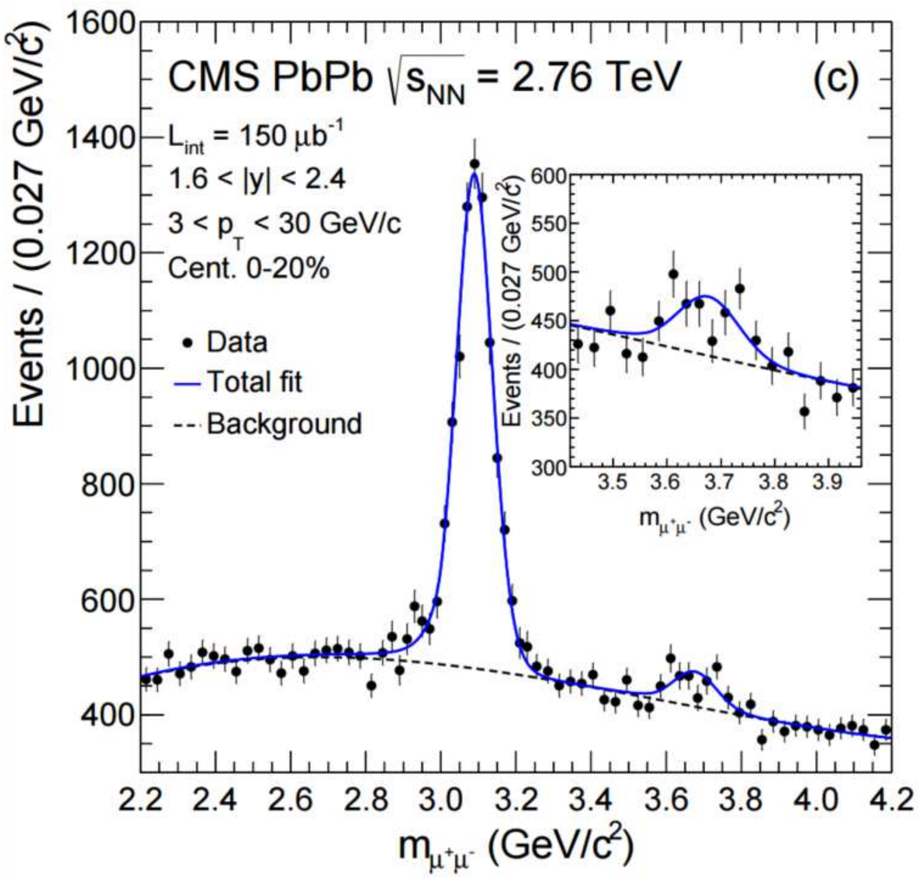
J/ψ v_2 vs. transverse momentum

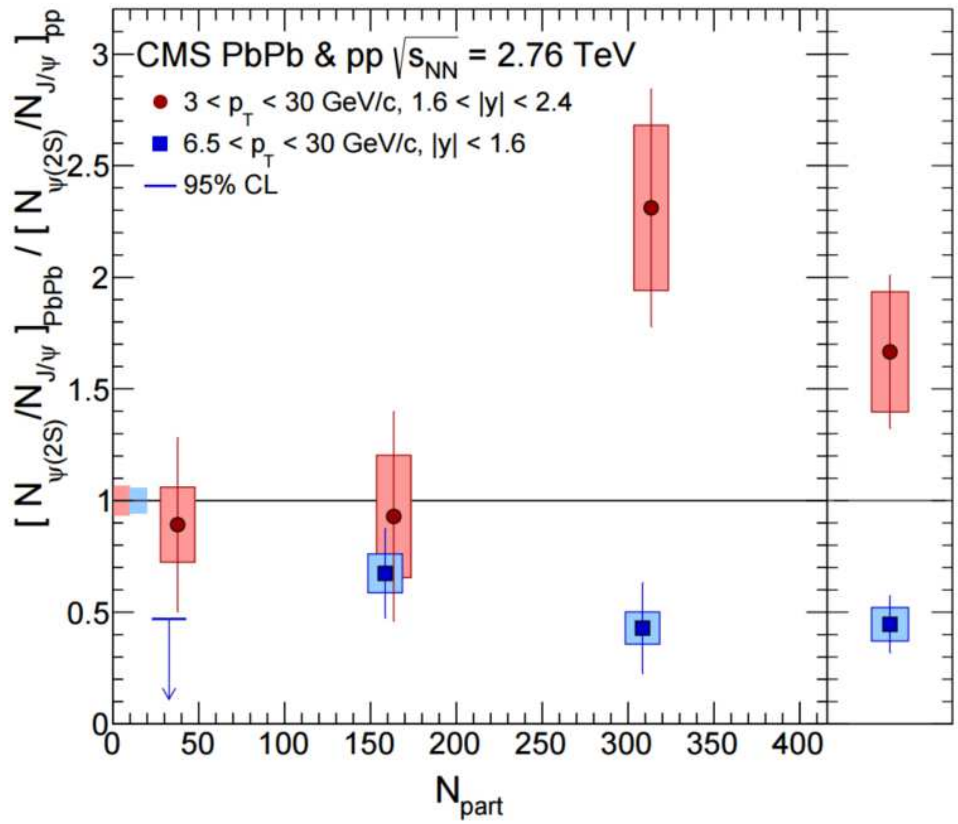


CMS observed non-zero prompt J/ψ v_2 in PbPb collisions
At high p_T: related to path length dependent energy loss
Smaller than inclusive hadron v_2

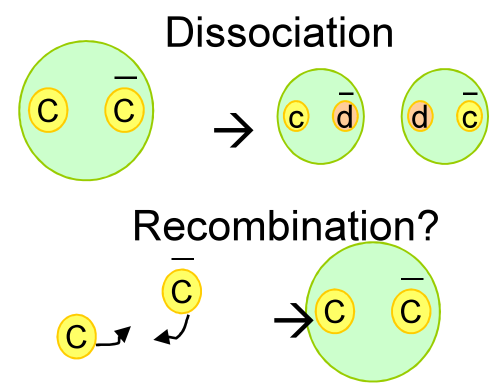
CMS PAS HIN-12-001

Ψ(2S) / J/Ψ Double Ratio





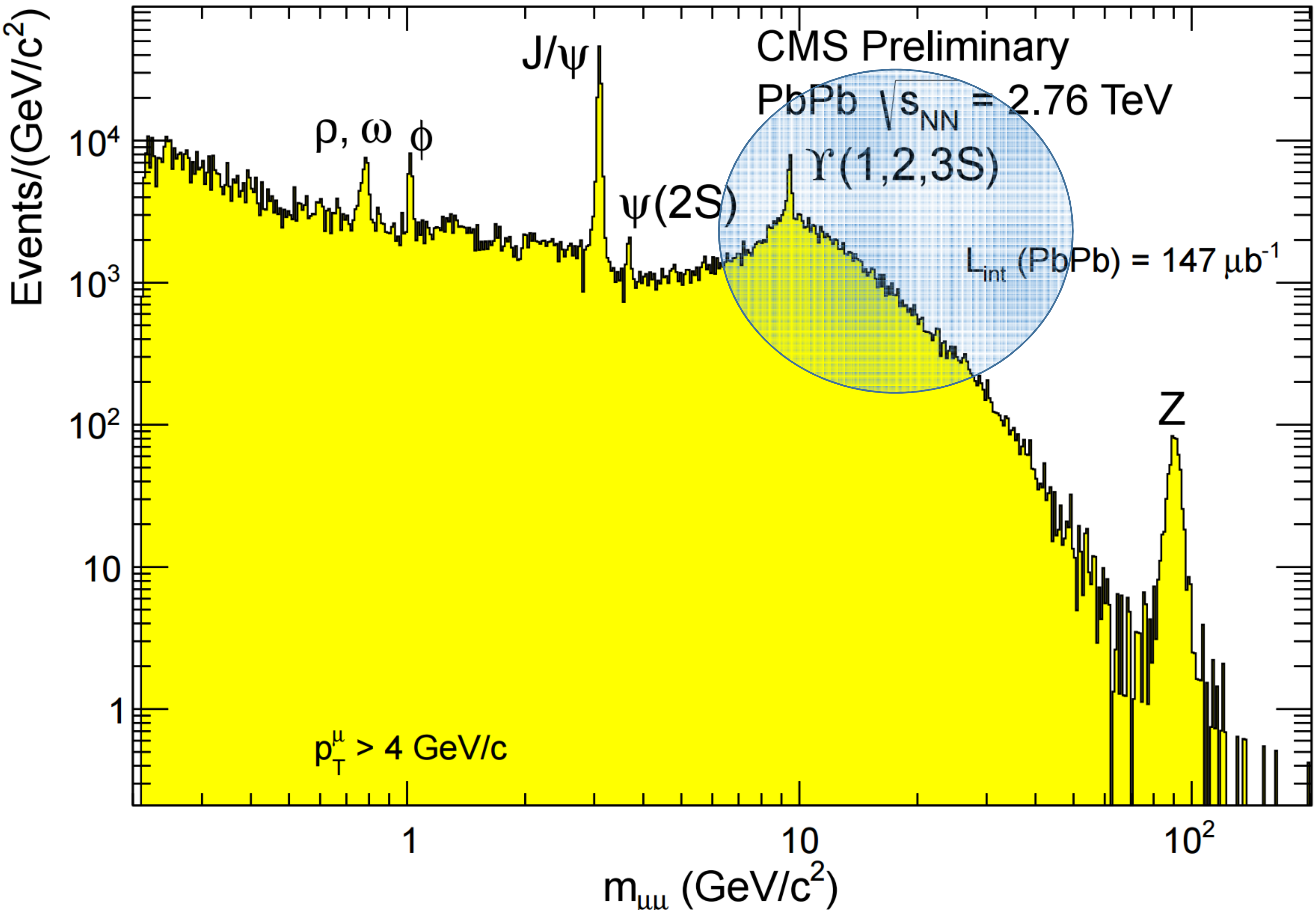
Double ratio $$\frac{\left(\frac{\psi(2S)}{J/\psi}\right)_{PbPb}}{\left(\frac{\psi(2S)}{J/\psi}\right)_{pp}}$$ >1



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

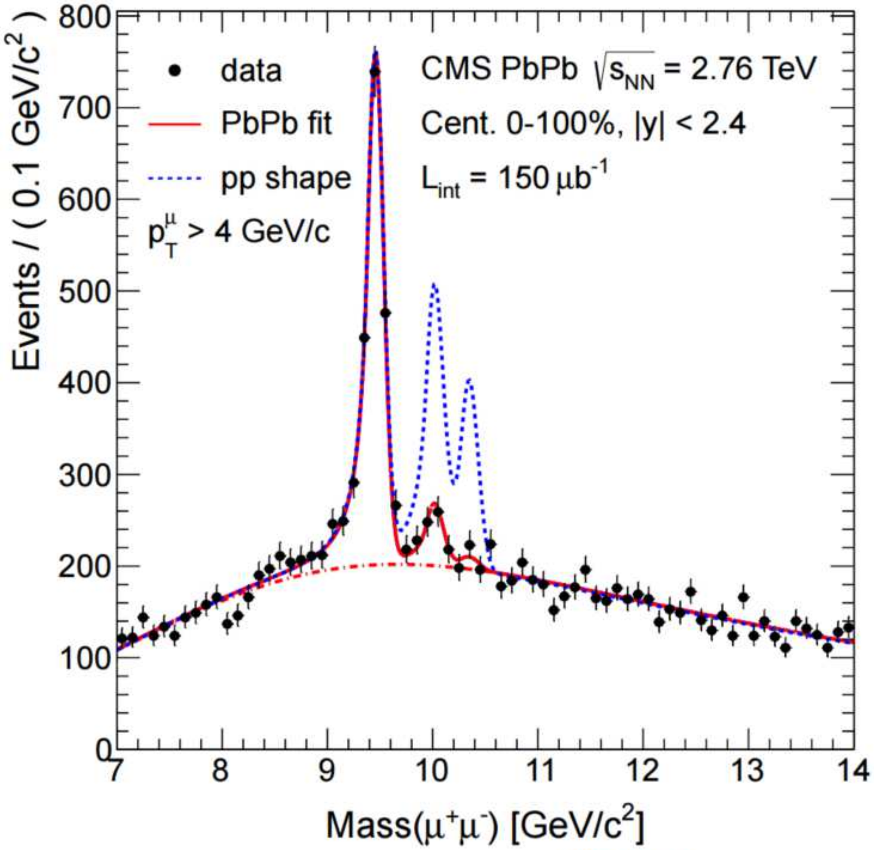
PRL 113 (2014) 262301

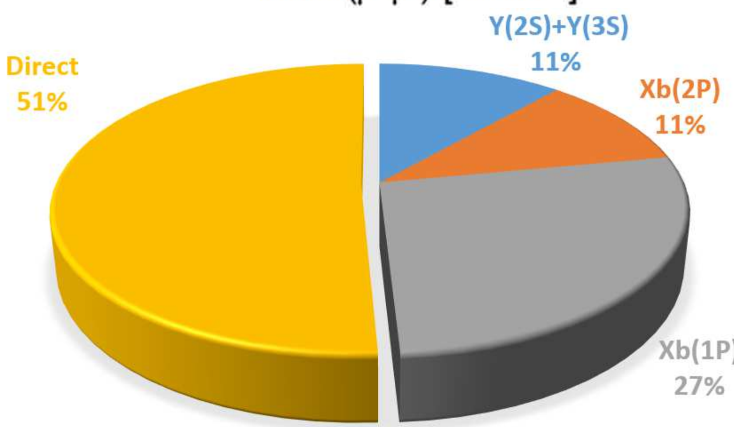
Quarkonia production: Dimuons

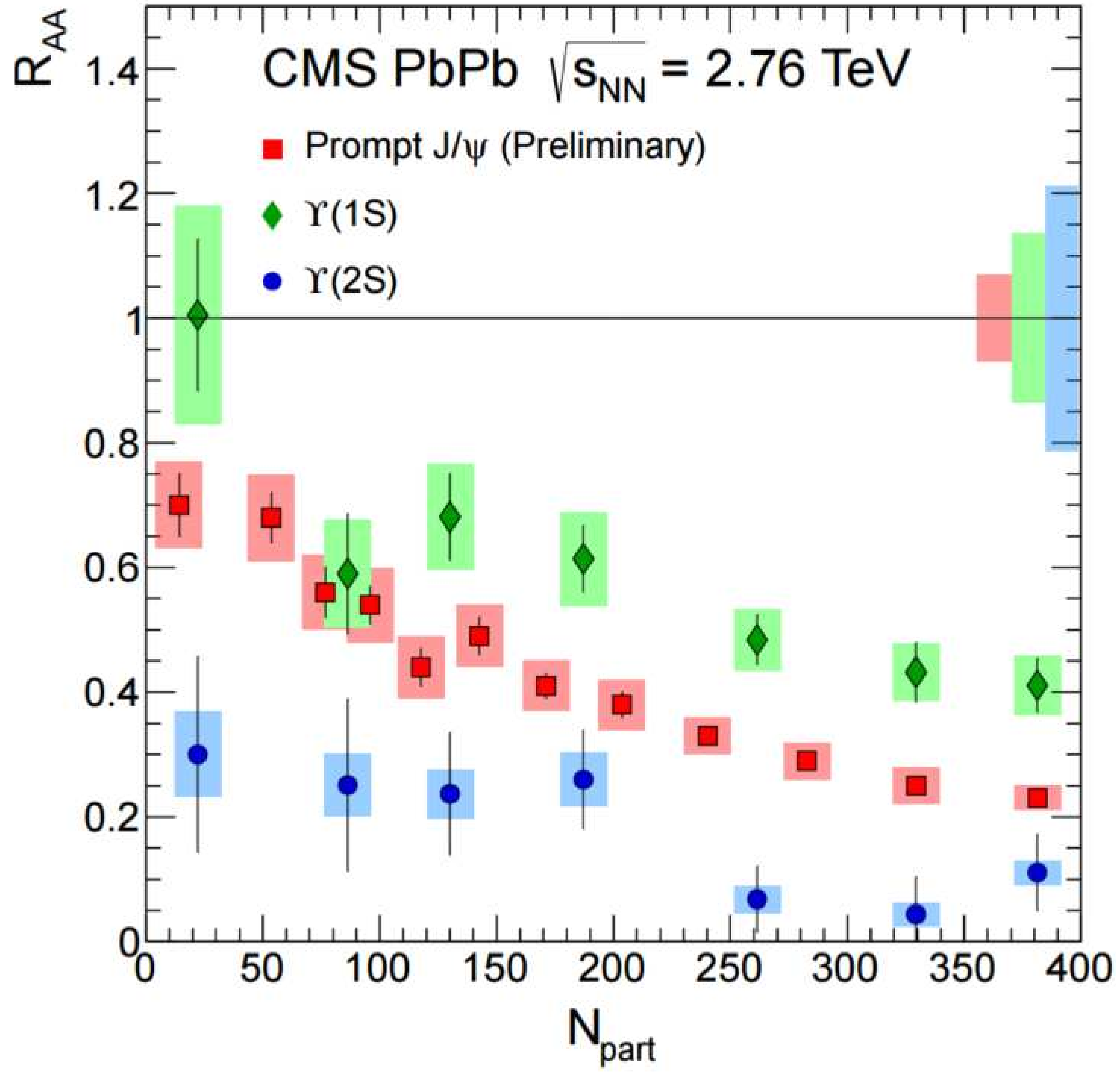


Upsilons in PbPb collisions

PRL 109 (2012) 222301



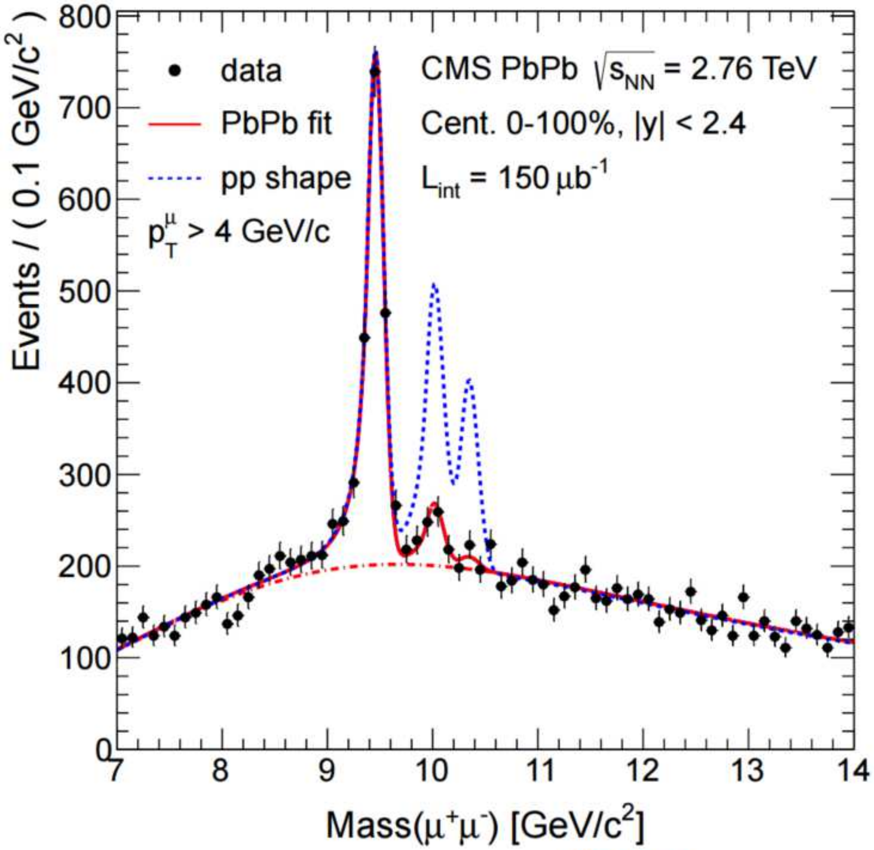


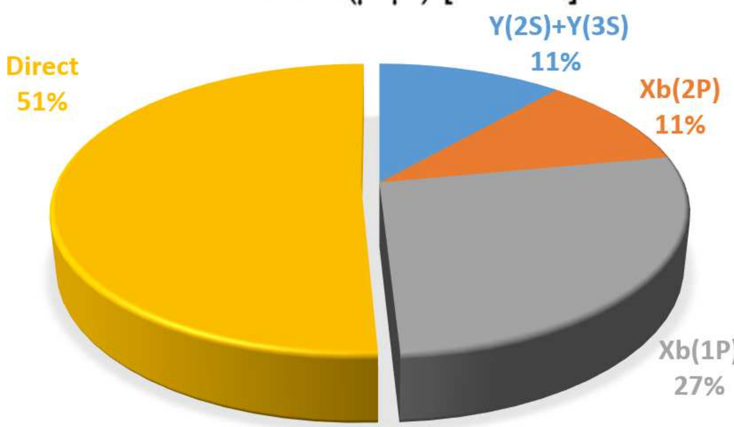


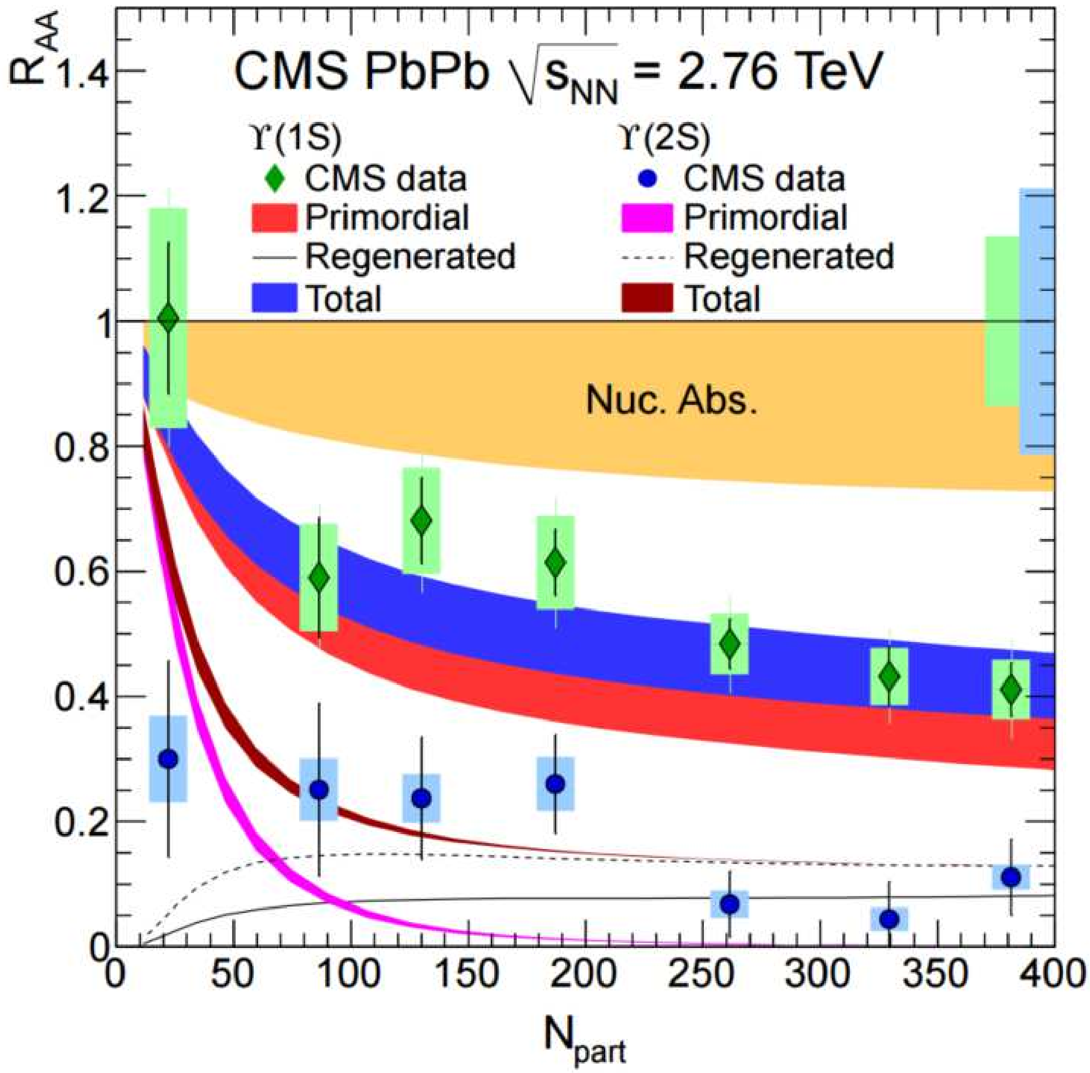
0-100% R_{AA} (Y(3S)) <0.1 (at 95% C.L)
Sequential suppression of the three states in order of their binding energy

Upsilons in PbPb collisions

PRL 109 (2012) 222301

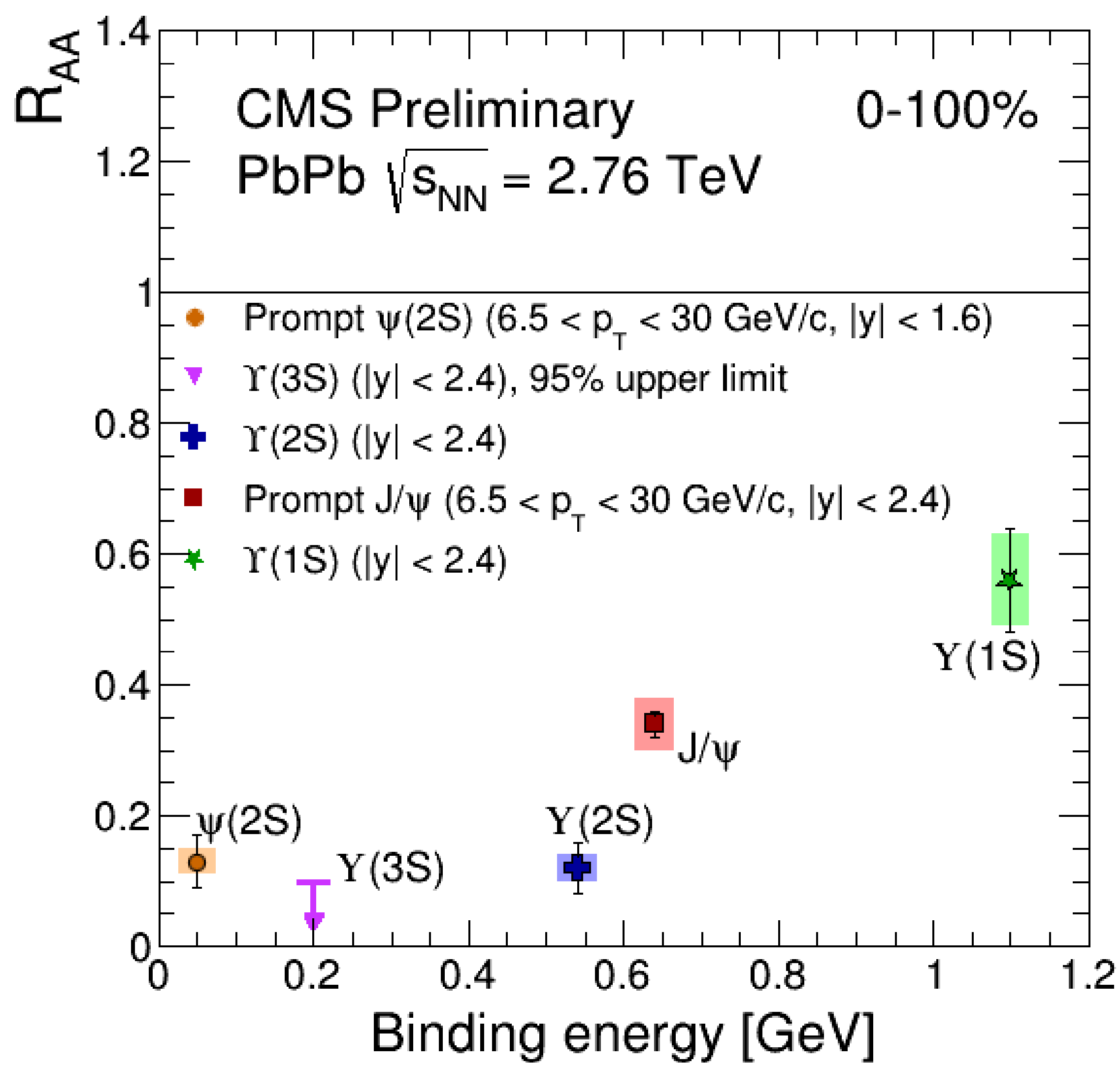




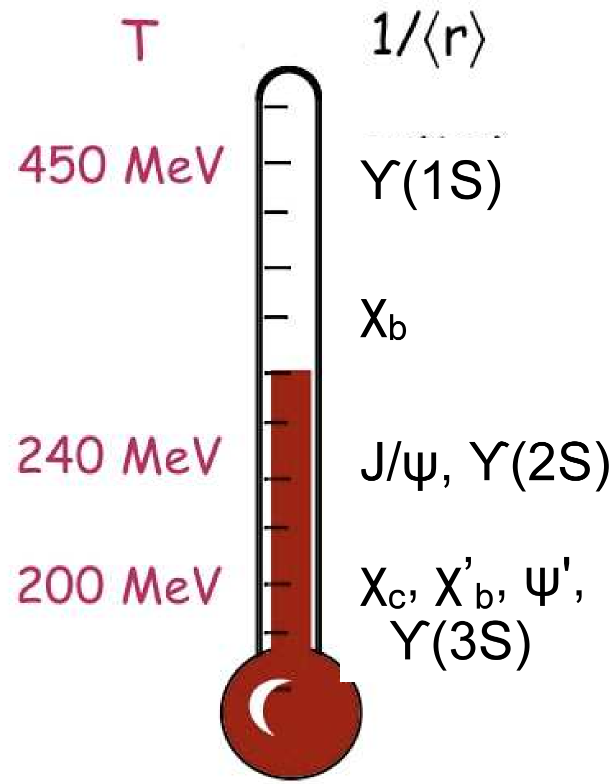


0-100% R_{AA} (Y(3S)) <0.1 (at 95% C.L)
Sequential suppression of the three states in order of their binding energy

Suppression of the five quarkonia in PbPb collisions



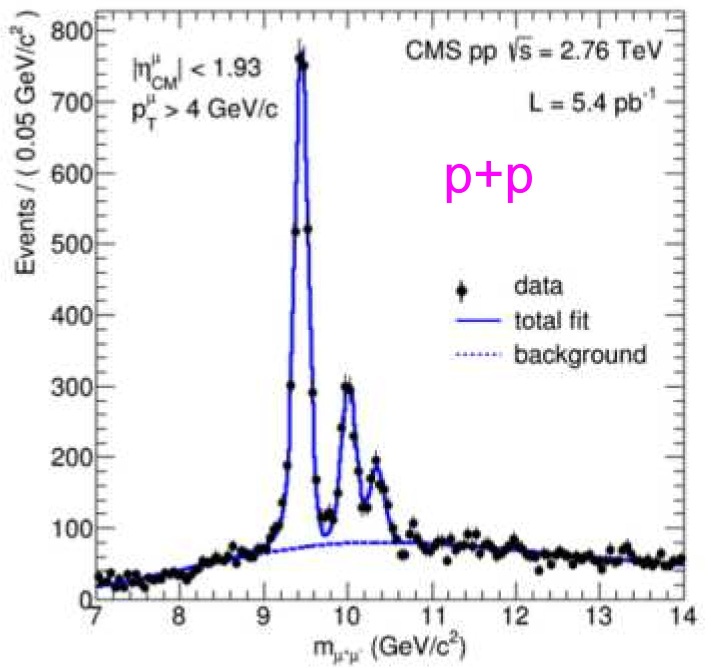
Matsui & Satz, PLB168 (1986) 415

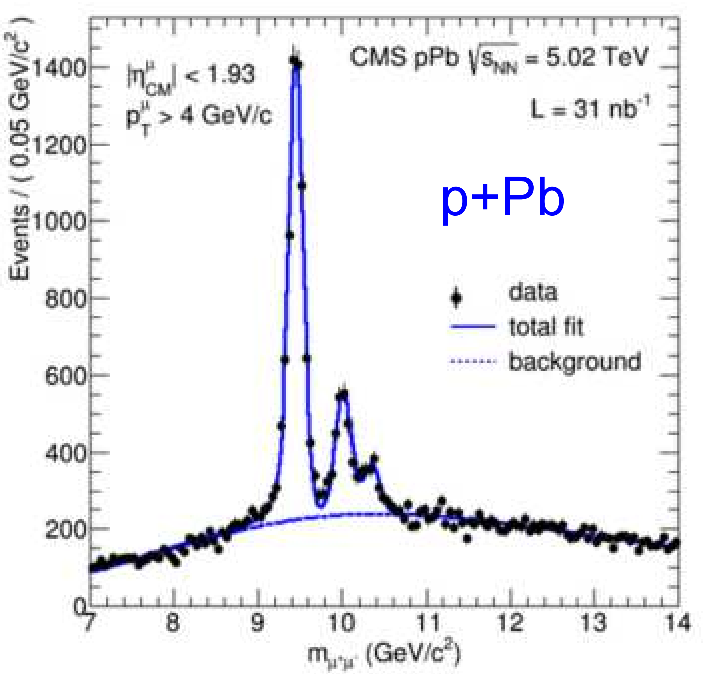


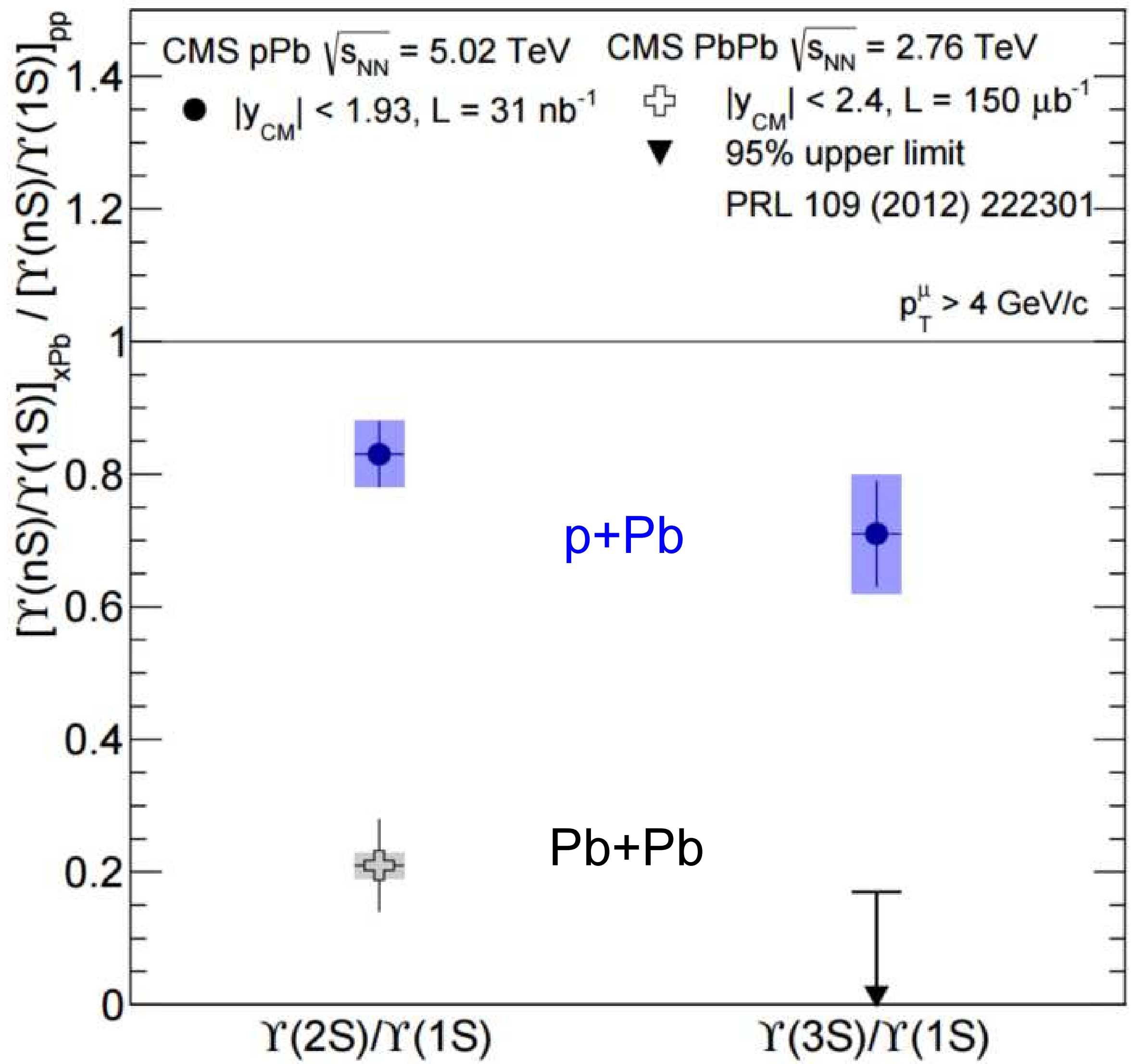
Mocsy, EPJC61 (2009) 705
BNL workshop in June

- 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

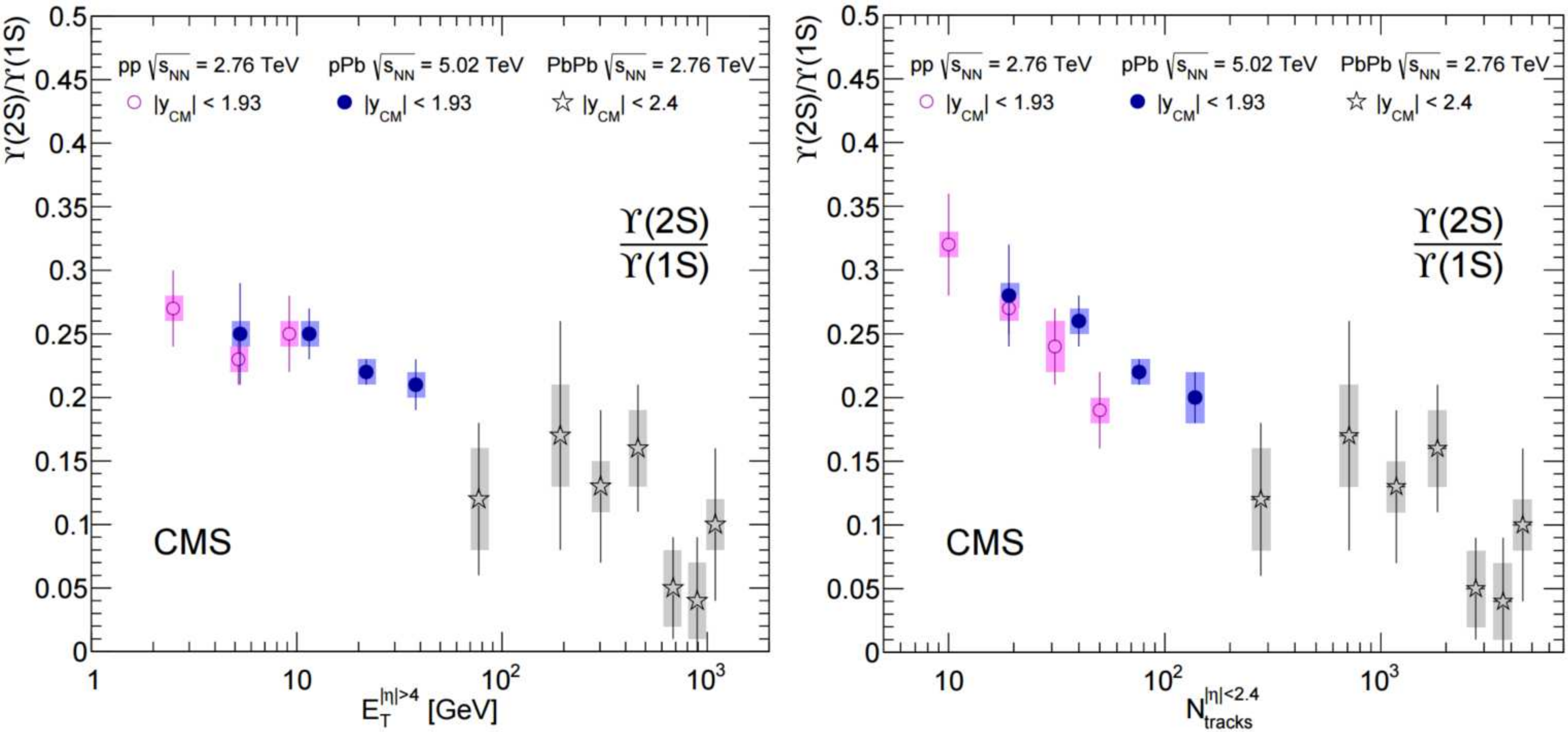
→ Final state effects in PbPb

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



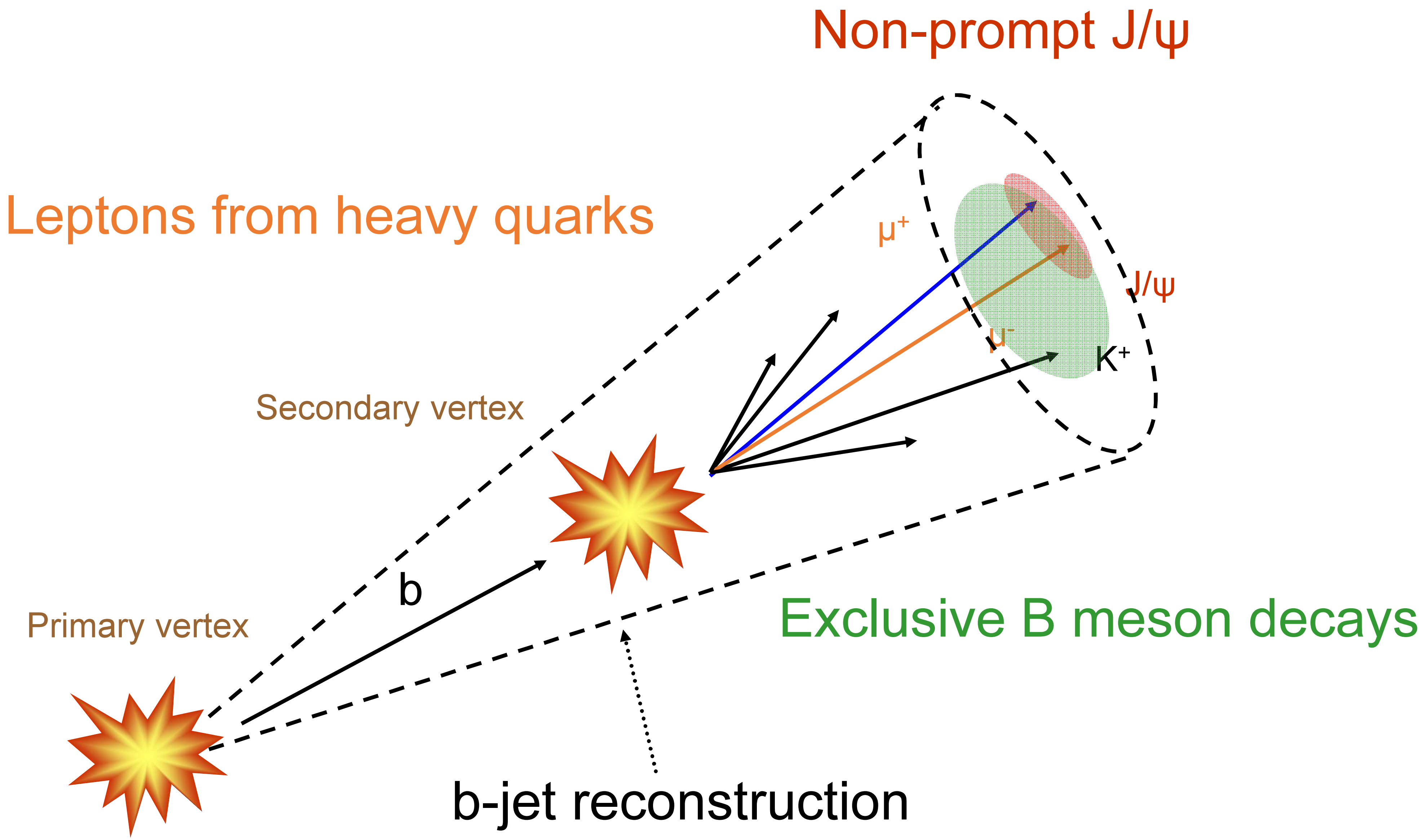
Υ(2S)/Υ(1S) ratio decreases as a function of event activity!

(1) More associated yield with Υ(1S)?

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

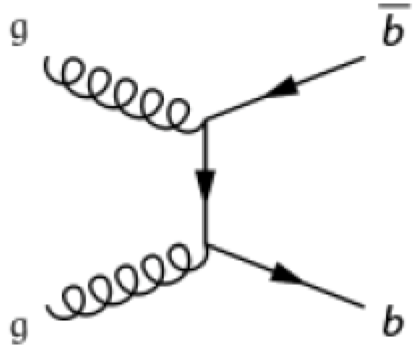
JHEP 04 (2014) 103

(b)-jet Quenching

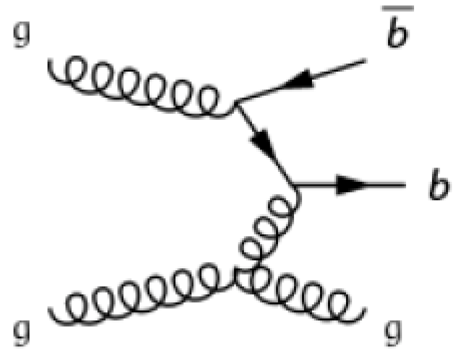


b-jet Production Mechanisms

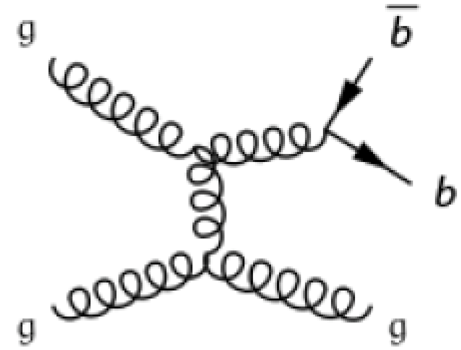
Flavor Creation (FCR)



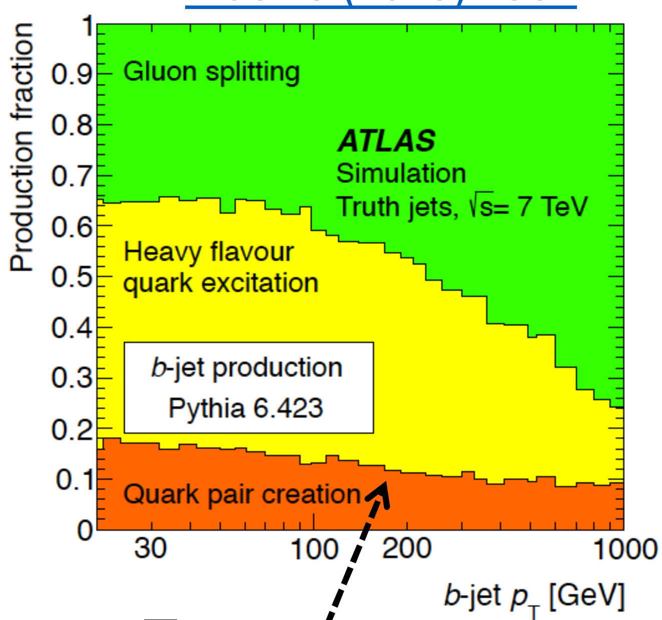
Flavor Excitation (FEX)



Gluon Splitting (GSP)



EPJC 73 (2013) 2301



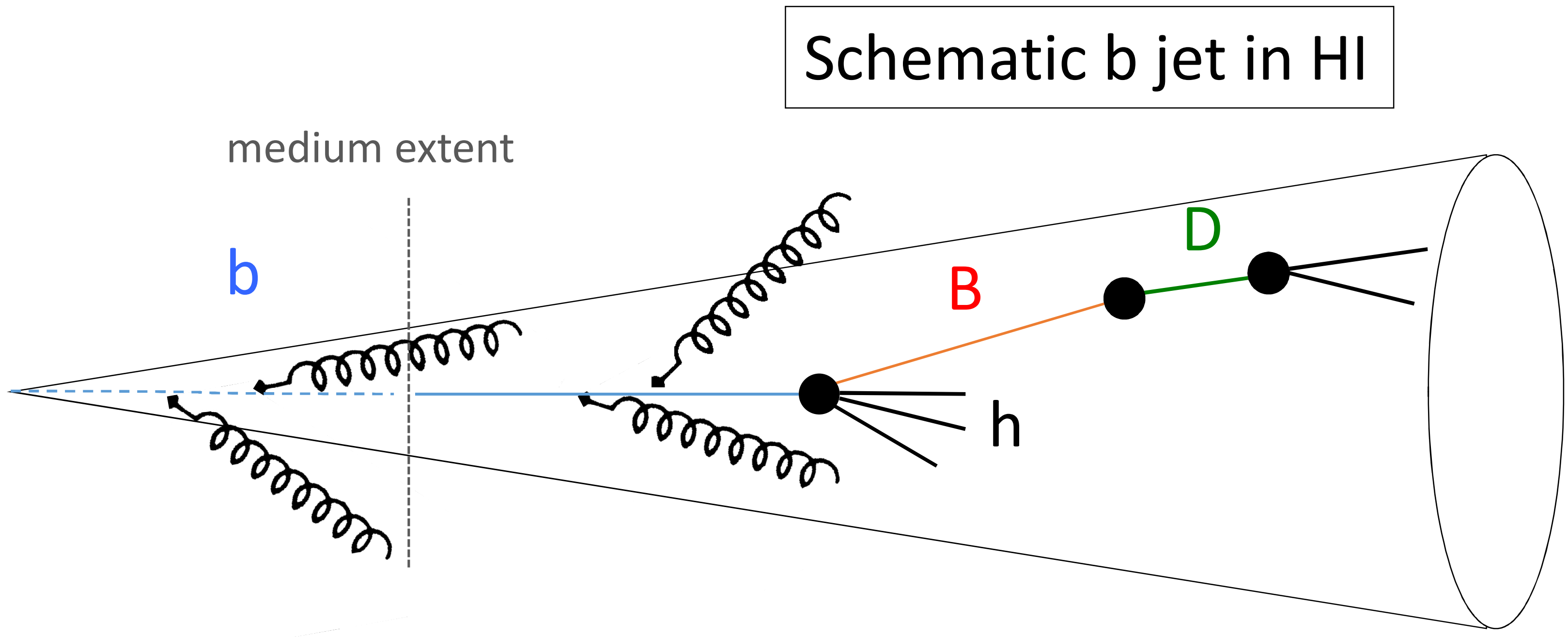
LO b-$\bar{b}$ production (FCR) sub-dominant at the LHC

At NLO:

- Excitation of sea quarks → b($\bar{b}$) + 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"

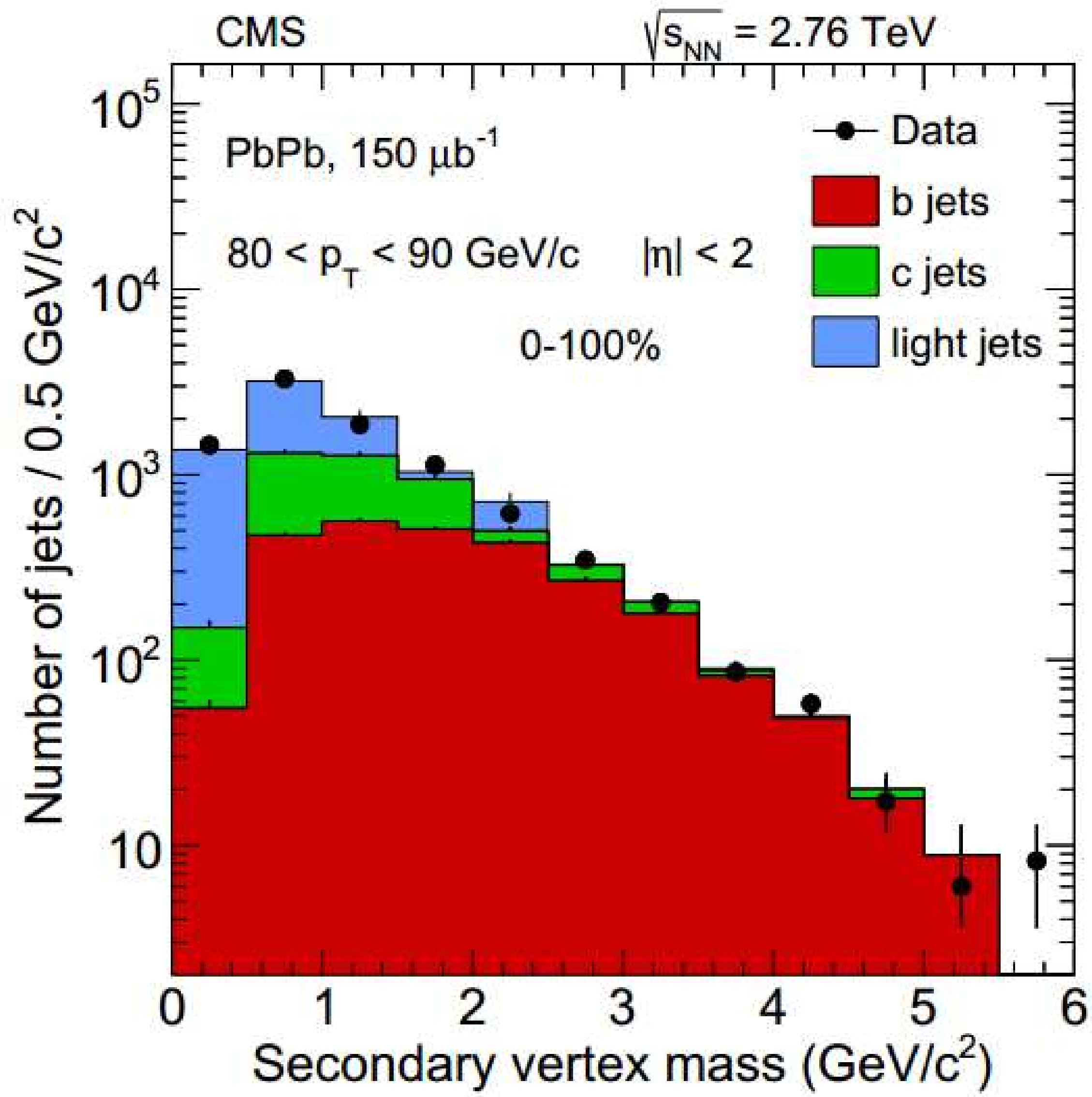
b-jet purity:

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

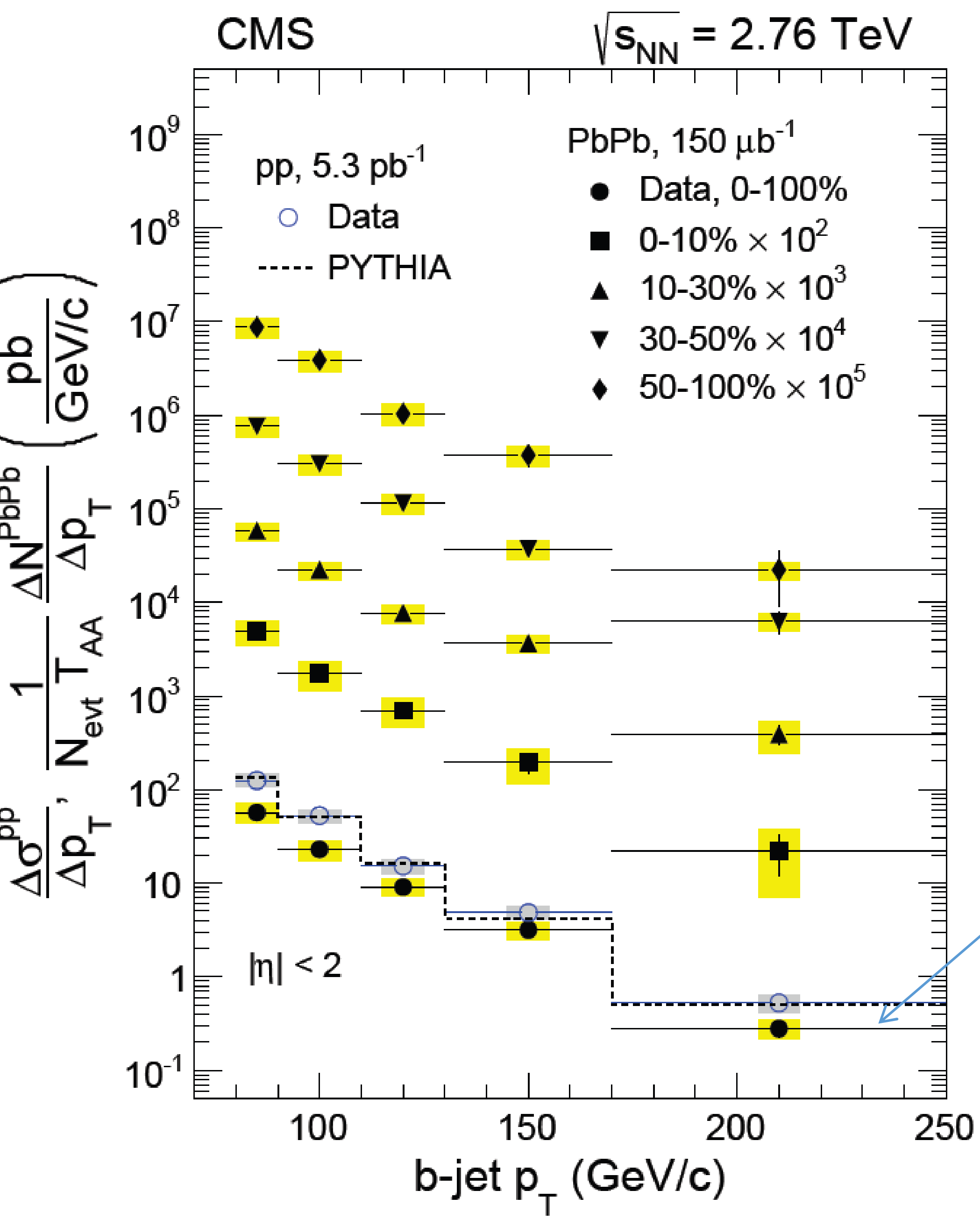
Monte Carlo simulation

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

CMS PAS HIN-14-007



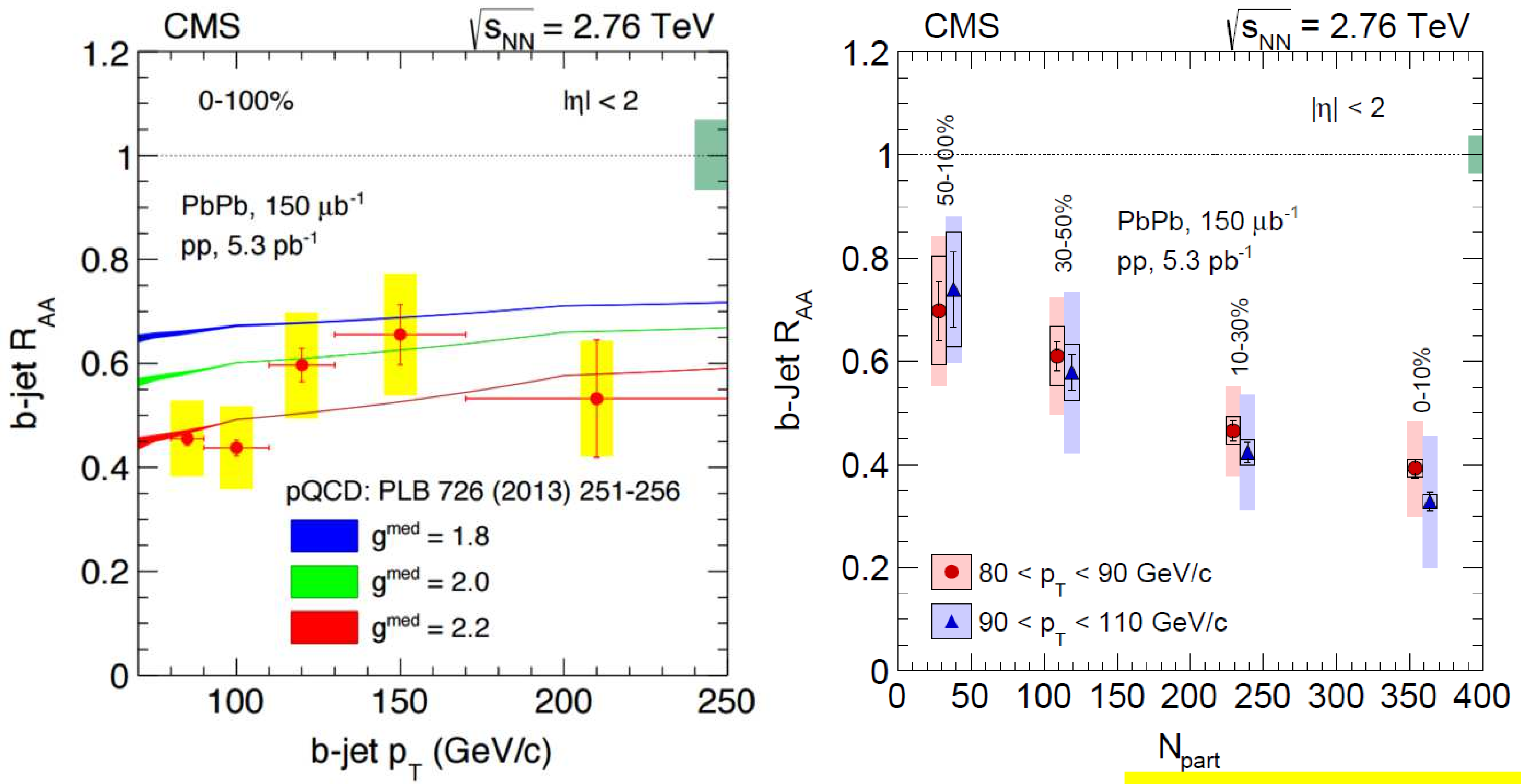
PbPb b-Jet Spectra



- 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)

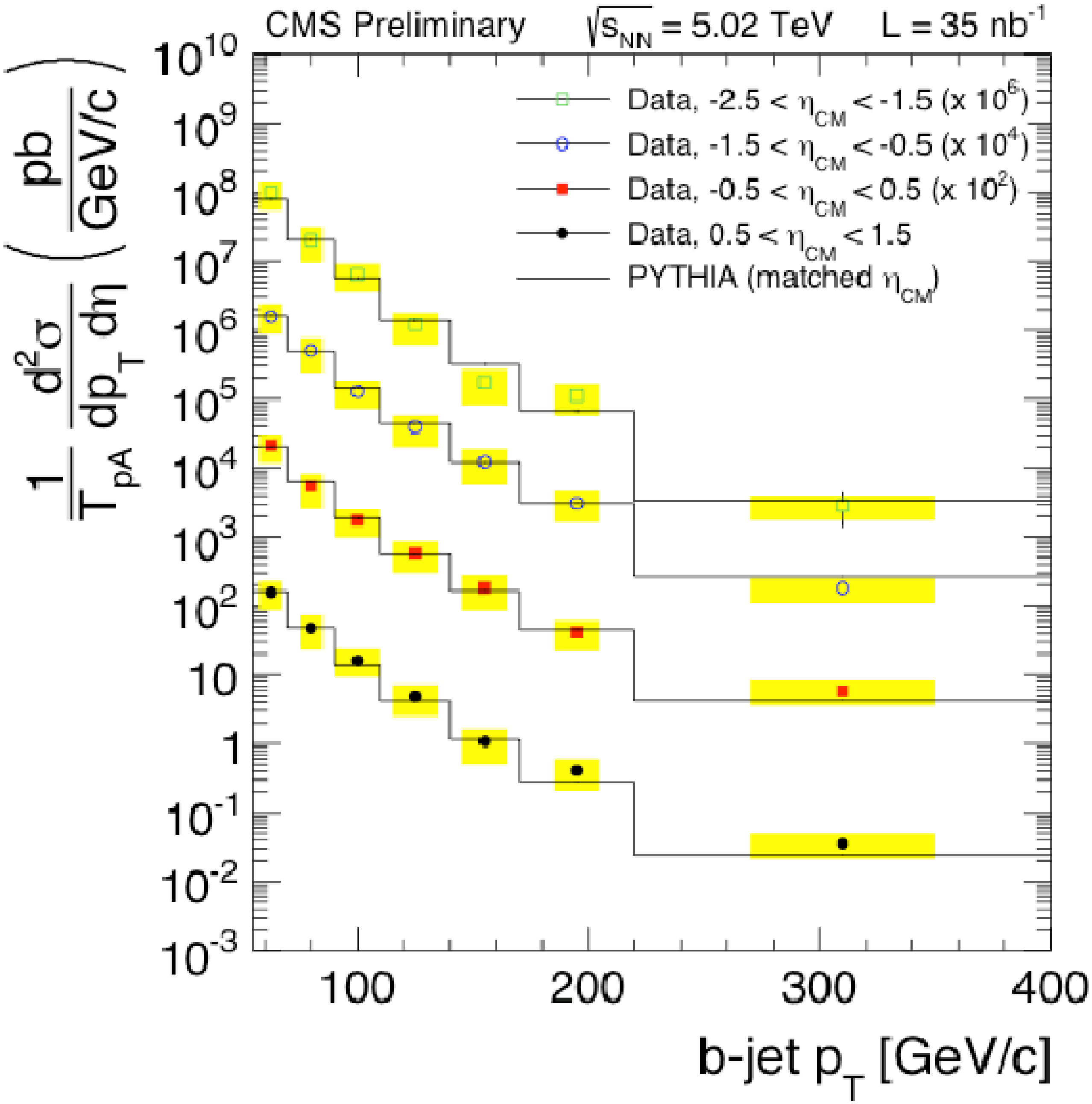
b-Jet R_{AA}



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?

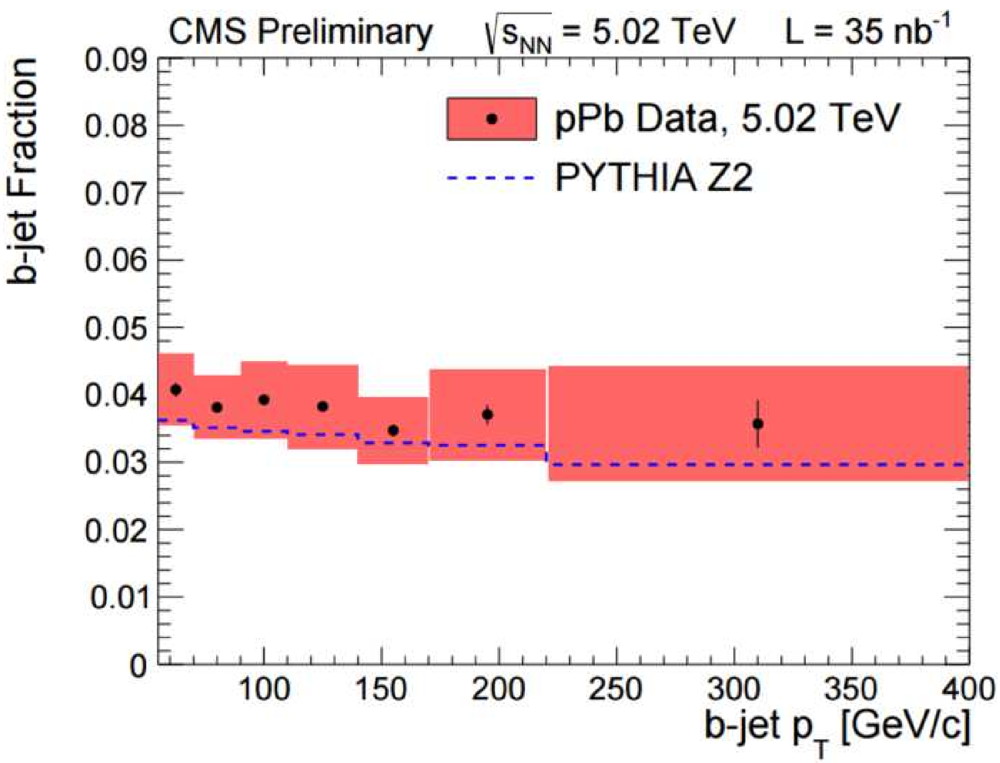
pPb b-jet Spectra

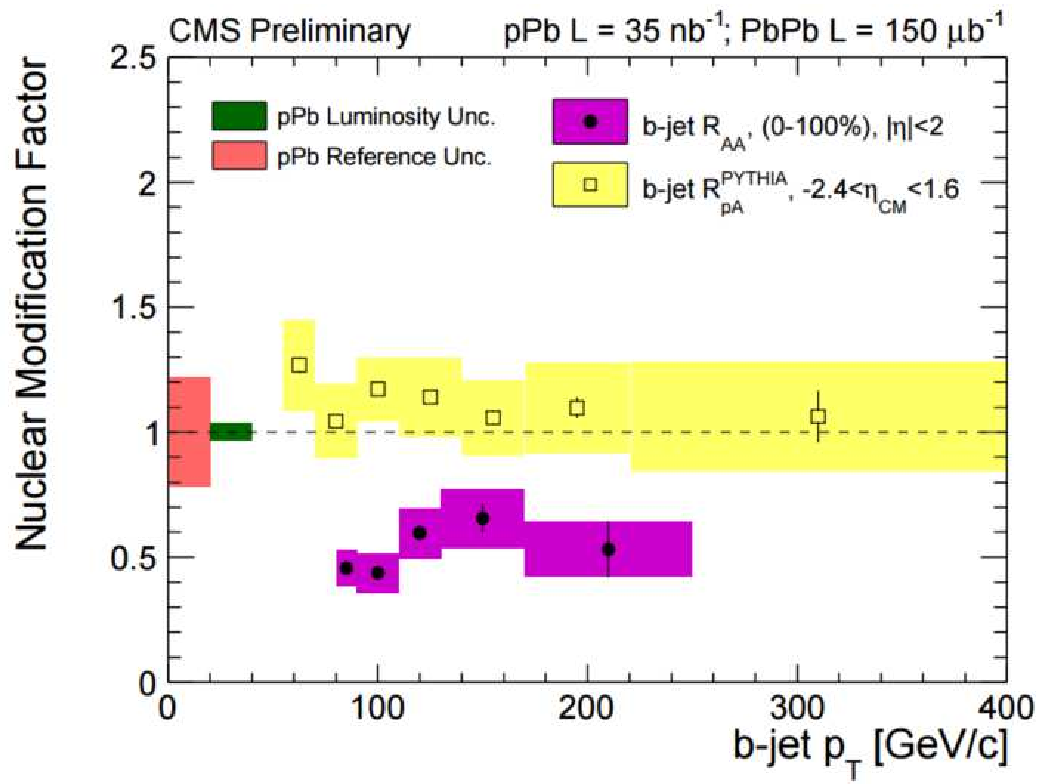


- b-jet spectra shown for various selections in η_{CM}
- pPb Spectra scaled by T_{pA} to be compared to PYTHIA reference
- Minimal suppression or enhancement is observed

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

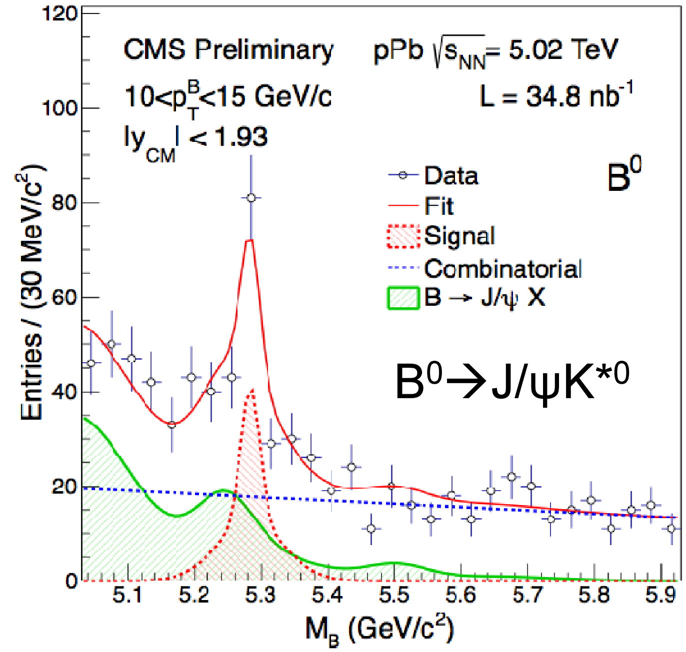
CMS PAS HIN-14-004

B Meson Production in pPb Collisions at 5.02 TeV

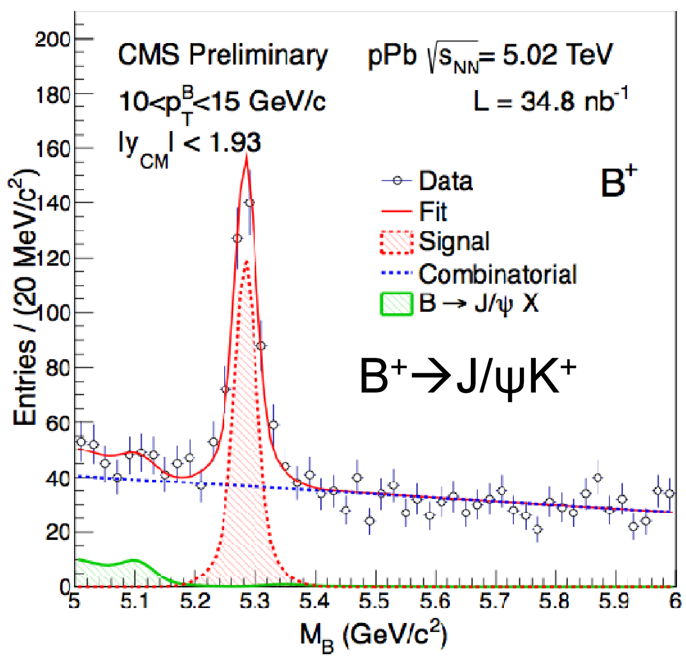
CMS PAS HIN-14-004

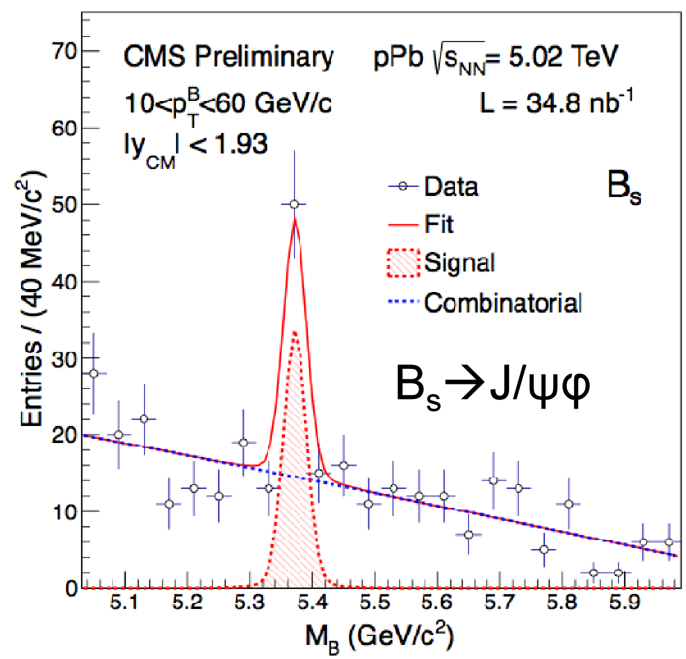
Three component fit for signal extraction:

- 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 $B^0 \rightarrow J/\psi K^{0*}$)



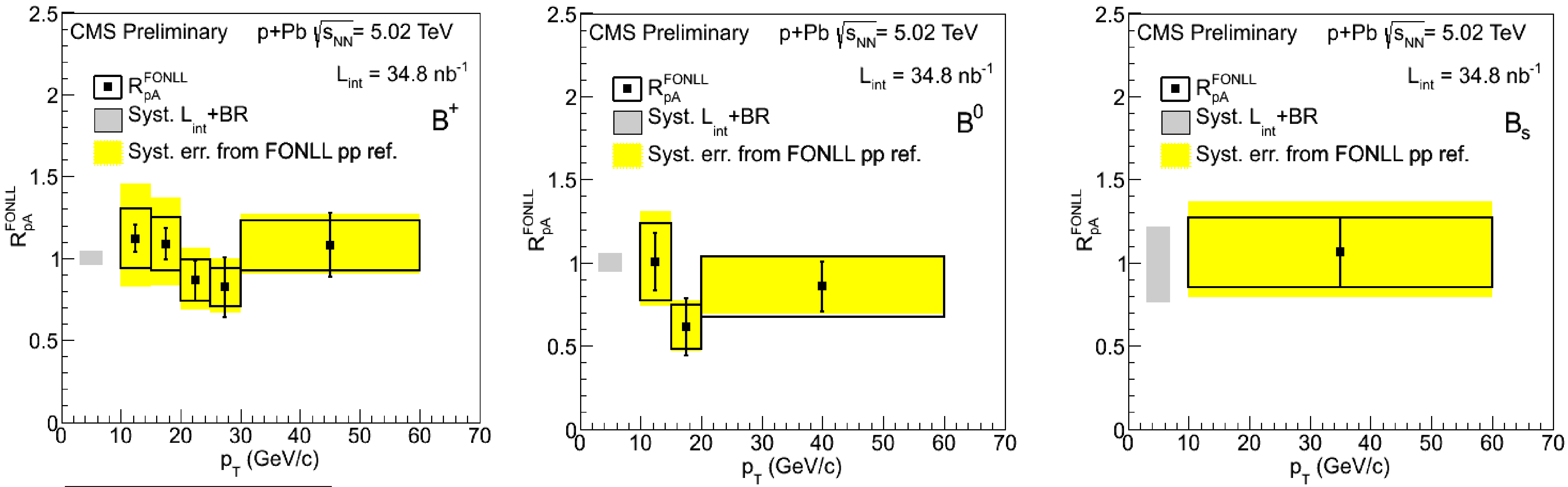
Fully reconstructed B meson signal in heavy ion collisions!





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

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

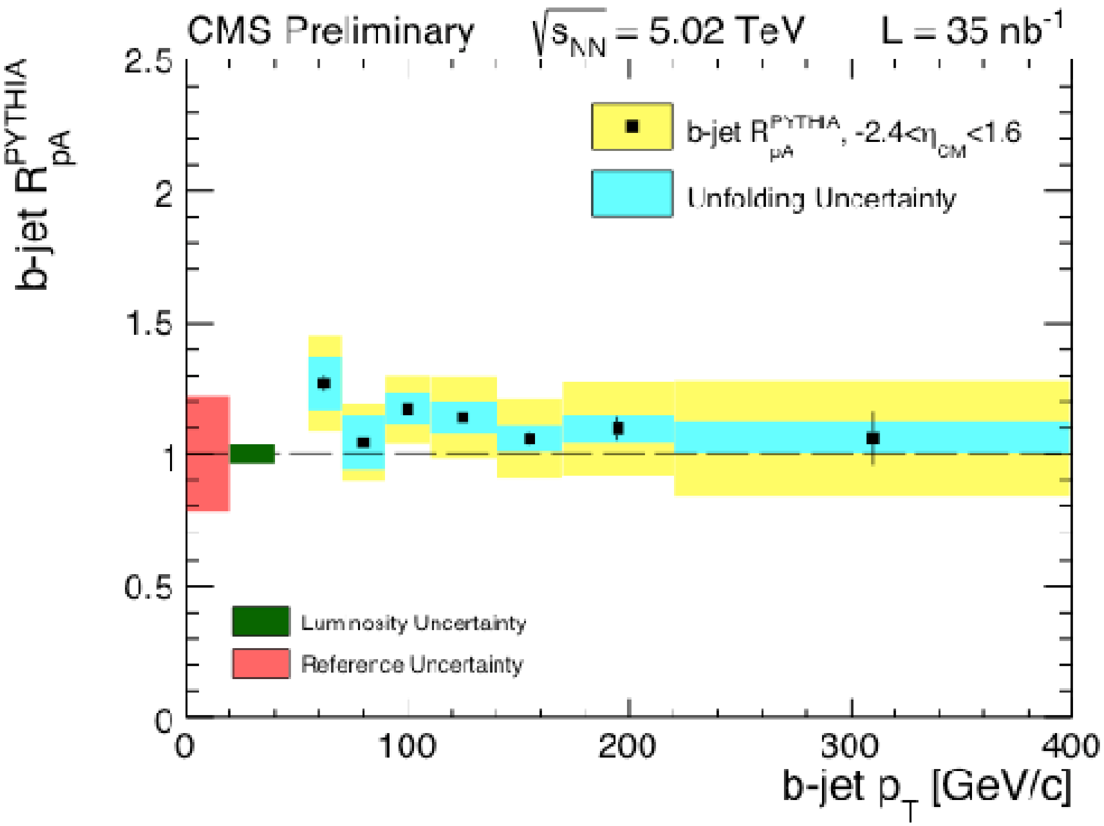


$|y_{CM}|<1.93$

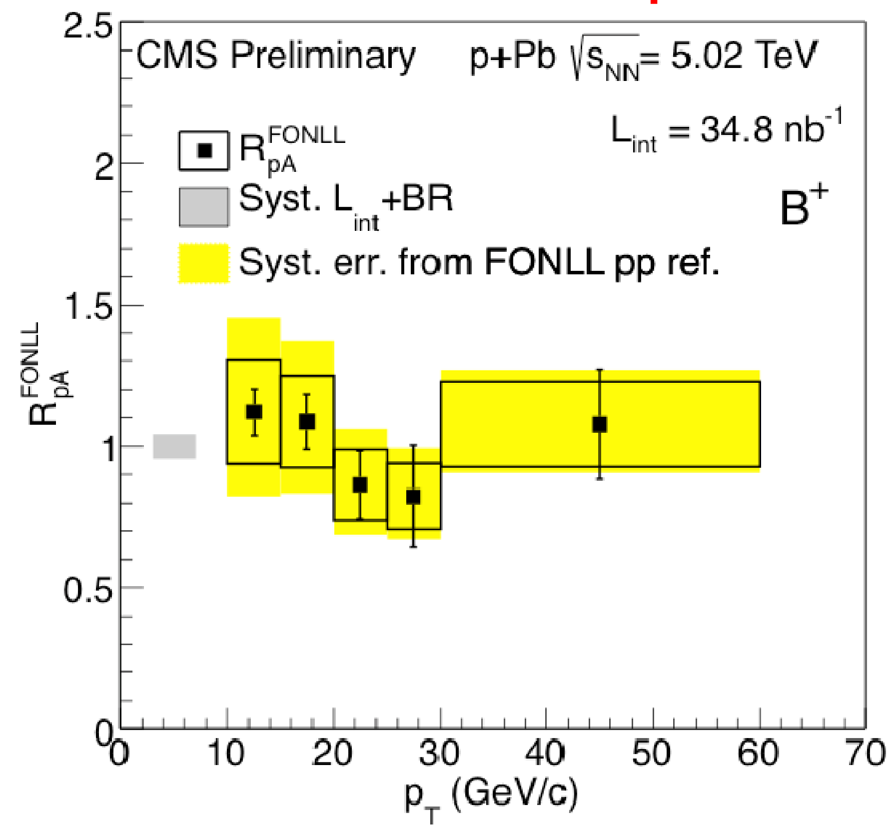
- R_{pA}^{FONLL} is compatible with unity within given uncertainties for the three B-mesons

CMS PAS HIN-14-004

b-jets vs. Fully Reconstructed B Mesons



p+Pb



- 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

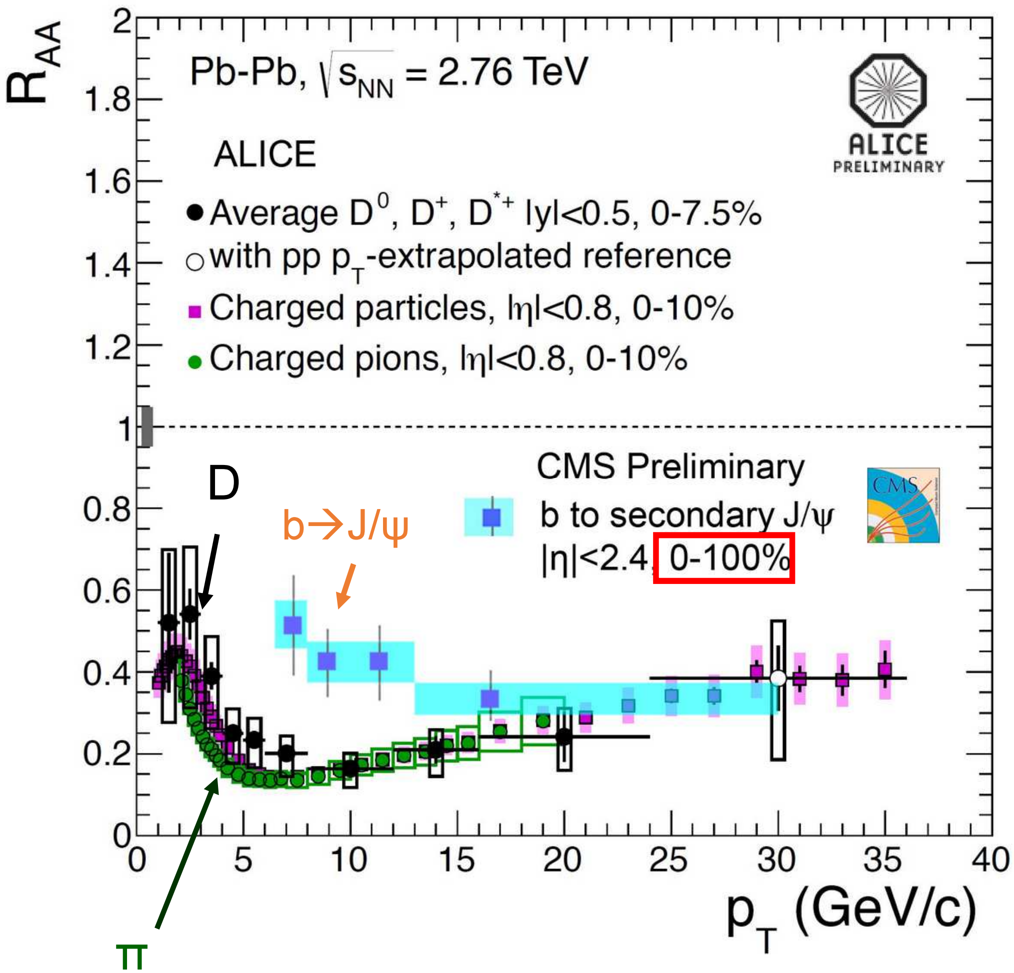
CMS PAS HIN-14-007

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)

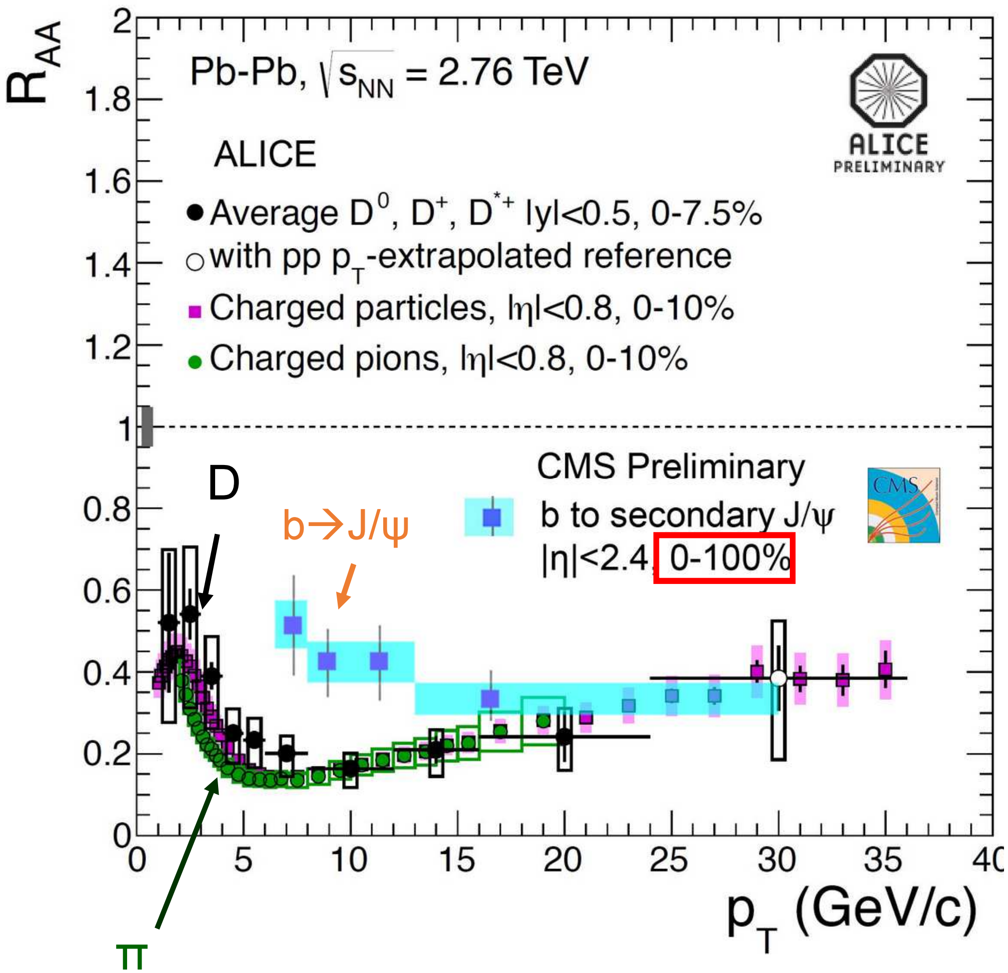
Pb+Pb



Flavor Dependence of Jet Quenching

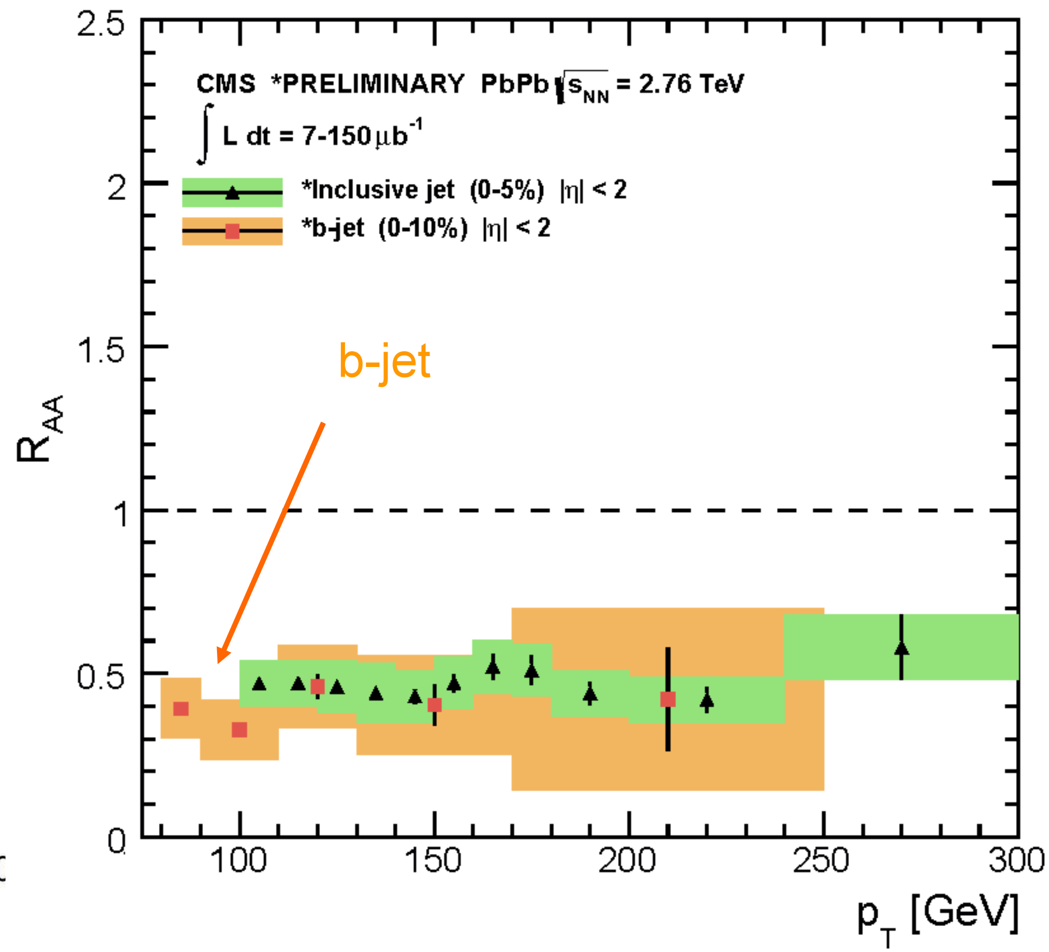
Indication of $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$ at low p_T

(However, spectra slope are different)



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

Pb+Pb



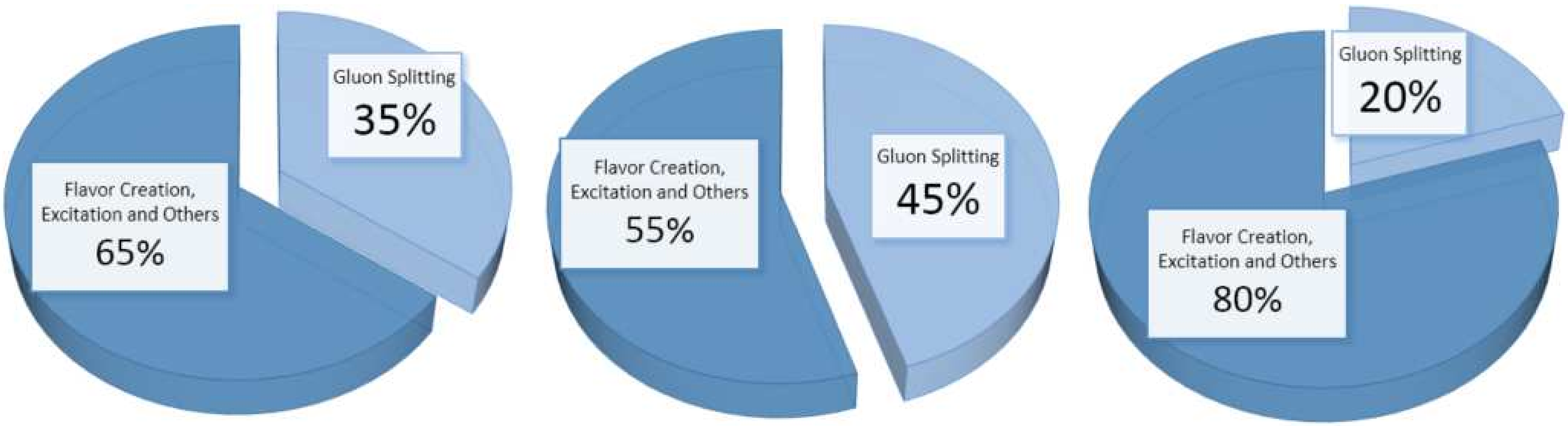
b quark jet (quark jet) ~ inclusive jet (dominated by gluon jets)?

Contribution from gluon splitting?

Gluon Splitting Contribution

- HF studies: matched partons are not necessary heavy quarks!

b jets	D mesons	Non-Prompt J/ψ
~30-40%	~40-50%	~20%

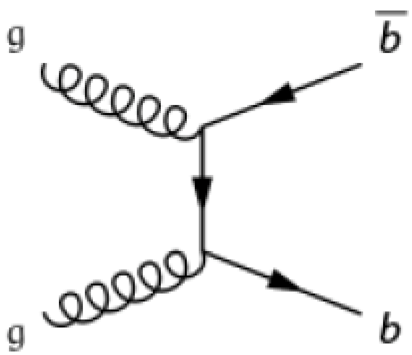


Estimated from PYTHIA 6

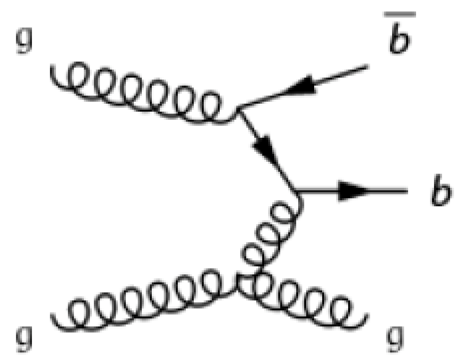
- **Non-negligible for both jets and hadrons.**
- Even more important for charm than for bottom at LHC energy!

Beyond b-jet, B and D R_{AA}?

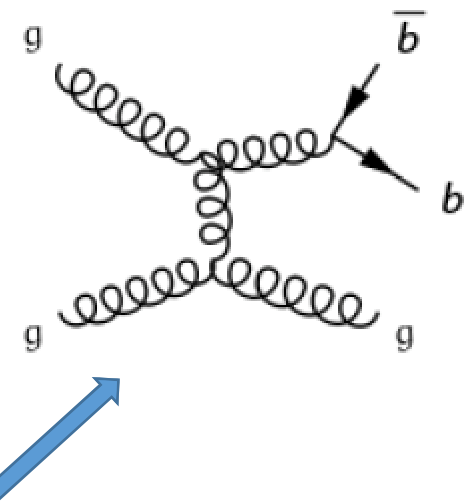
Flavor Creation (FCR)



Flavor Excitation (FEX)



Gluon Splitting (GSP)

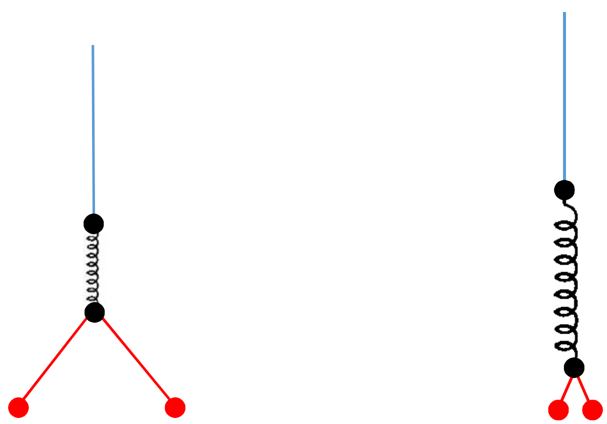


Can we remove / suppress GSP?

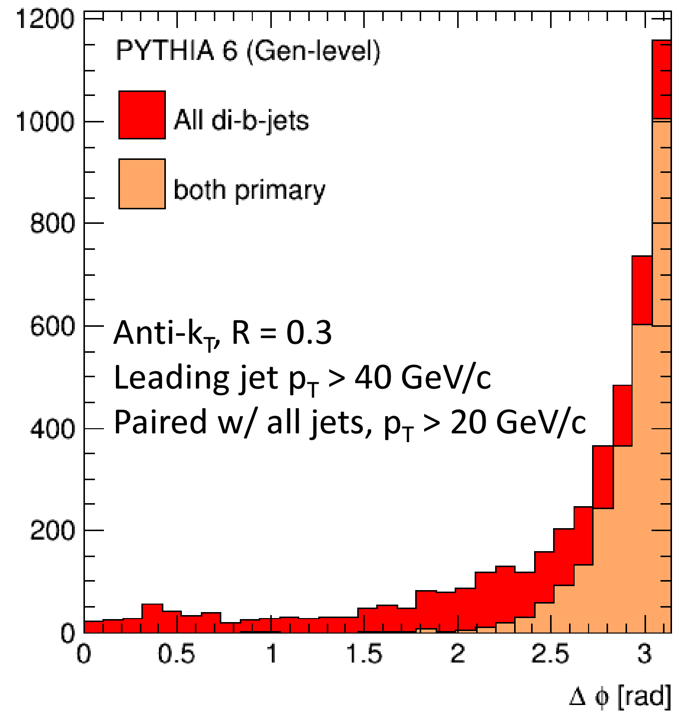
Angular dependence of gluon splitting

Plot from Matthew Nguyen

Hard splitting   Soft splitting



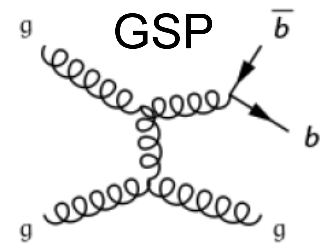
- High Q^2 splitting
  - Tend to give 3-jet topology
  - More b-jet-like w.r.t. e-loss
- Low Q^2 splitting
  - May be clustered as a single jet
  - More gluon-like w.r.t. e-loss



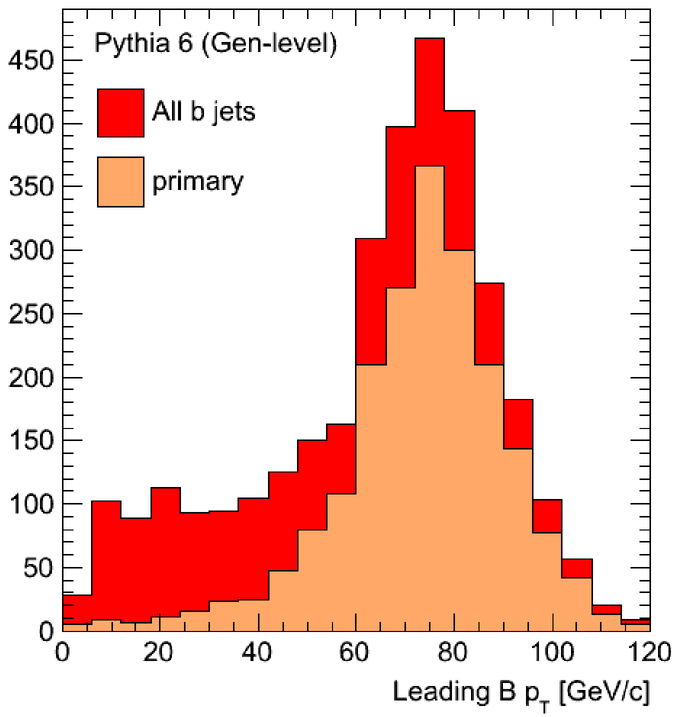
- Smooth variation between topologies
- Merged jets visible
- Some GSP back-to-back
- ⚠ Pythia poorly describes angular dependence

Leading b subjet / hadron

Cut on hard fragmenting b jets to suppress Gluon Splitting contamination?



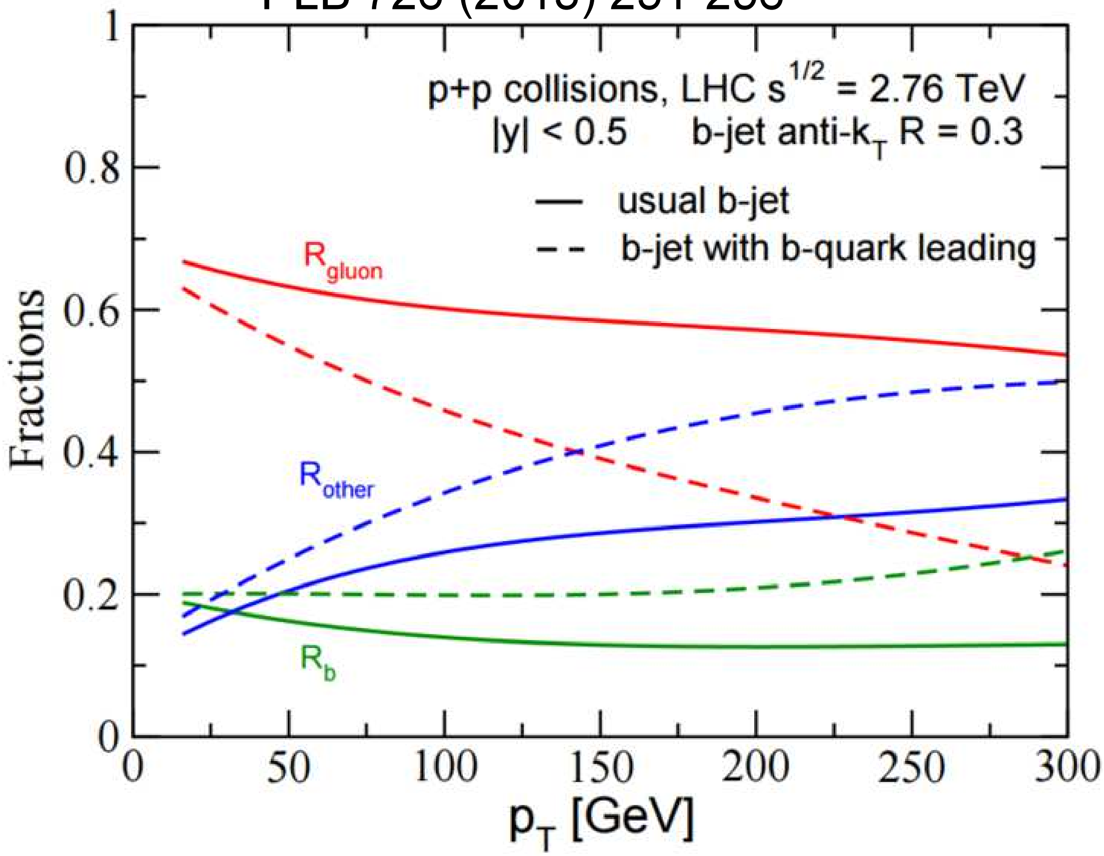
b-jet $80<p_T<120$ GeV/c



Plot from Matthew Nguyen

Hadron p_T does give some separation between primary and split gluon jets

PLB 726 (2013) 251-256

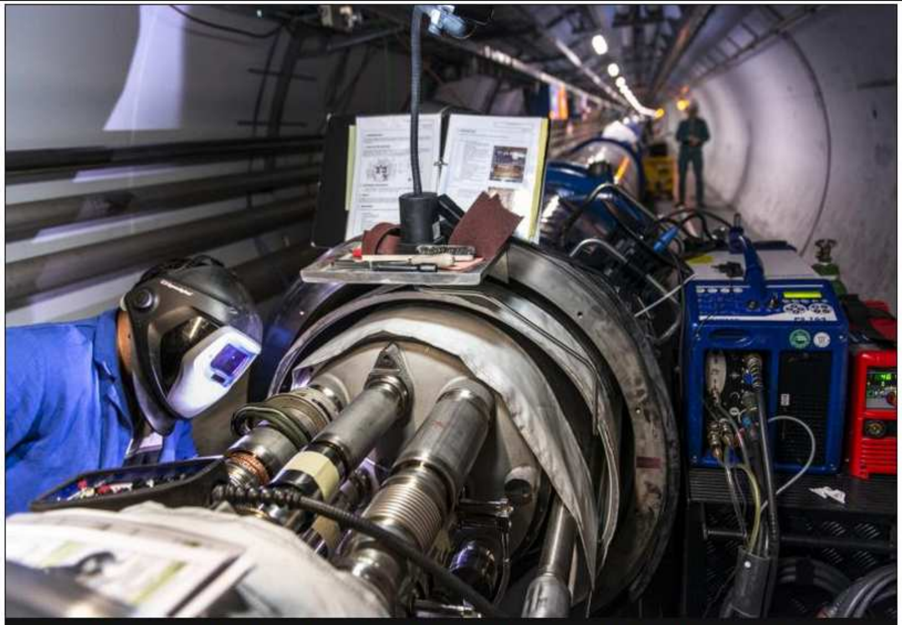


Requiring a leading b-quark reduces the Gluon Splitting contribution

Outlook of Run II

2015 Run II

- p+p at 5 and 13 TeV
- Pb+Pb at 5 TeV

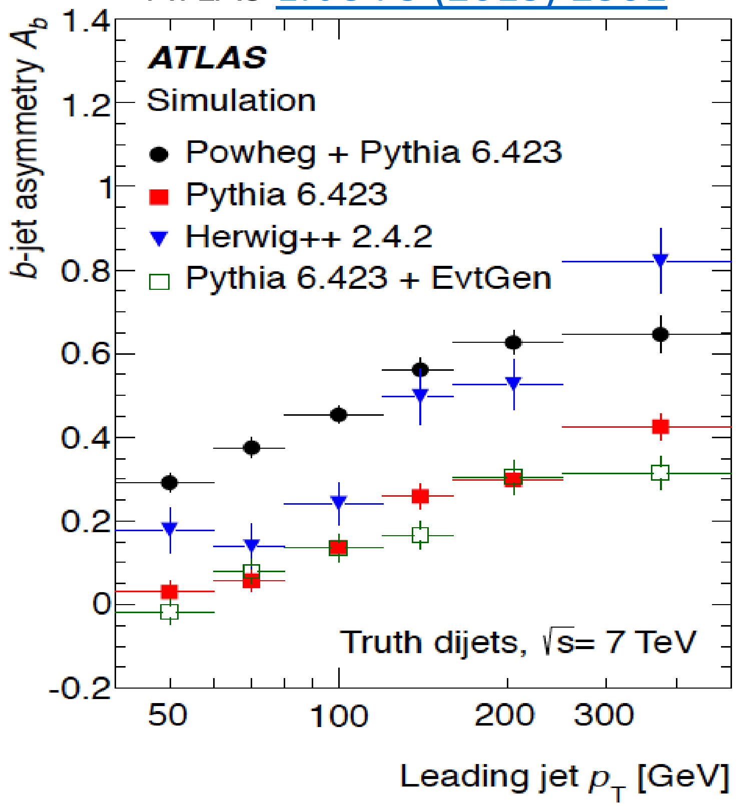


To operate at higher energy, the LHC was shut down for consolidation work to be performed. Some 1,700 magnet interconnections were reinforced, including more than 10,000 superconducting splices. Photo Maximilien Brice/CERN

b-jet p_T Asymmetry

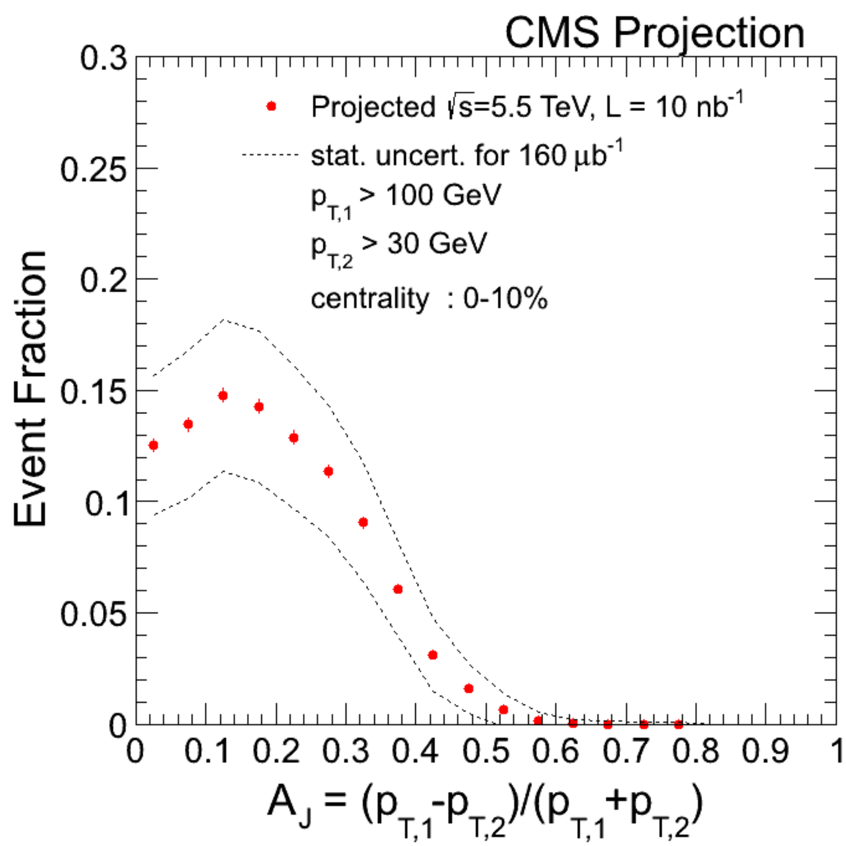
Simulation for pp @ 7 TeV

ATLAS EPJC 73 (2013) 2301



PbPb Projection for HL-LHC

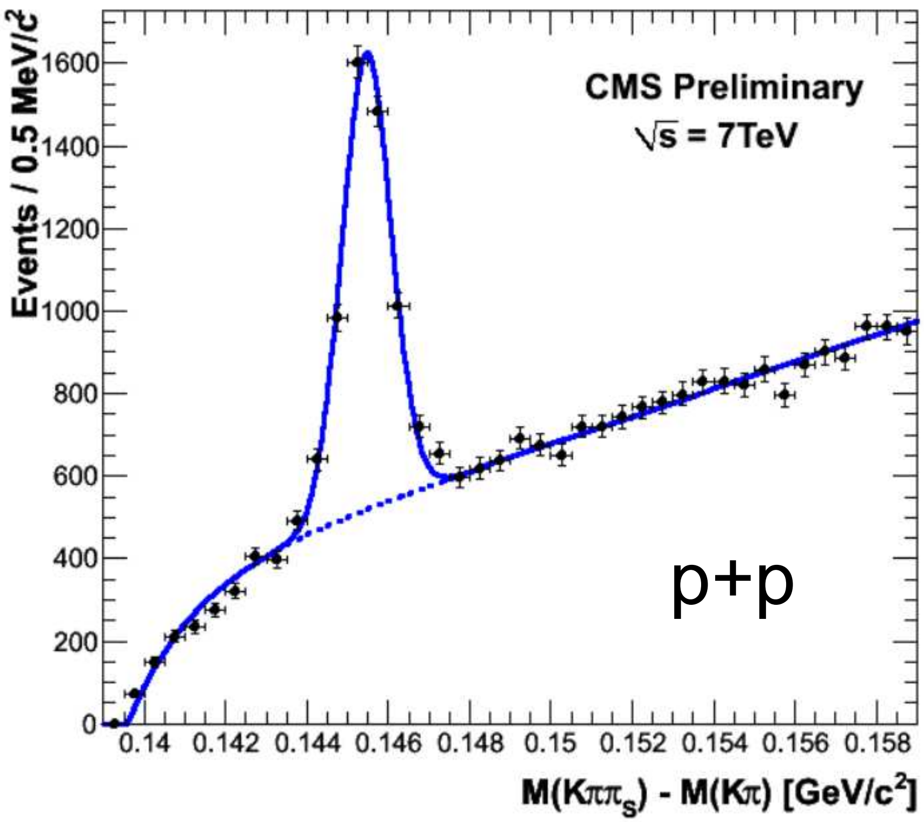
Doubly tagged di-b-jets

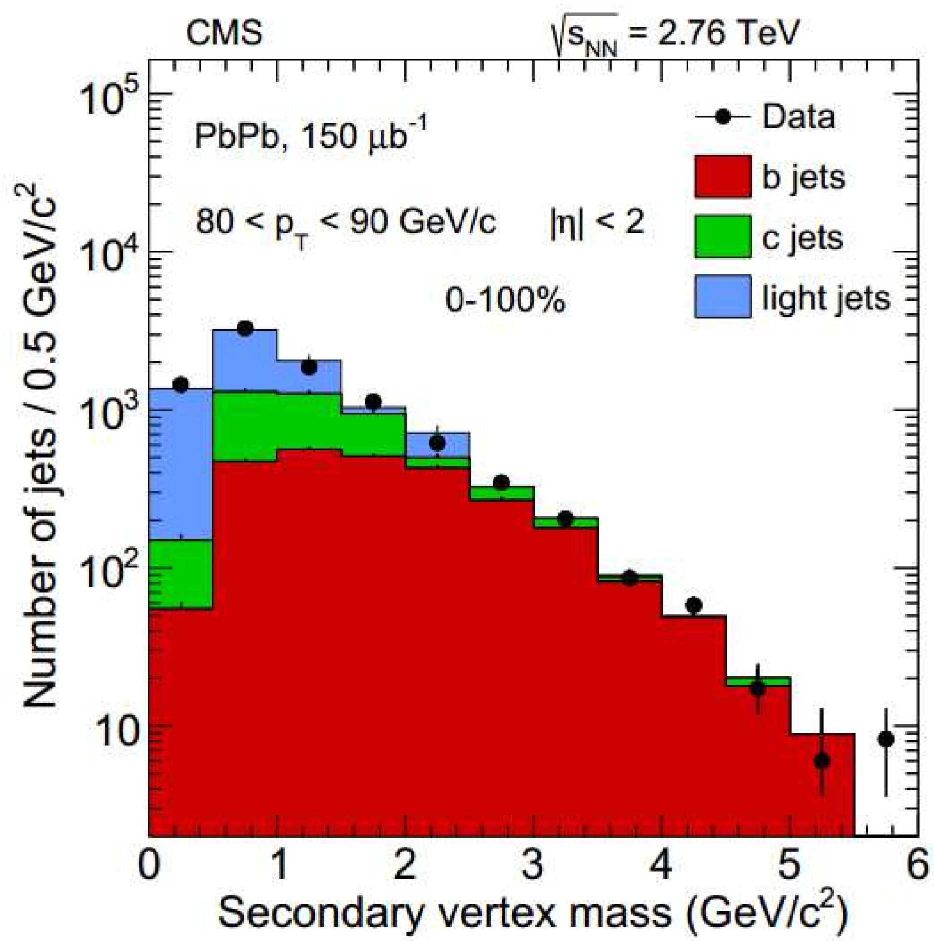


CMS-PAS-FTR-13-025

- Much reduced systematics for A_J w.r.t. inclusive jet spectra
- Large Δφ selection: a sample dominated by primary b jets from flavor creation

D meson and charm jet cross-section

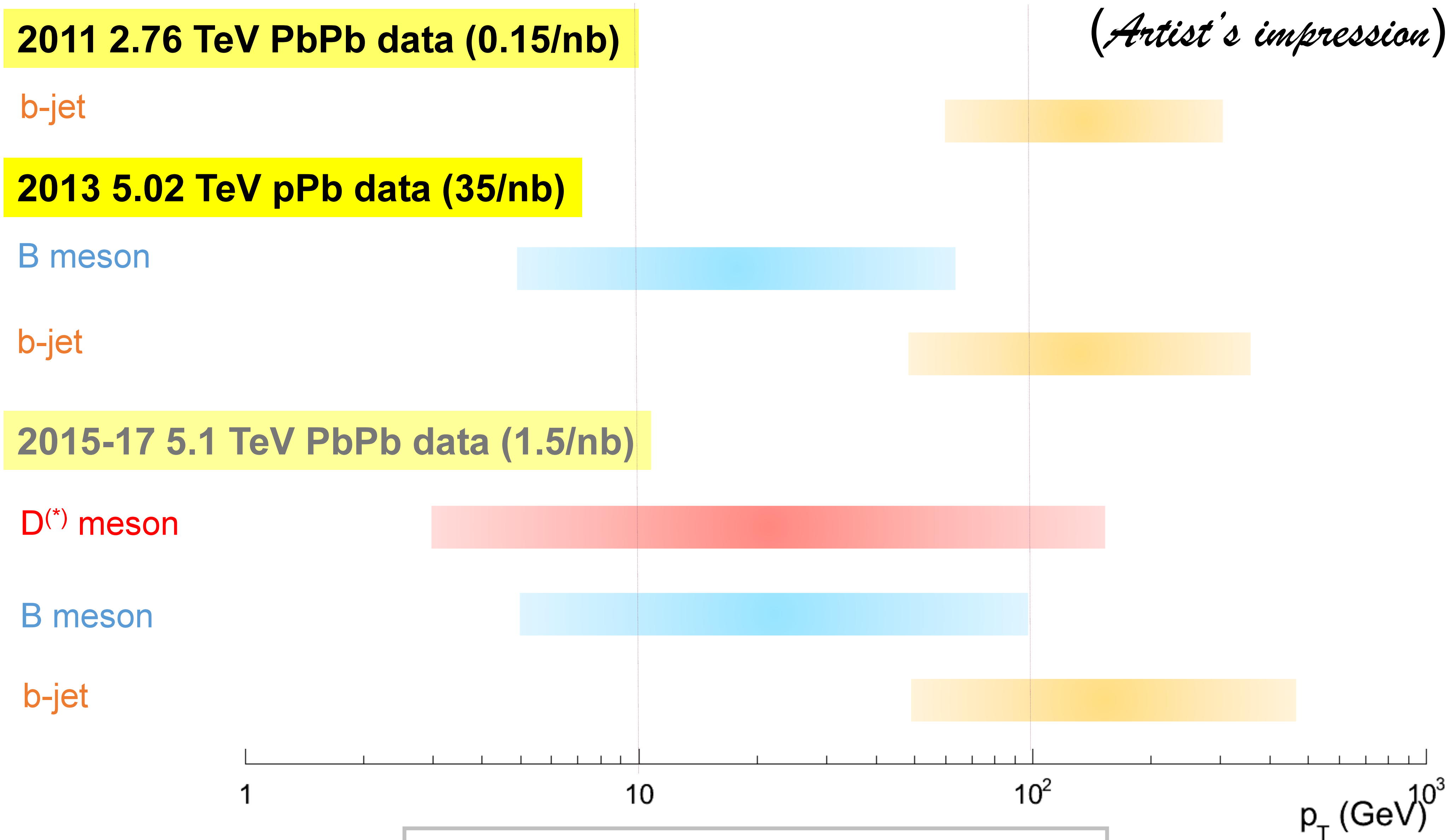




D / D* meson reconstruction without particle identification

- c-jet Rate ~ 2-2.5x b jets
- More difficult to tag
  - Shorter cτ 100-300 μm
  - Smaller multiplicity
  - Softer vertices

Statistical Reach in 2015 and beyond



HL-LHC (10/nb): (b)-jet quenching at O(TeV)
ttbar production

Summary and Outlook

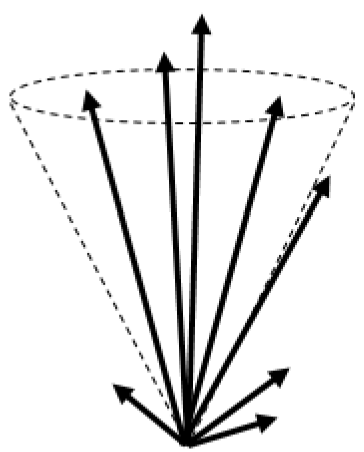
- CMS Results and Data Tables:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

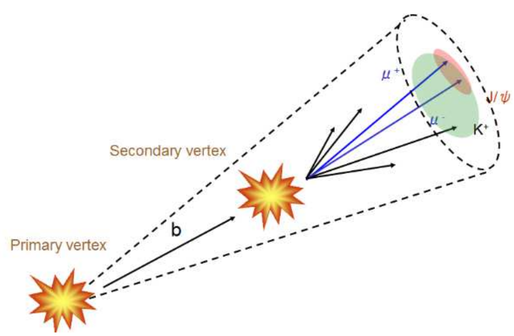
- LHC Run II and III data will solve open questions
  - More "exclusive"
  - Quarkonia production:
    - High statistics Charmonia and Bottomonia spectra measurements
      - Can we understand / separate the direct and feed-down quarkonia?
      - "Turn on" of the quarkonia suppression in the peripheral events
      - Can we understand more about recombination of J/ψ, ψ(2S) and Y states?
    - Elliptic flow measurement of Charmonia (and Bottomonia)
  - Flavor dependence of parton energy loss:
    - High precision B(D) meson and b(c)-jet spectra and flow measurements
    - HF jet pair asymmetries and angular correlations
    - HF jet "fragmentation functions" / sub-jet structure
    - Multiple channels (dijet, photon-jet, W/Z-jet) to separate gluon, light quark and heavy quark jets

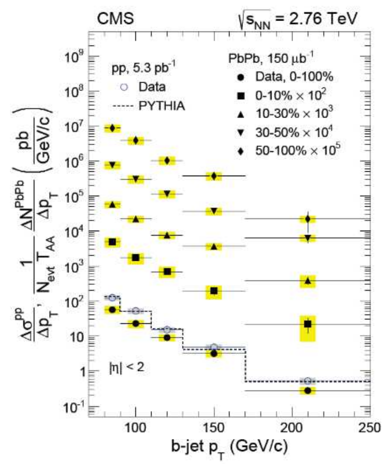
Backup slides

b-jet Analysis Strategy

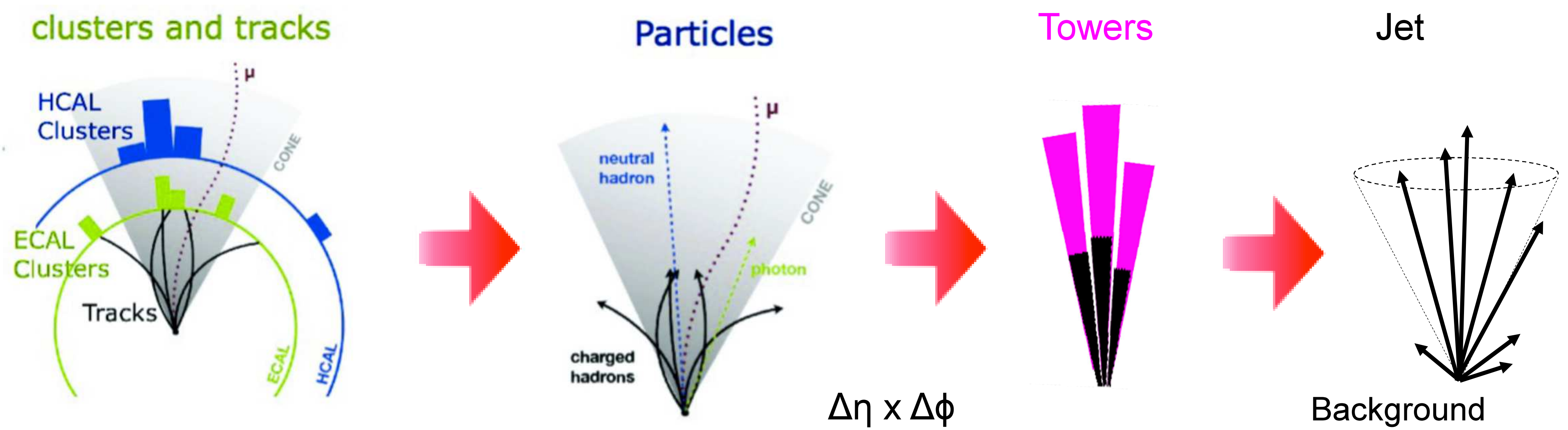
Jet reconstruction → b-jet tagging Purity determination → Efficiency correction and resolution unfolding







Jet Reconstruction and Composition



$\Delta\eta \times \Delta\phi$
0.076 x 0.076 in barrel

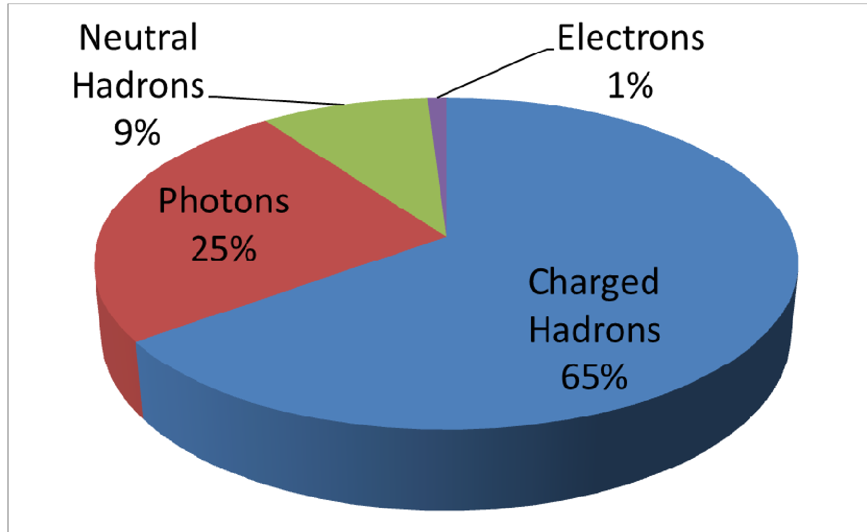
Background subtraction and jet clustering

Anti-k_T algorithm is used in most CMS publication

On average, charged hadrons carry 65% of the jet momentum

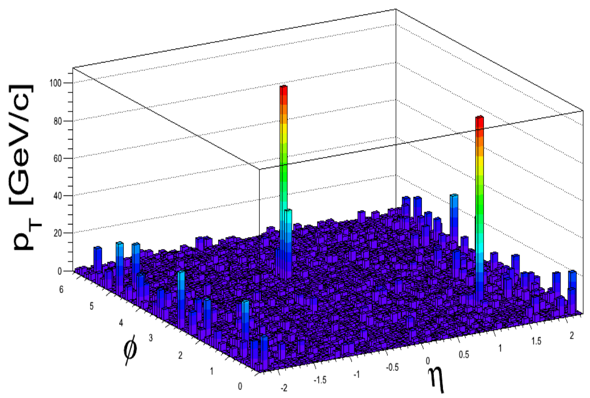
Measure the known part
Correct the rest by MC simulation

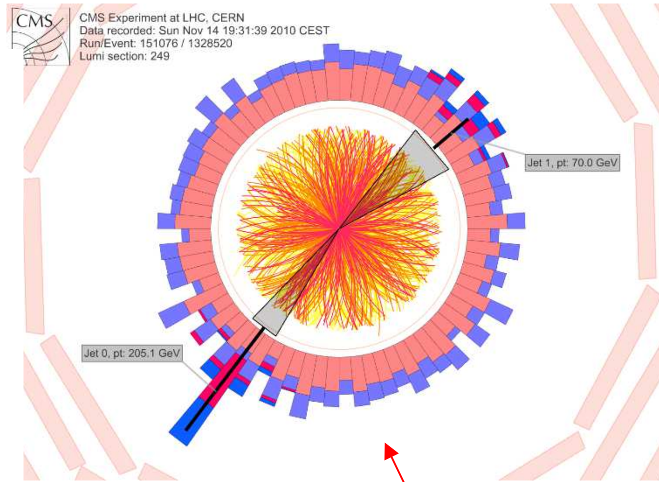
Optimize the use of calorimeter and tracker
Example: “Particle Flow” in CMS

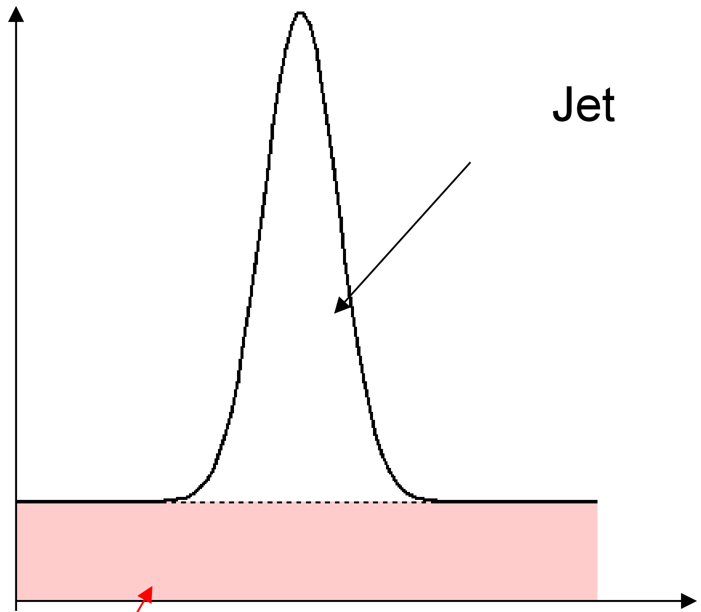


A typical high p_T jet

Underlying Event Background





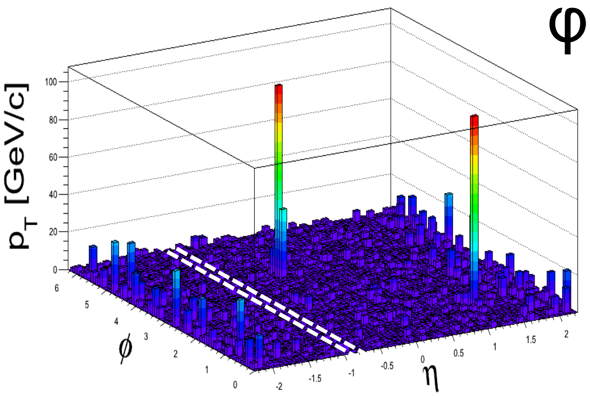


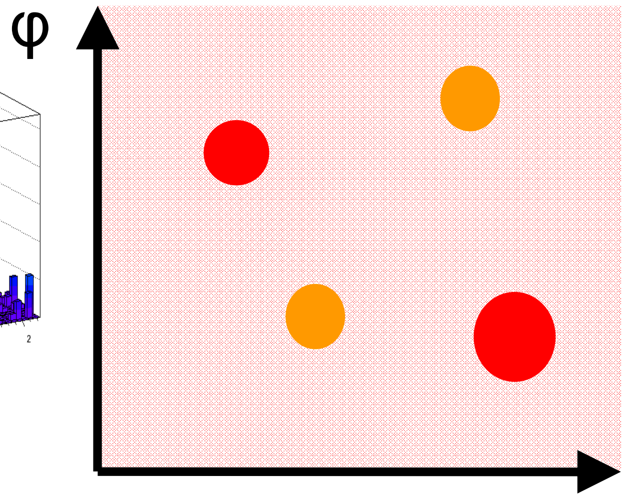
Multiple parton interaction

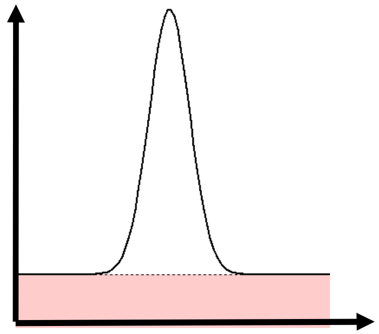
Large underlying event from soft scattering

Need background subtraction

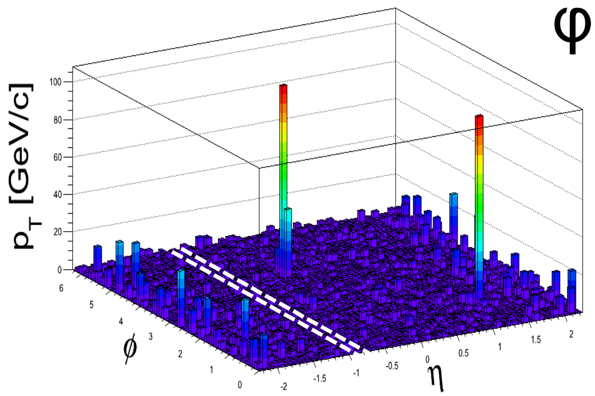
Background Subtraction

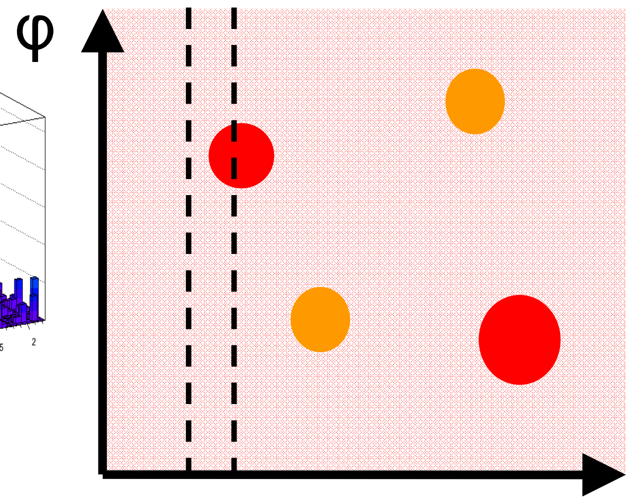




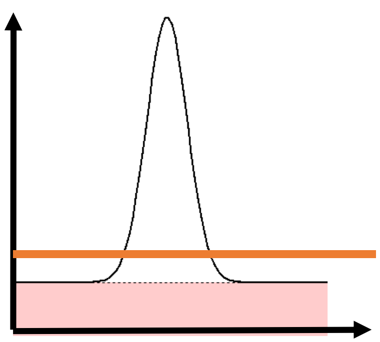


Background Subtraction





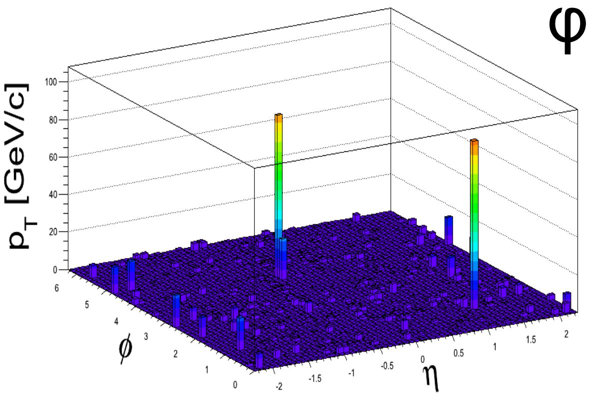
1. Background energy per tower calculated in strips of η. Pedestal subtraction

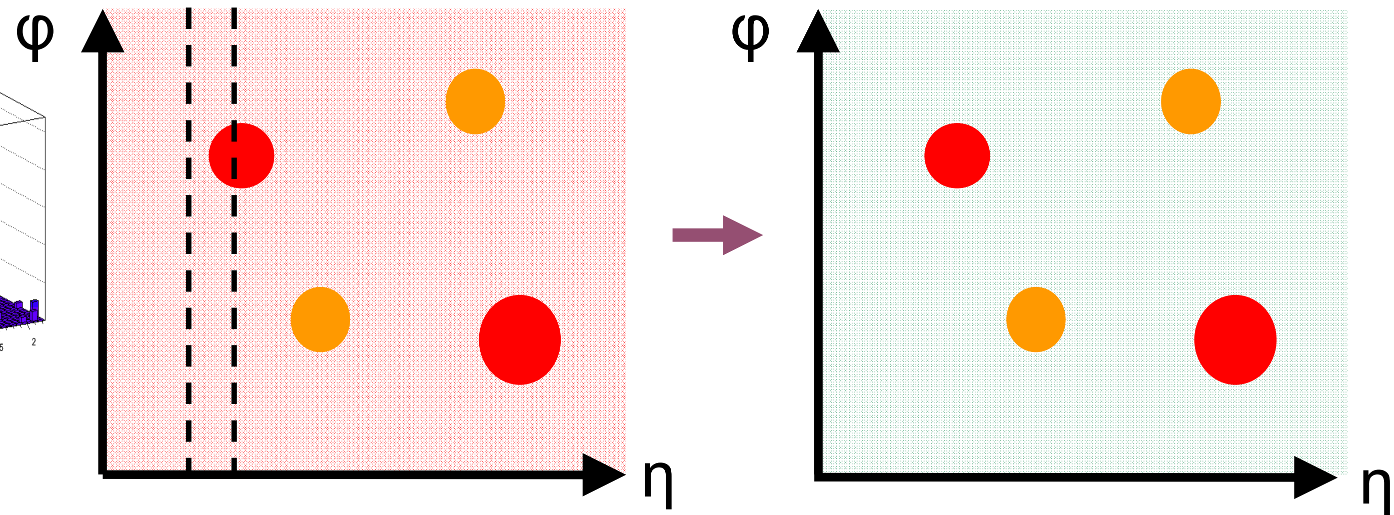


Background level

Estimate background
for each tower ring of constant η
estimated background = $\langle p_T \rangle + \sigma(p_T)$
- Captures dN/dη of background
- Misses ϕ modulation – to be improved

Background Subtraction





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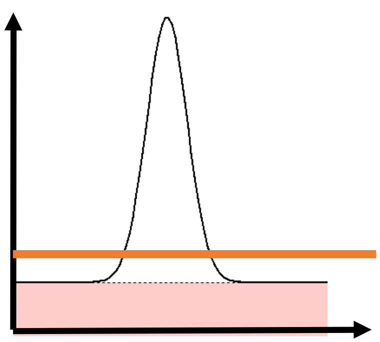
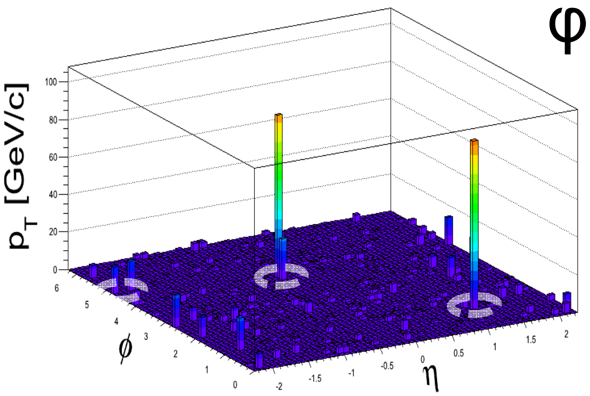
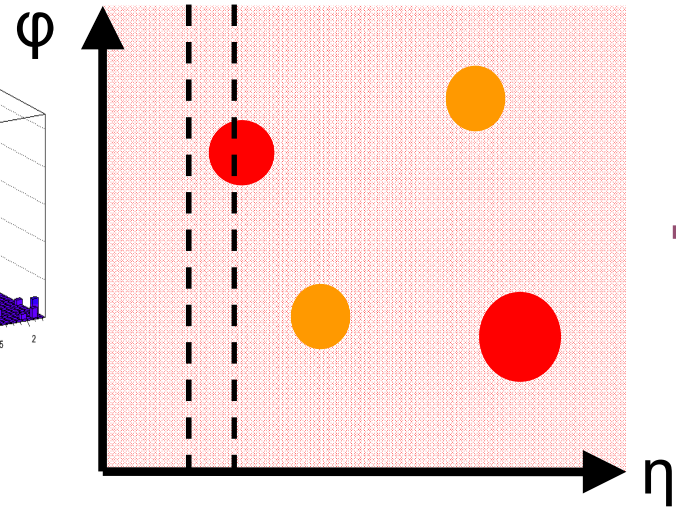


Background level

Background Subtraction





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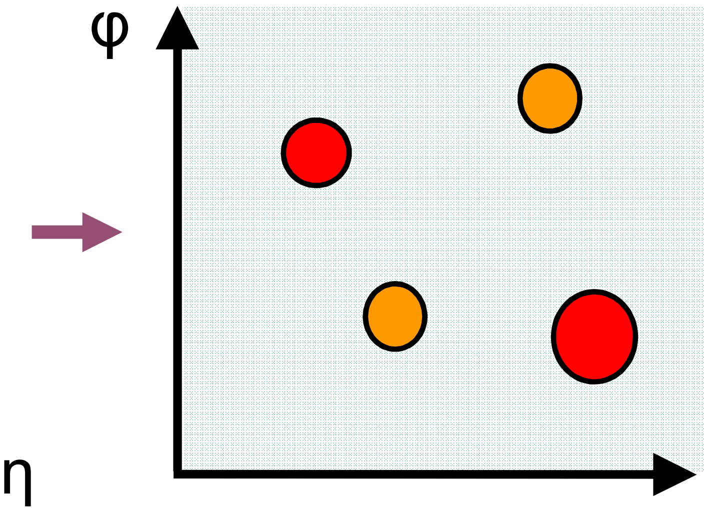
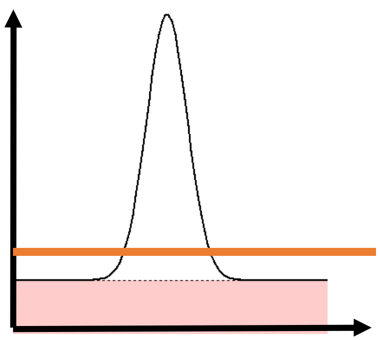
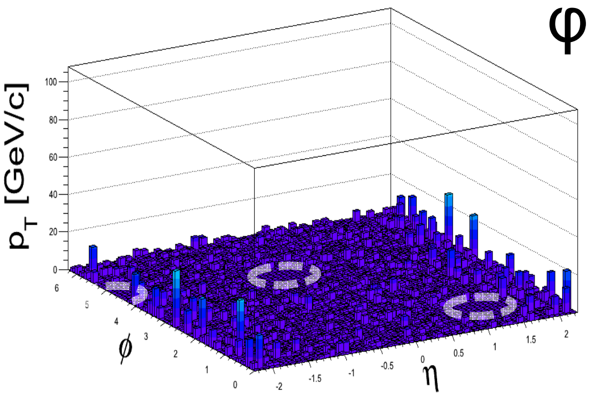


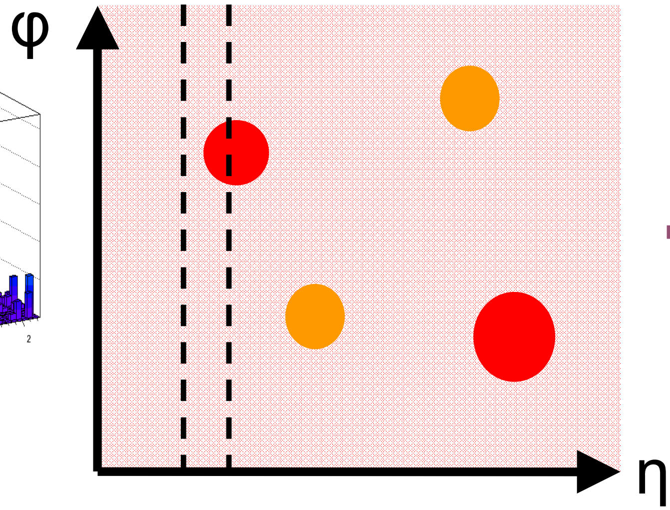
2. Run anti k_T algorithm on background subtracted towers



Background level

Background Subtraction





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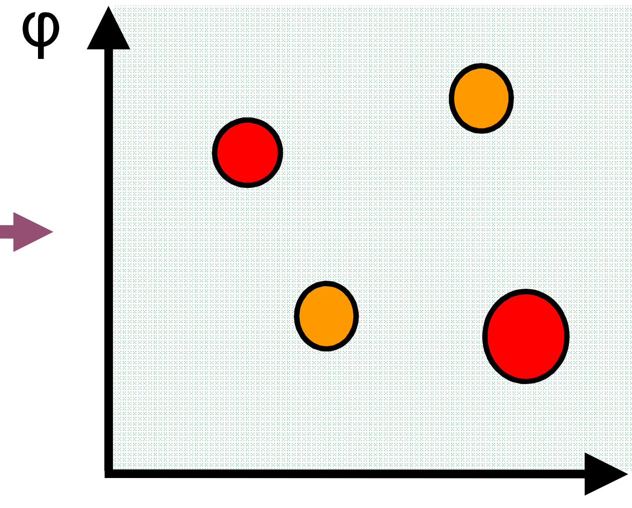

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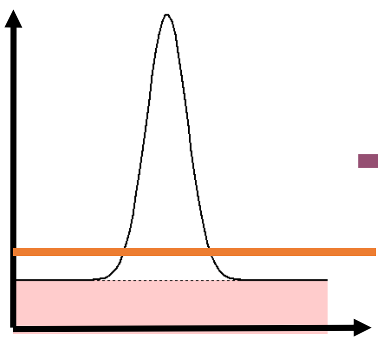
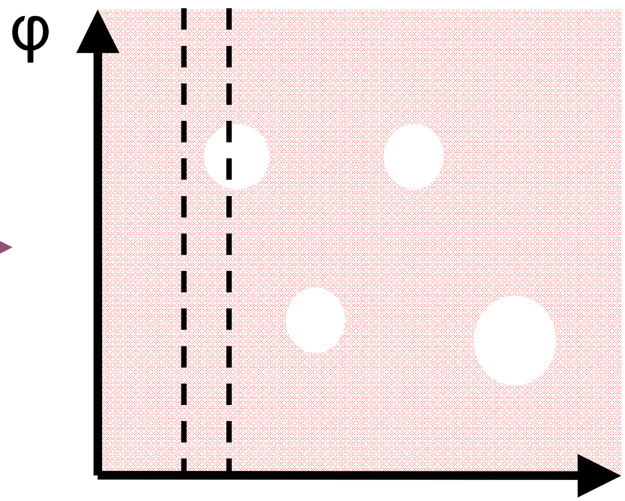
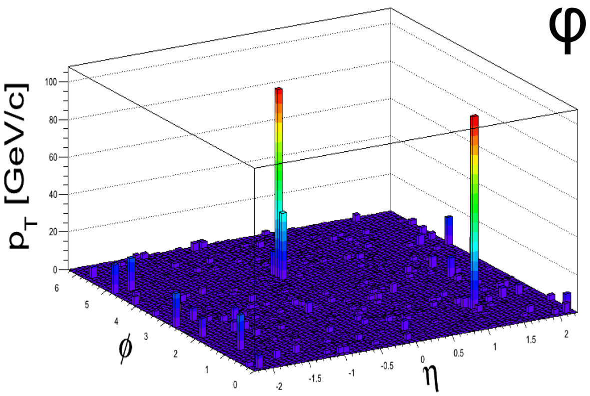


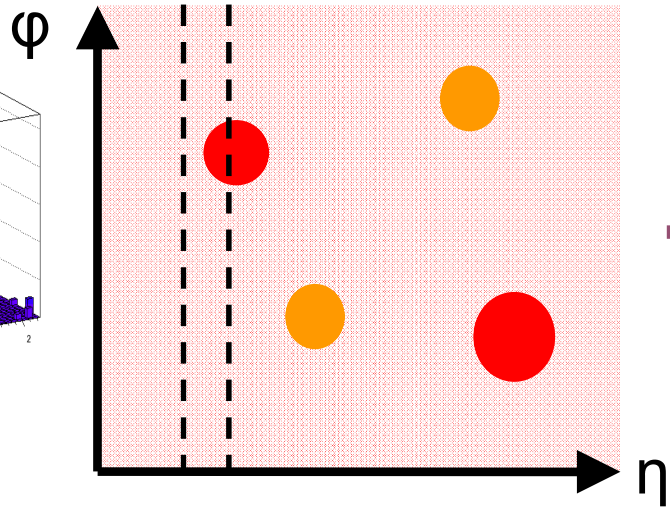
Background level



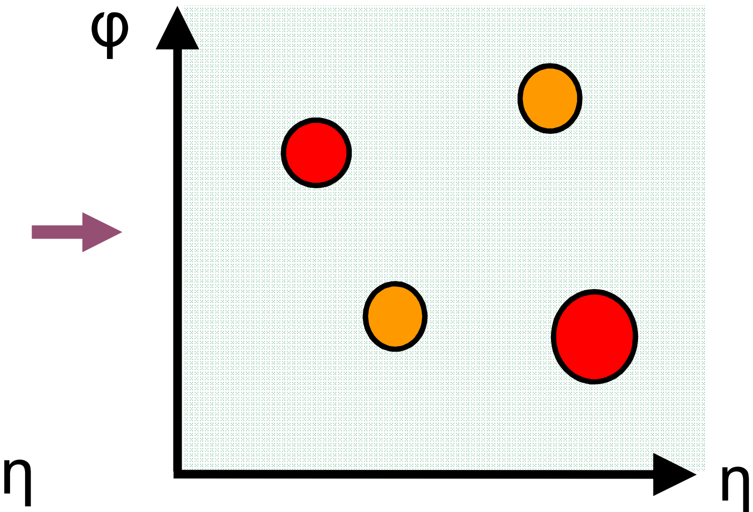
3. Exclude reconstructed jets

Background Subtraction

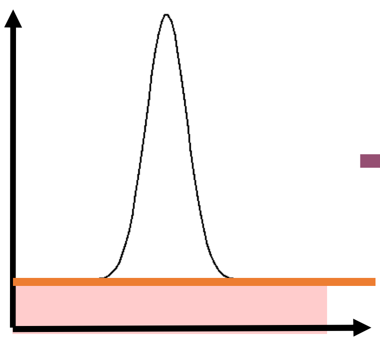




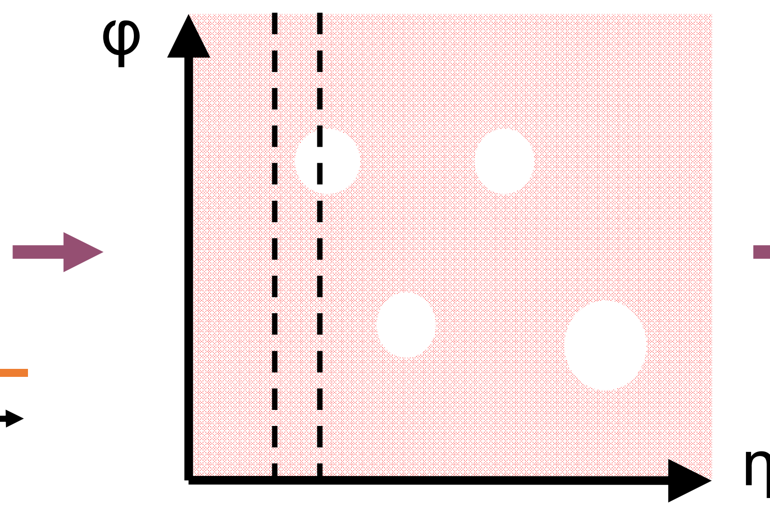
1. Background energy per tower calculated in strips of η. Pedestal subtraction



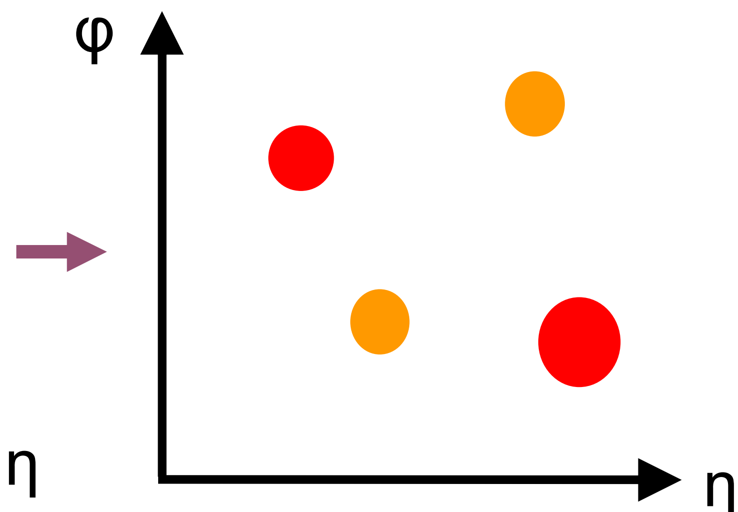
2. Run anti k_T algorithm on background subtracted towers



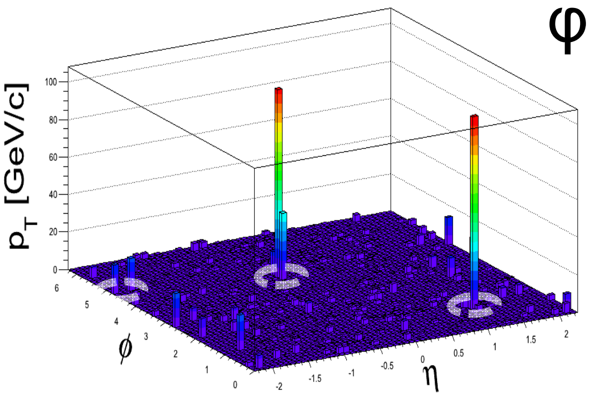
Background level

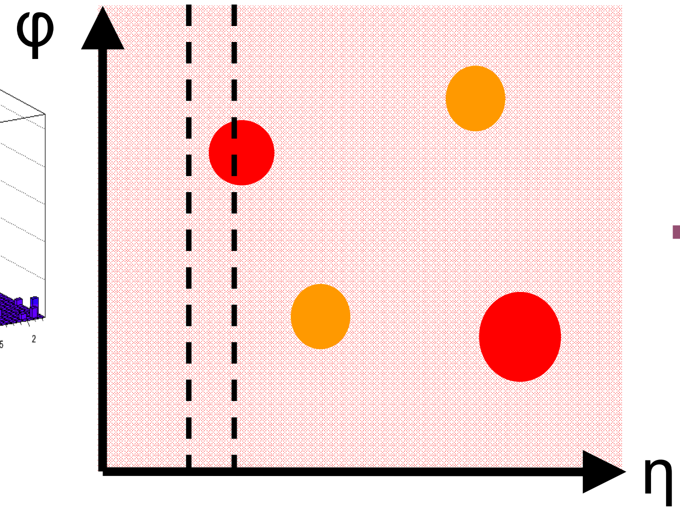


3. Exclude reconstructed jets
Recalculate the background energy



Background Subtraction





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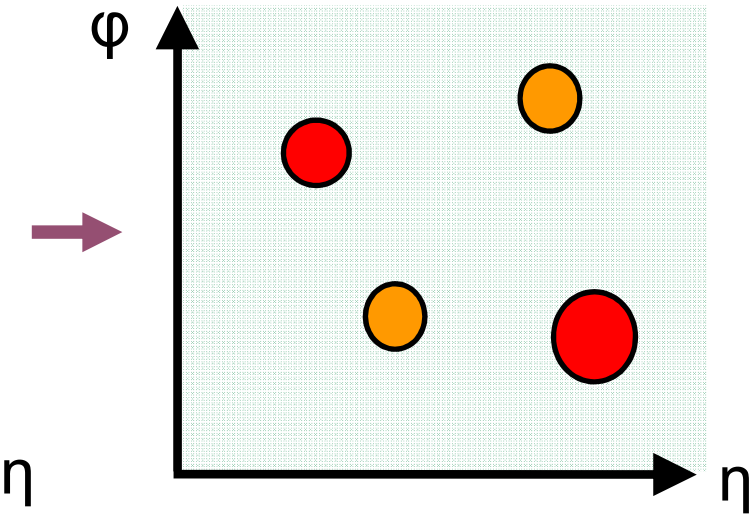

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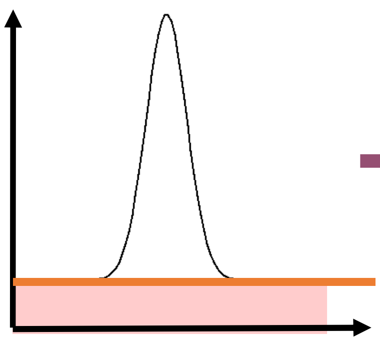
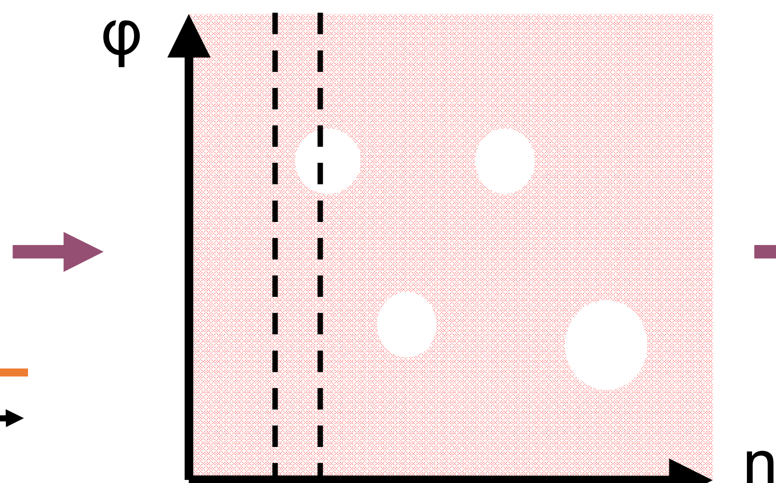
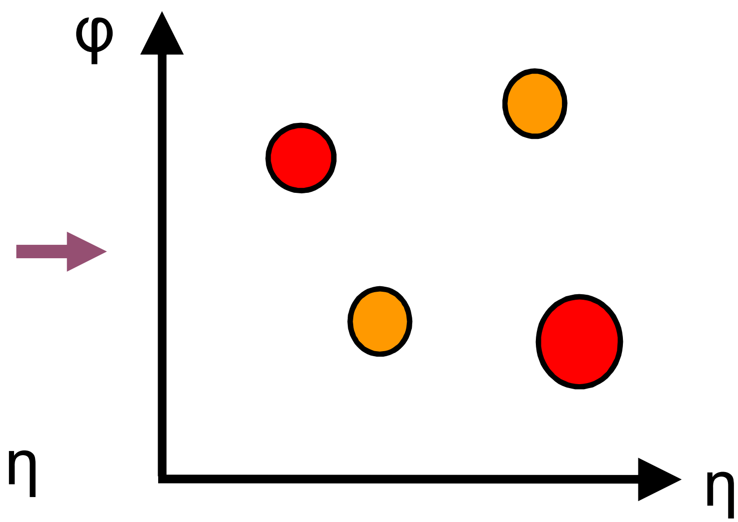


Background level

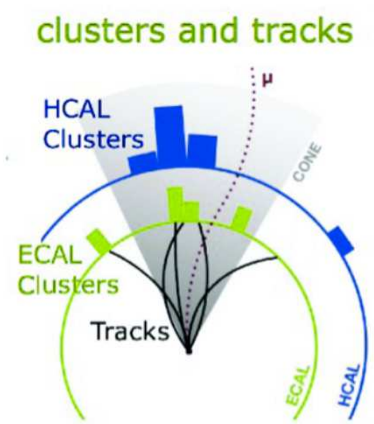


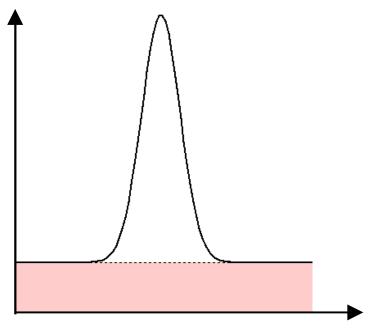
3. Exclude reconstructed jets
Recalculate the background energy

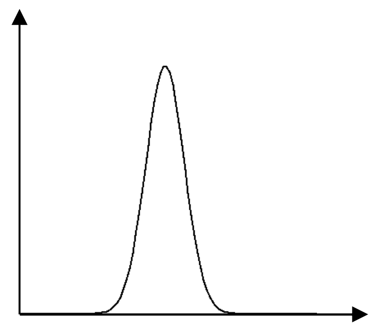


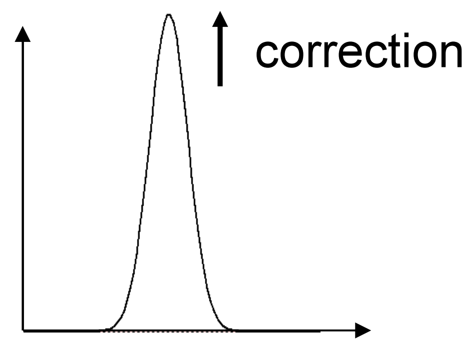
4. Run anti k_T algorithm on background subtracted towers to get final jets

Summary of Jet Reconstruction









Raw jet energy → Background subtraction → Jet energy correction → Jet energy

Background subtraction: Remove underlying events contribution

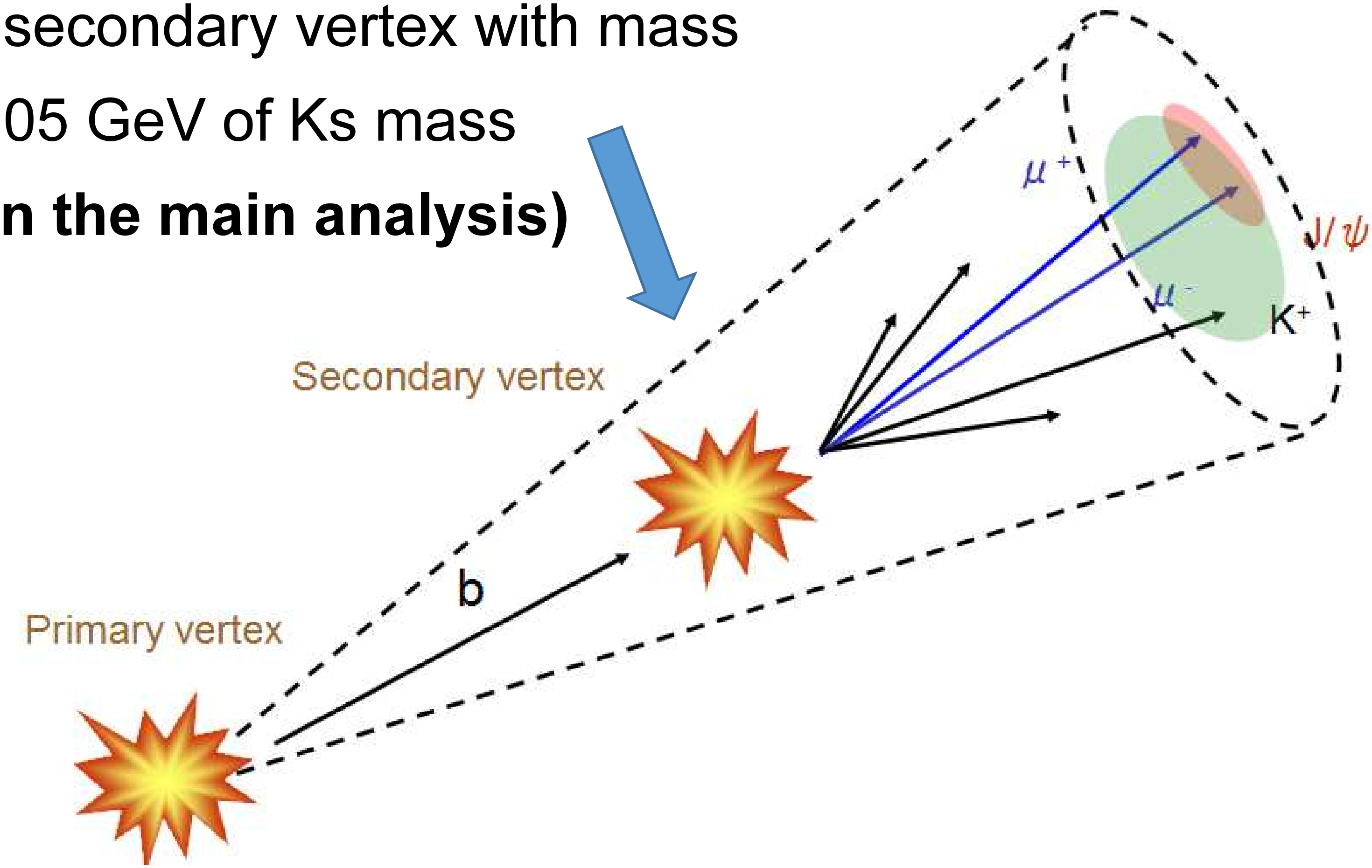
Jet energy correction: MC Simulation PYTHIA

b-jet tagging algorithms used in heavy ion collisions

(1) Secondary vertex tagger: use 3D flight distance significance

Veto on secondary vertex with mass within 0.05 GeV of Ks mass

(Used in the main analysis)



b-jet tagging algorithms used in heavy ion collisions

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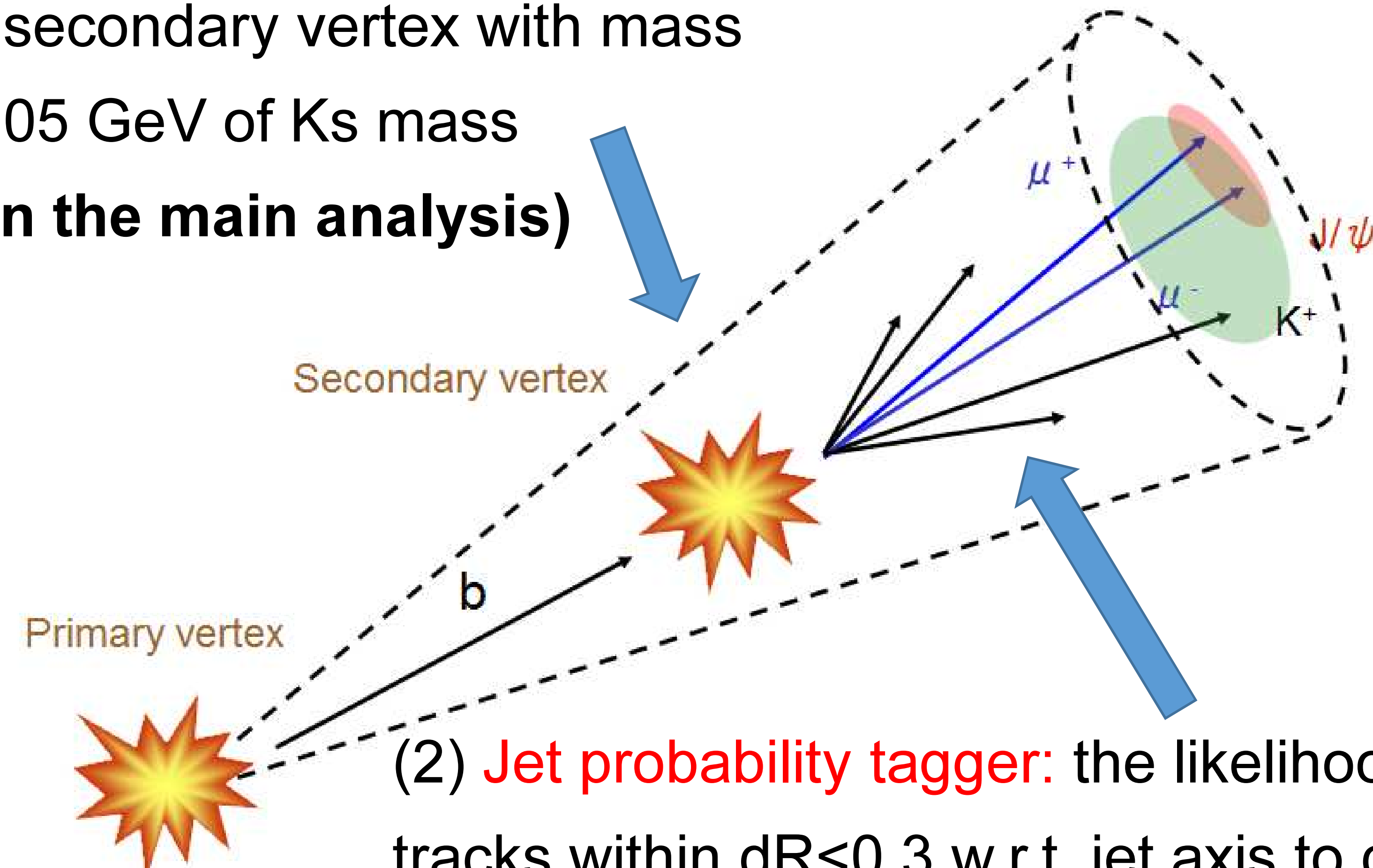
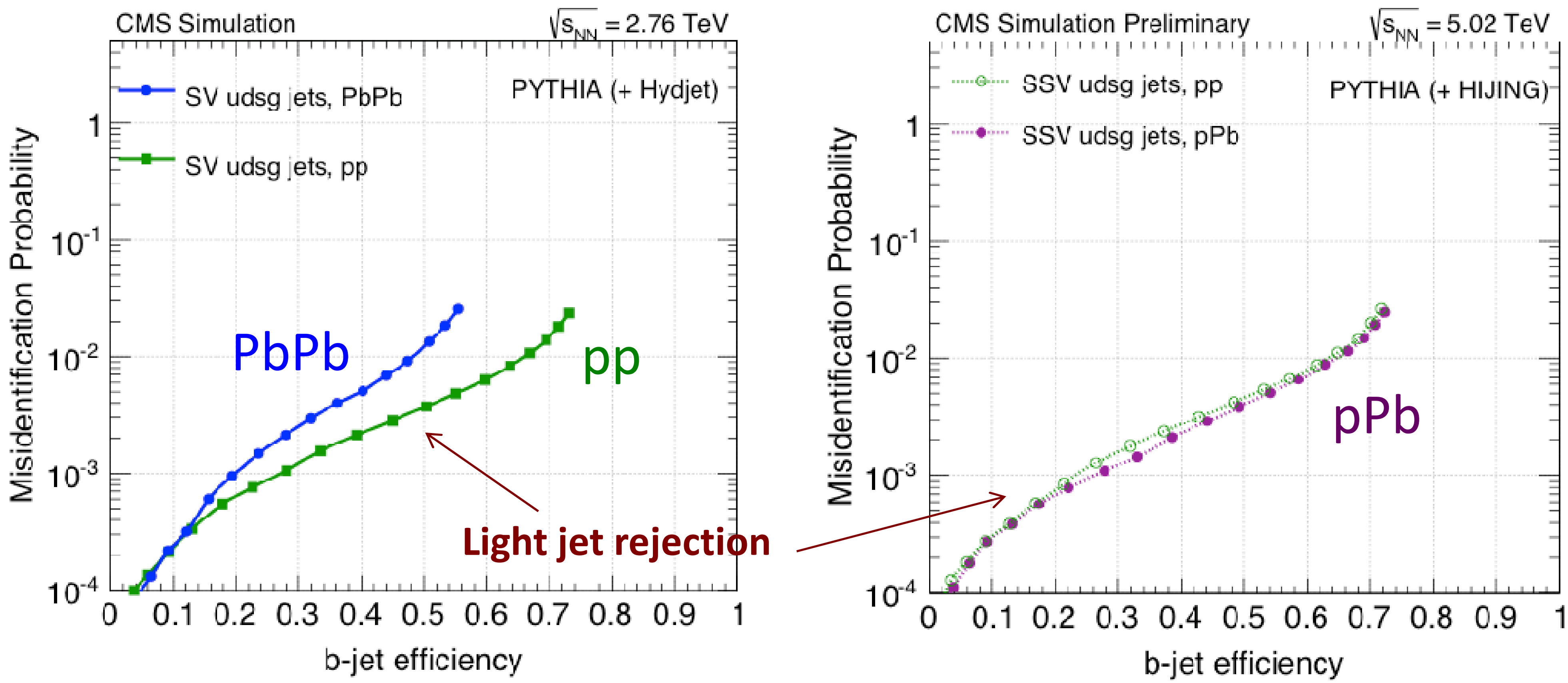


(2) Jet probability tagger: the likelihood of the tracks within dR<0.3 w.r.t. jet axis to come from the **primary vertex** using the impact parameter significance. **(Used as "reference tagger")**

Tagging Performance in Simulation

Performance in PbPb

Performance in pPb

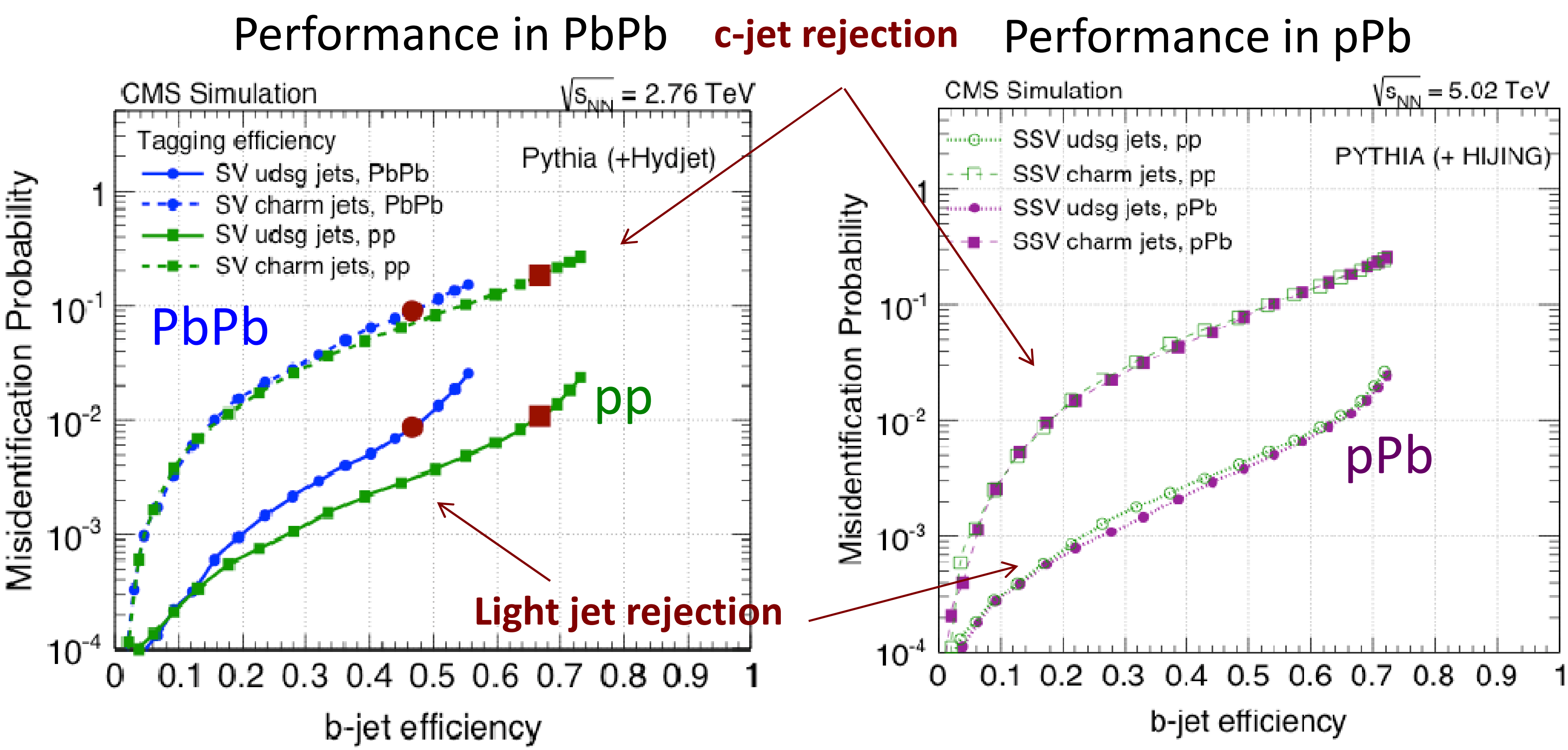


- b-jet efficiency plotted against probability of misidentifying a light jet as a b-jet using secondary vertex tagger
- pPb and pp have identical reconstruction procedures ➔ very similar tagging performance

CMS PAS HIN-12-003

CMS PAS HIN-14-007

Tagging Performance in Simulation



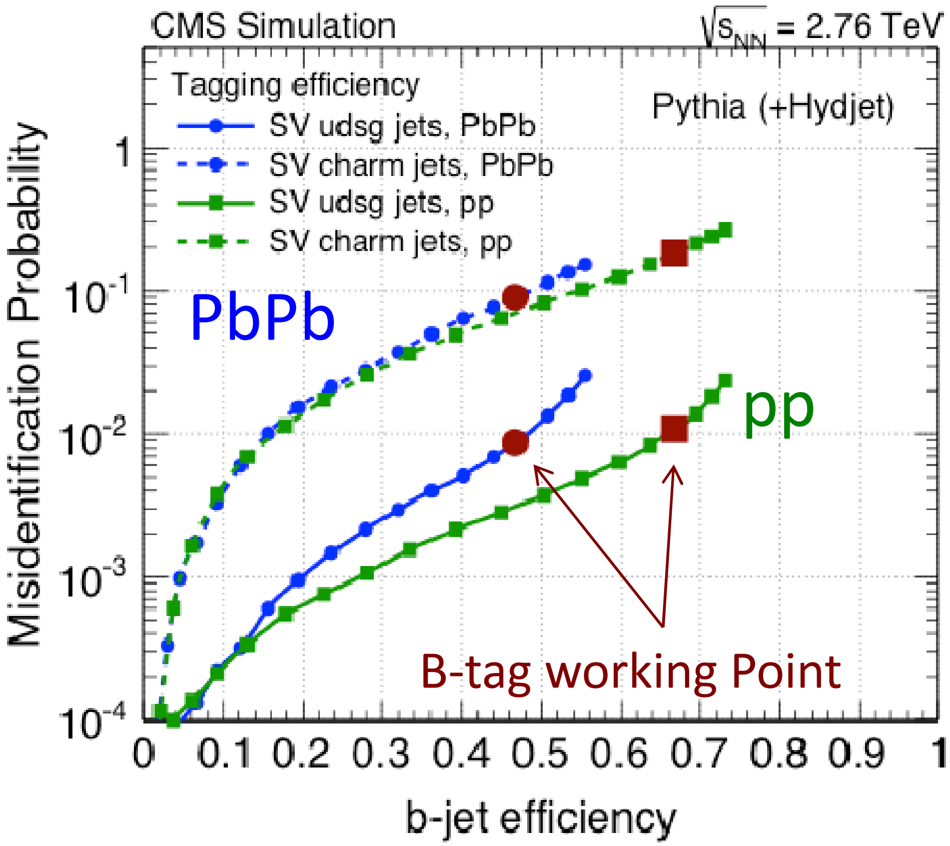
- b-jet efficiency plotted against probability of misidentifying a light/charm jet as a b-jet using secondary vertex tagger
- pPb and pp have identical reconstruction procedures ➔ very similar tagging performance

CMS PAS HIN-12-003

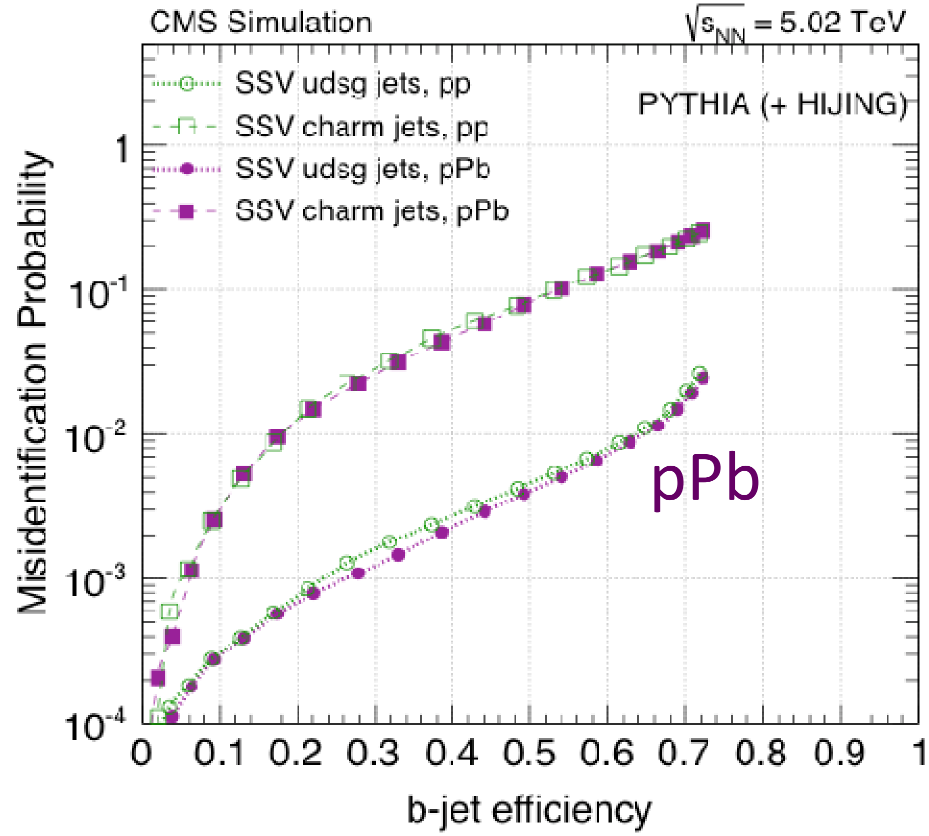
CMS PAS HIN-14-007

Tagging Performance in Simulation

Performance in PbPb



Performance in pPb

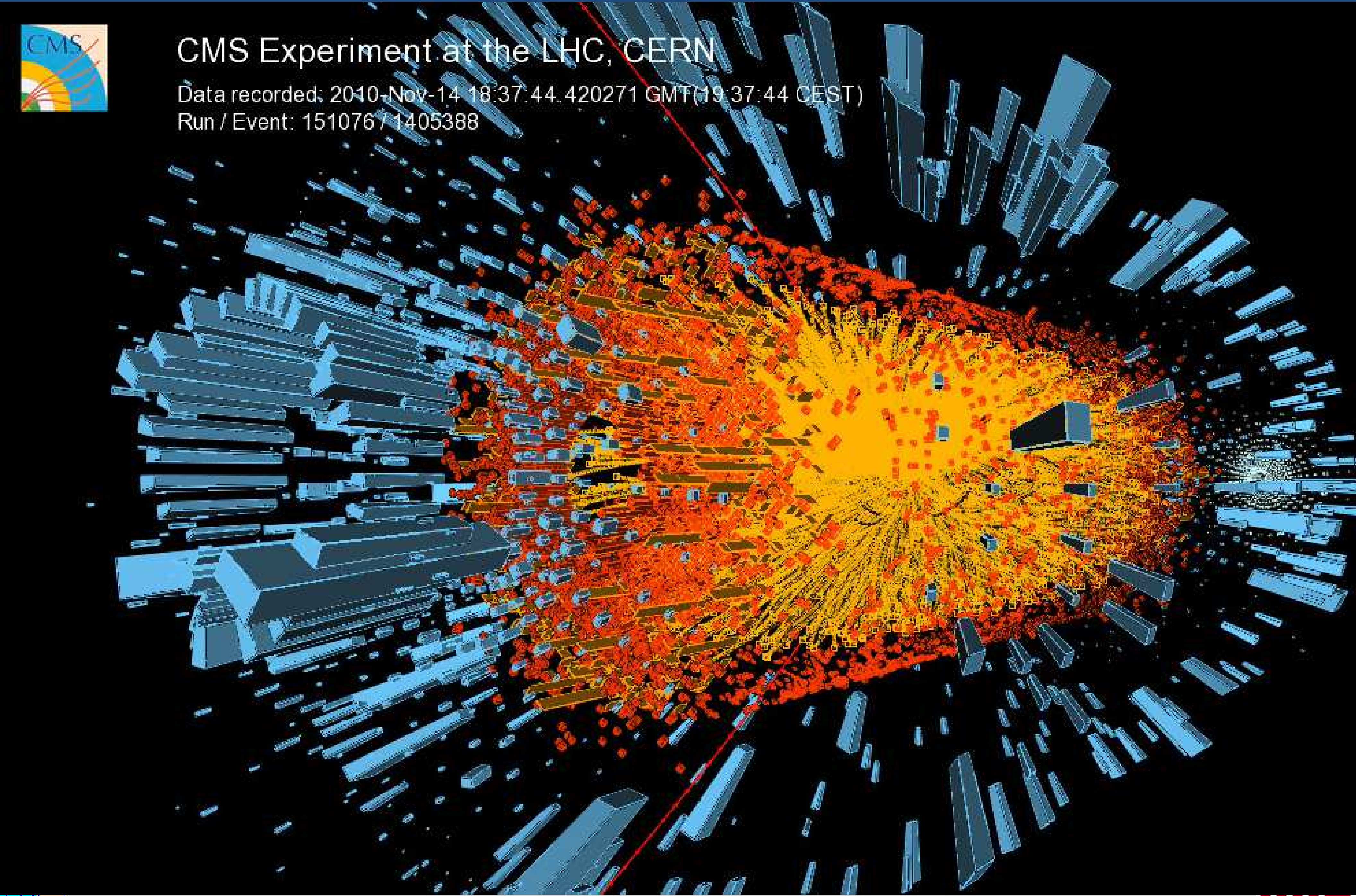


- b-jet tagging working point: reject 99% of the light jet rejection and 90% of the charm jet

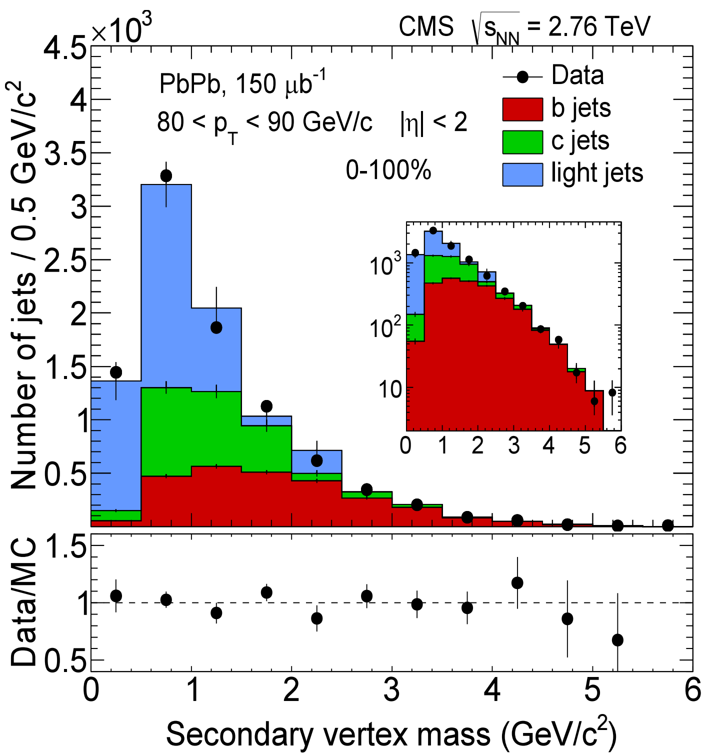
CMS PAS HIN-12-003

CMS PAS HIN-14-007

Heavy Ion Collision Recorded by the CMS Detector



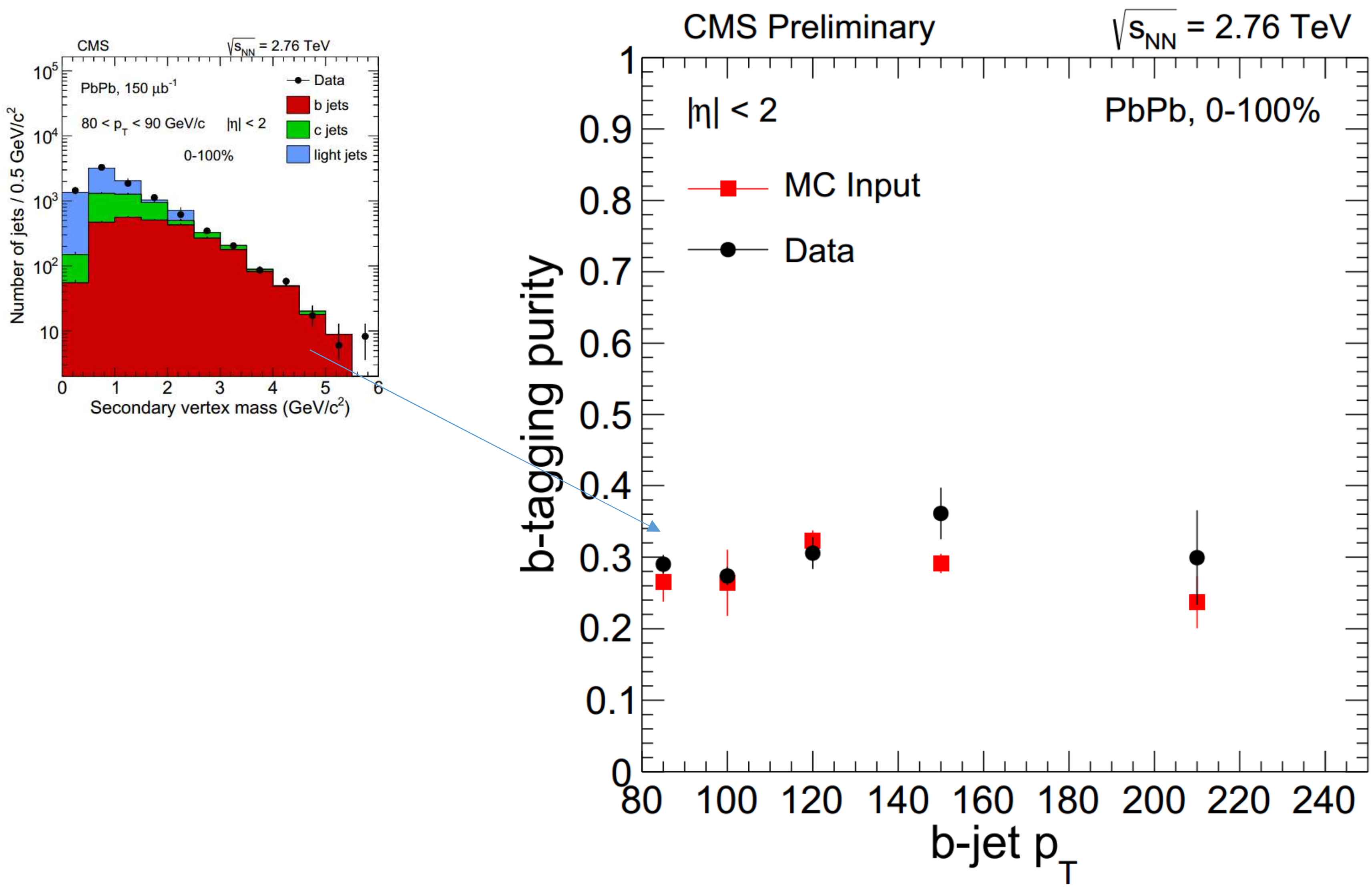
Combinatorial b jets in PbPb?



- Back of the envelope
  - bb x-section, |η|< 2 ≈ 45 μb
  - pp inelastic x-section = 55 mb
  - For n_{part} = 1000, O(1) b jet/evt
  - ~ 1% overlap prob. for ΔR < 0.3
  - Comparable to b jet rate!

- The real rate much smaller as UE b's are much softer
- Pythia+Hydet: 2% of tagged jets in 0-20% match to UE b
- Flavor matched to Pythia signal event only → combinatorial jets are INCLUDED in the light jet template (as they should)

b-jet Purity vs. b-jet Transverse Momentum



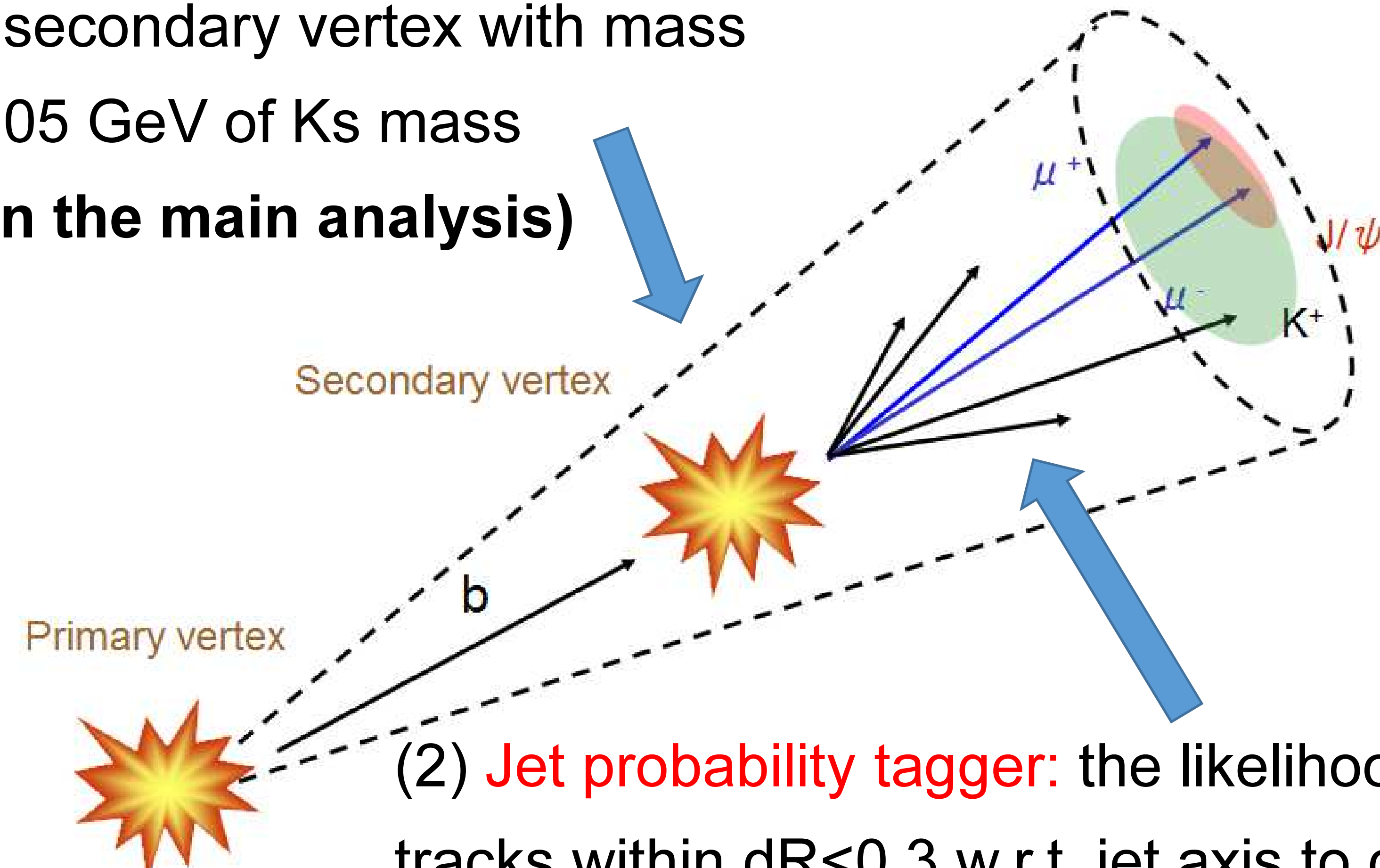
- Good agreement between data and MC simulation was observed

b-jet tagging algorithms used in heavy ion collisions

(1) Secondary vertex tagger: use 3D flight distance significance

Veto on secondary vertex with mass within 0.05 GeV of Ks mass

(Used in the main analysis)

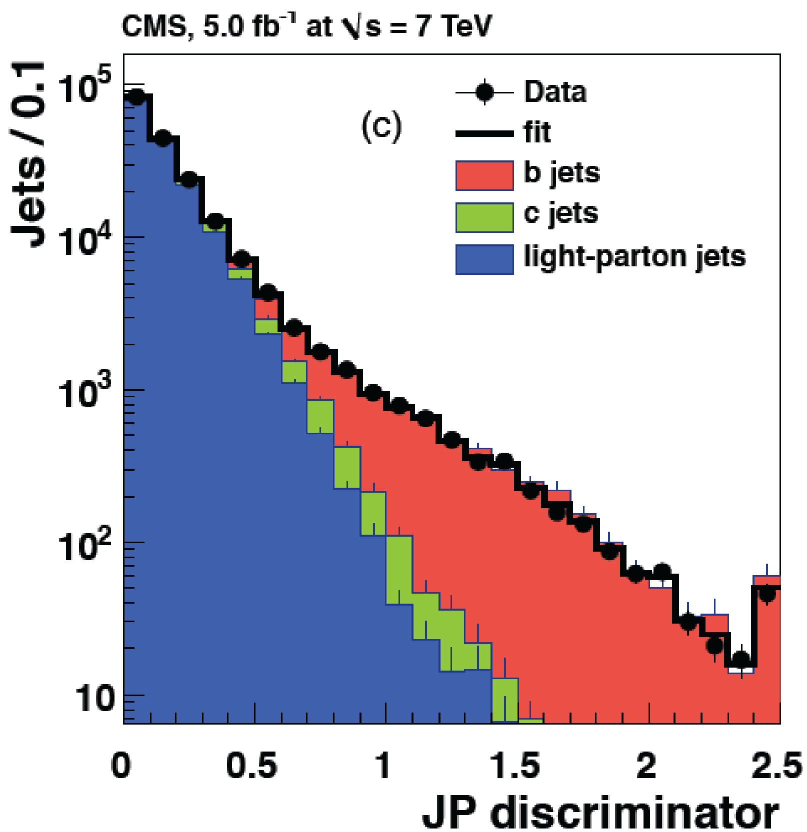


(2) Jet probability tagger: the likelihood of the tracks within dR<0.3 w.r.t. jet axis to come from the **primary vertex** using the impact parameter significance. **(Used as “reference tagger”)**

Data-driven Tagging Efficiency: Reference Tagger Method

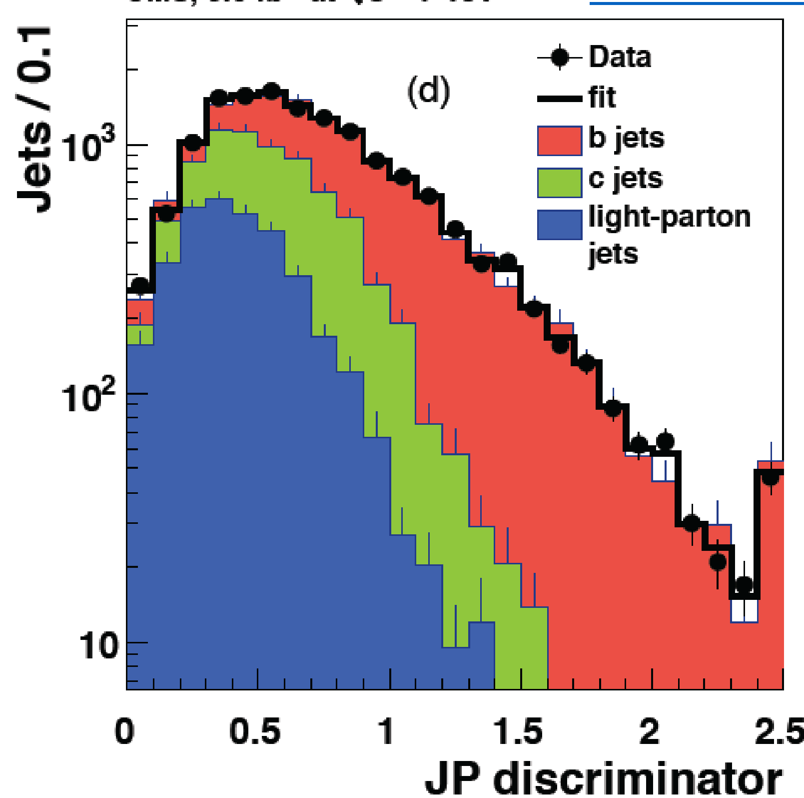
Idea: use a weakly correlated tagger, Jet Probability Tagger (JP), to derive Secondary Vertex (SV) tagging efficiency

Before SV selection



After SV selection

arxiv:1211.4462



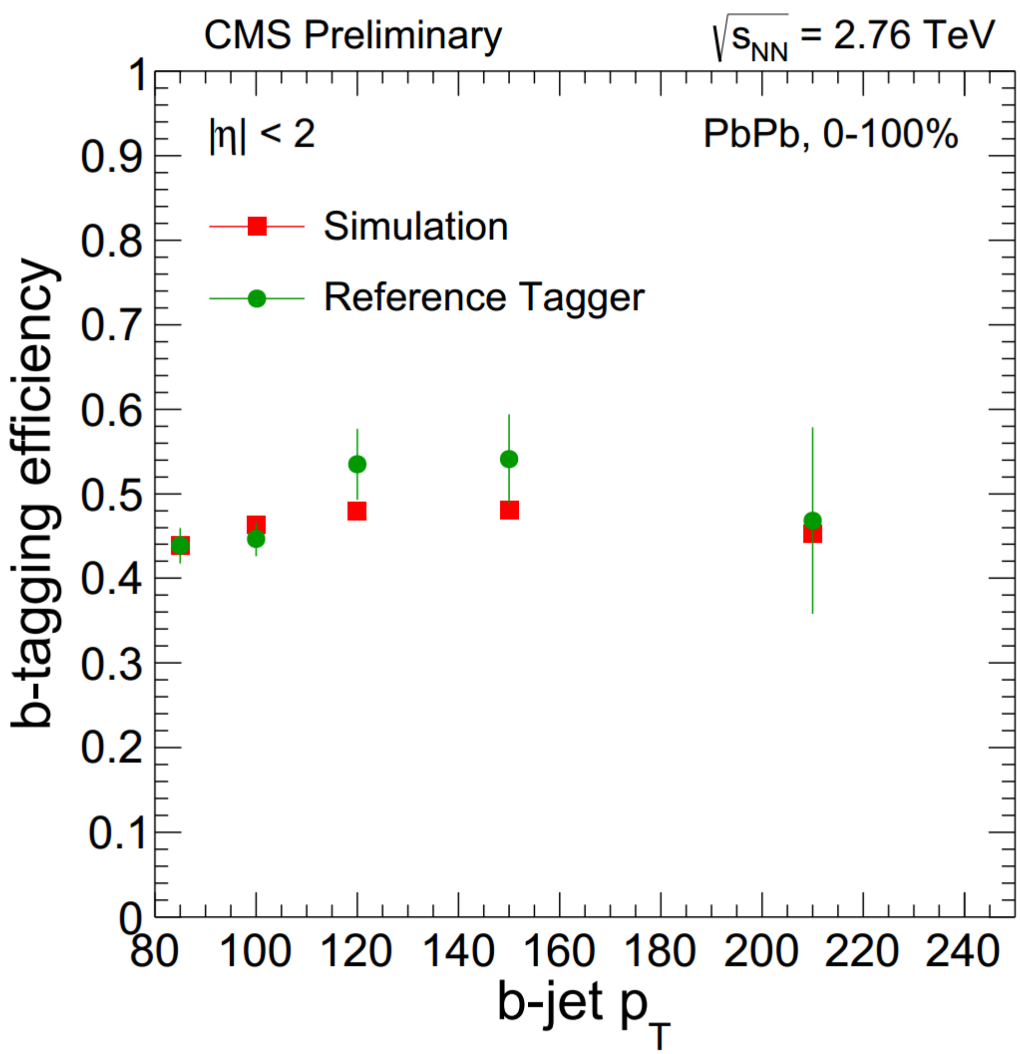
$$\varepsilon_b(\text{data}) = \frac{C_b f_b^{tag} N_{data}^{tag}}{f_b^{notag} N_{data}^{notag}}$$

f_b = purity from template fit

C_b = fraction of jets with Jet Probability Tagger information (~ 98%)

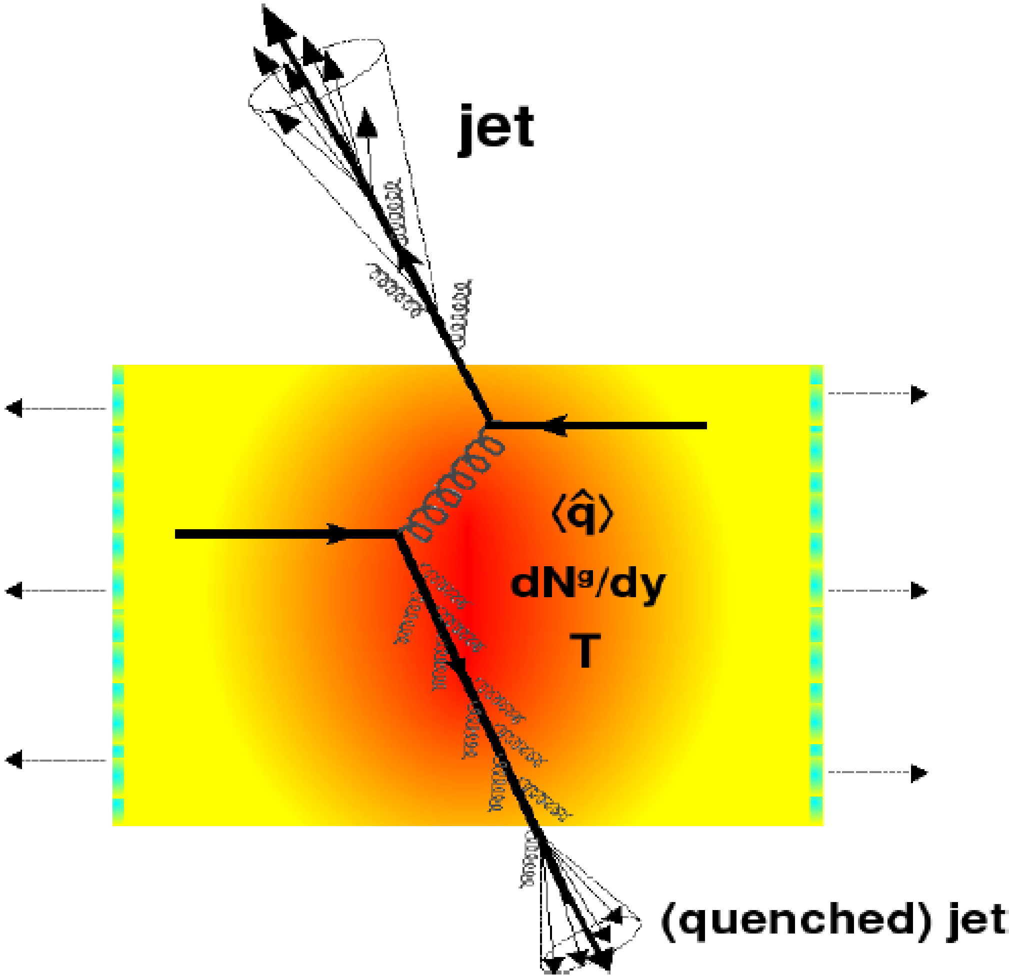
Data-driven b-tagging efficiency

$$\varepsilon_b(\text{data}) = \frac{C_b f_b^{tag} N_{data}^{tag}}{f_b^{notag} N_{data}^{notag}}$$

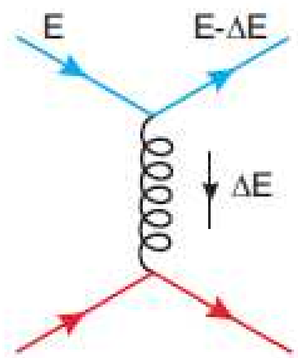


- MC tagging efficiency used as main result
- Good agreement between data-driven and MC efficiencies was observed
- Differences quoted as systematics

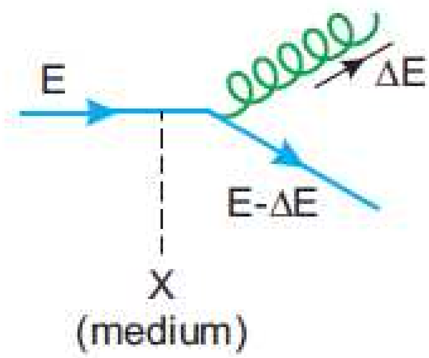
Jet Quenching



Collisional energy loss

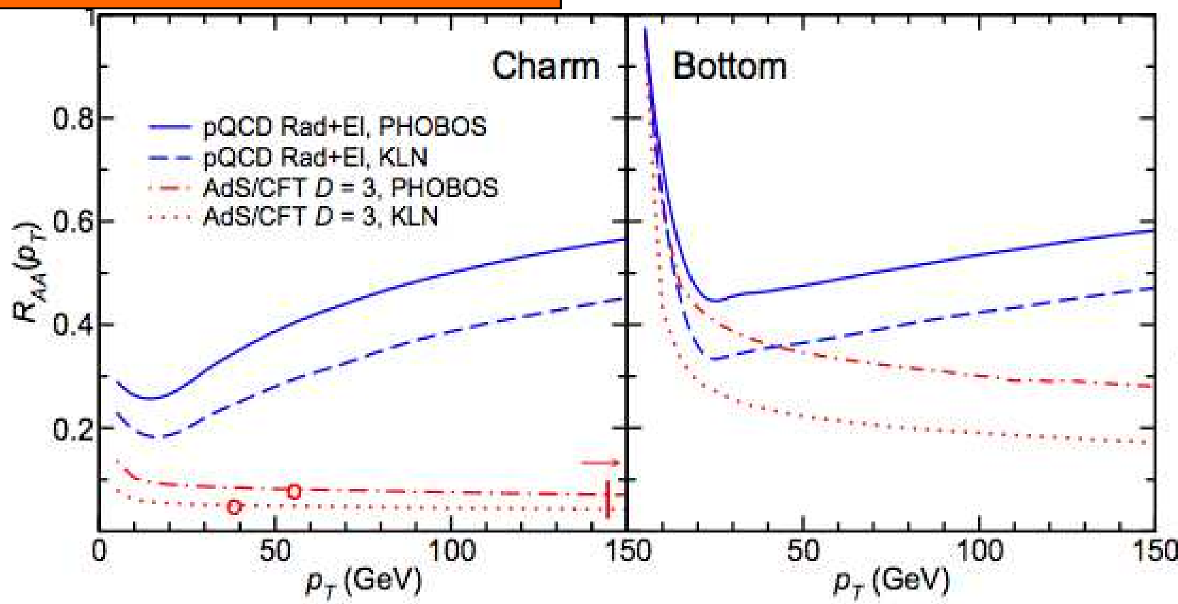


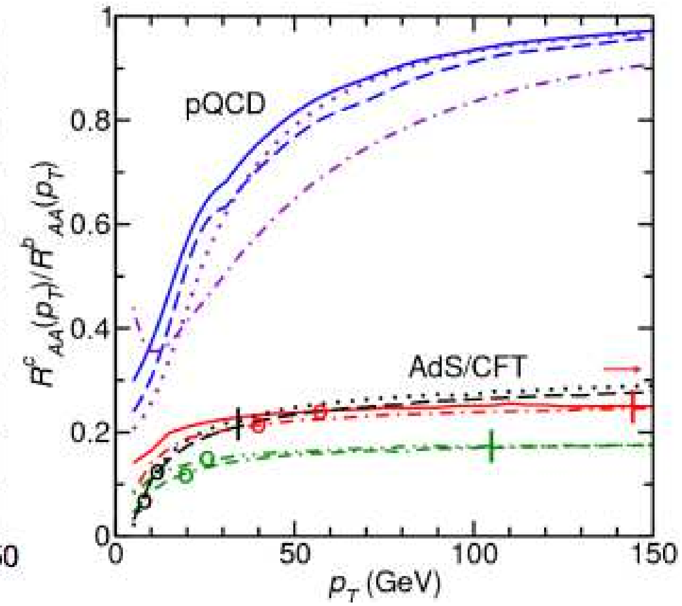
Radiative energy loss



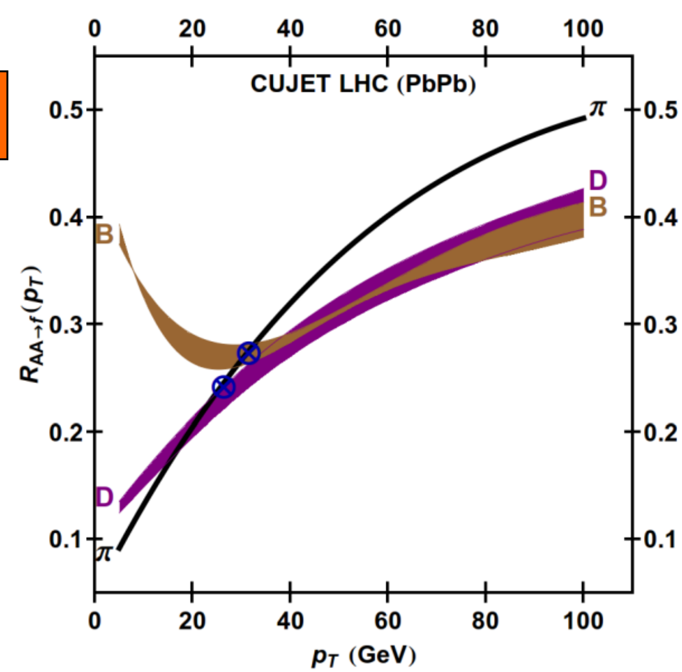
Motivation for Heavy Flavor Studies

J. Phys. G35: 054001 (2008)





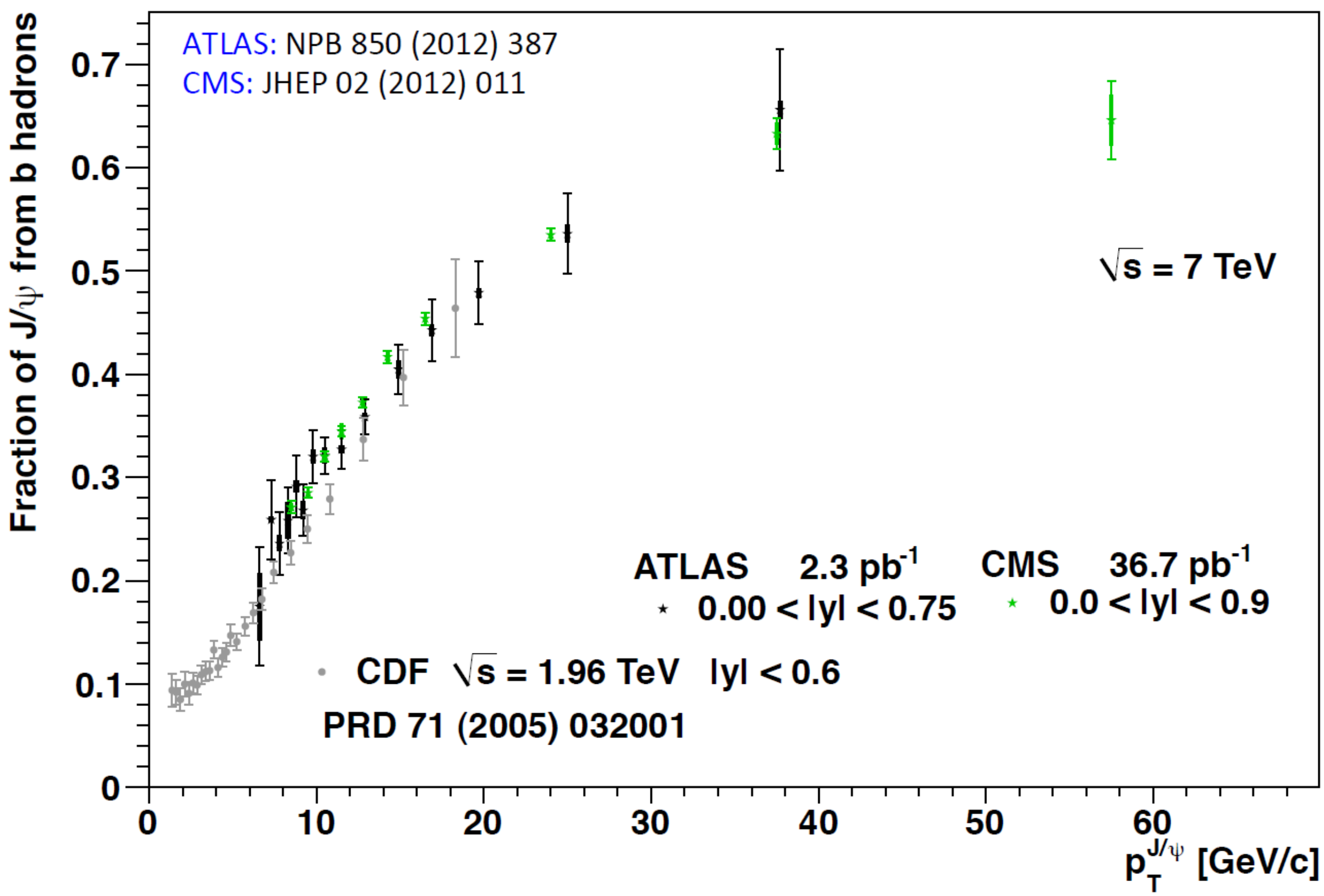
PRL 108, 022301 (2012)

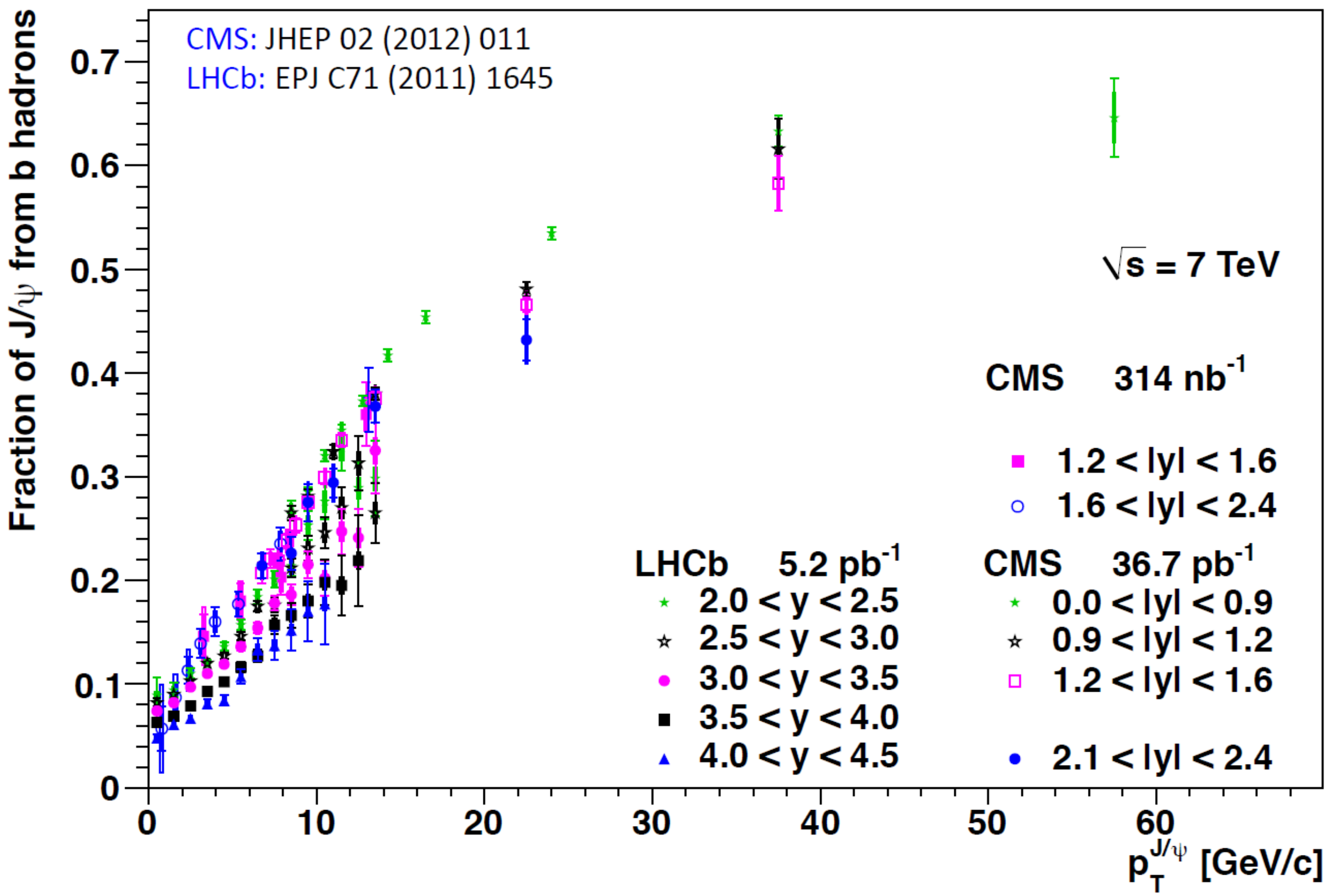


At high p_T:

Very different prediction from pQCD and Ads/CFT (?)

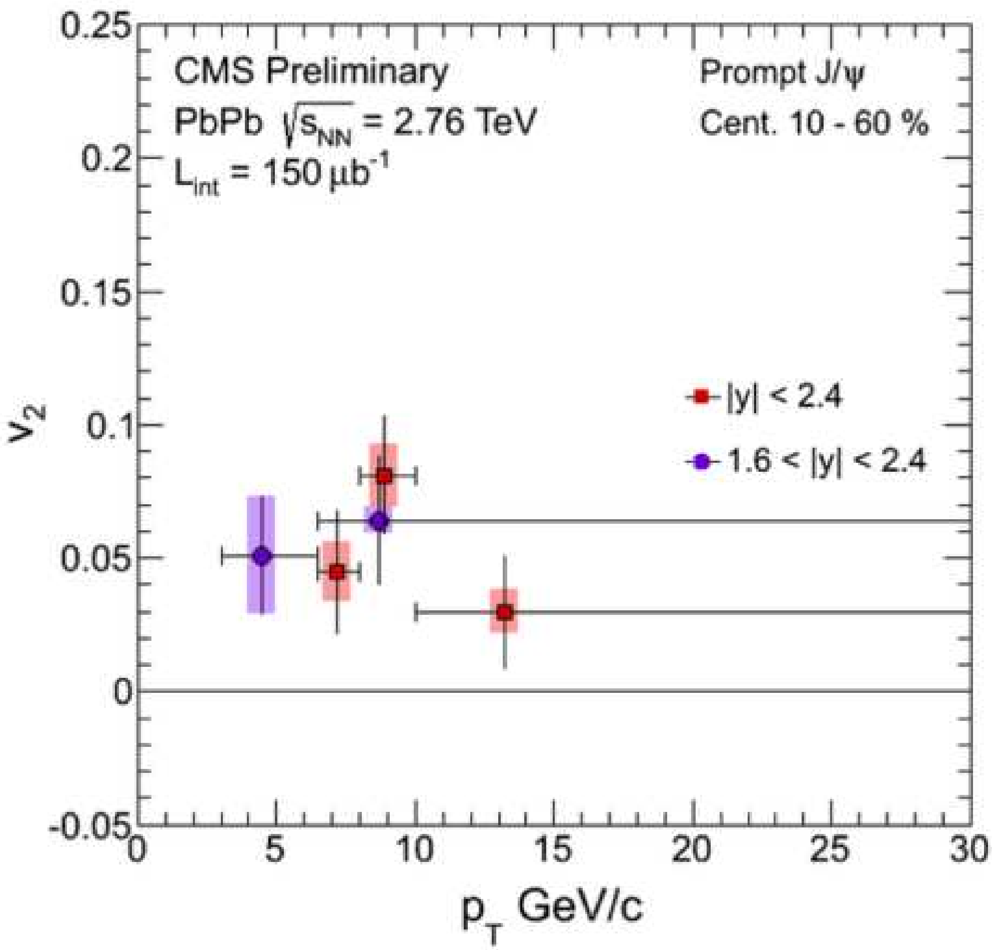
pQCD: Mild difference between light and heavy flavor mesons

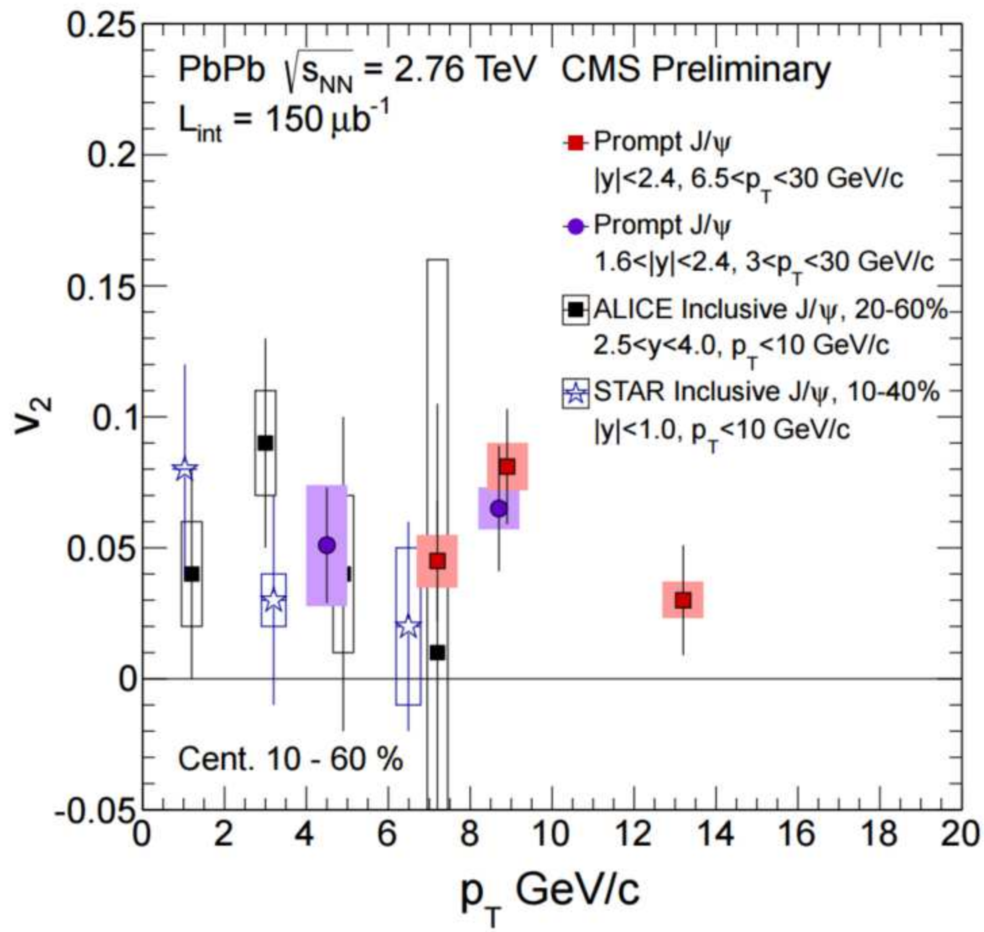

ATLAS: NPB 850 (2012) 387
CMS: JHEP 02 (2012) 011
Fraction of J/ψ from b hadrons
√s = 7 TeV
ATLAS 2.3 pb-1
0.00 < |y| < 0.75
CMS 36.7 pb-1
0.0 < |y| < 0.9
CDF √s = 1.96 TeV |y| < 0.6
PRD 71 (2005) 032001
p_T^{J/ψ} [GeV/c]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
10
20
30
40
50
60


CMS: JHEP 02 (2012) 011
LHCb: EPJ C71 (2011) 1645
Fraction of J/ψ from b hadrons
√s = 7 TeV
CMS 314 nb⁻¹
1.2 < |y| < 1.6
1.6 < |y| < 2.4
LHCb 5.2 pb⁻¹
2.0 < y < 2.5
2.5 < y < 3.0
3.0 < y < 3.5
3.5 < y < 4.0
4.0 < y < 4.5
CMS 36.7 pb⁻¹
0.0 < |y| < 0.9
0.9 < |y| < 1.2
1.2 < |y| < 1.6
2.1 < |y| < 2.4
p_T^{J/ψ} [GeV/c]

J/ψ v_2 vs. transverse momentum

PRL 109 (2012) 222301

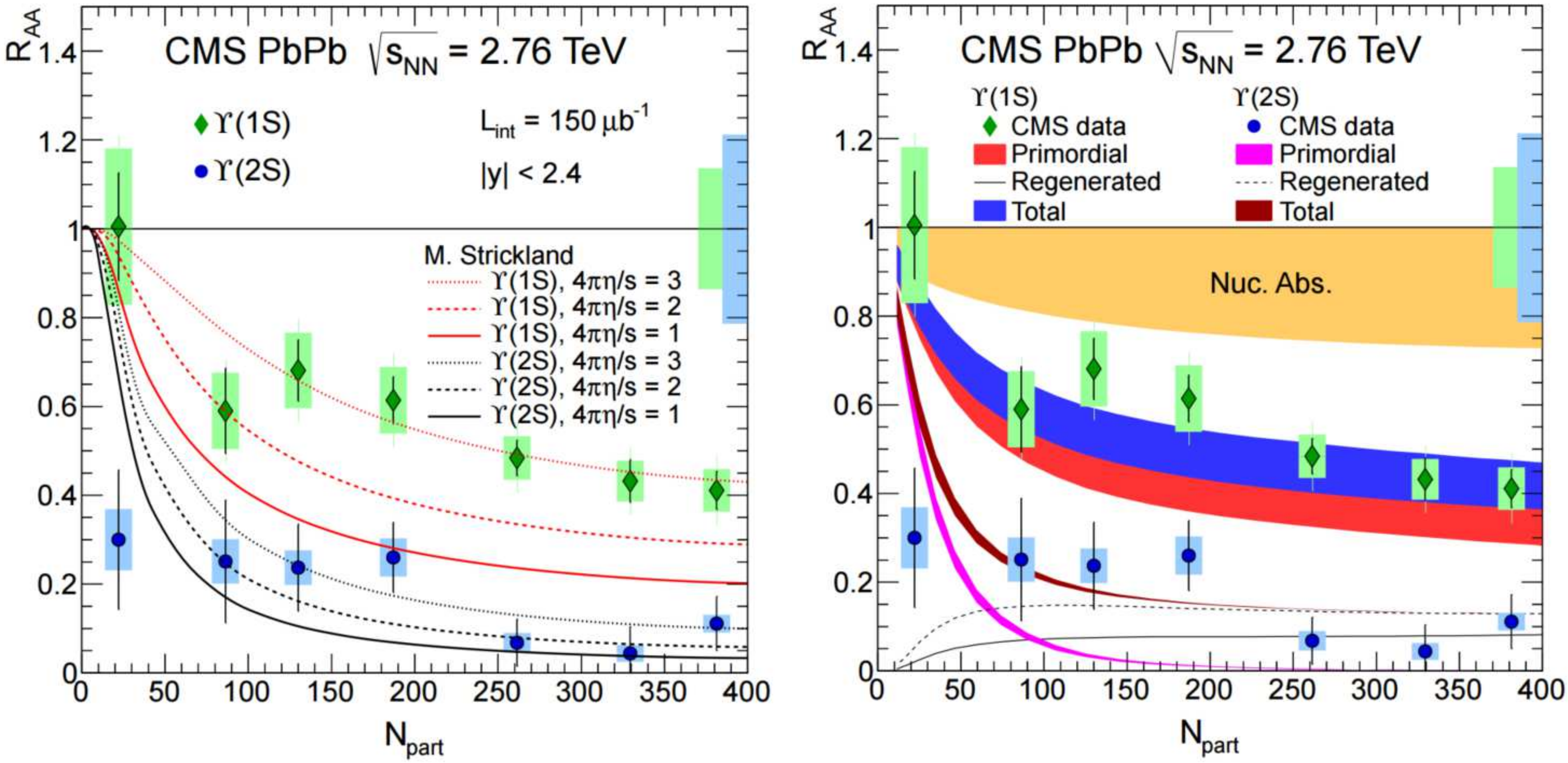




CMS PAS HIN-12-001

Upsilons in PbPb collisions

PRL 109 (2012) 222301

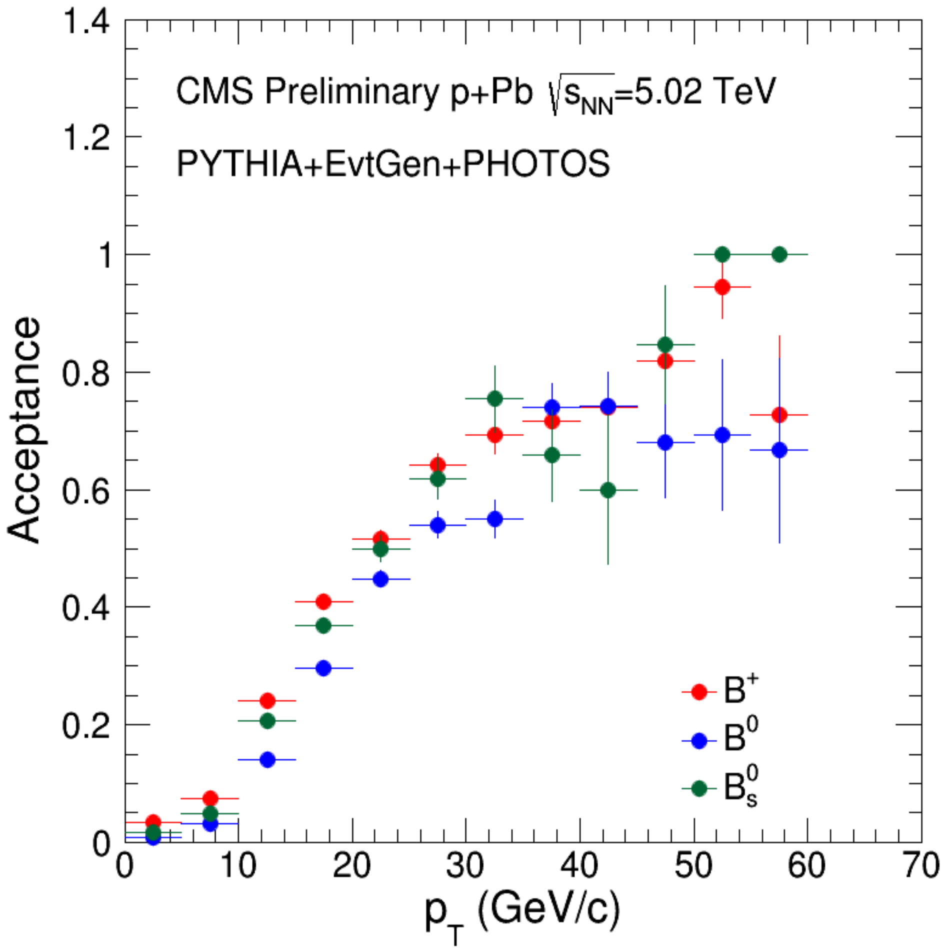


B meson production in pPb collisions

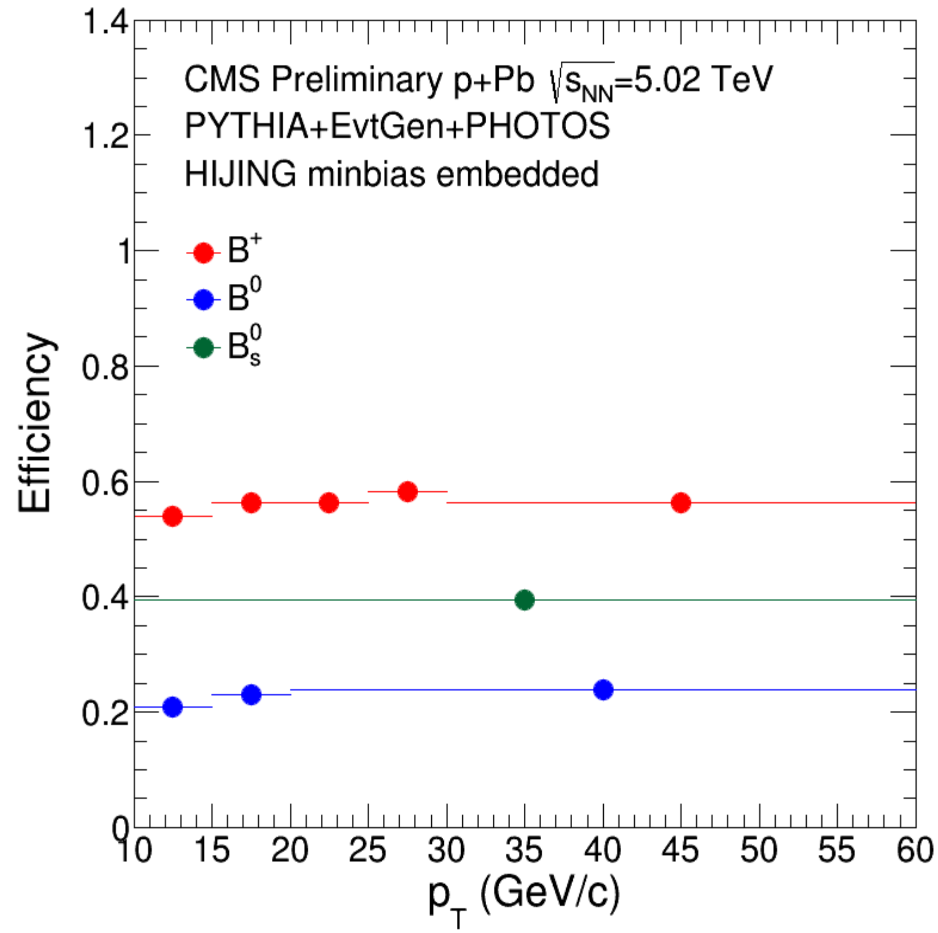
CMS PAS HIN-14-004

- Raw yields are corrected by acceptance and efficiency

Acceptance



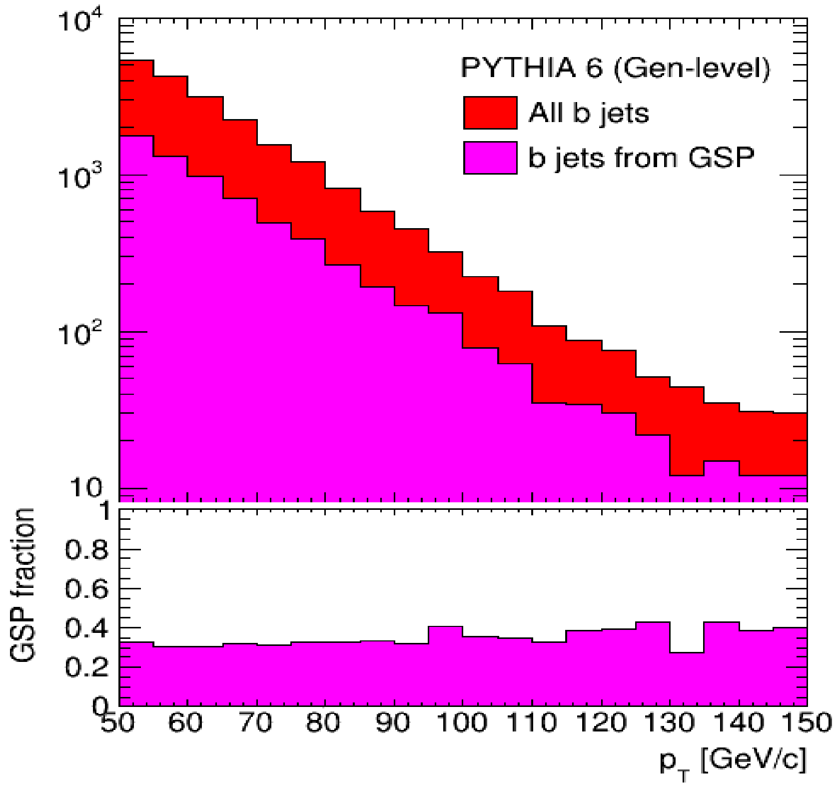
Efficiency



Gluon Splitting Contribution

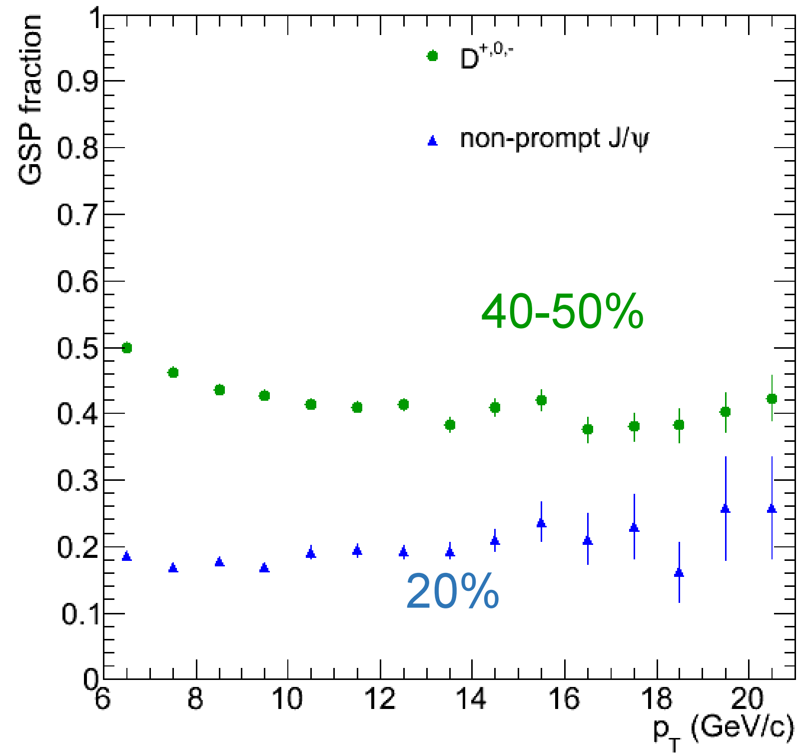
- HF studies: matched partons are not necessary heavy quarks!

b jets



30-40%

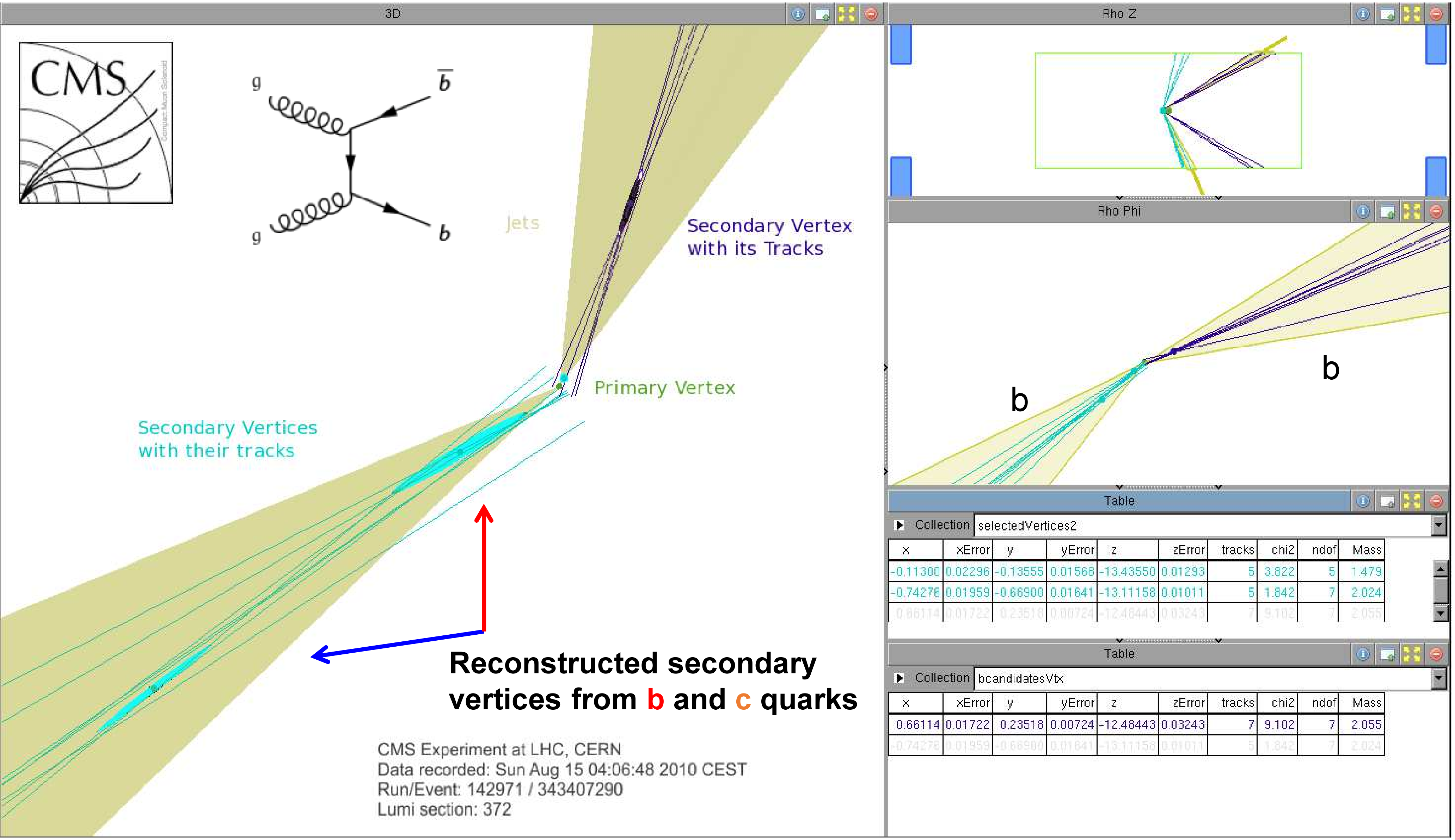
D mesons, non-prompt J/ψ



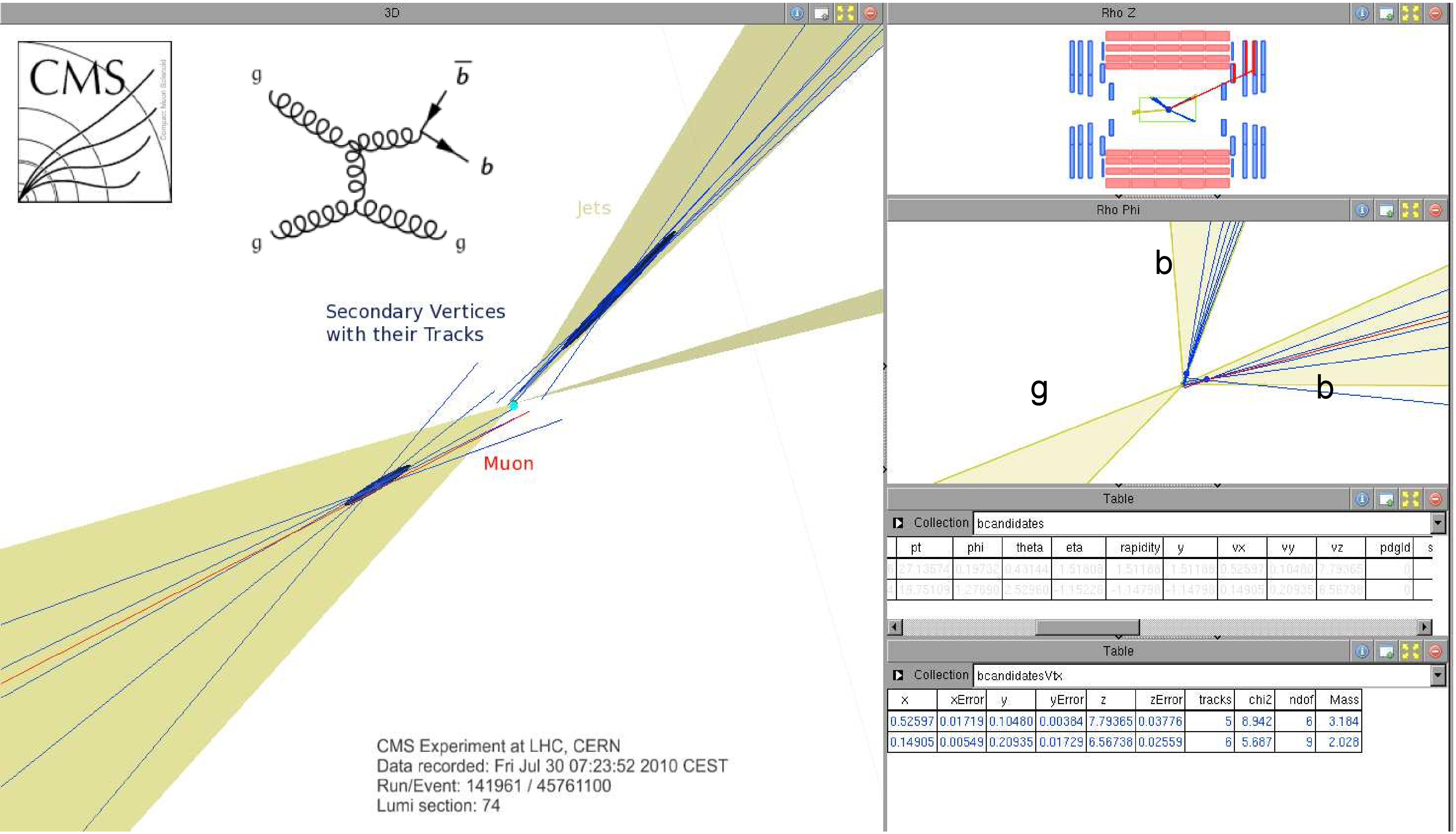
PYTHIA 6
(From Matthew Nguyen)

- **Non-negligible for both jets and hadrons.**
- Even more important for charm than for bottom at LHC energy!

Flavor Creation Candidate (pp @ 7 TeV)

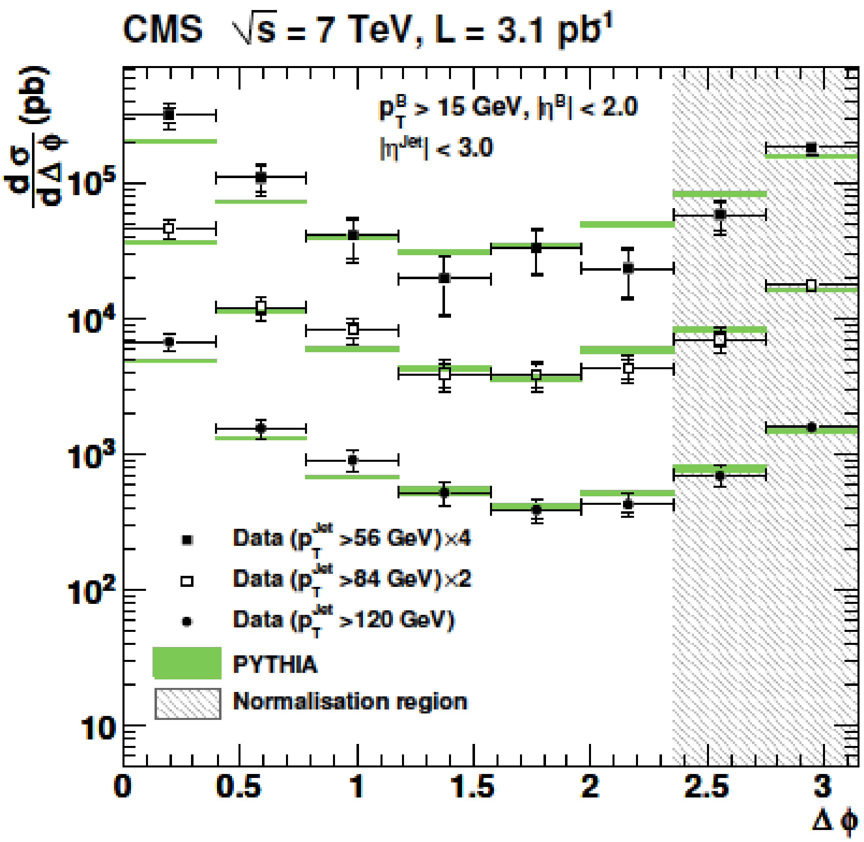


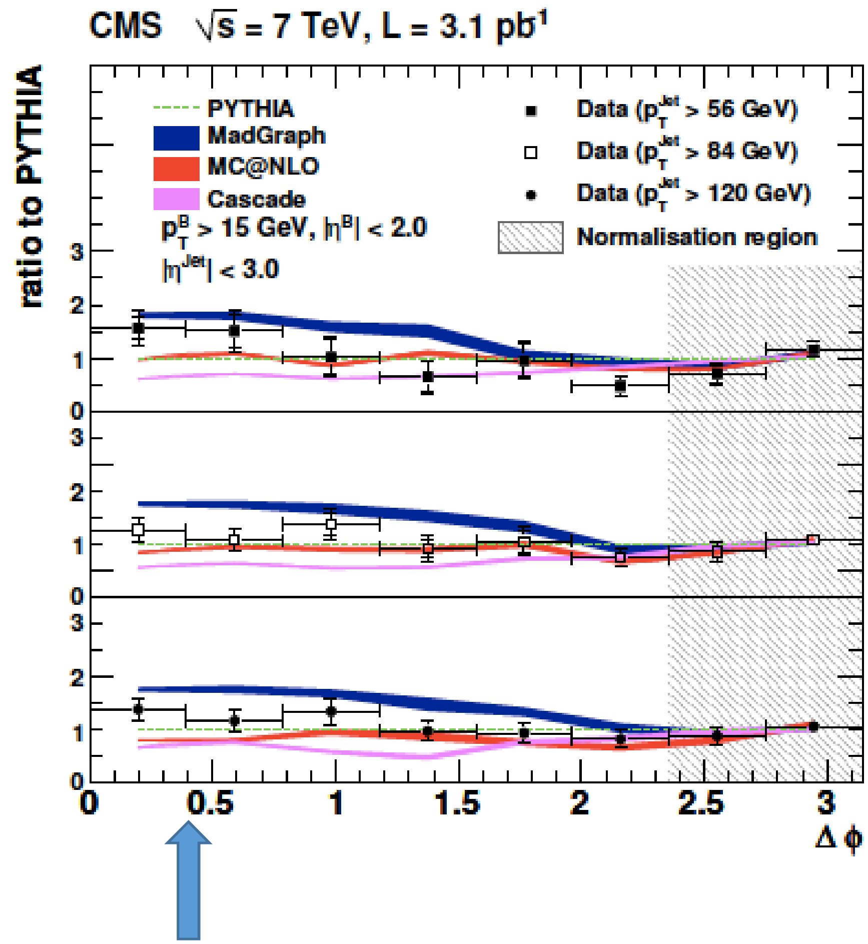
Gluon Splitting Candidate (pp @ 7 TeV)



B-Bbar Angular Correlations in pp

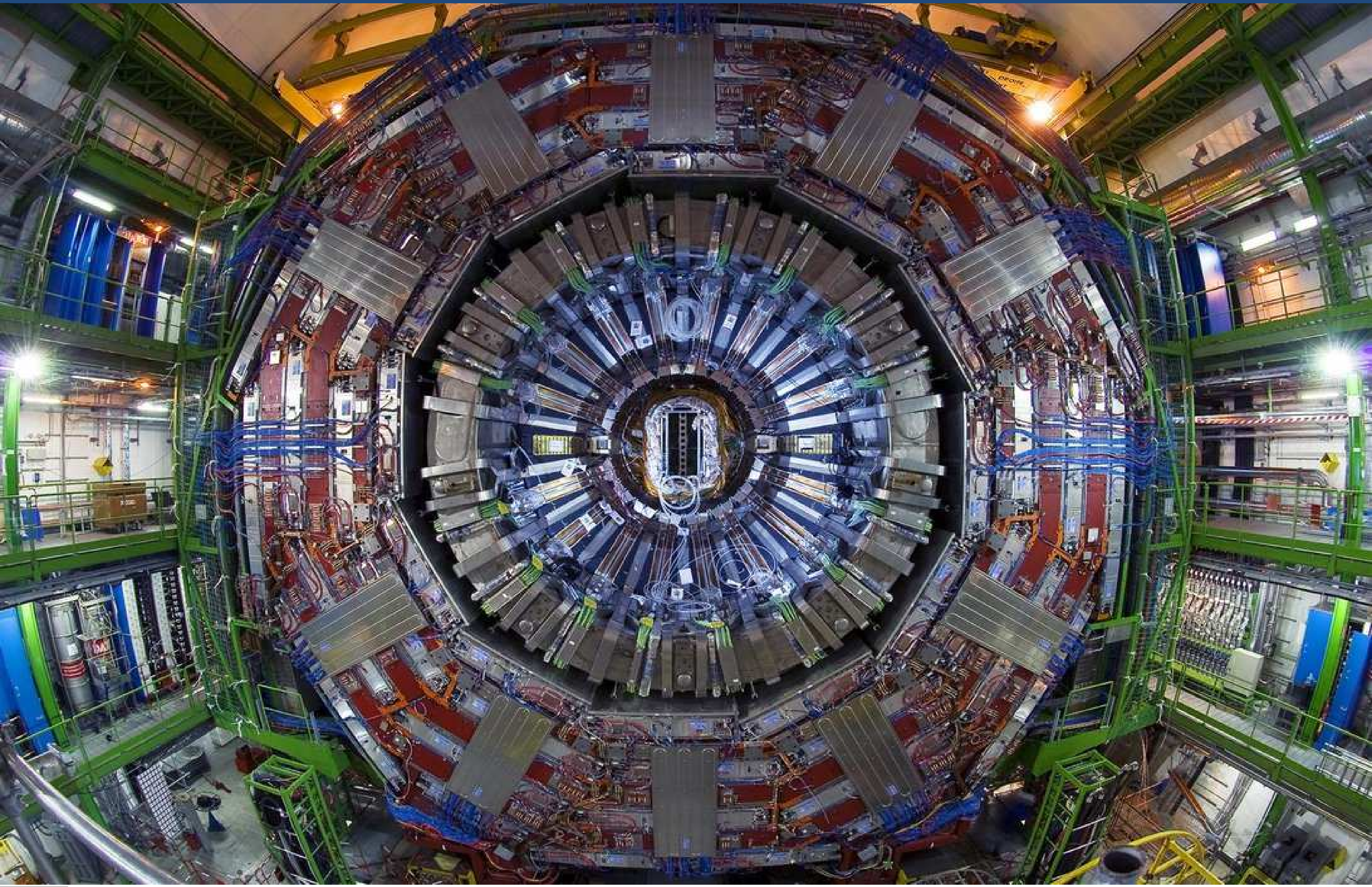
JHEP 1103 (2011) 136





- Angular correlations of di-b-jets sensitive to GSP contribution
- "Inclusive vertex finder" adept at separating nearby b vertices
- Most generators (including PYTHIA) under predict small angle jet rate

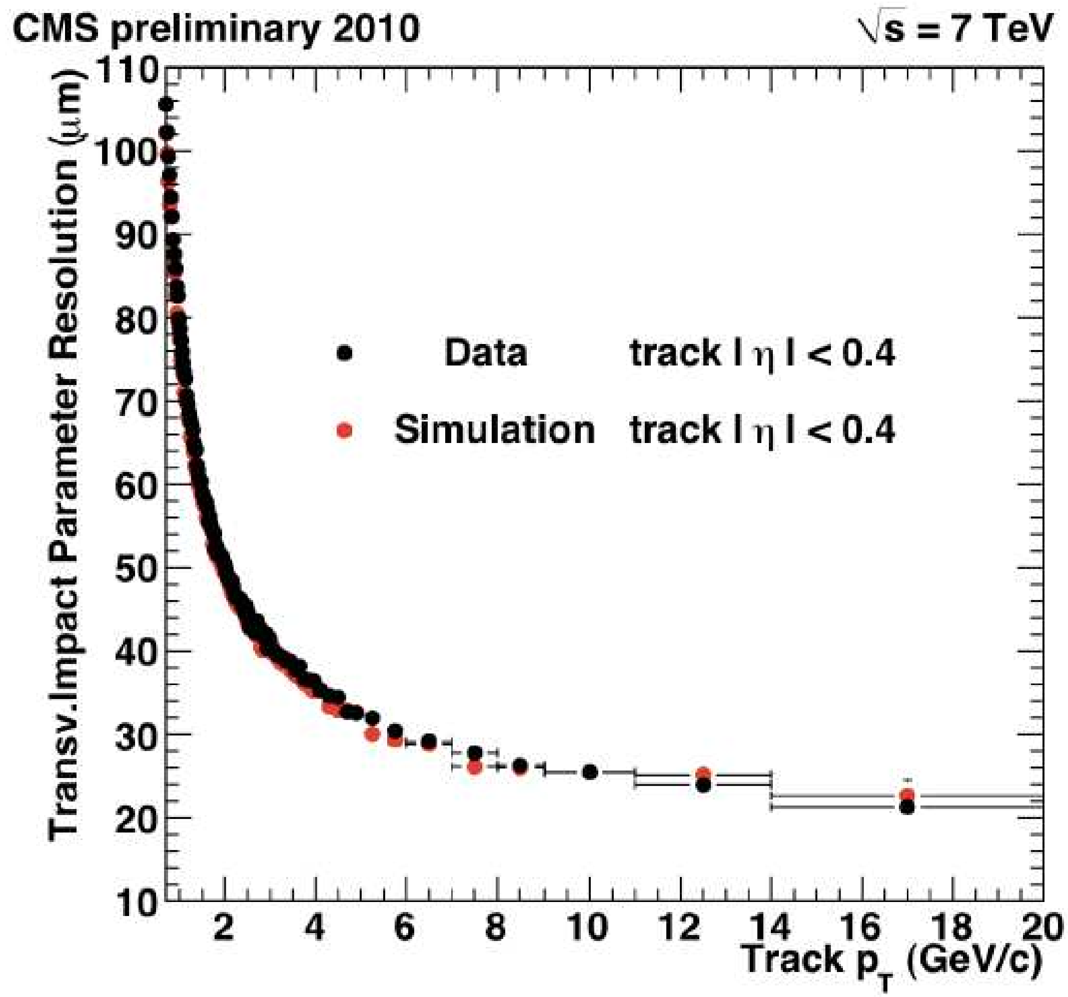
CMS Detector



CMS Track Impact Parameter (IP) Resolution

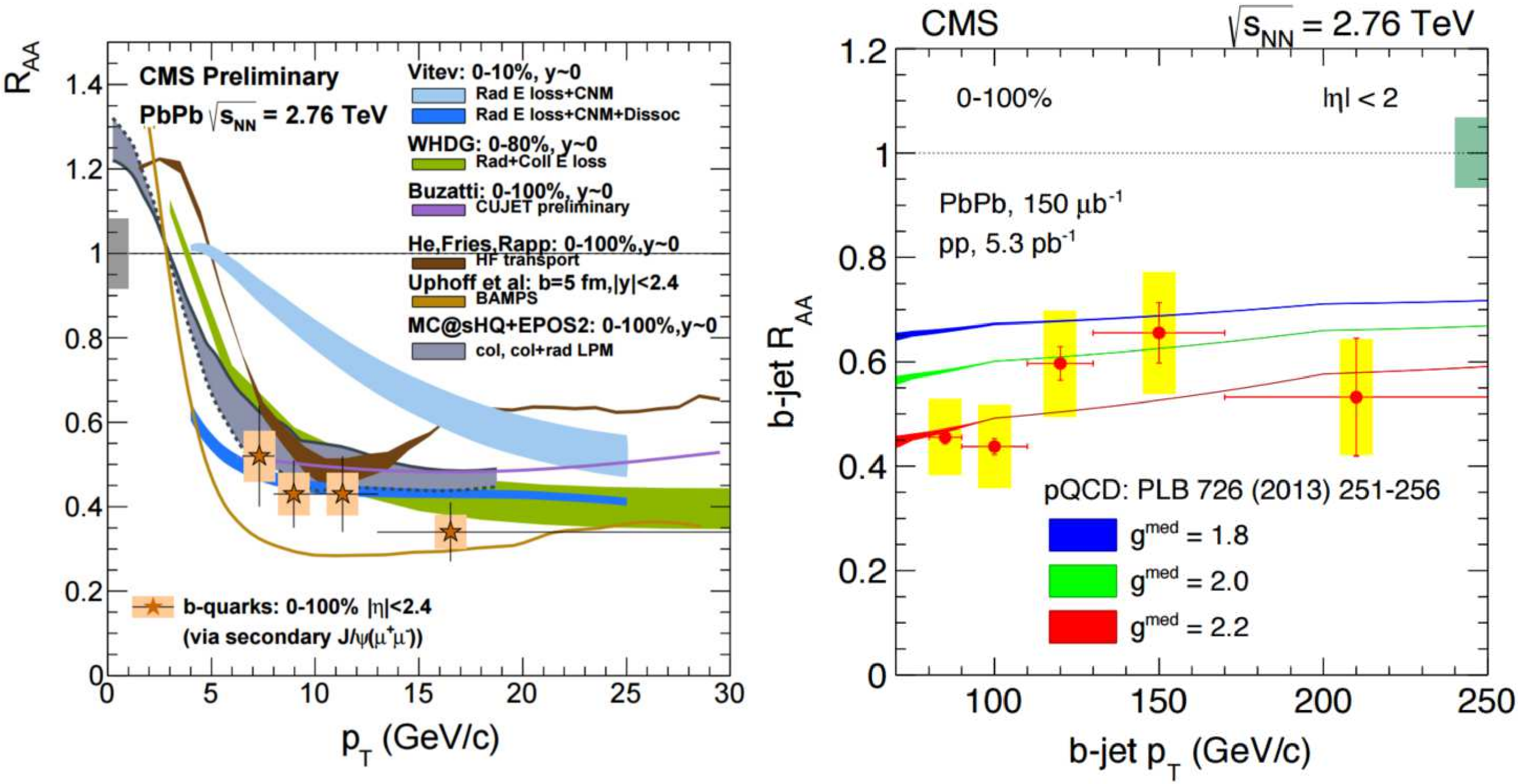
CMS-PAS-TRK-10-005

- Excellent pixel spatial resolution in both rφ and z directions
- Track impact parameter resolution
  - 100 (20) μm @ 1 (20) GeV/c
- Accurate GEANT simulation



~ 15-20 μm (rφ and z) at high p_T

Data meets theory

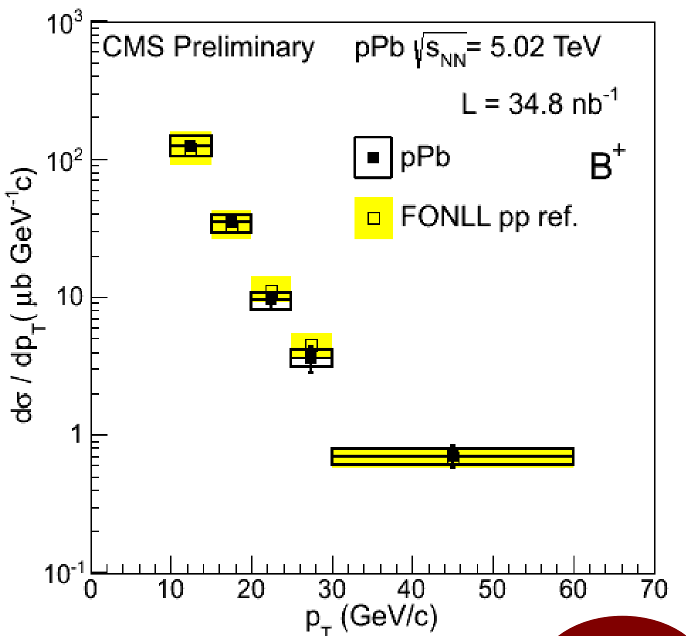


Differential Cross-section

$$\left.\frac{d\sigma^{B}}{dp_T}\right|_{|y_{CM}|<1.93} = \frac{1}{2}\frac{1}{\Delta y\,\Delta p_T}\frac{\left.N^{B}\right|_{|y_{CM}|<1.93}}{(\mathrm{Acc}\times\epsilon)\cdot \mathrm{BR}\cdot L_{\mathrm{int}}}.$$

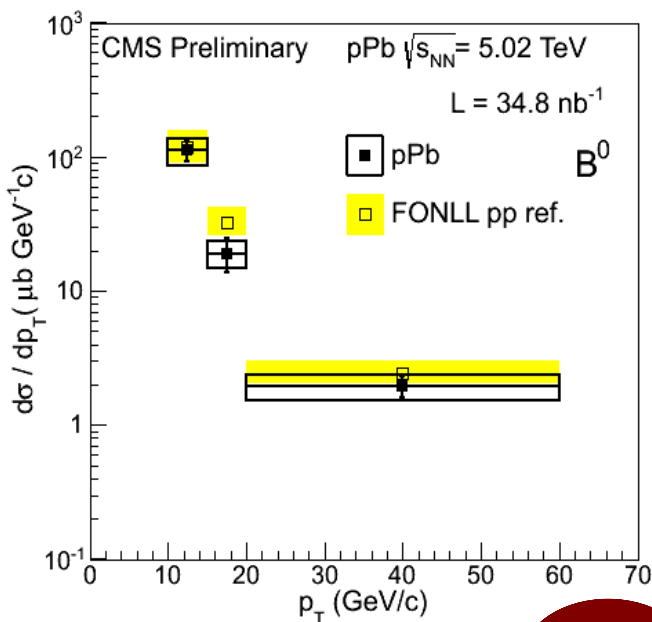
- pp reference : FONLL calculation is used
  - (agreement with CDF, ATLAS and CMS data)

http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html



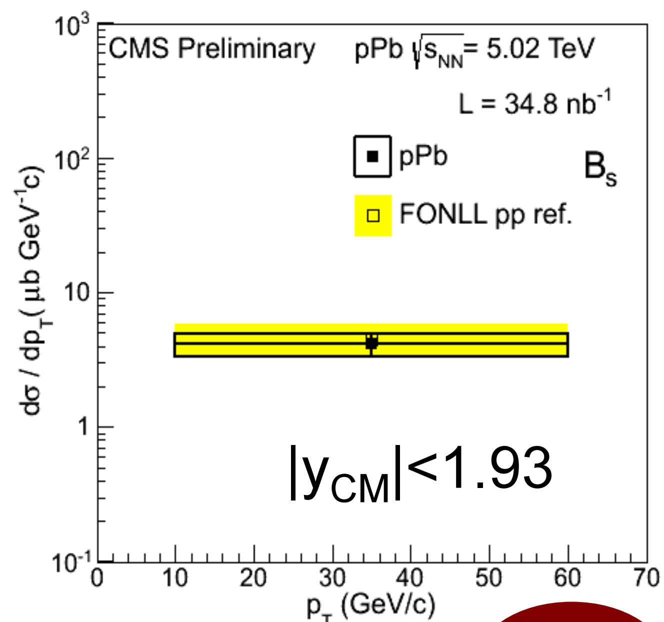
$B^+ \rightarrow J/\psi K^+$

B^+



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

B^0



$B_s \rightarrow J/\psi\varphi$

B_s^0