Thoughts on HF measurements and flavor dependence of jet quenching

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HI Physics in the 2020's

MIT, Cambridge, USA

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Major issues related to HF meson

- Heavy quark production cross-section
- The role of shadowing
- Hardronization mechanism
- Collisional energy loss vs. radiative energy loss
- Could we see the flavor dependence of Eloss?

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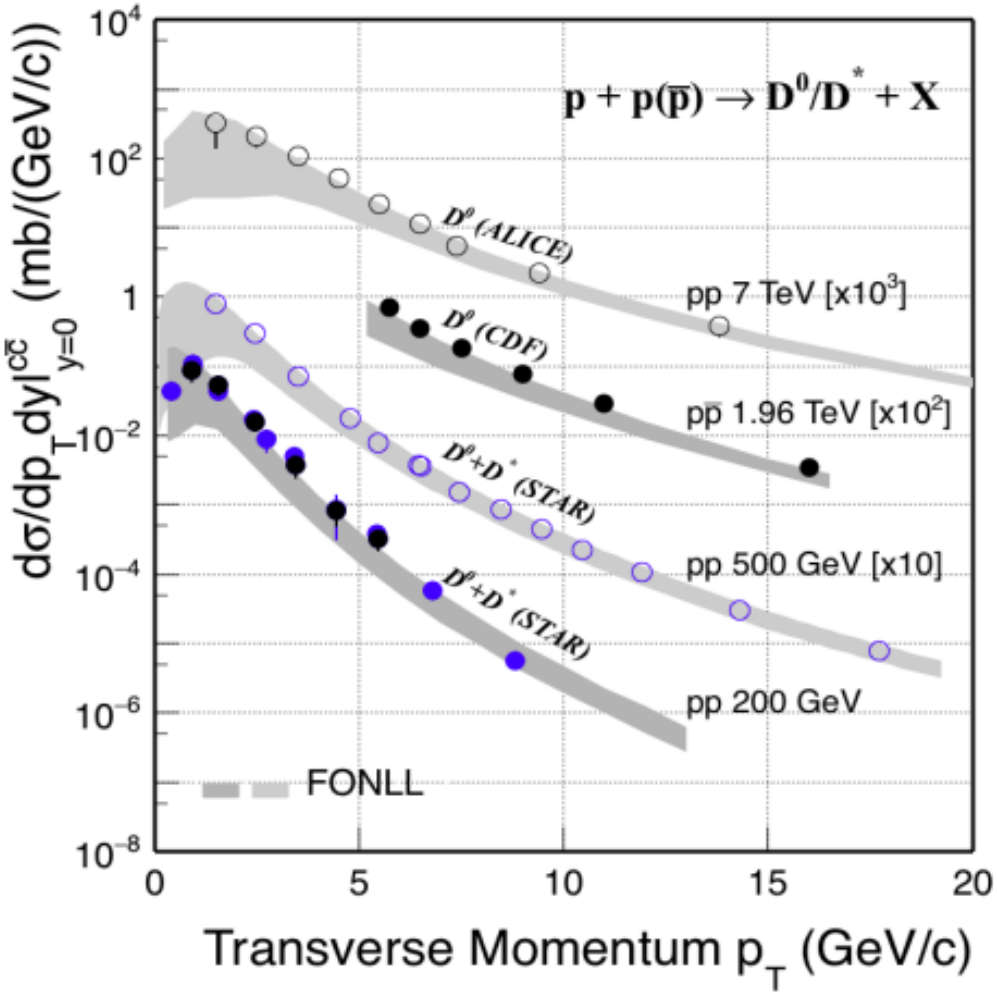
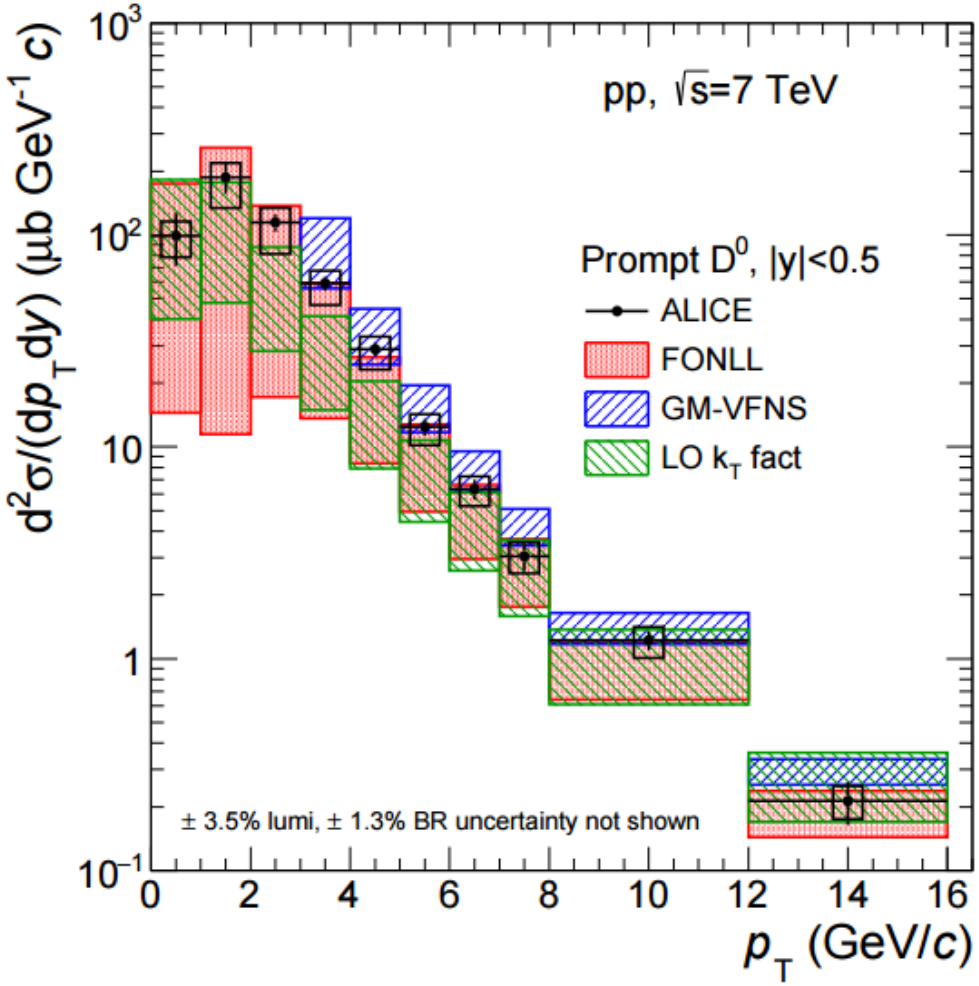
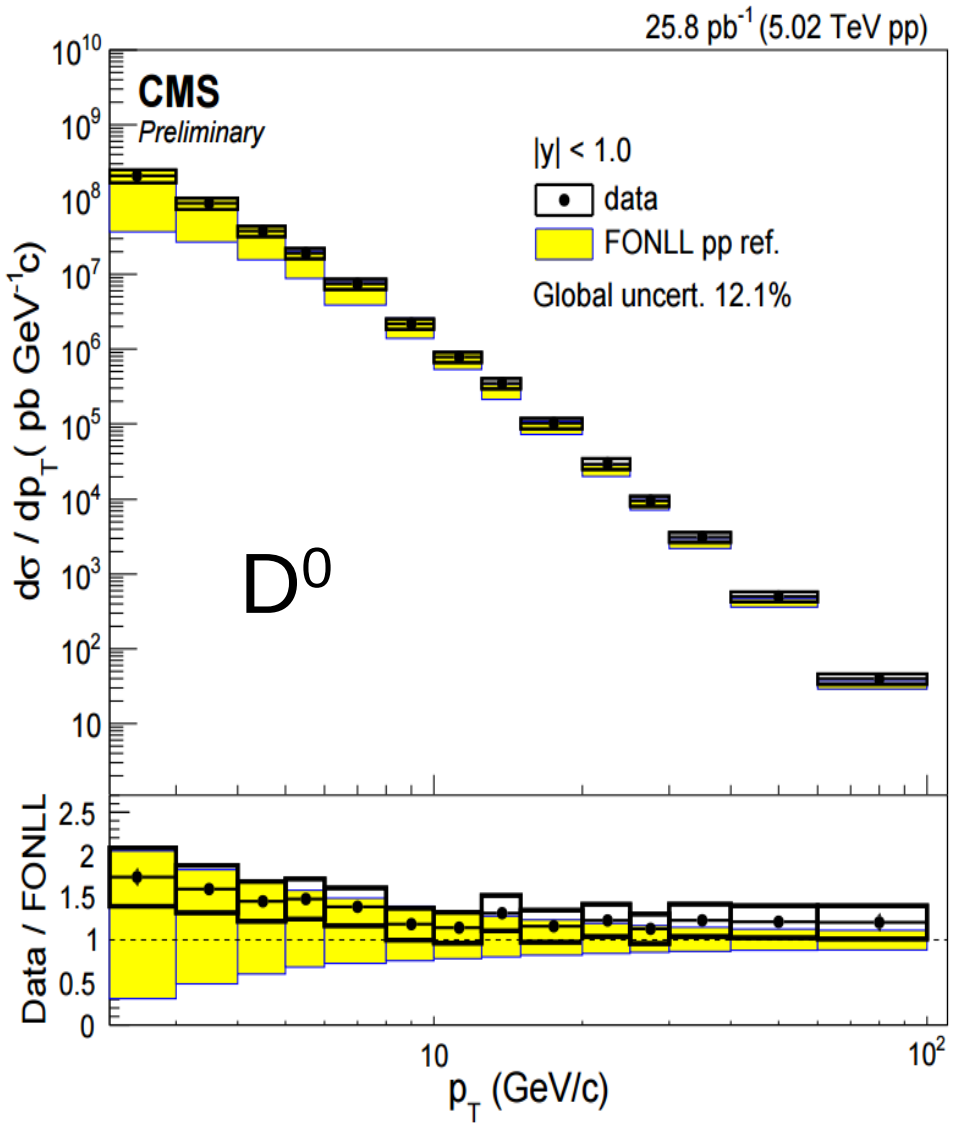
D meson measurement at low p_T

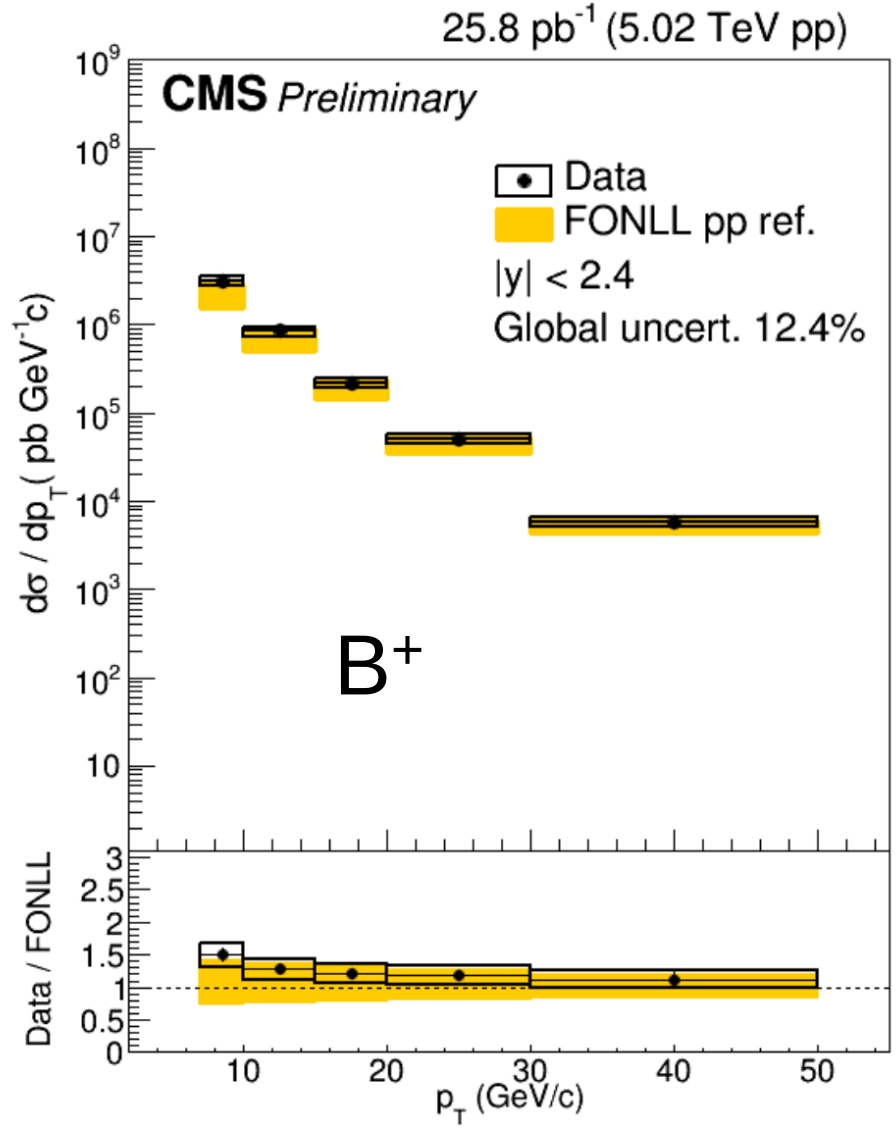




Calculations are in agreement with FONLL calculations
However, the theoretical uncertainty at low pT is very large (up to 50%)

D^0 and B^+ meson in pp





What is really used in the models are the c quark or b quark p_T spectra...

Motivates D meson and B meson jet fragmentation function measurements to validate our understanding

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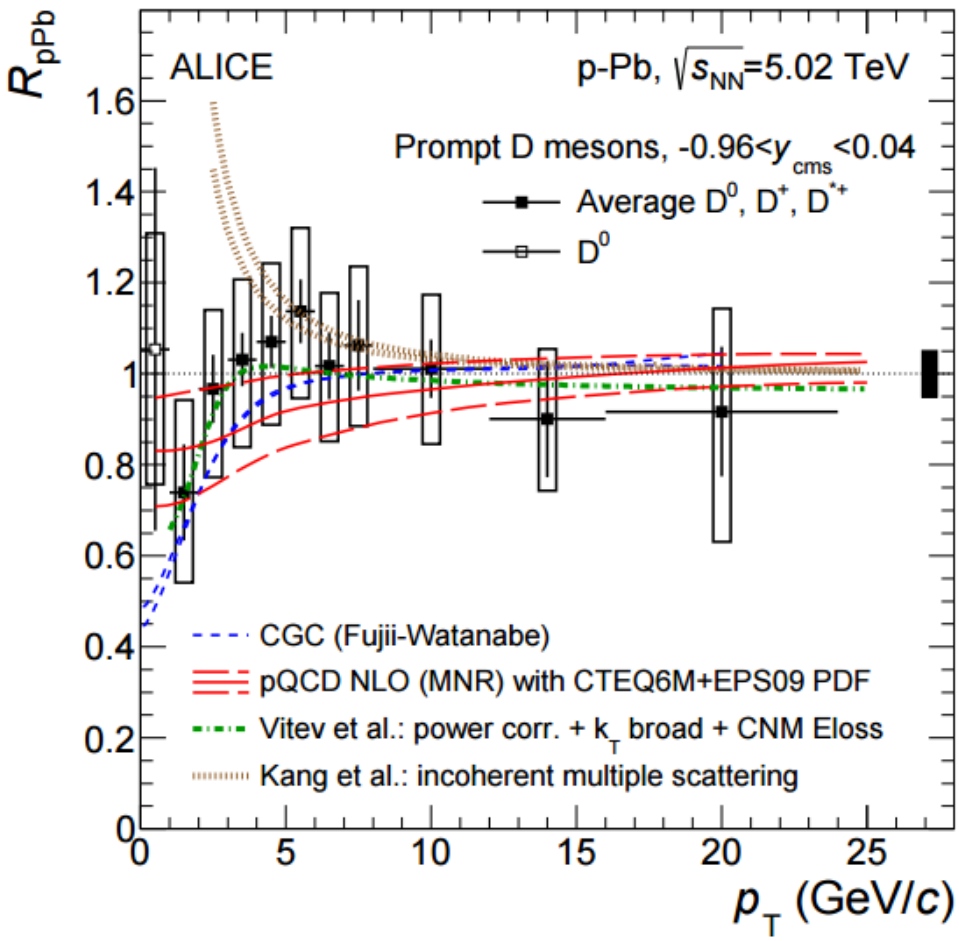
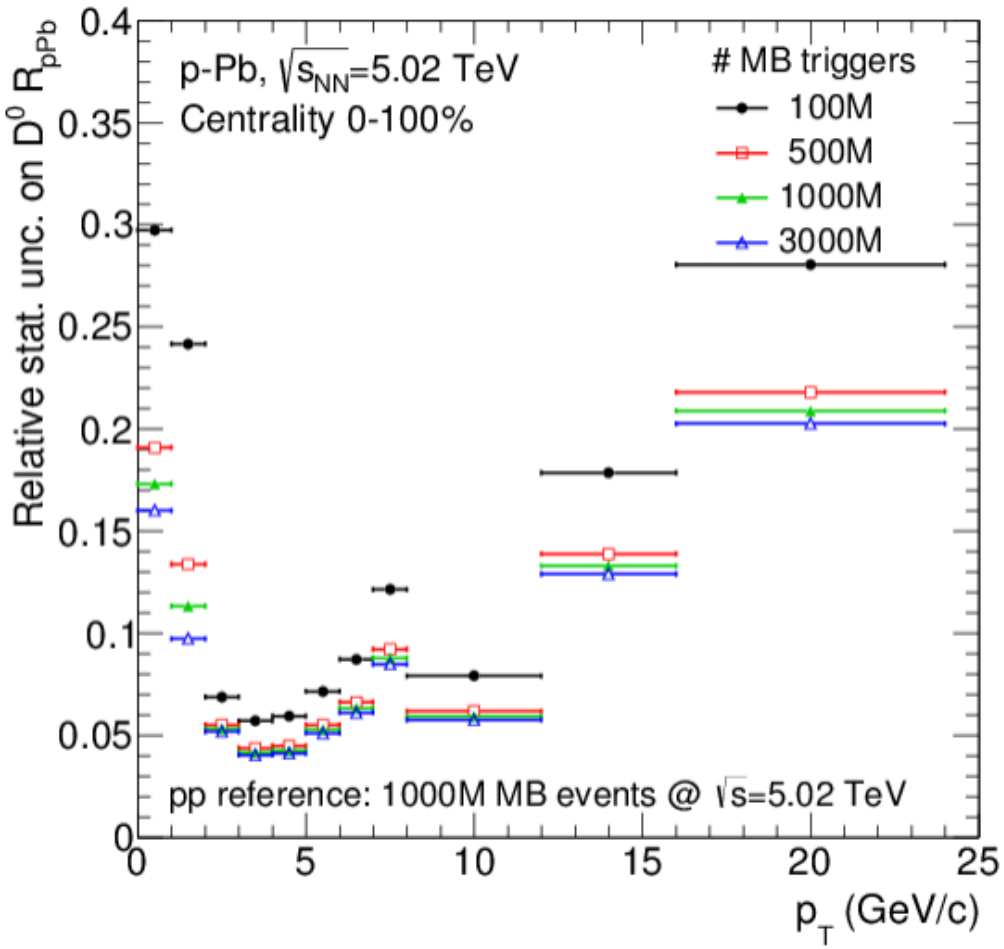
Shadowing from D R_{pA}



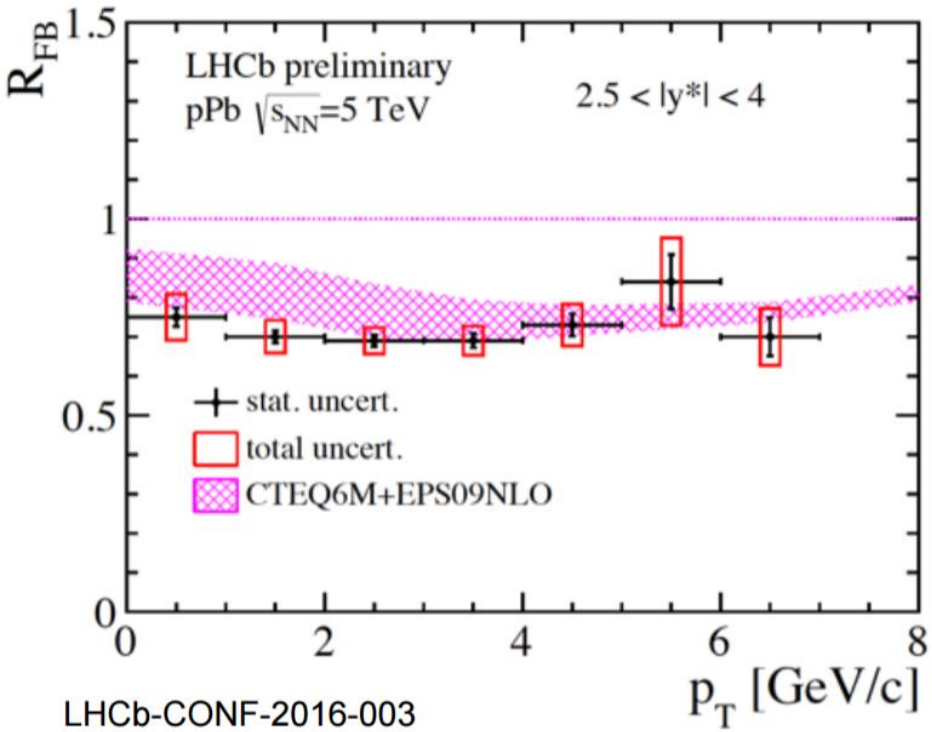


Direct measurement of D R_{pPb} , sensitivity limited by the current uncertainties

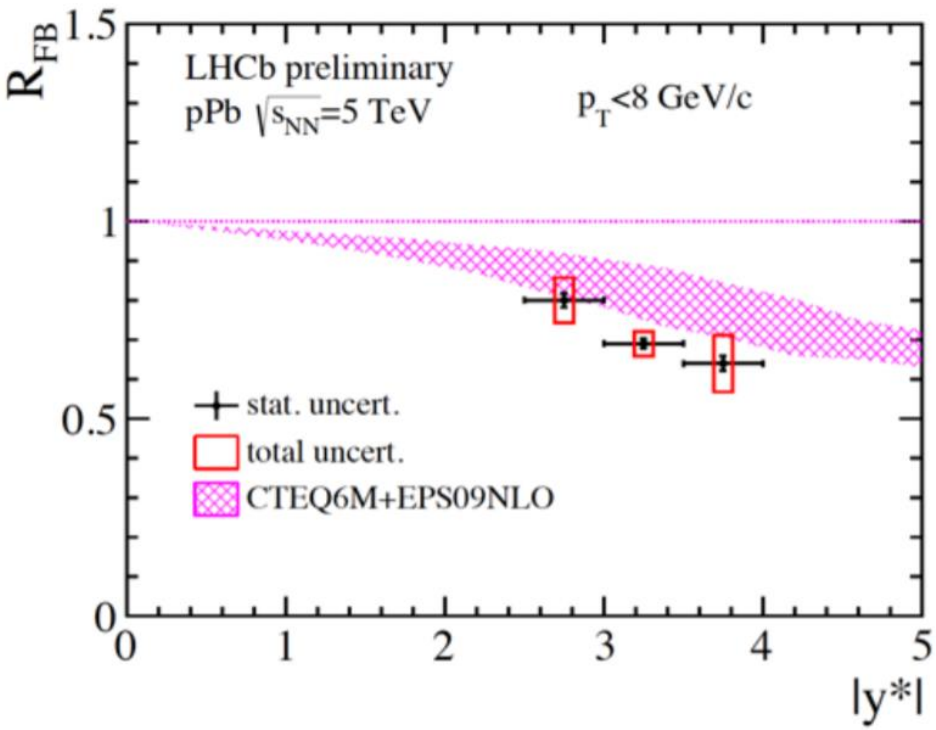
Could be done by ALICE, LHCb and CMS data taken in 2016 pPb run

(+ pp ref run for ALICE)

LHCb D^0 meson measurement



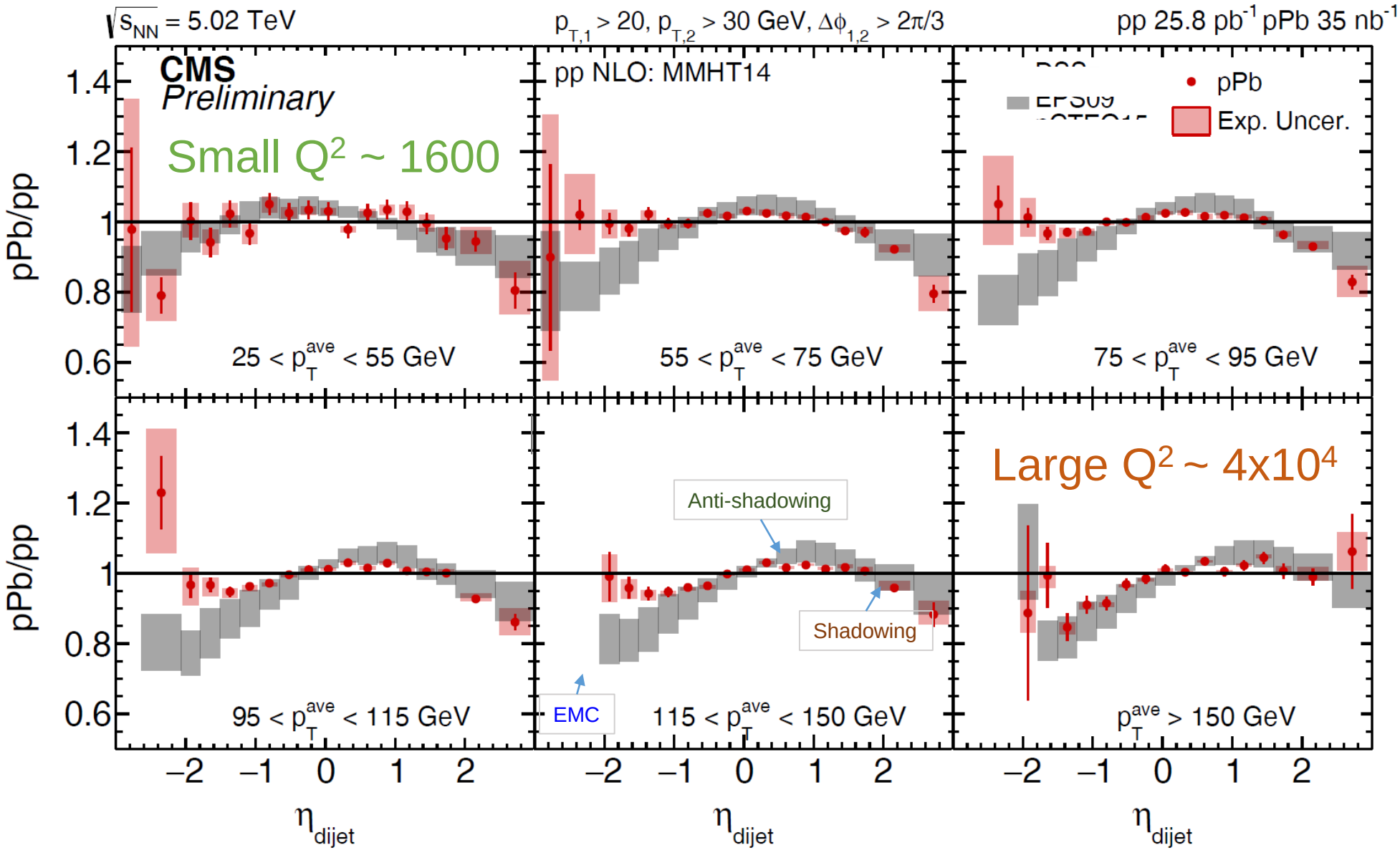
LHCb-CONF-2016-003



Precise measurement from LHCb: data consistent with the lower edge of the pQCD calculation using EPS09.

Forward backward ratio: ~ shadowing / EMC region

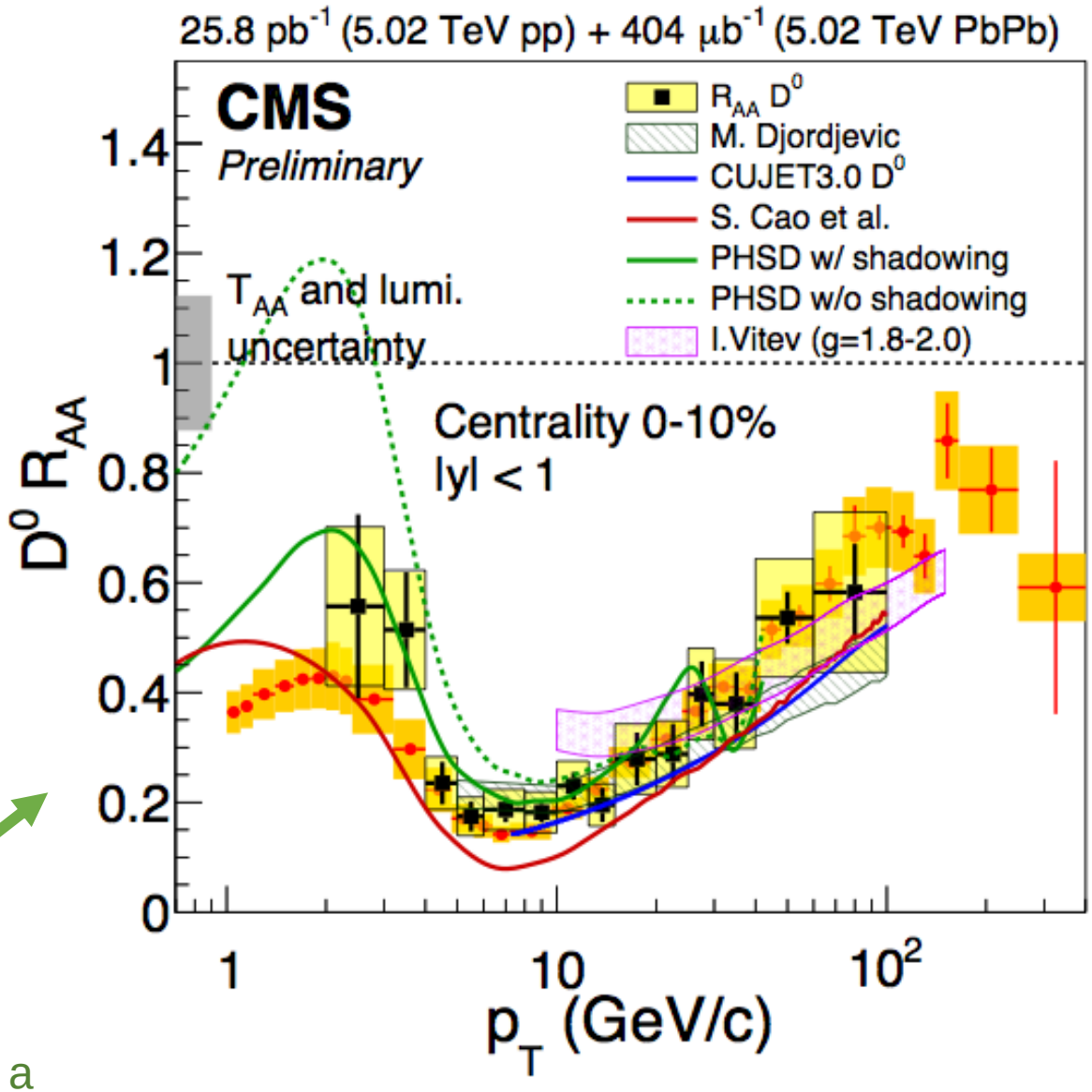
CMS dijet η data at large Q^2



Consistent with EPS09 at the edge of the uncertainty band. Deviation in the EMC region.

Consistent picture between CMS dijet data and LHCb D^0 data

CMS D^0 R_{AA} vs Predictions



PHSD with shadowing gives a better description of the CMS preliminary result

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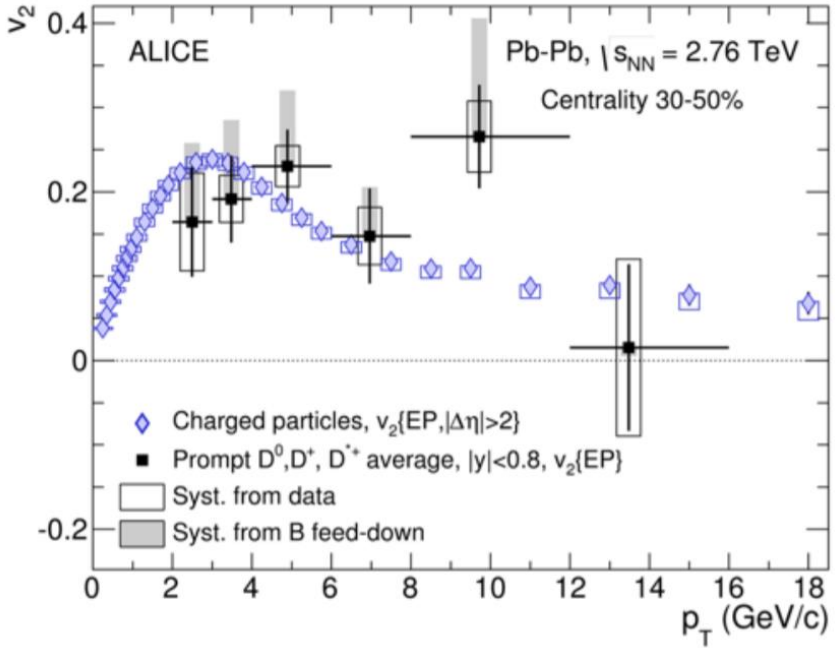
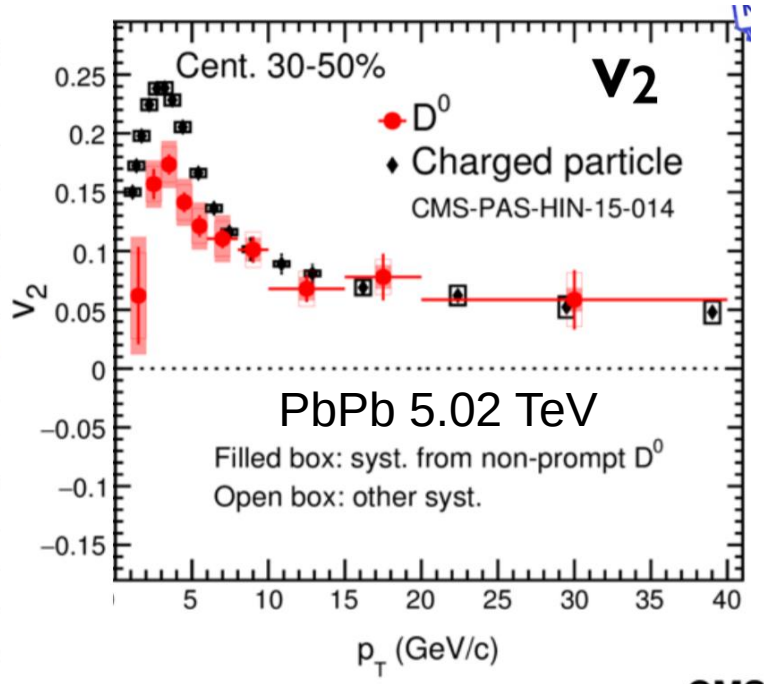
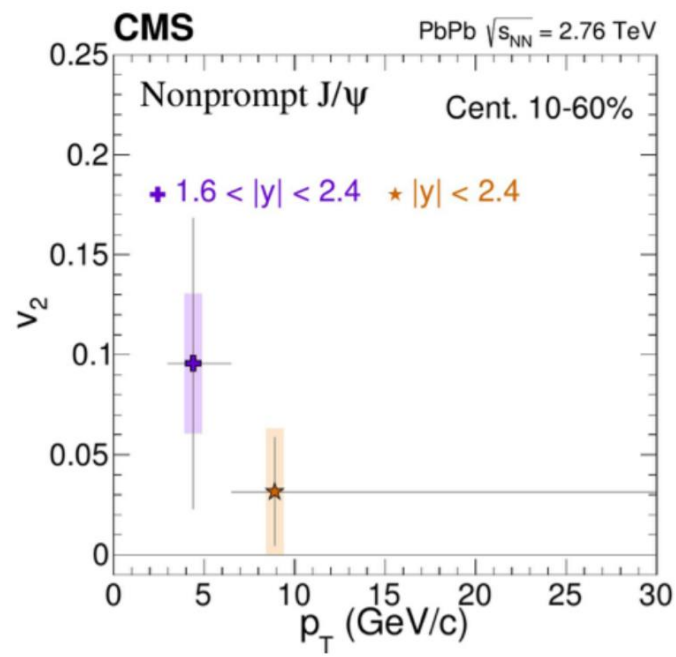
Interpretation of v2 data

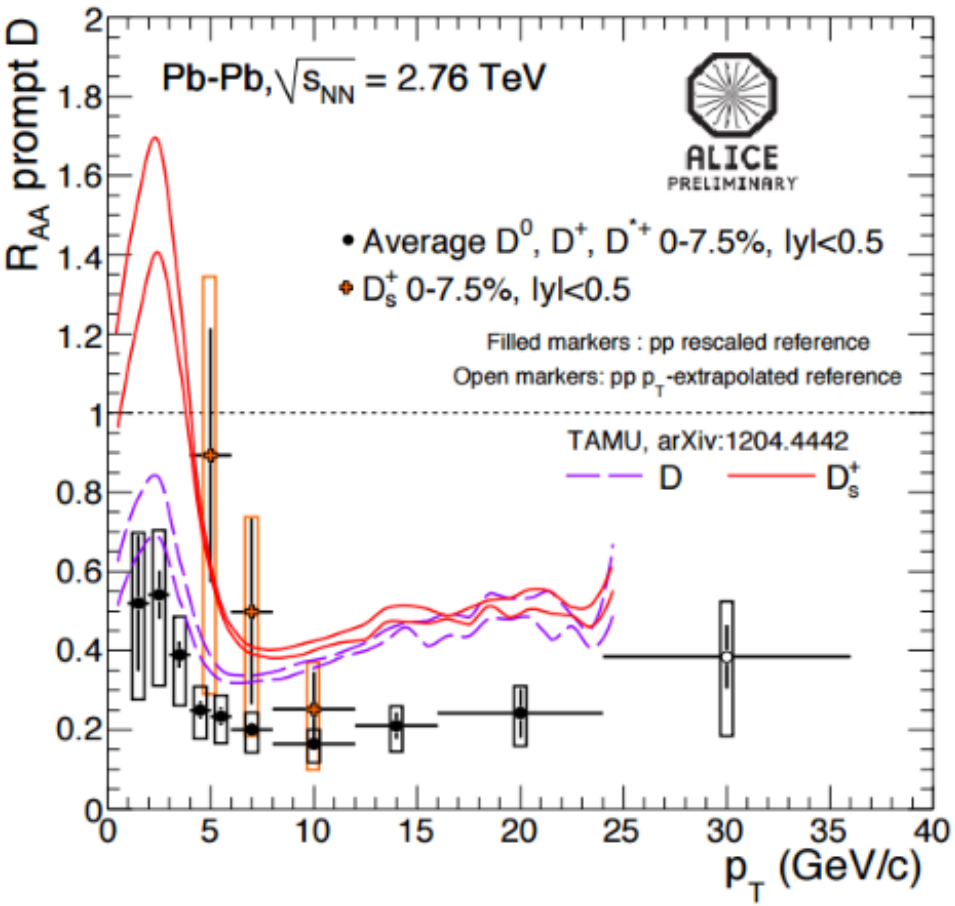


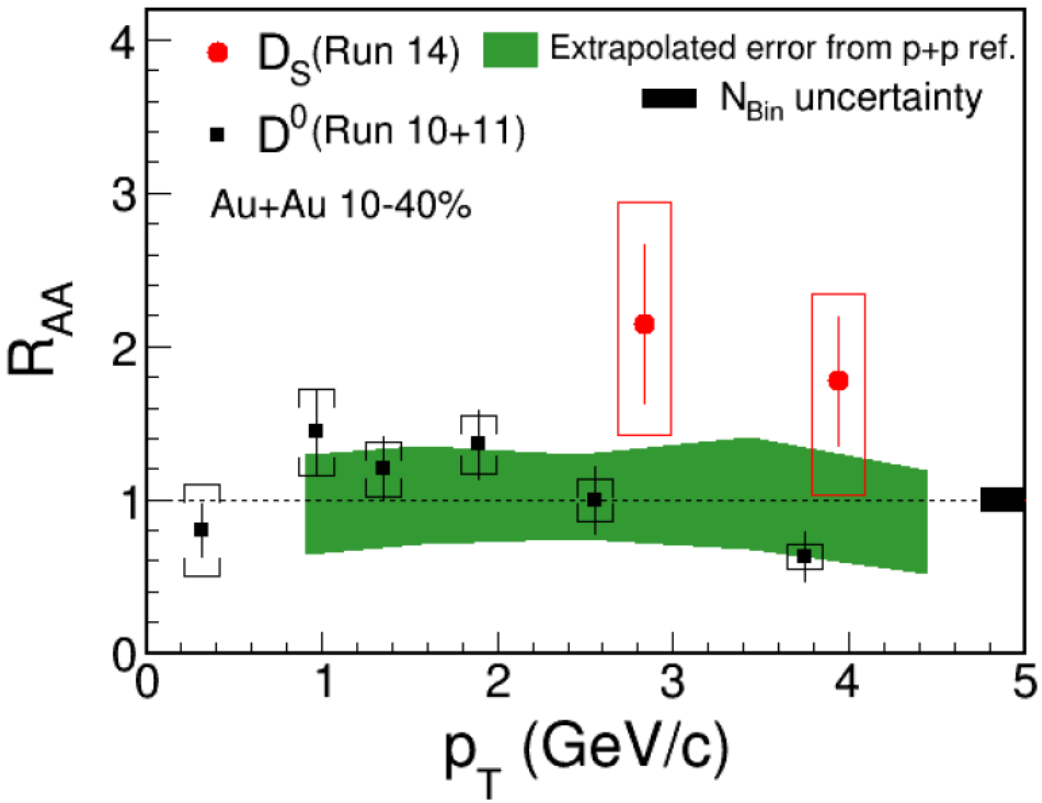




- Significant flow signal observed in D0, v_2 vs p_T different from charged particles
- Need theoretical calculations at LHC energy without c quark v_2 to answer if the charm quarks flows
- Correlation analysis between D^0 and charged particle v2
- 2020s: Follow up on the real measurement B(b->J/ψ) v_2 at RHIC and LHC

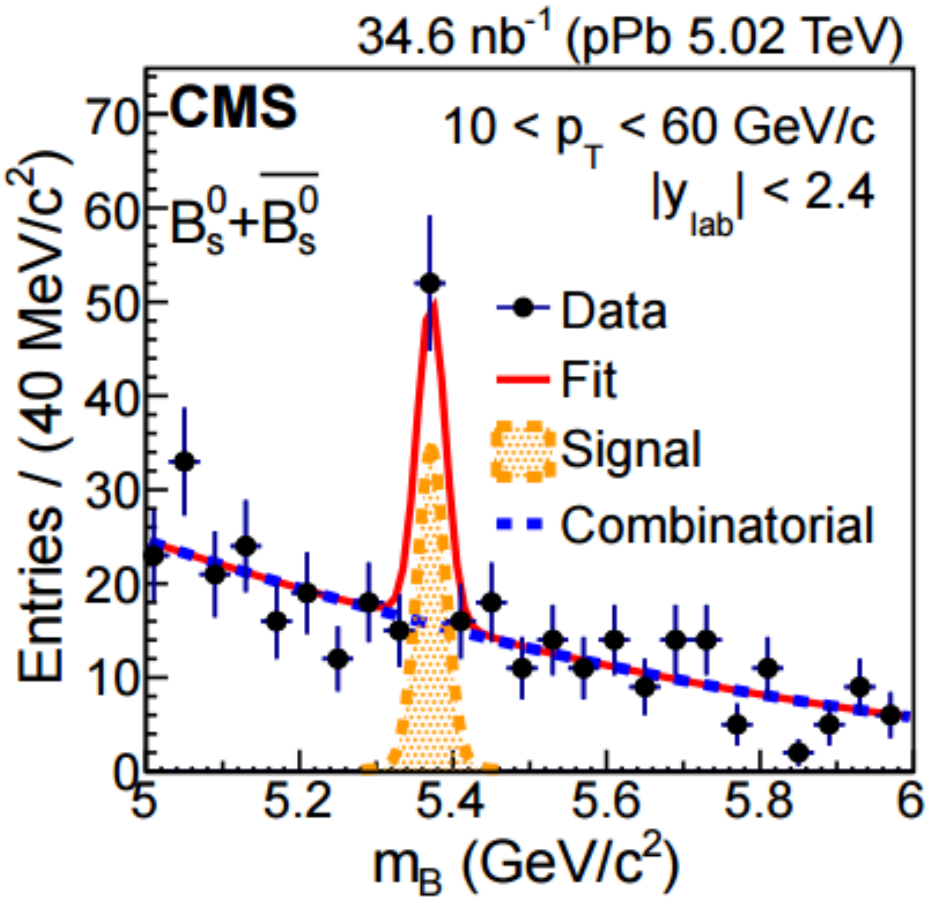
Hadronization effect

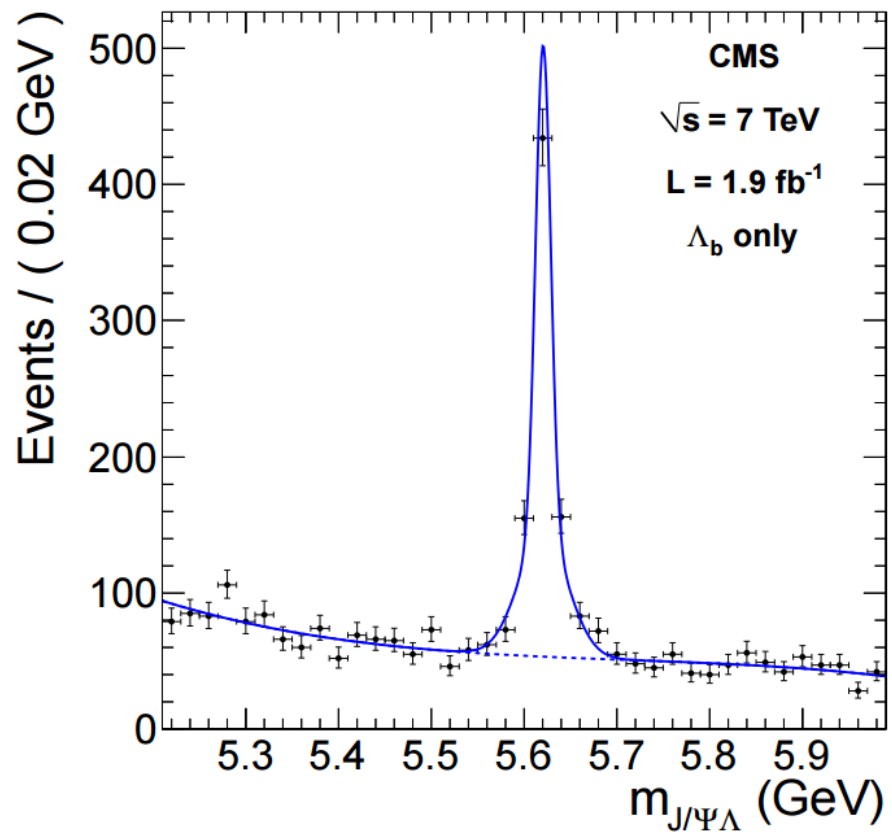




ALICE will update the D_s measurements with 2015 data
(In principle, CMS could also contribute to D_s measurement)
Expect high statistics measurement from RHIC
Now - 2020s: B_s, Λ_c, Λ_b measurements are becoming feasible by LHC experiments

Projected performance for B_s and Λ_b with 10/nb





B_s: Projected statistical uncertainty is around 3% in PbPb p_T = 7-10 GeV/c (L = 10/nb)

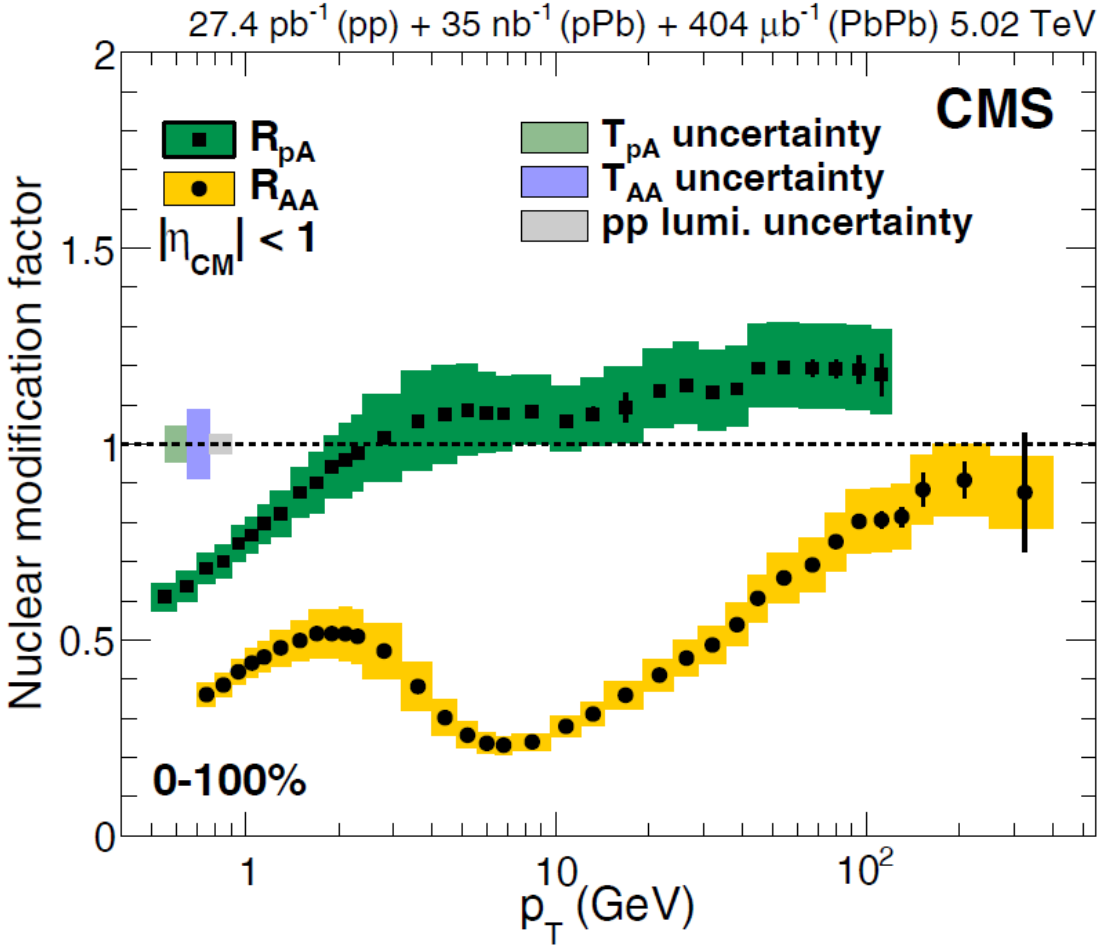
[~30-60x of the statistics shown in this plot]

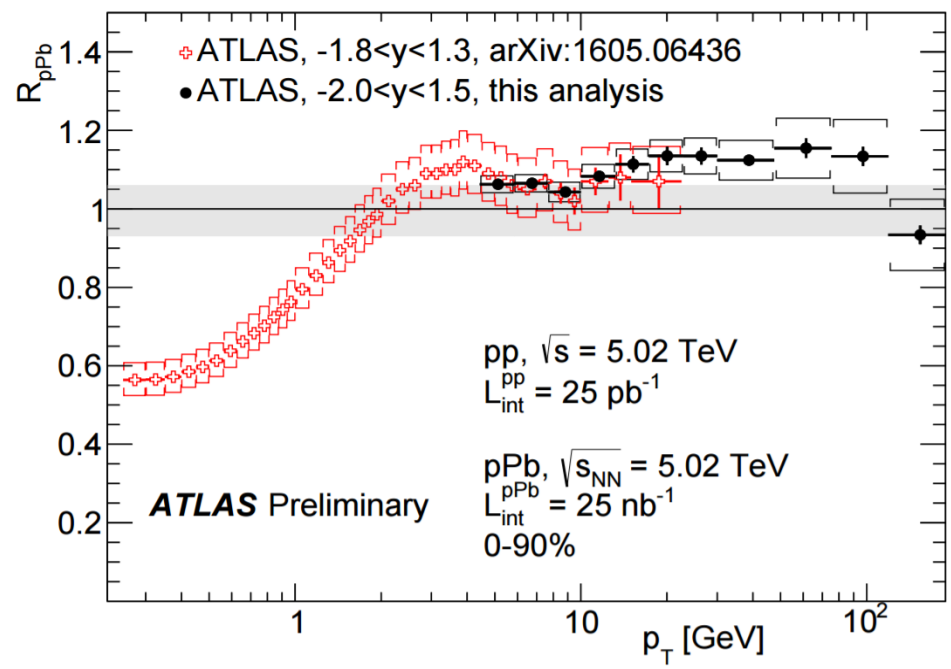
Λ_b: Projected statistical uncertainty is around 15% in PbPb p_T = 7-10 GeV/c (L = 10/nb)

[~ 1/4 – 1/8 of the statistics shown in this plot]

Run IV data would help to provide those rate probes

Charged Hadron R_{pA}





To be submitted to JHEP

Charged Hadron R_{pA} is consistent with the published jet R_{pA}
Relevant for the interpretation of the charged particle R_{AA}

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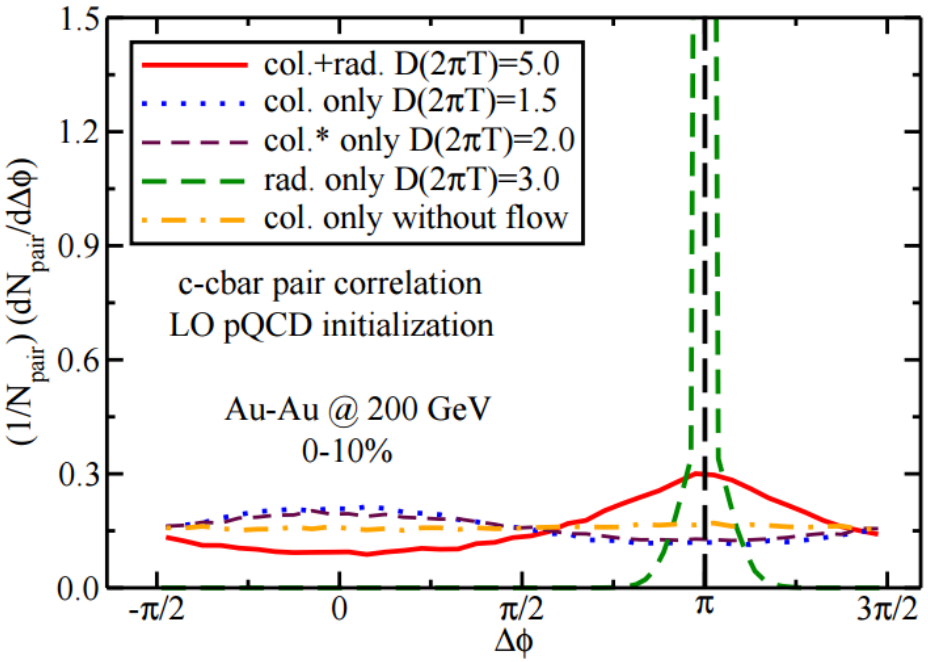
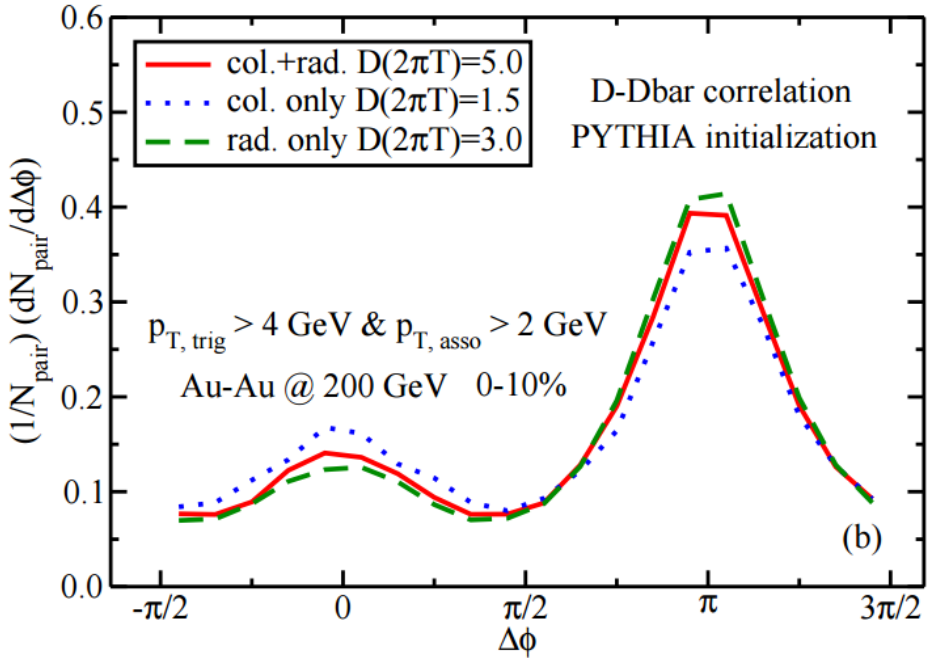
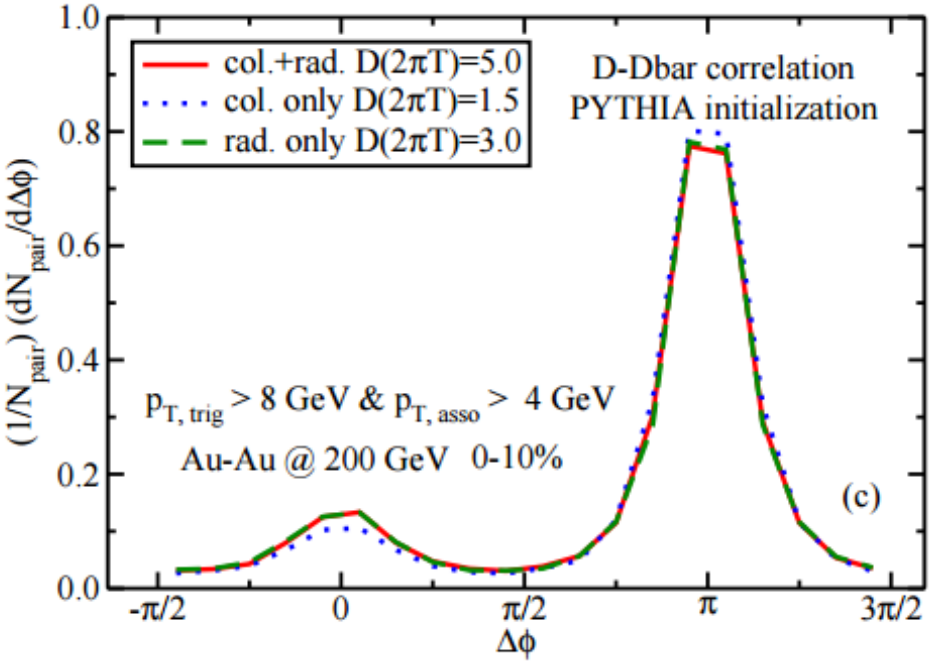
D-Dbar correlation



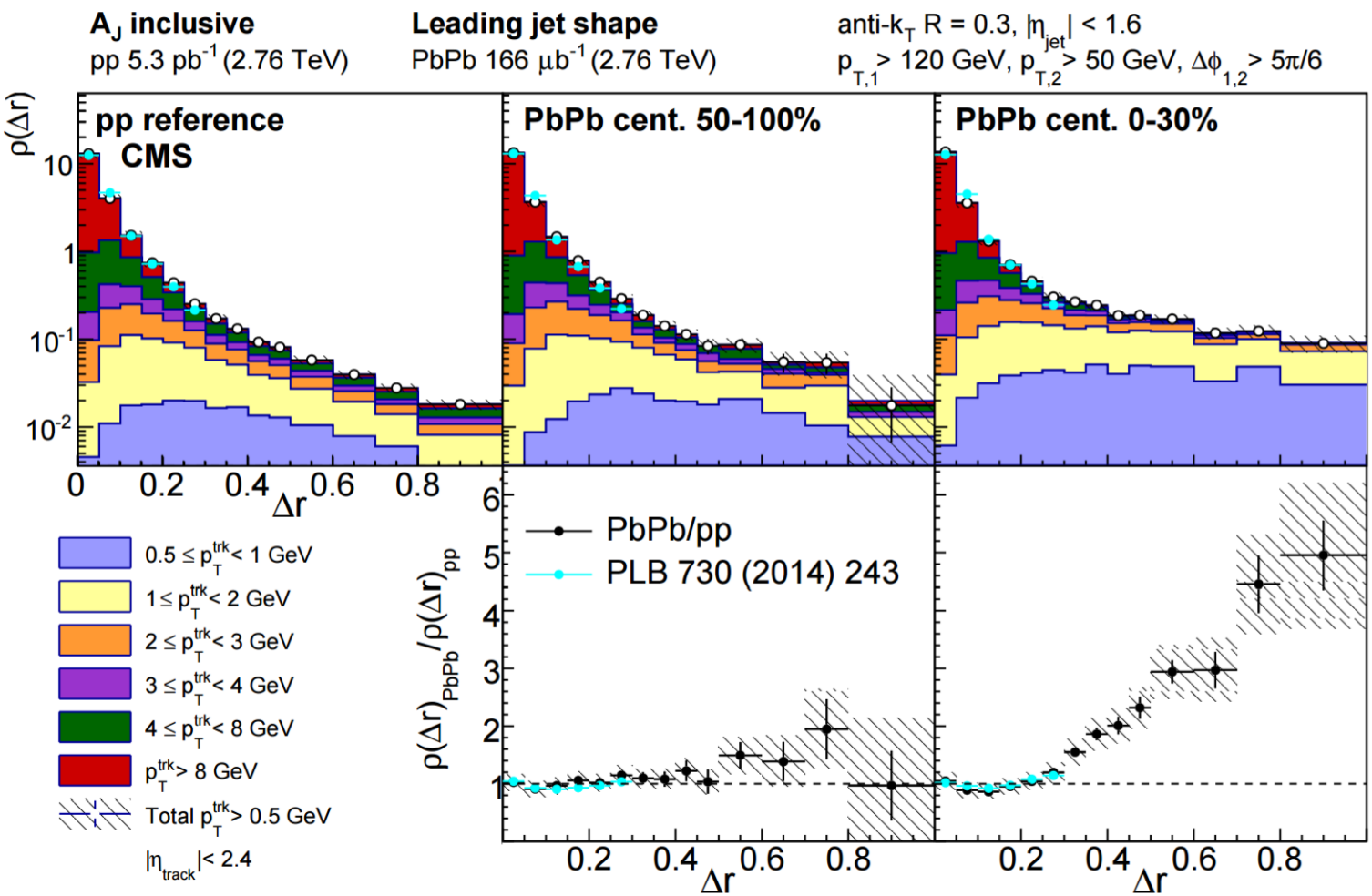




- D-hadron correlation has been studied by ALICE in pp and pPb collisions
- DD(bar) correlation in pp was studied by LHCb, **to be done in PbPb by ALICE / CMS**
- Difference between prediction with collisional and radiative energy loss goes away quickly as p_T increases…

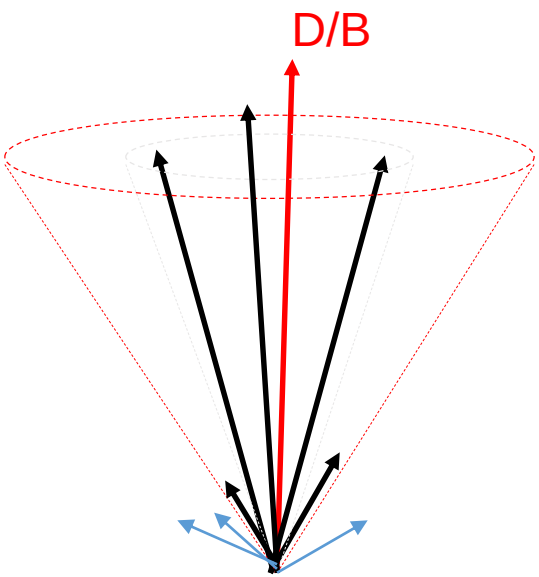
D/B-jet and D/B-photon correlation

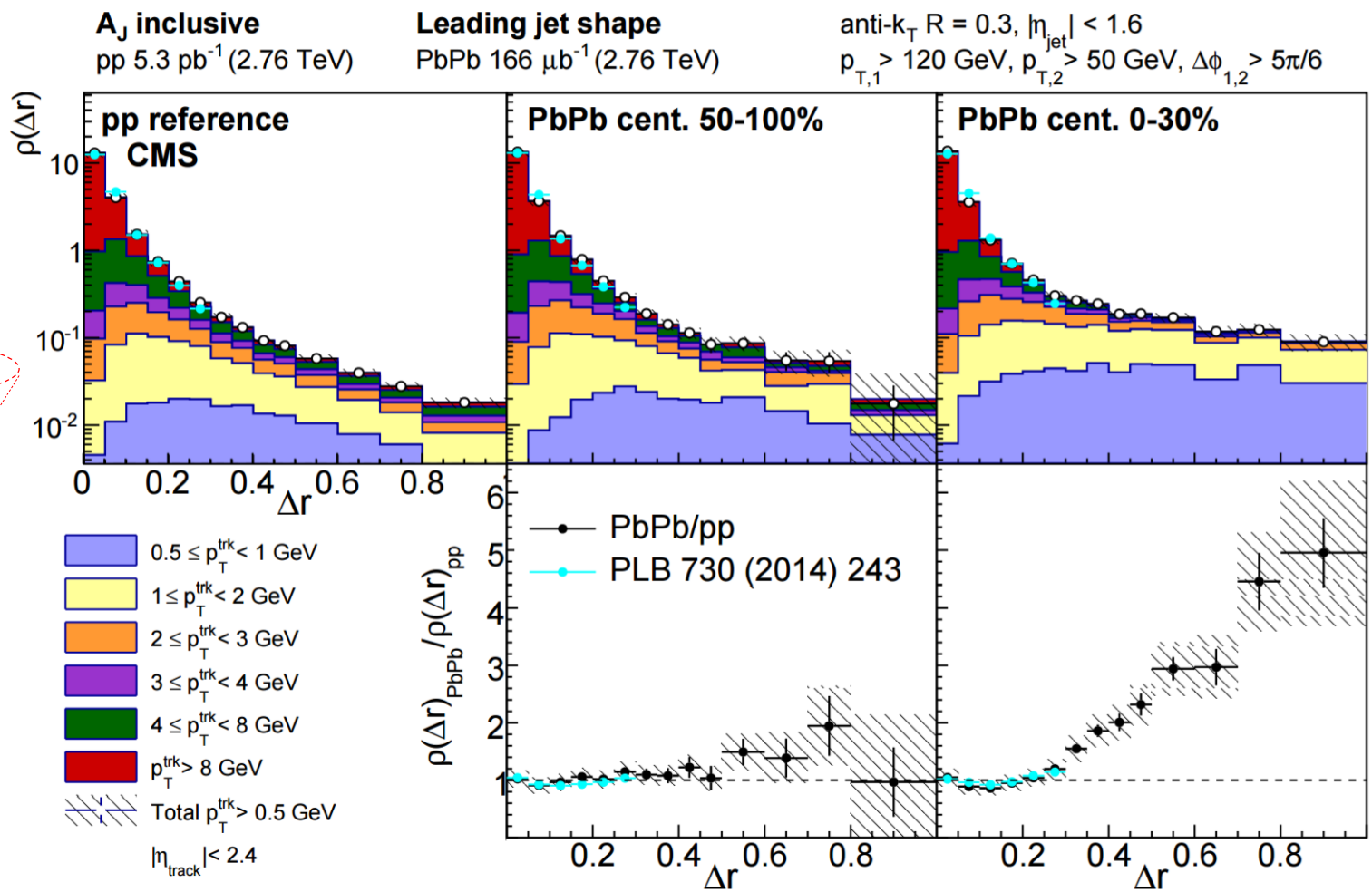
HF version of
this measurement



- **Propose to study D/B-jet and D/B-photon correlation at RHIC and LHC**
- D meson and B meson as a tool to study the fate of the intermediate p_T HF partons
- Relatively **less likely** to come from medium response, mass scale >> medium scale
- Jet and photon as a proxy to the initial parton direction

D/B-jet and D/B-photon correlation





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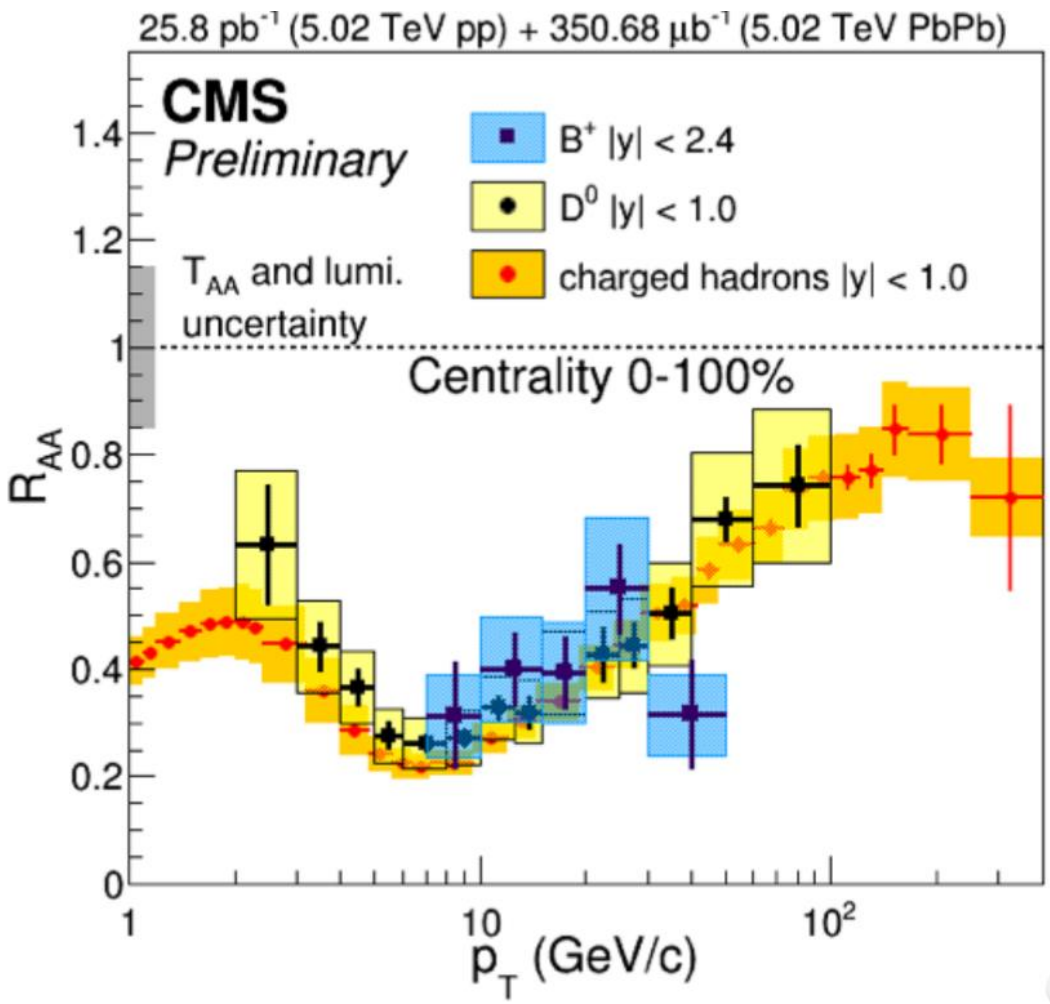
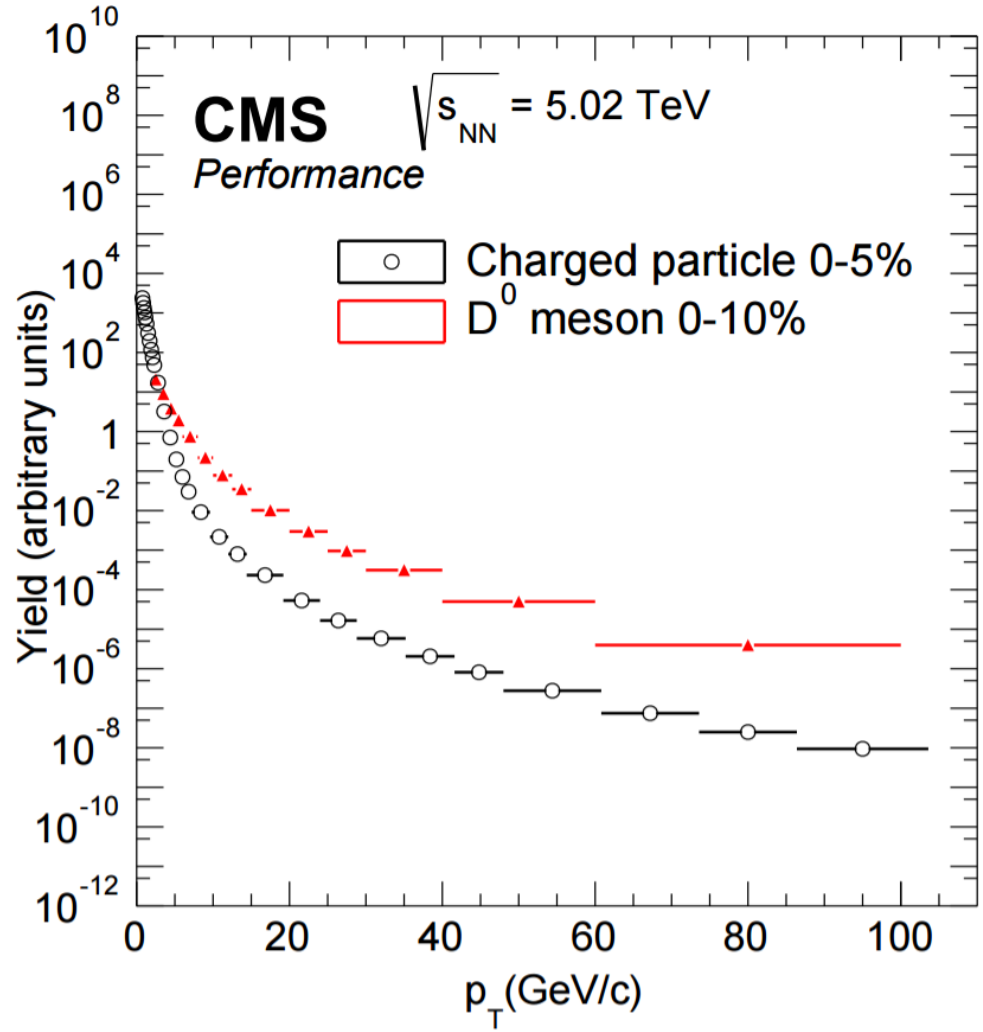
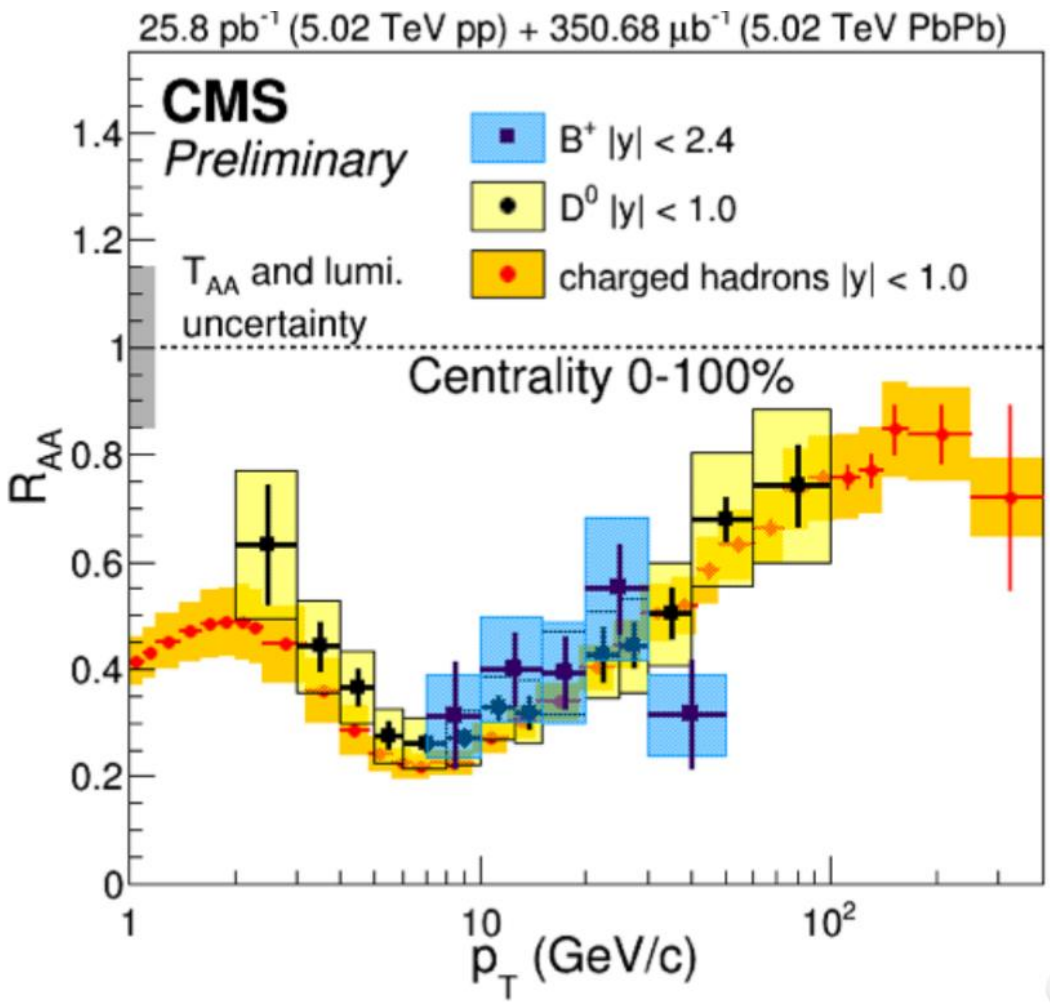
B / D / charged hadron

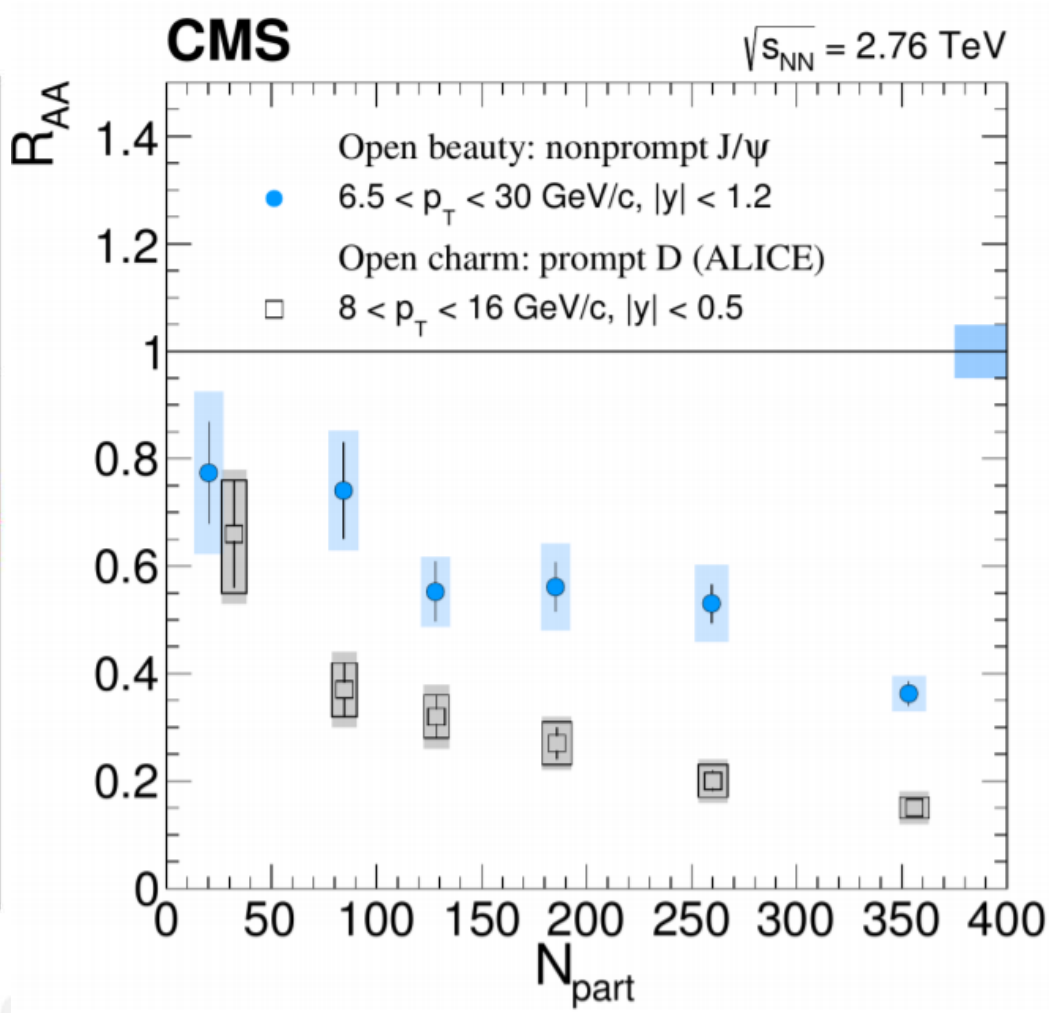




No significant difference between CMS B^+ D^0 and charged hadron R_{AA} in PbPb at 5.02 TeV

B meson vs. non-prompt J/ψ

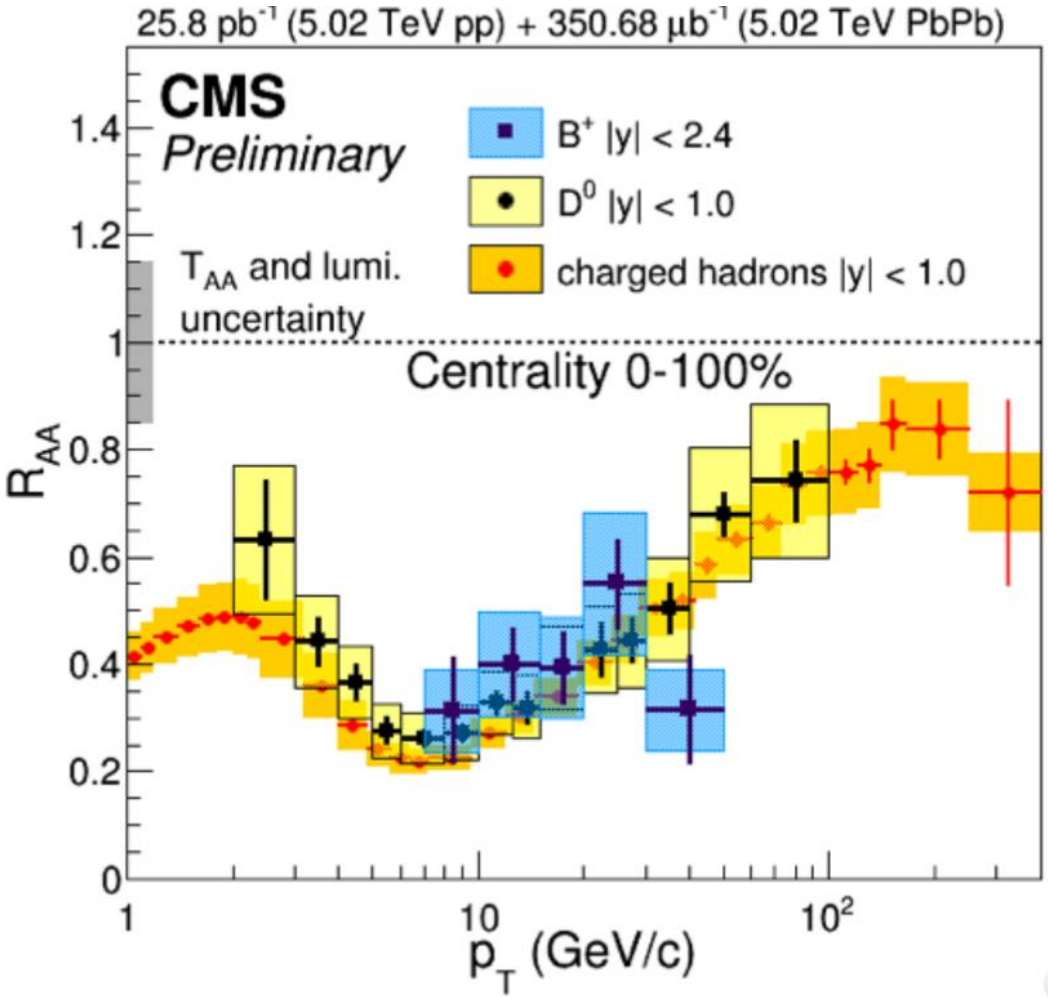


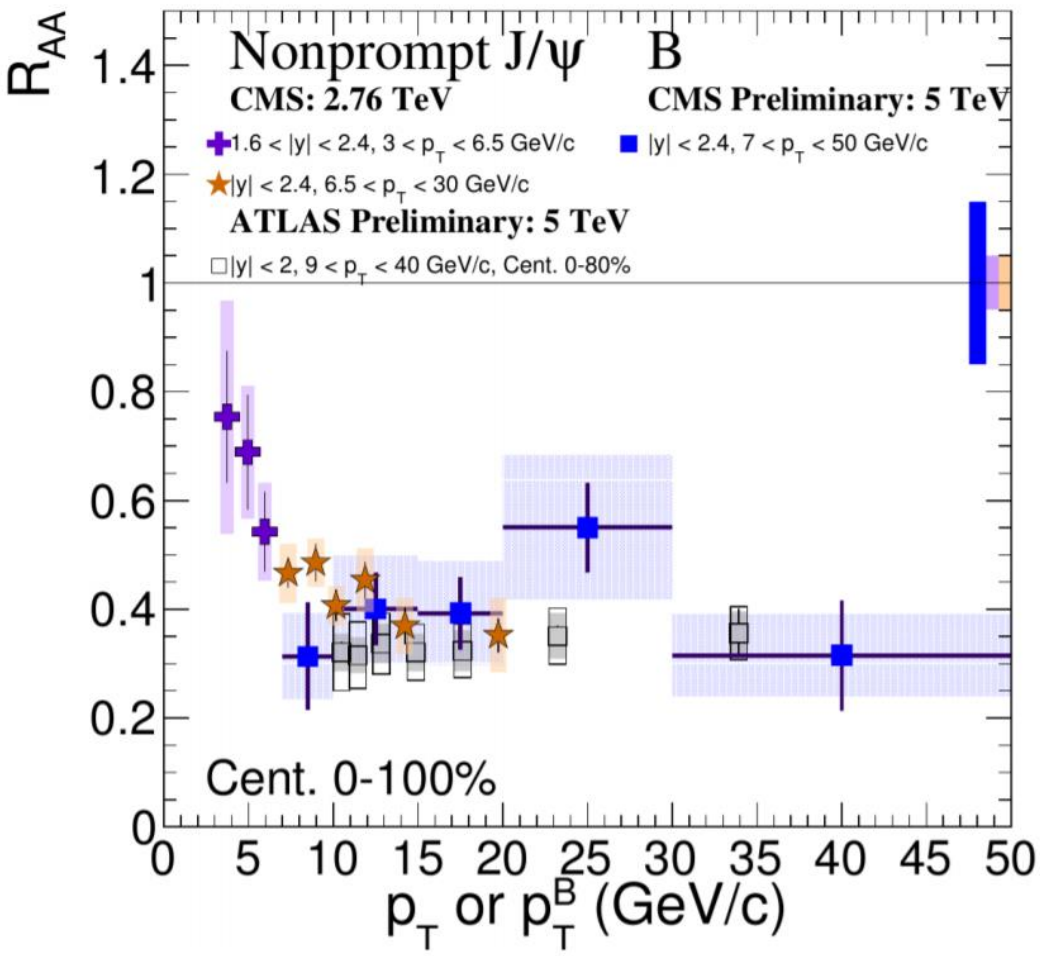


No significant difference between CMS B^+ and D^0 R_{AA} in PbPb at 5.02 TeV

Significant difference between CMS non-prompt J/ψ and ALICE D meson in PbPb at 2.76 TeV

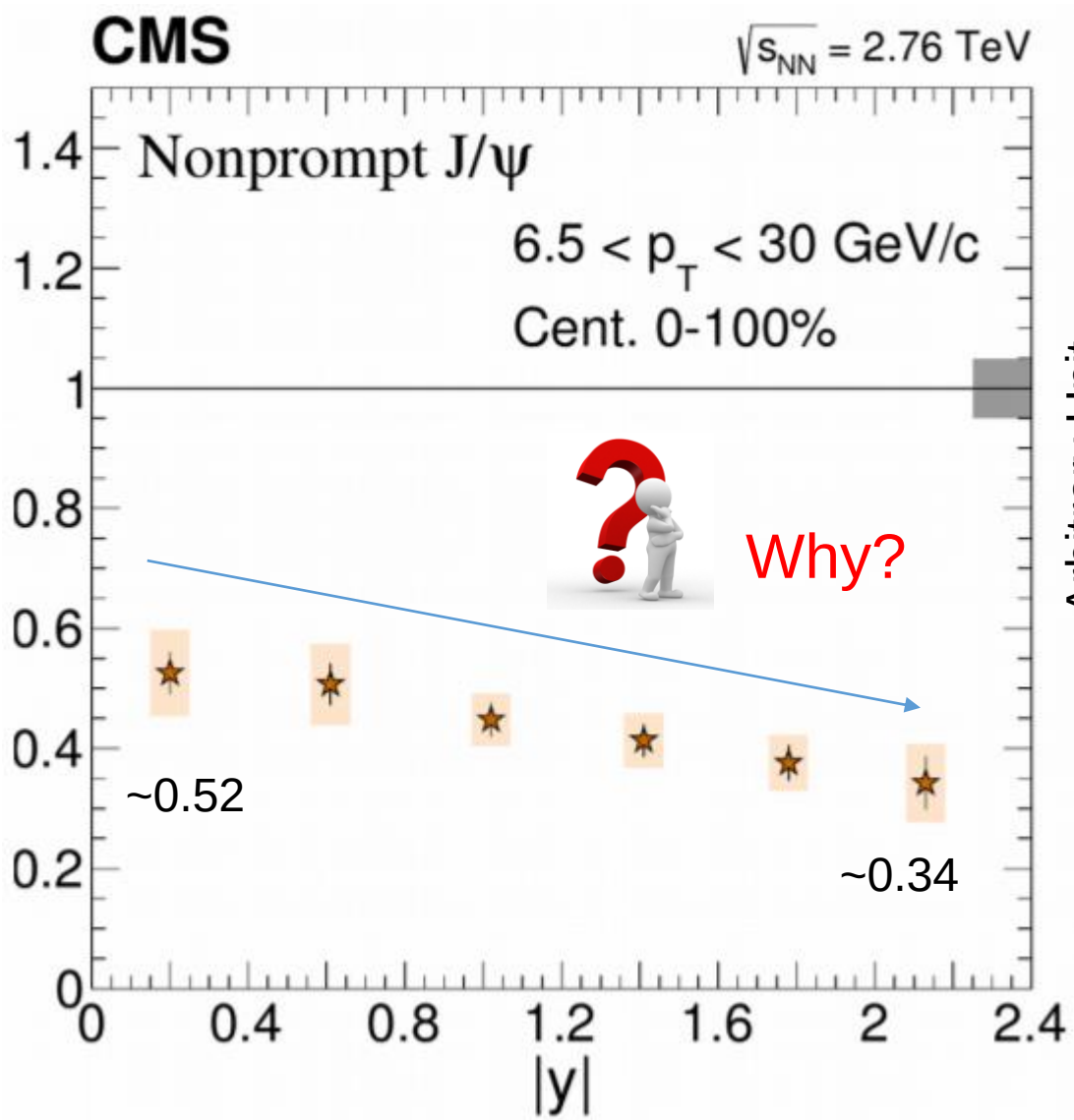
B meson vs. non-prompt J/ψ



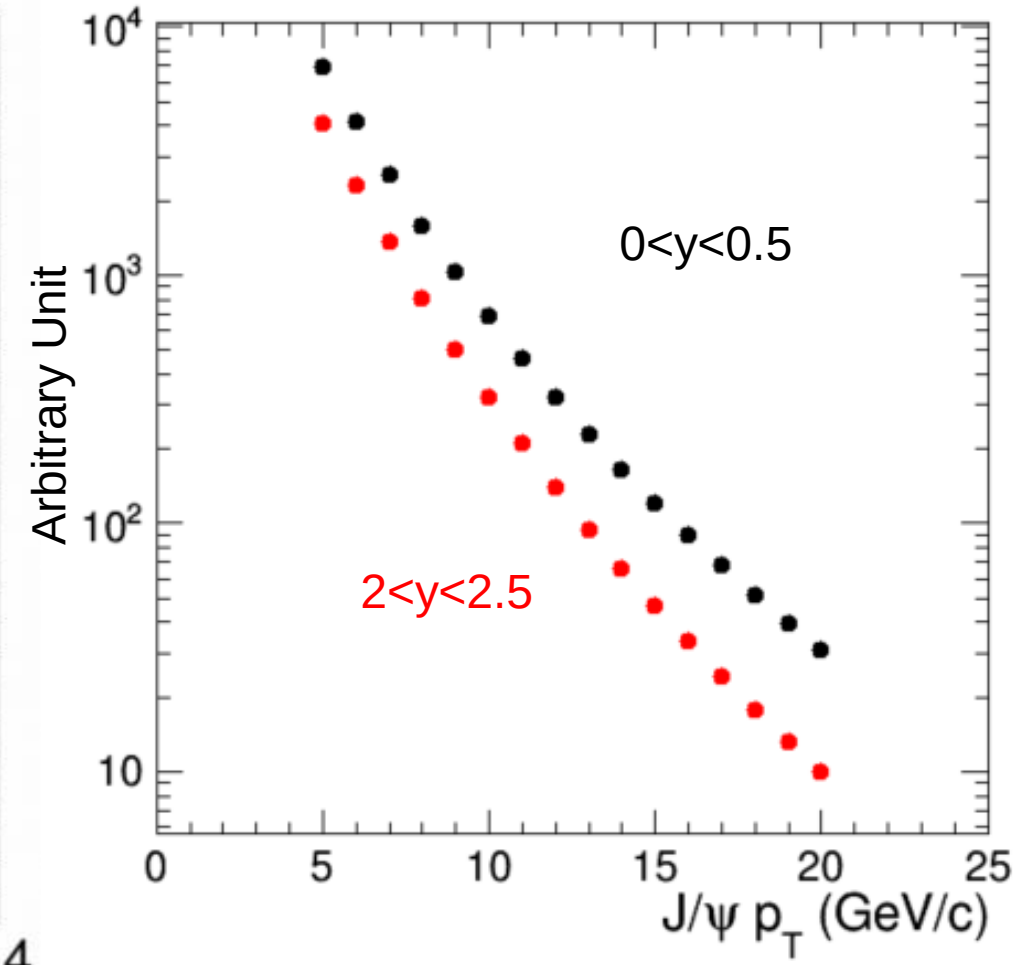


No significant difference between B^+, non-prompt J/ψ R_{AA}

b to J/ψ R_{AA}



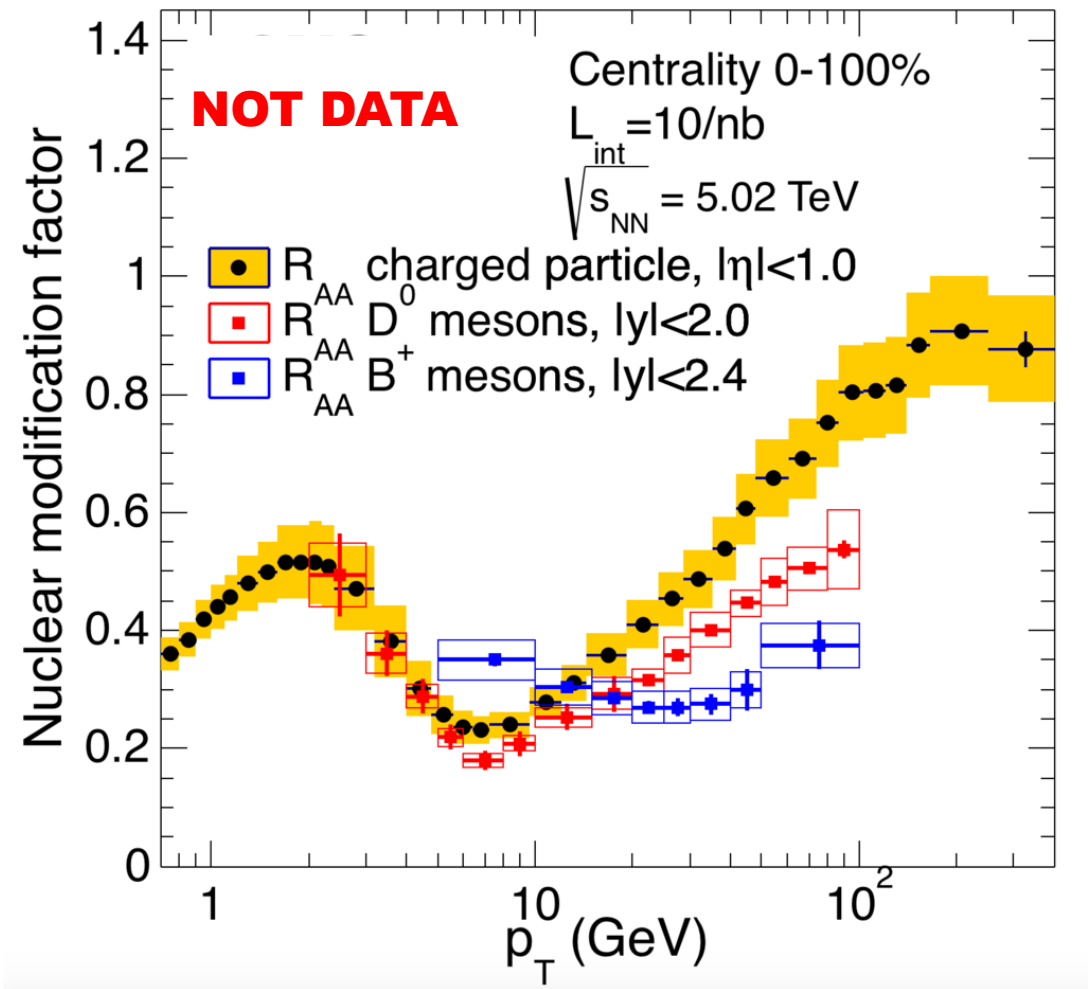
FONLL calculation on b->J/ψ



The reason could be associated with the rapidity dependence of the suppression

To be followed up with B^+ R_{AA} with |y|<1 and its the rapidity

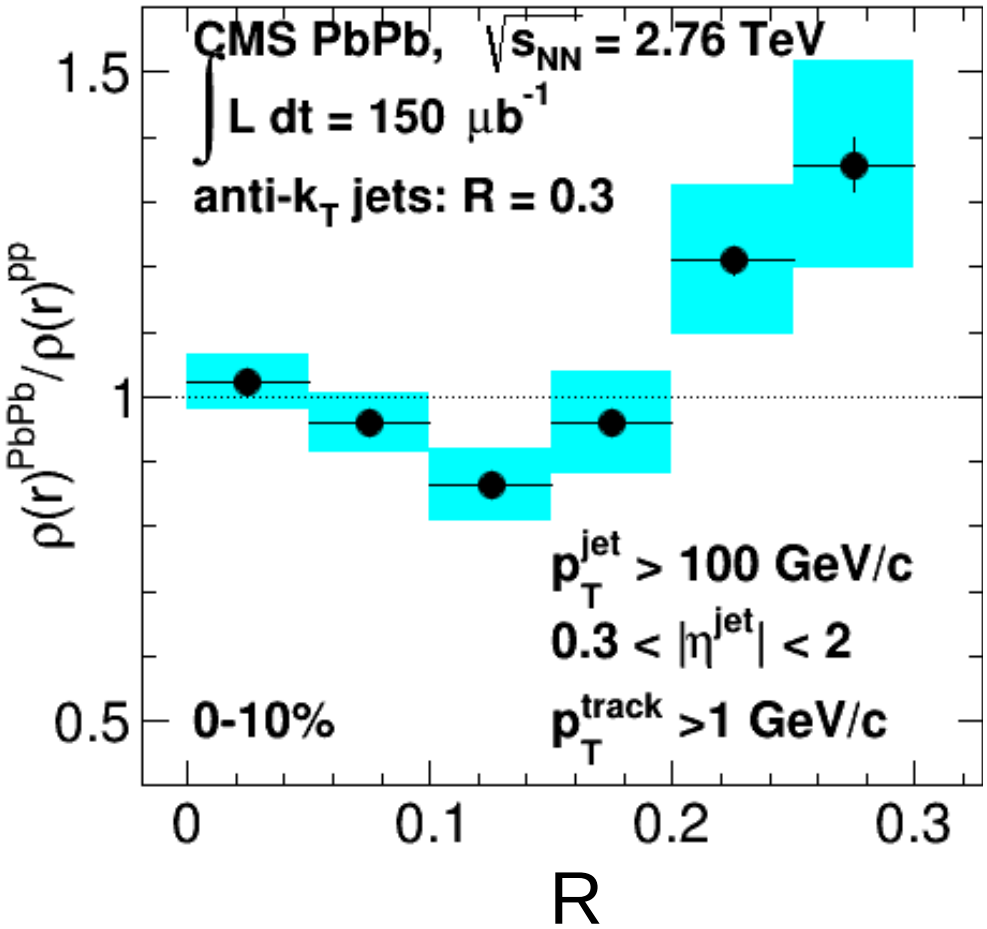
Future (Run II+III) ~20-30x more data



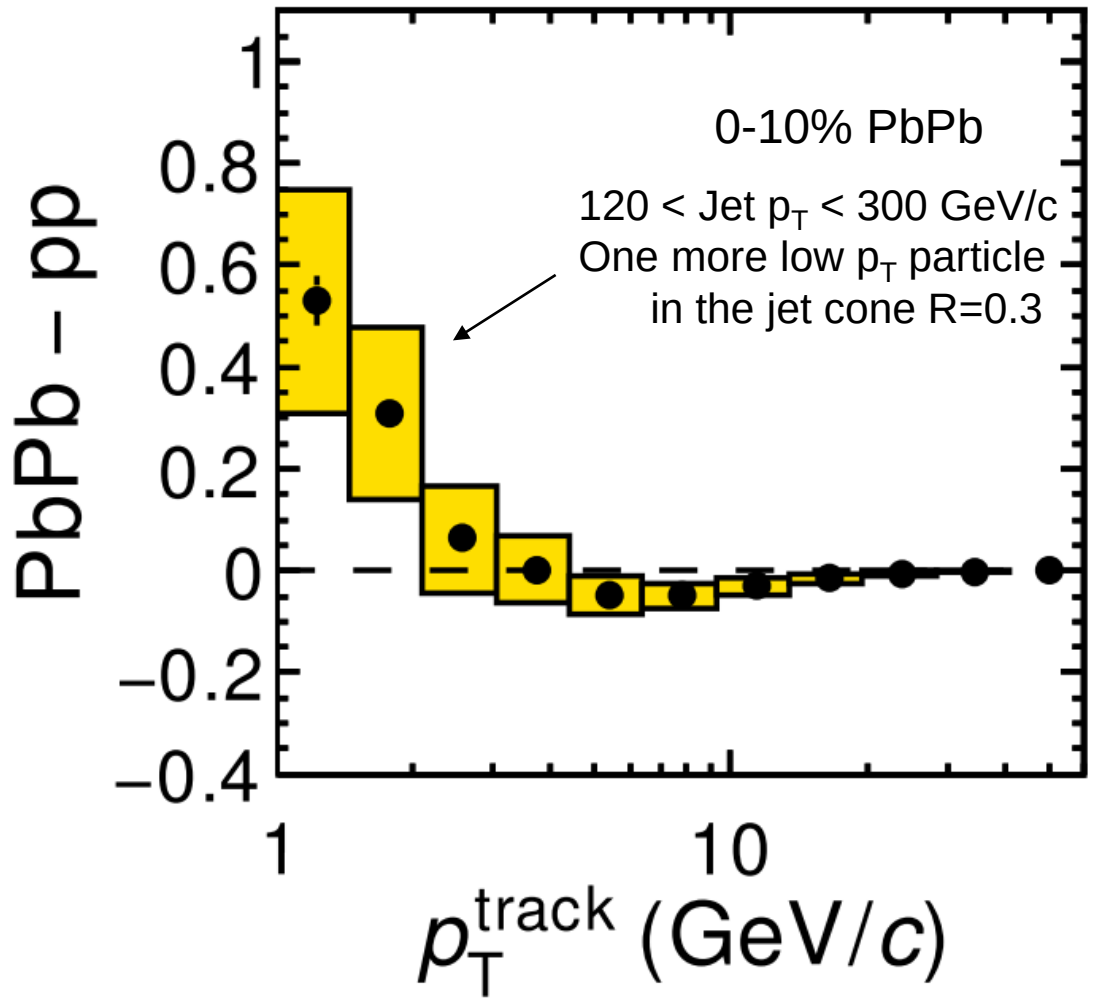
- High precision charged particle, D^0 and B^+ R_{AA} and v_N data!
- Access to multiple B^+, B^0 and B_s decay channels
- Jet / photon tagged HF mesons: provide multiple checks on medium modifications of the HF meson kinematics distributions

Quark vs. Gluon

Jet shape **PbPb / pp**



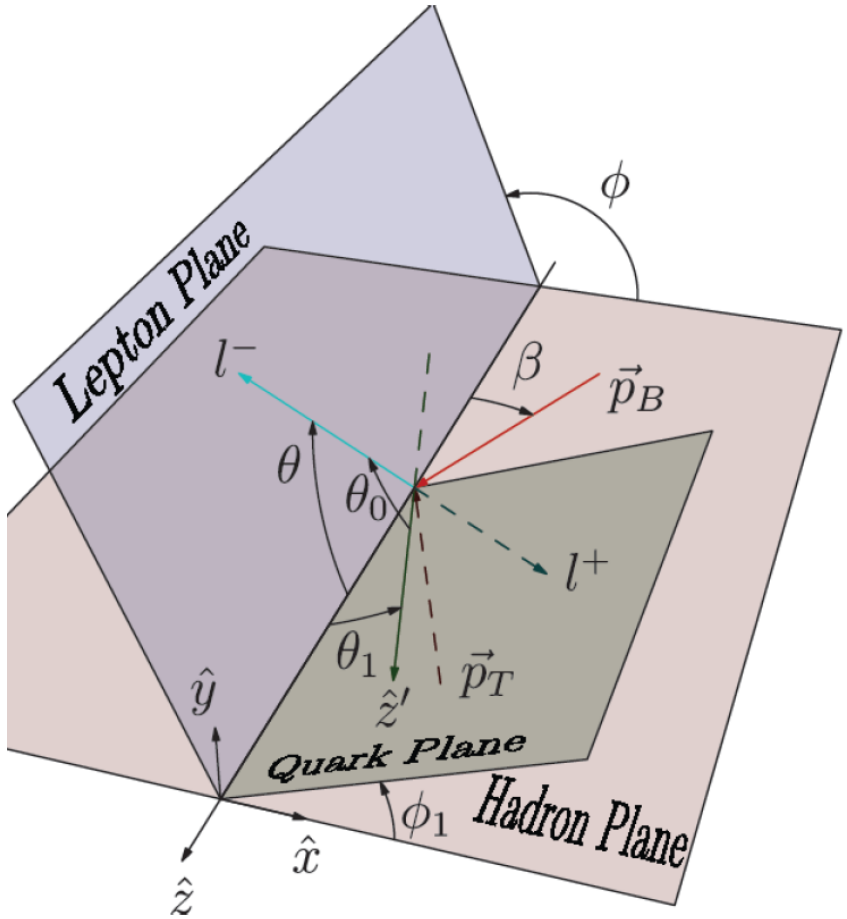
Charged particle in cone PbPb - pp



- Jets are modified in medium
- Separate quark and gluon: use high p_T jets (and groomed jet substructure) to increase the scale difference between medium and the hard scattering
- Can we separate quark and gluon jets without touching the jets?

Z decay kinematics in Collins–Soper Frame

Collins-Soper Frame



$$\frac{d\sigma}{d\Omega} \propto (1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{A_2}{2}\sin^2\theta\cos 2\phi + A_3 \sin\theta\cos\phi + A_4\cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi. \quad (3)$$

$$A_0 = \langle \sin^2\theta_1 \rangle$$

$$A_1 = \frac{1}{2}\langle \sin 2\theta_1 \cos\phi_1 \rangle$$

$$A_2 = \langle \sin^2\theta_1 \cos 2\phi_1 \rangle$$

$$A_3 = a\langle \sin\theta_1 \cos\phi_1 \rangle$$

$$A_4 = a\langle \cos\theta_1 \rangle$$

$$A_5 = \frac{1}{2}\langle \sin^2\theta_1 \sin 2\phi_1 \rangle$$

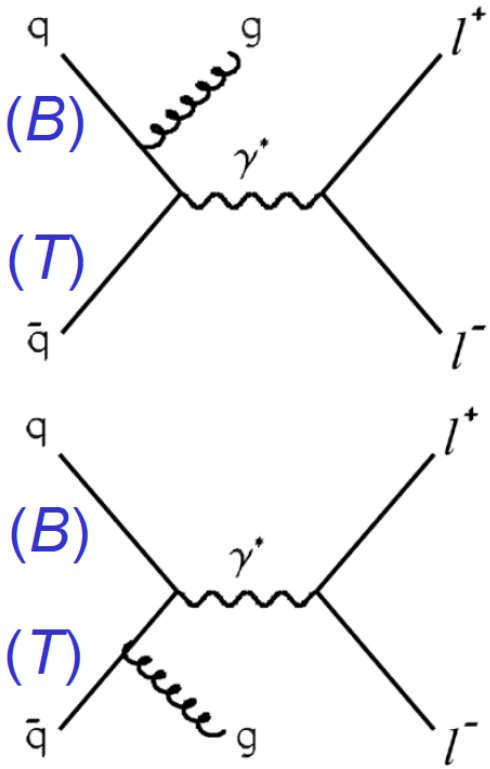
$$A_6 = \frac{1}{2}\langle \sin 2\theta_1 \sin\phi_1 \rangle$$

$$A_7 = a\langle \sin\theta_1 \sin\phi_1 \rangle$$

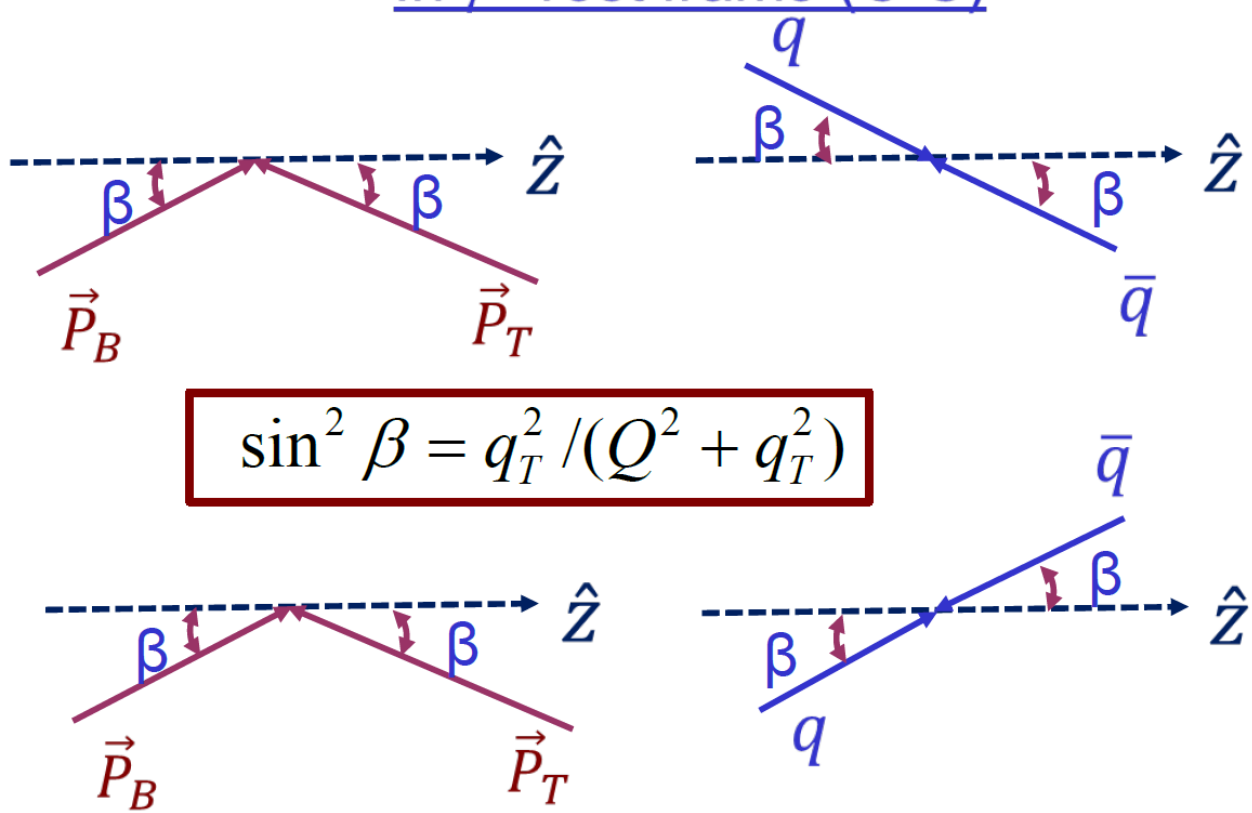
Discussion with Jen-Chieh Peng

Z boson decay kinematics

1) $q\bar{q} \to \gamma^*(Z^0)g$



In γ^* rest frame (C-S)



$$\sin^2\beta = q_T^2/(Q^2+q_T^2)$$

$\theta_1 = \beta$ and $\phi_1 = 0$; $A_0 = A_2 = \sin^2\beta$

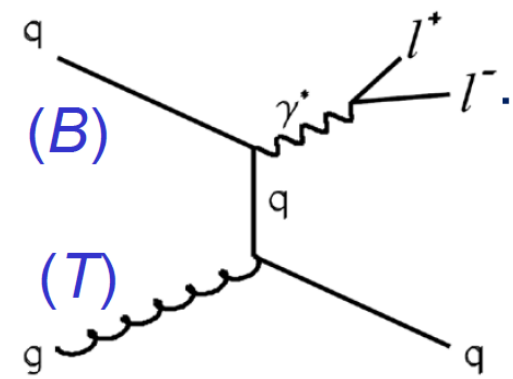
$$\lambda = \frac{2-3A_0}{2+A_0} = \frac{2Q^2-q_T^2}{2Q^2+3q_T^2}; \quad \nu = \frac{2A_2}{2+A_0} = \frac{2q_T^2}{2Q^2+3q_T^2}$$

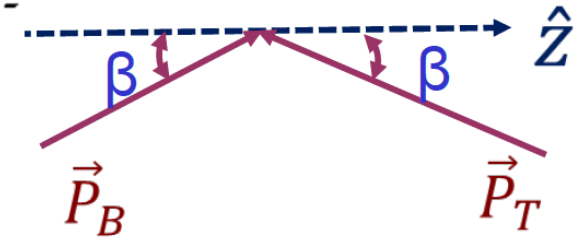
16

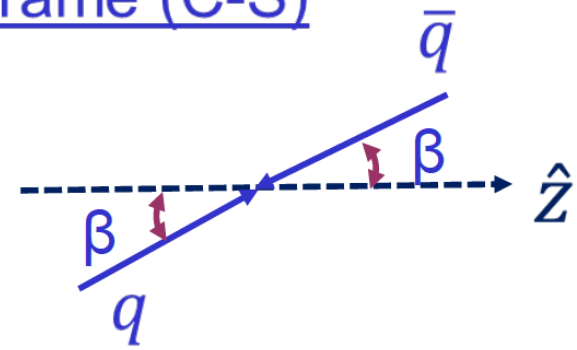
Z boson decay kinematics

2) $qg \rightarrow \gamma^*(Z^0)q$

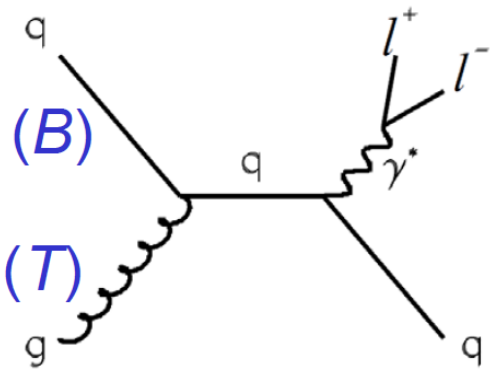
In γ^* rest frame (C-S)

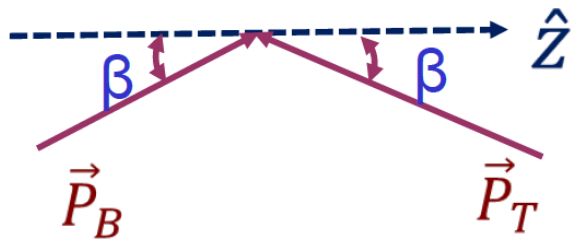


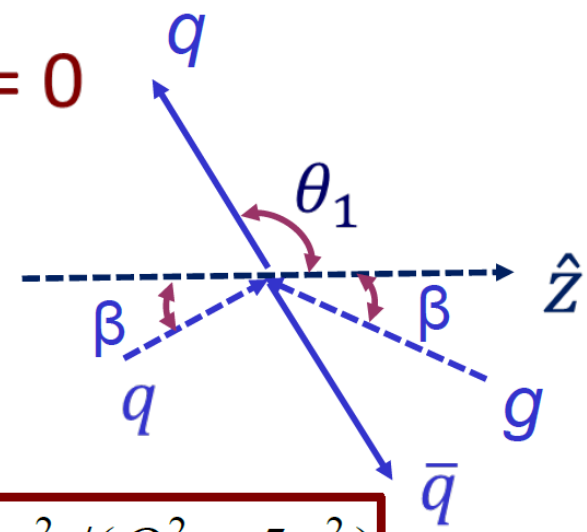




$\theta_1 = \beta$ and $\phi_1 = 0$



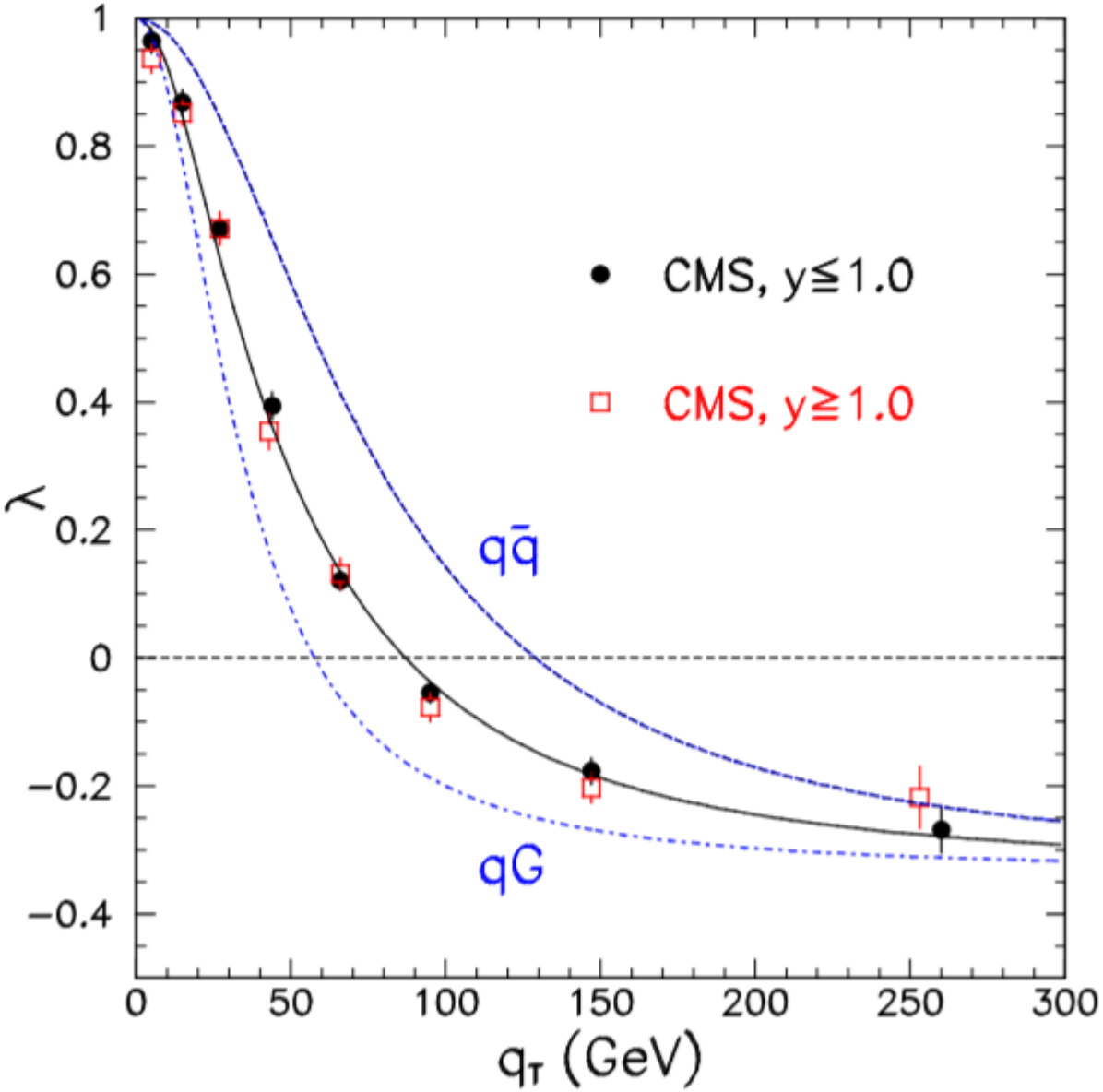




$\theta_1 > \beta$ and $\phi_1 = 0$; $A_0 = A_2 \approx 5q_T^2/(Q^2 + 5q_T^2)$

$$\lambda = \frac{2 - 3A_0}{2 + A_0} = \frac{2Q^2 - 5q_T^2}{2Q^2 + 15q_T^2}; \quad \nu = \frac{2A_2}{2 + A_0} = \frac{10q_T^2}{2Q^2 + 15q_T^2}$$

Quark and Gluon Jet Fraction



$$\lambda = \frac{2Q^2 - q_T^2}{2Q^2 + 3q_T^2} \quad \text{for} \quad q\bar{q} \to Zg$$

$$\lambda = \frac{2Q^2 - 5q_T^2}{2Q^2 + 15q_T^2} \quad \text{for} \quad qG \to Zq$$

For both processes
λ = 1 at q_T = 0 (θ_1=0°)
λ = -1/3 at q_T = ∞ (θ_1=90°)

Data can be well described with a mixture of 58.5% qG and 41.5% $q\bar{q}$ processes

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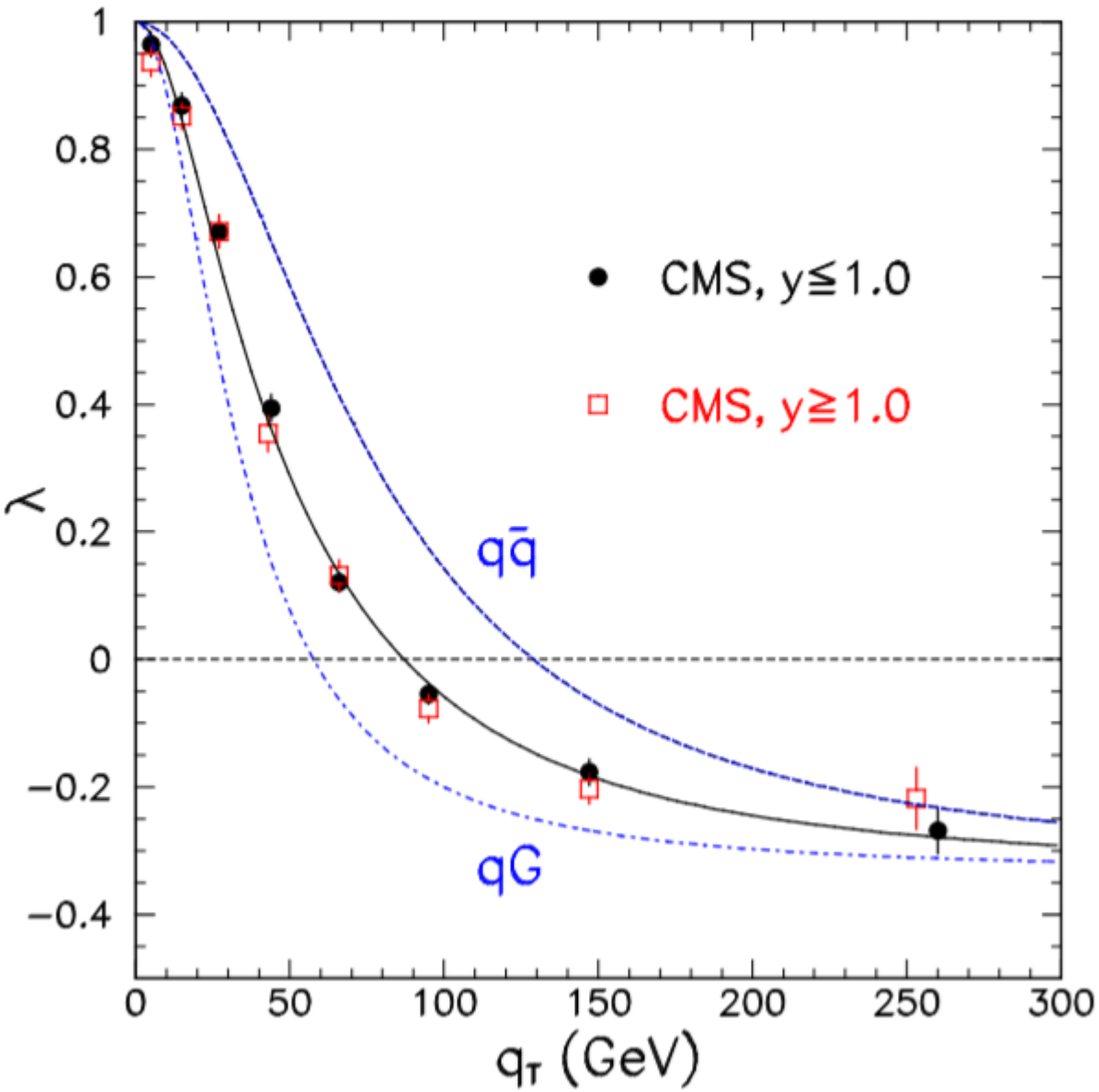
Quark and Gluon Jet Fraction



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Idea: Selection on the away side jet could change the fraction of Z boson coming from qq and qG scattering

With Z polarization studies, one could measure possible modification of

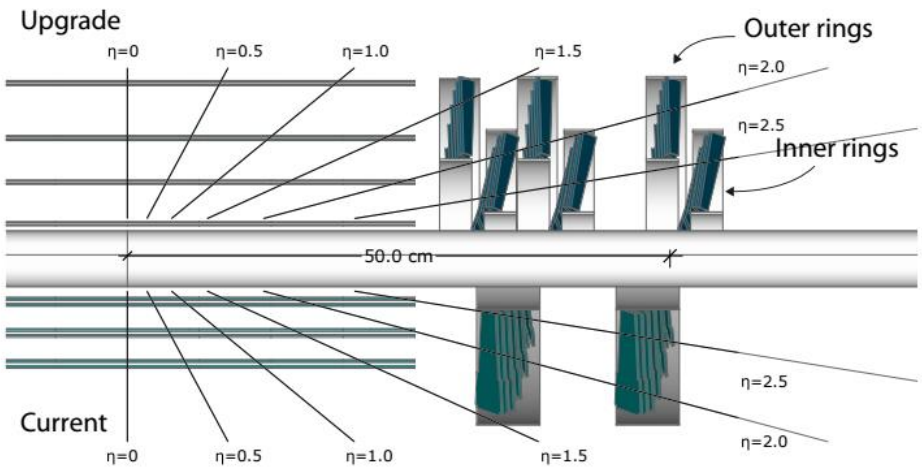
(1) Z production in pPb and PbPb compared to pp

(2) The flavor dependence of the jet modification in [pT spectra, shape and fragmentation function]

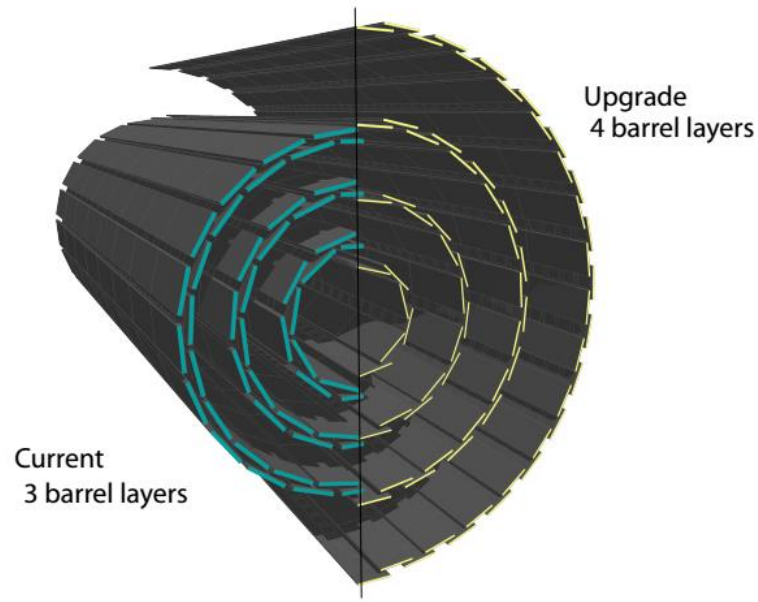
To be done with high statistics Run II+III data (and Run IV data)

Possible caveat: consideration of NLO corrections

Pixel Upgrade (2016 YETS)



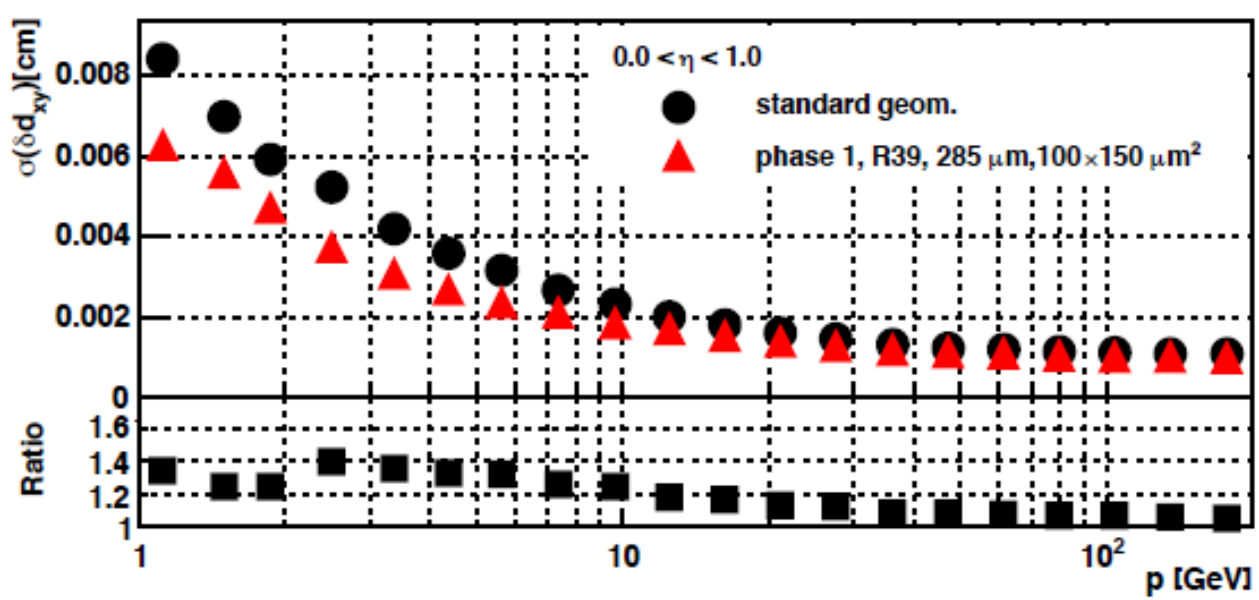
(a) Barrel and For



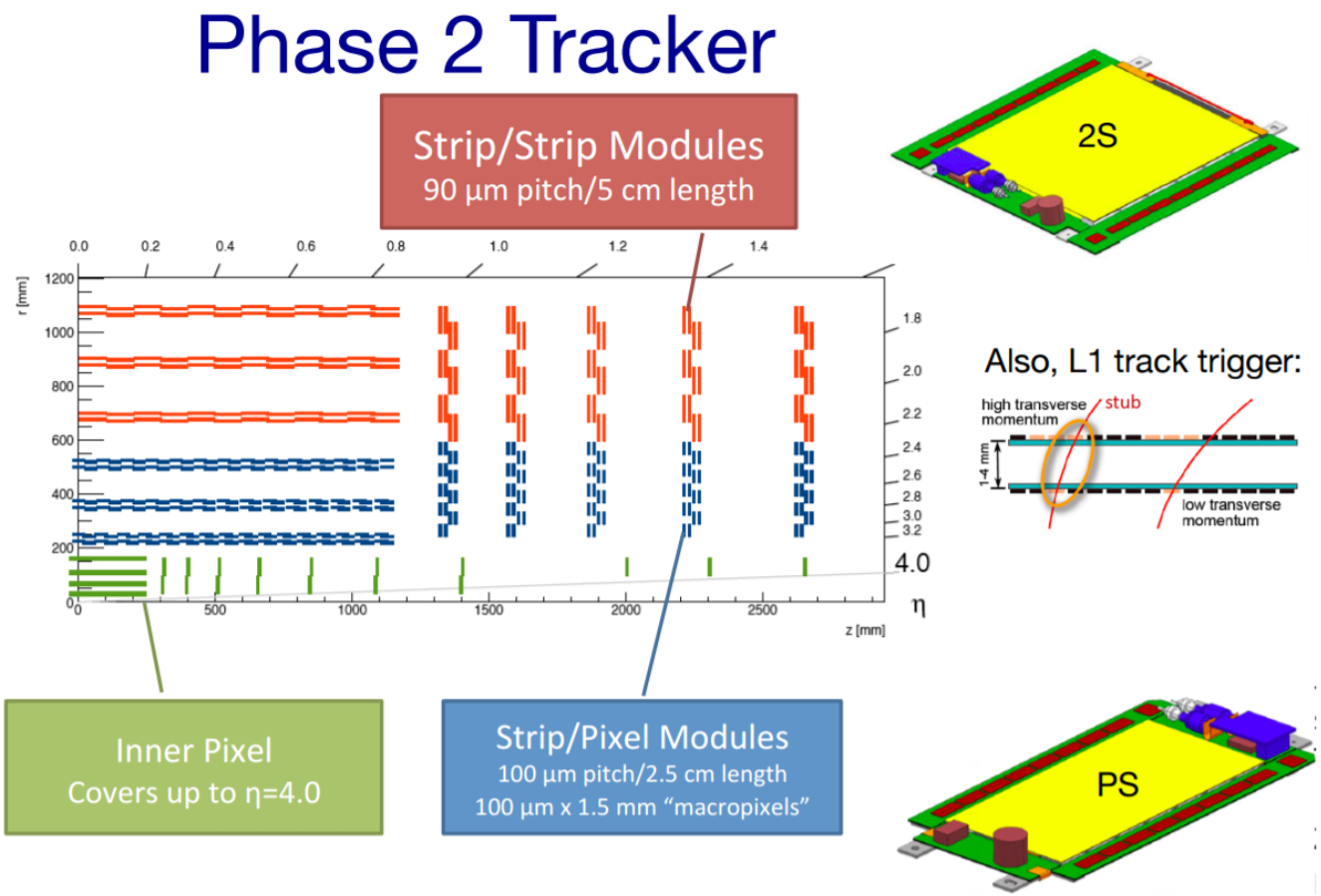
(b) Barrel

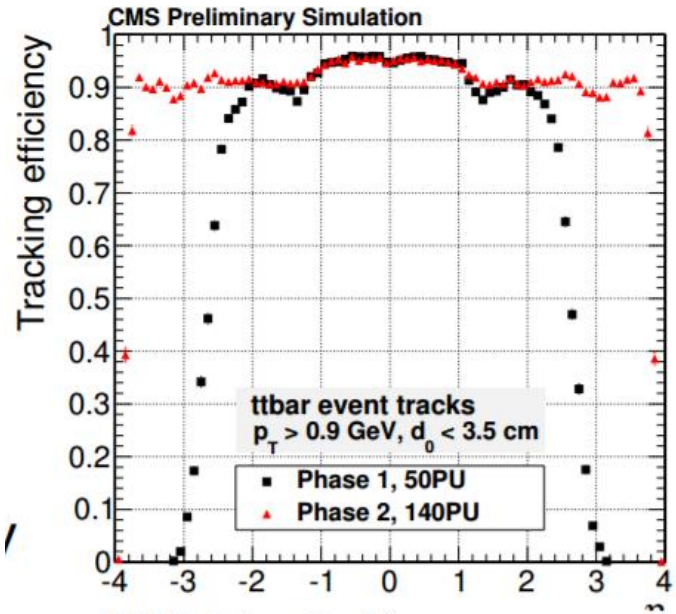
~40% better impact parameter resolution at low track p_T

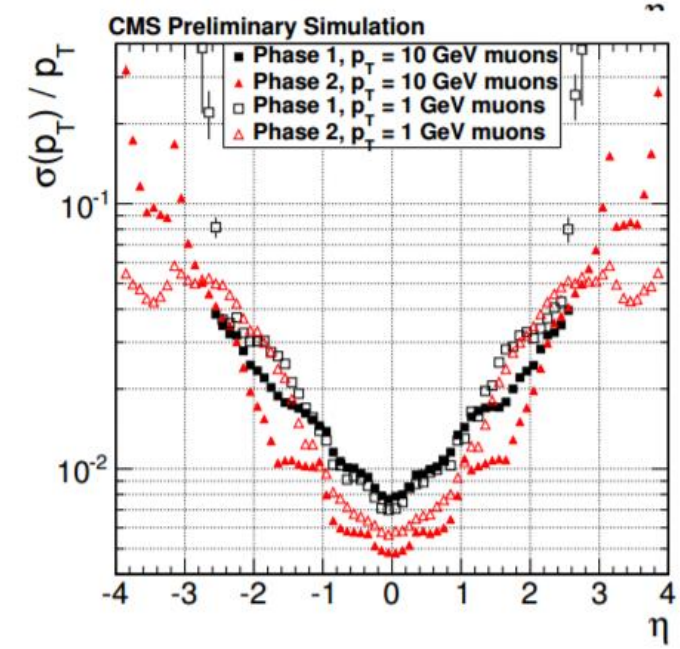
Significant reduction of the fake track rate, and improvement of the b(c)-jet tagging and D^0 meson reconstruction efficiency



CMS Phase 2 upgrade (2024)





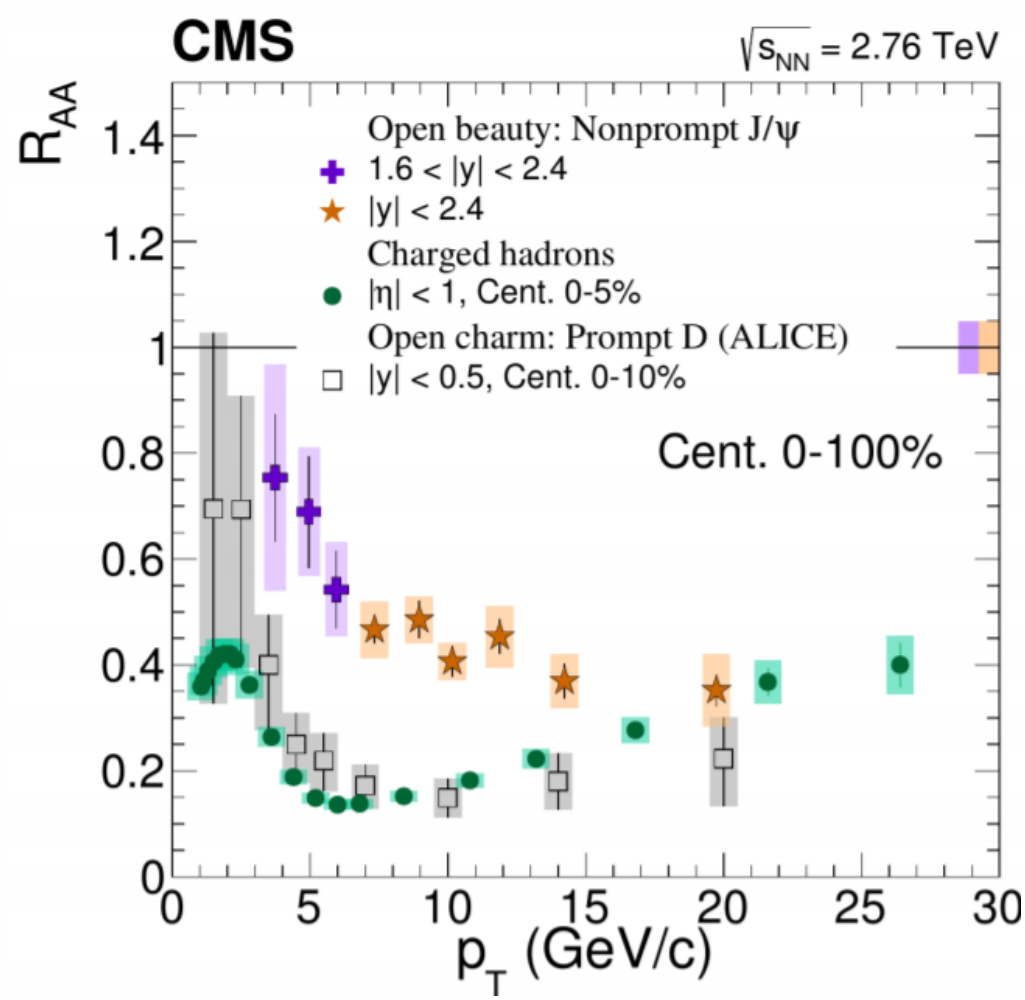


- Tracking capability up to η=4
- Possible muon tagging up to η=3-4

Summary

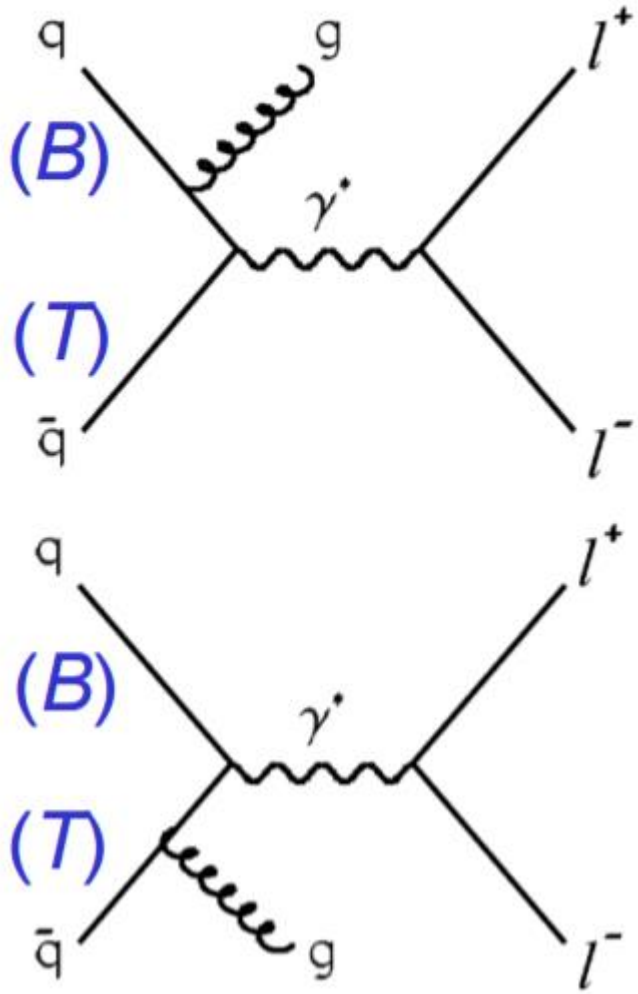
- Heavy quark production cross-section
  - Precise measurement of B and D spectra down to low p_T in pp
  - D and B fragmentation function in pp, pPb and PbPb
- The role of shadowing
  - D and B R_{pA} from ALICE, LHCb and CMS
  - Dijet η with Run II data from CMS (ATLAS)
- Hardronization mechanism
  - D v_2 measurement in pPb vs. event size
  - Charm+X: D_s, Λ_c
  - Bottom+X: B_s, Λ_b with CMS Run II+III (+IV) data
- Collisional energy loss vs. radiative energy loss
  - Precision measurement of D, B and non-prompt J/ψ RAAs at RHIC and LHC
  - D-photon, D-jet measurement (CMS / ATLAS / sPHENIX)
  - D-D and D-hadron measurements (ALICE, CMS)
- Could we see the flavor dependence of Eloss?
  - Precision measurement of HF RAAs at RHIC and LHC
  - High p_T jet substructure for the separation of quark and gluons, (bbar) jets
  - High statistics Z-tagged jet studies (Run II+II (+IV))

Backup slides

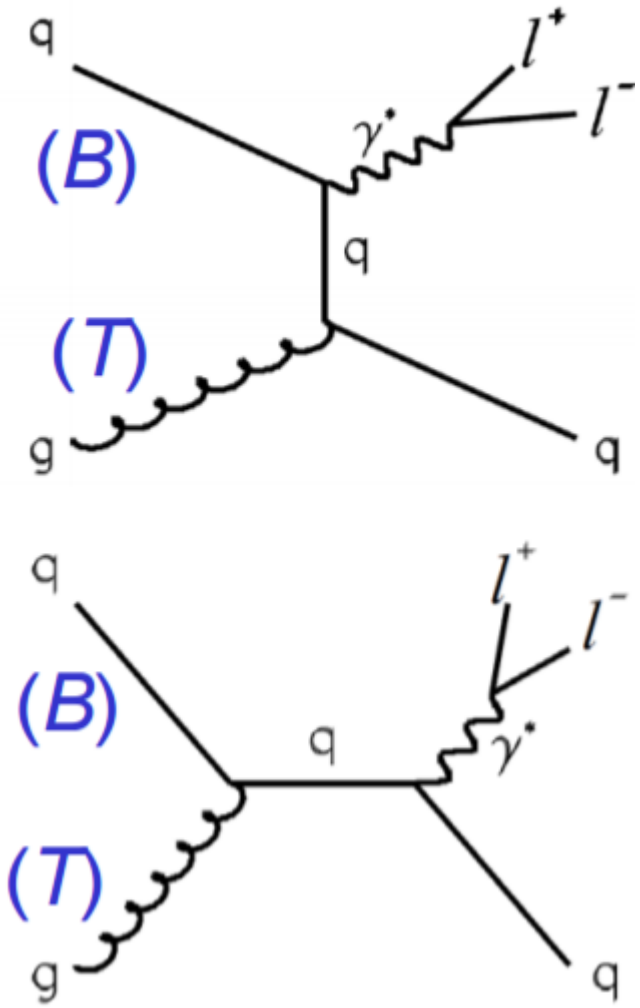

CMS
$\sqrt{s_{NN}}$ = 2.76 TeV
R_{AA}
Open beauty: Nonprompt J/ψ
1.6 < |y| < 2.4
|y| < 2.4
Charged hadrons
|η| < 1, Cent. 0-5%
Open charm: Prompt D (ALICE)
|y| < 0.5, Cent. 0-10%
Cent. 0-100%
p_T (GeV/c)

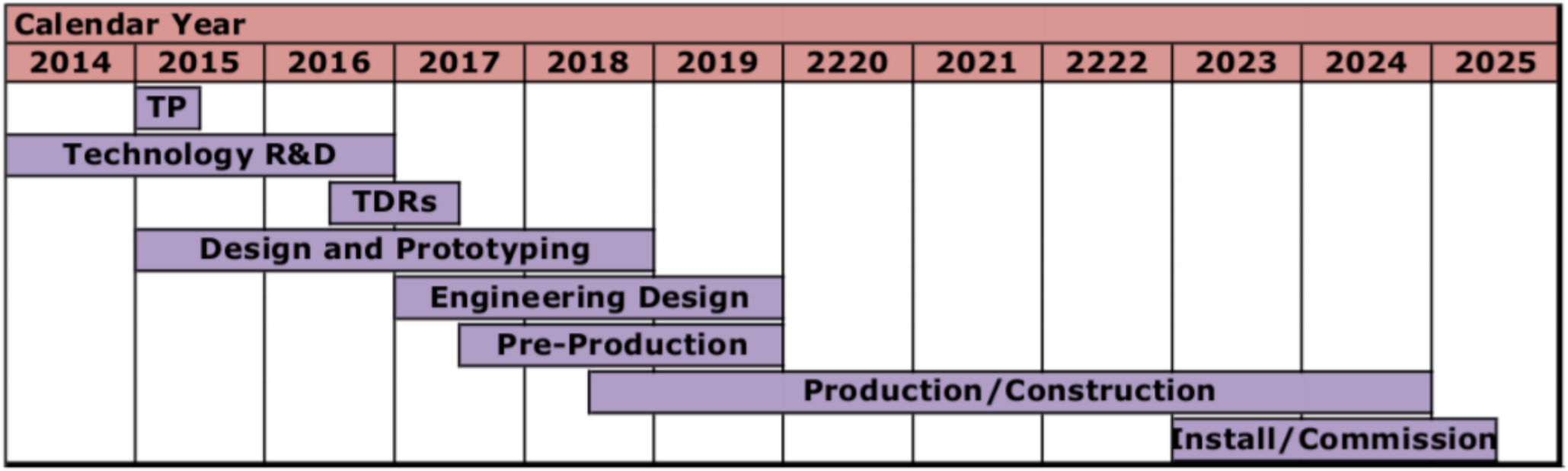
Z-jet production in $O(\alpha_s)$

1) $q\bar{q} \rightarrow \gamma^*(Z^0)g$

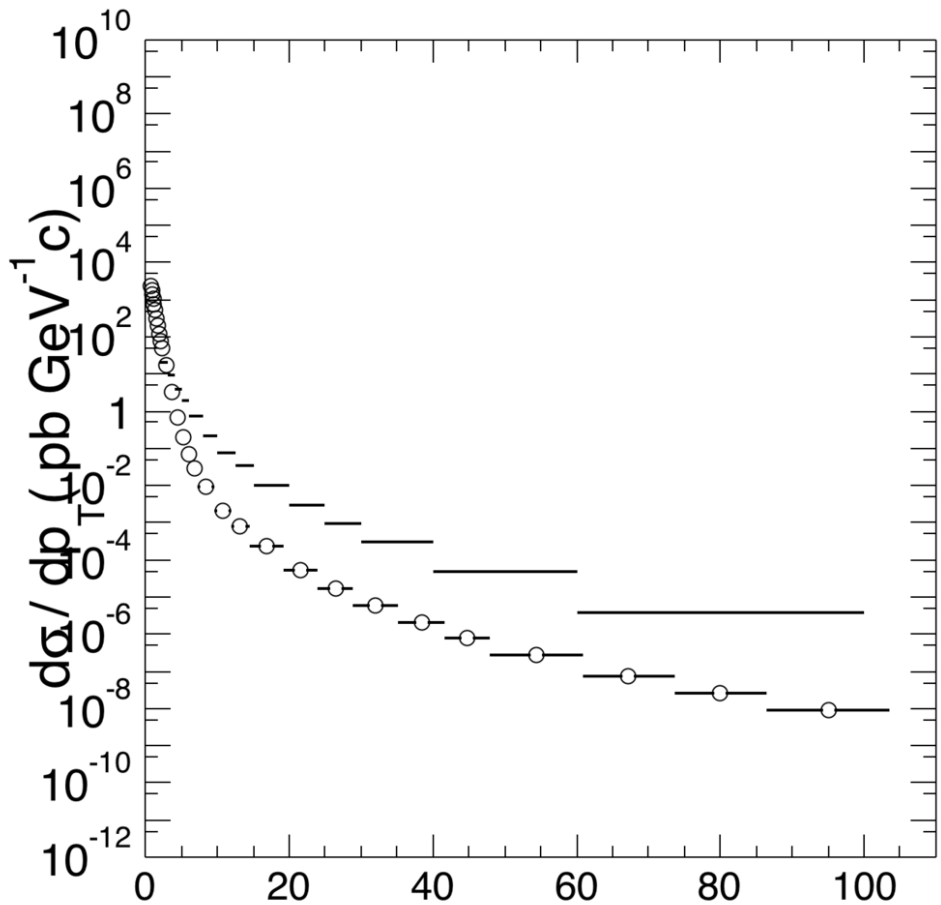


2) $qg \rightarrow \gamma^*(Z^0)q$




Calendar Year
2014
2015
2016
2017
2018
2019
2220
2021
2222
2023
2024
2025
TP
Technology R&D
TDRs
Design and Prototyping
Engineering Design
Pre-Production
Production/Construction
Install/Commission

D vs


$d\sigma / dp_T$ (μb GeV^{-1}c)
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
0
20
40
60
80
100