What have we learnt with CMS on flavour dependence ?

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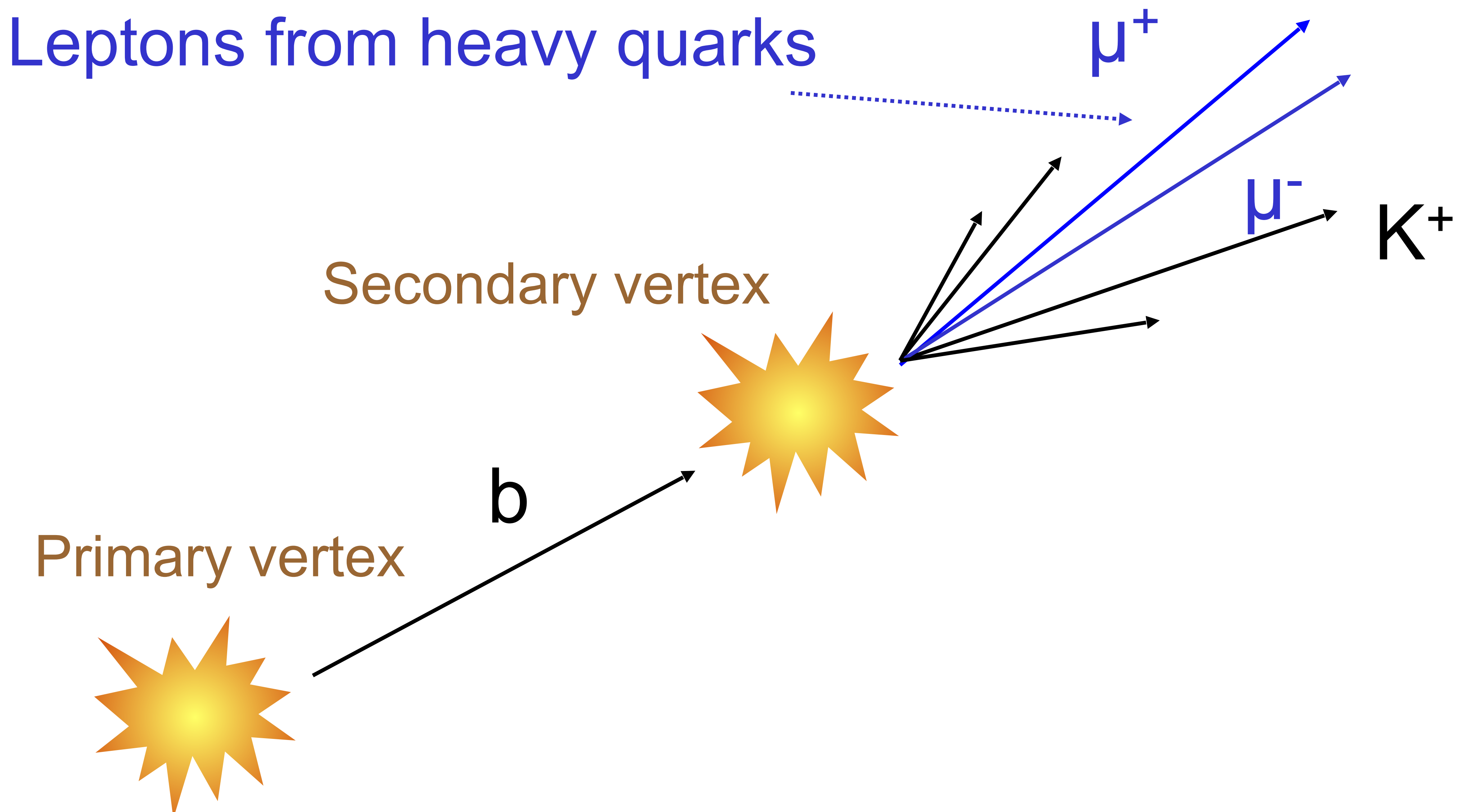
Massachusetts Institute of Technology (MIT)

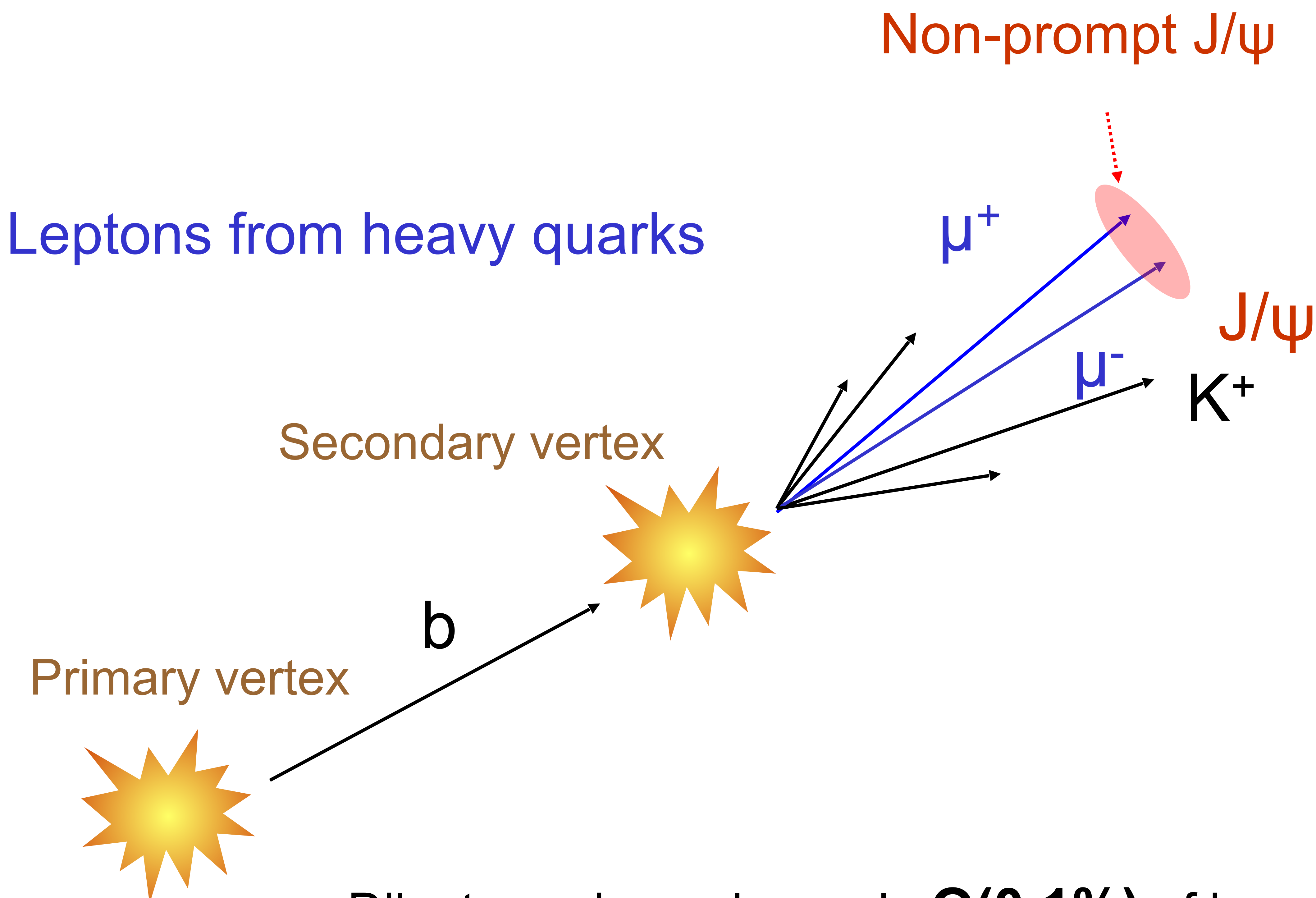
25-27 July 2016
Ecole Polytechnique (Paris)

How to measure beauty with CMS



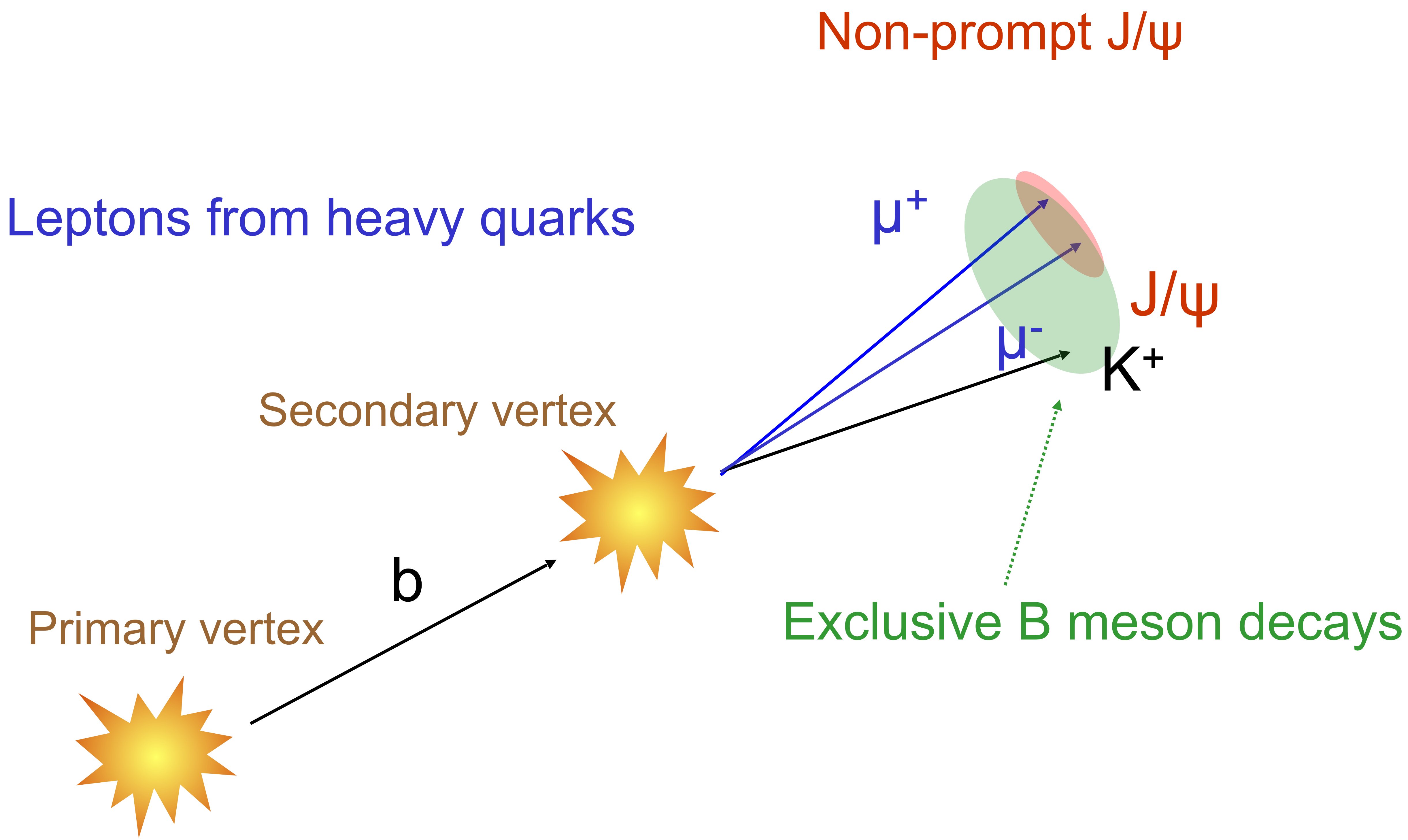
Sample **O(10%)** of b cross-section

How to measure beauty with CMS



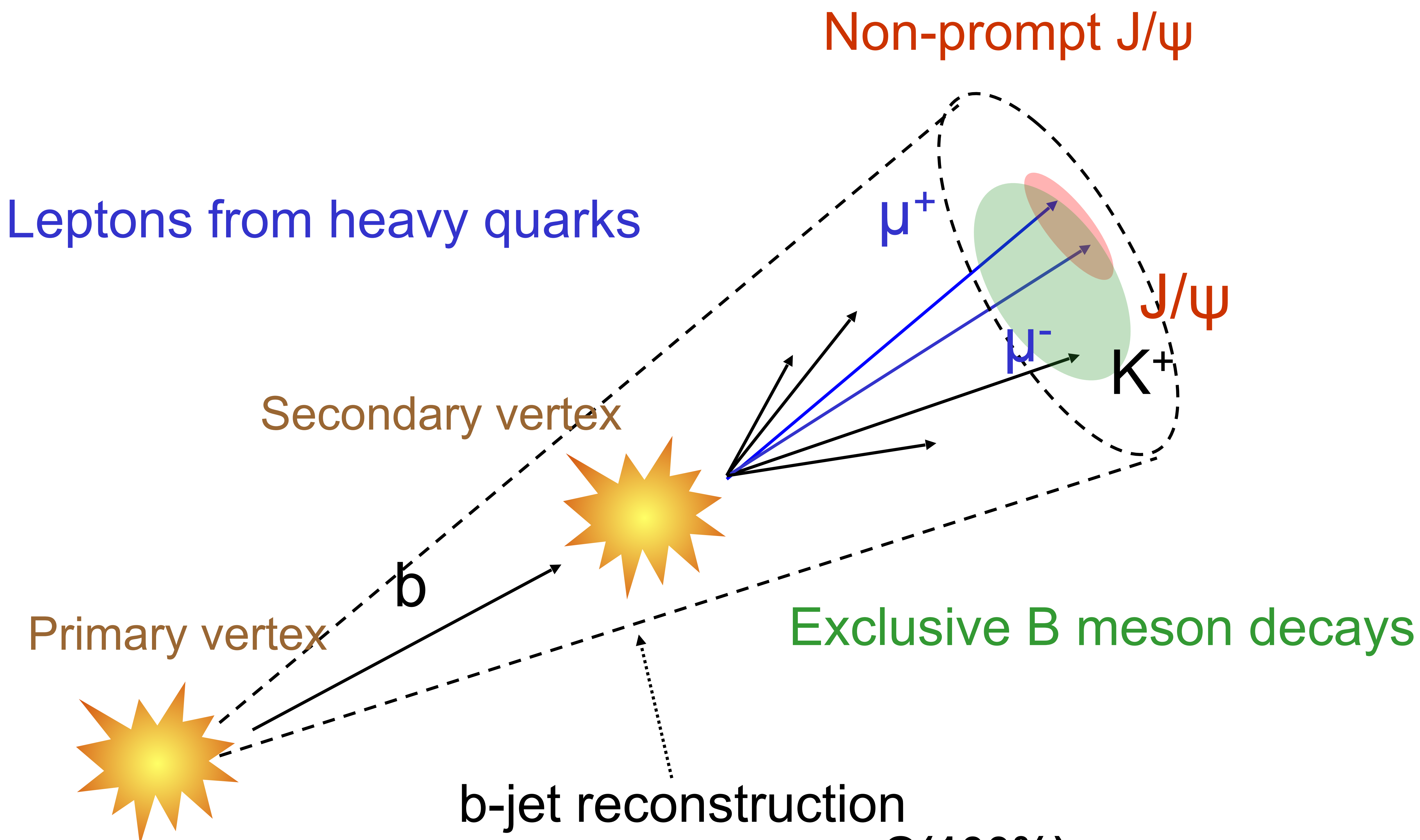
Dileptons channel sample **O(0.1%)** of b cross-section

How to measure beauty with CMS



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

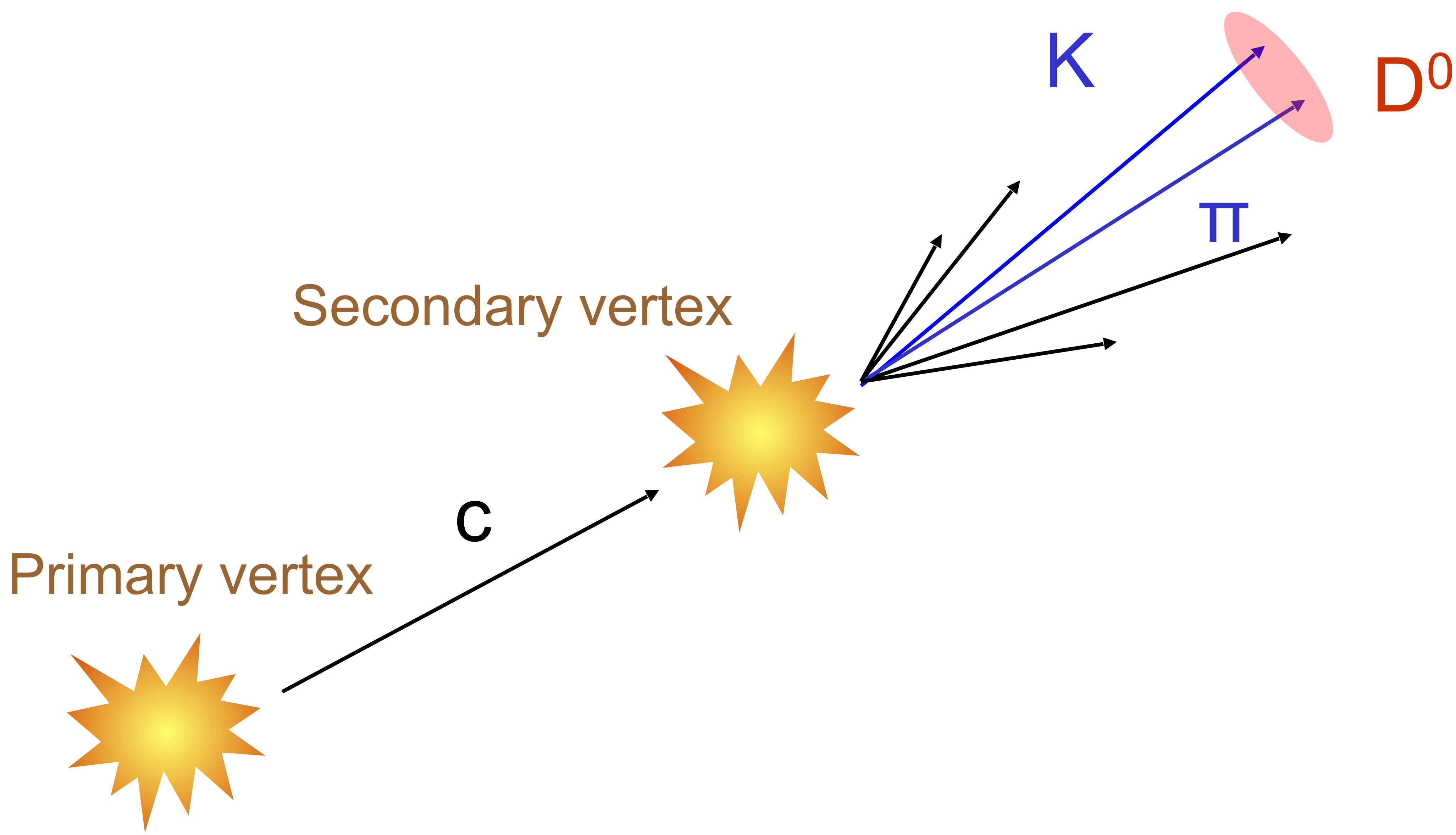
How to measure beauty with CMS



b-jet reconstruction

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

How to measure charm with CMS



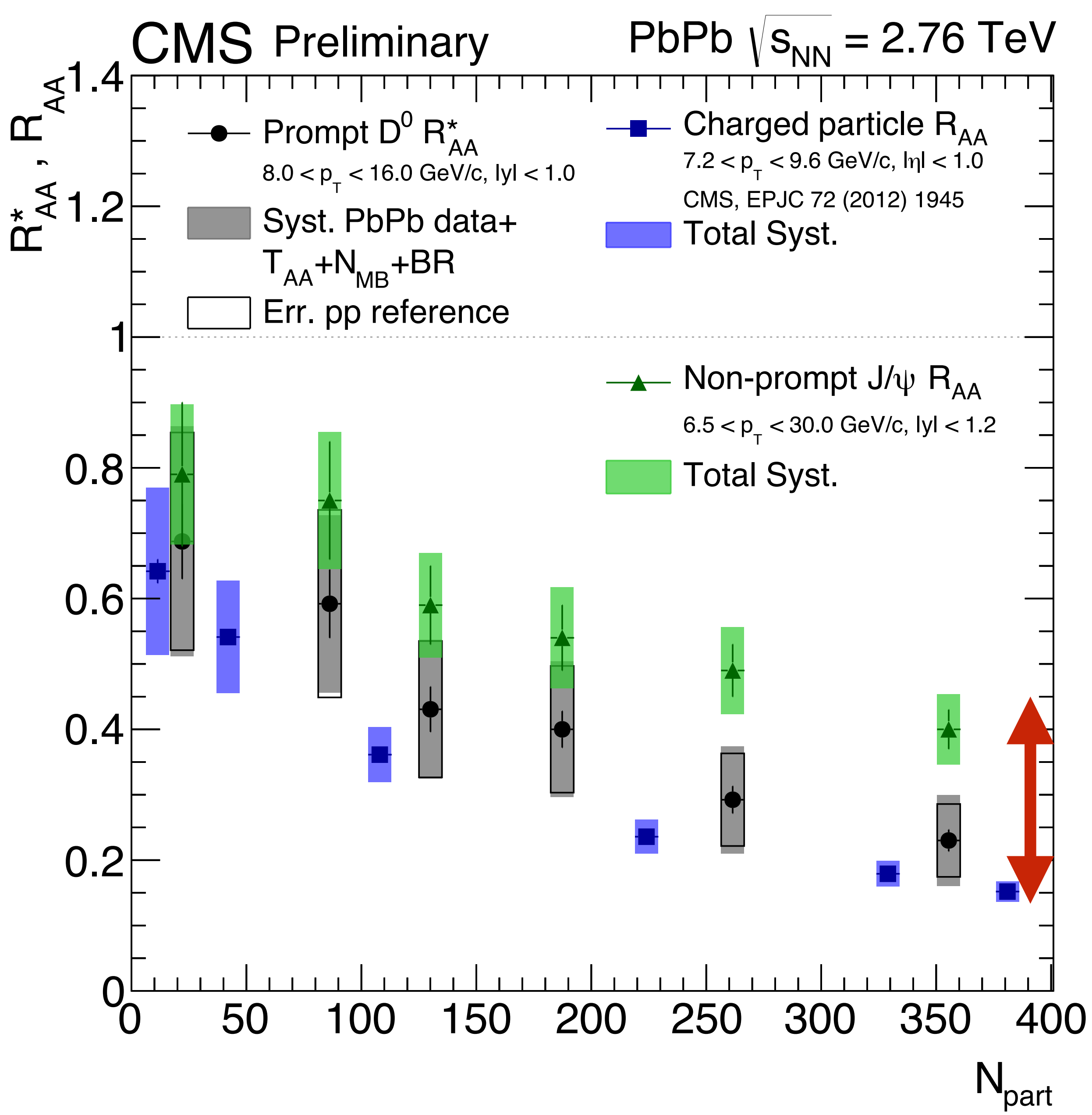
$D^0 \rightarrow K\pi$ decay channels sample **O(0.01%)** of c cross-section

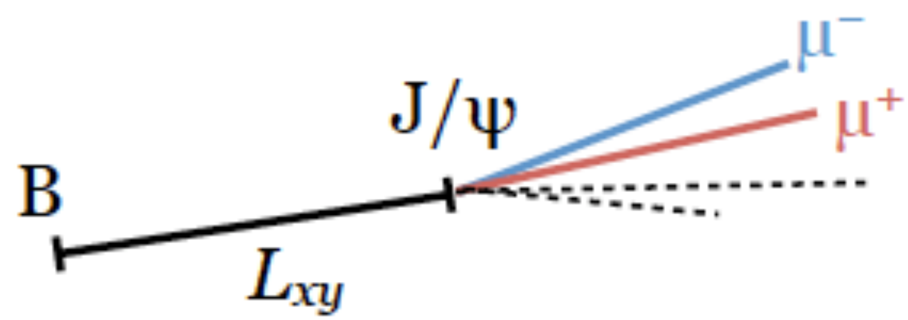
Run I heavy flavour analysis

non-prompt J/ψ measurements

CMS-HIN-15-005

Getting closer to the b-quark kinematics!



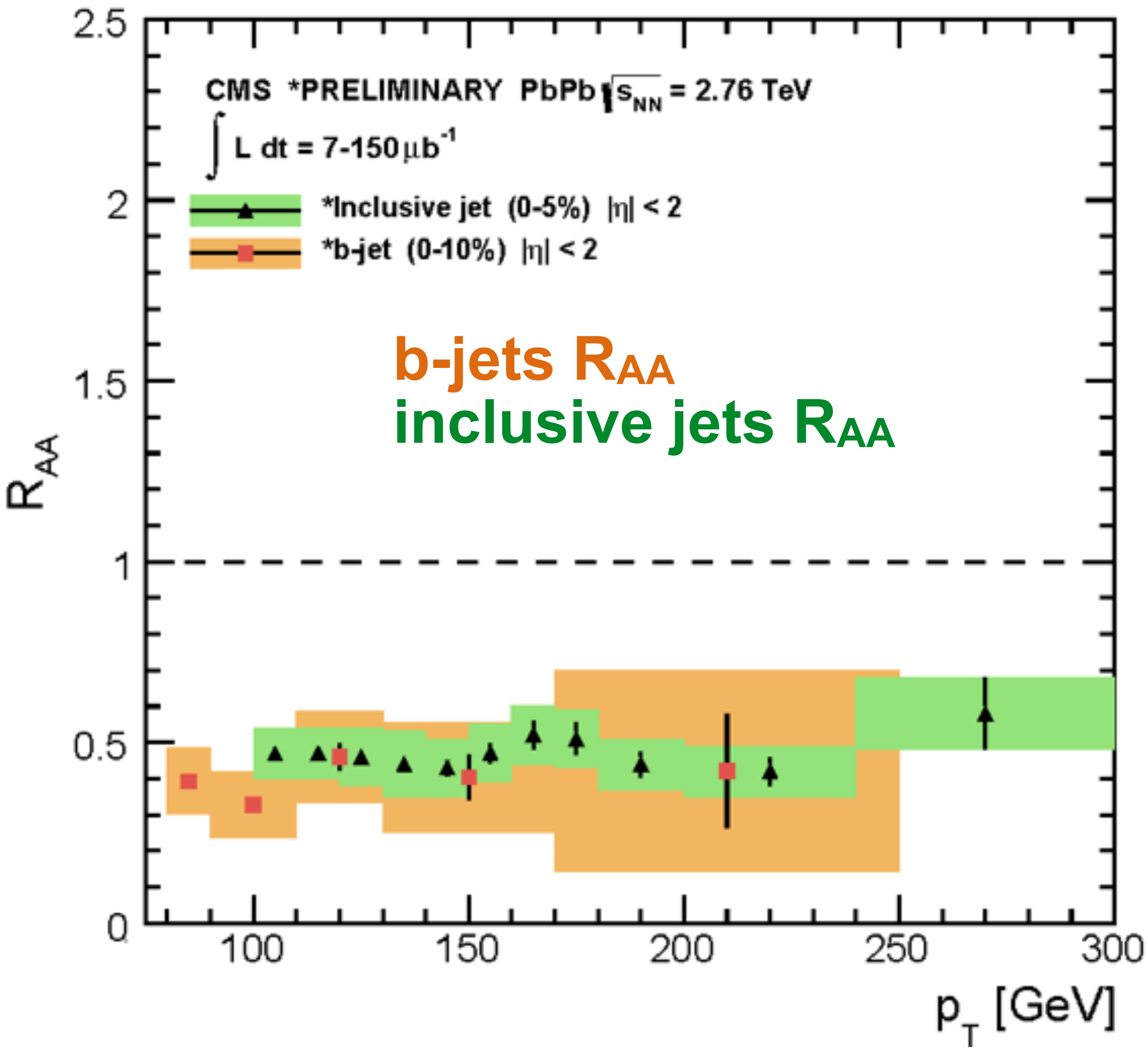


Charged particle
Non prompt J/ψ
D mesons

Hints of different suppression for **D mesons** and **non-prompt J/ψ** at low p_T!

b-jet nuclear modification in PbPb at 2.76 TeV

b-jets tagged by selecting displaced secondary vertices (SV) in the jet cone



b-jets R_{AA} shows strong suppression (factor~3) observed in central PbPb collisions (0-5%)

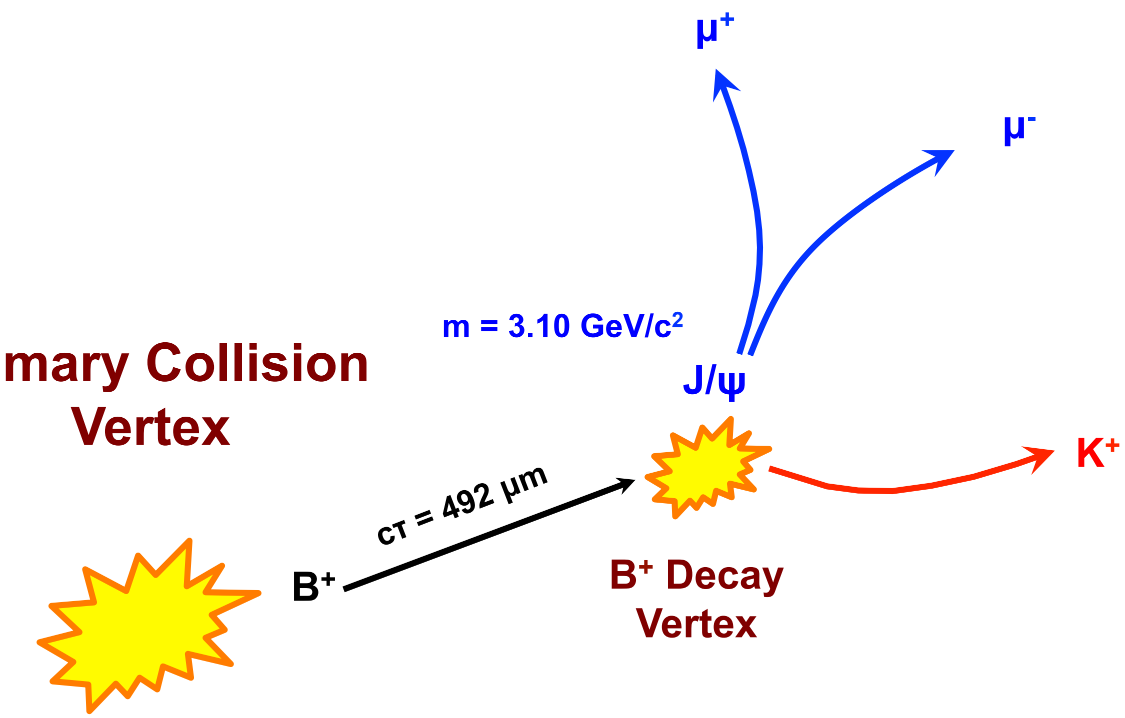
Same suppression observed for b-jets and inclusive jets in the same centrality

Are we measuring the energy loss of gluons in both cases (gluon splitting)?

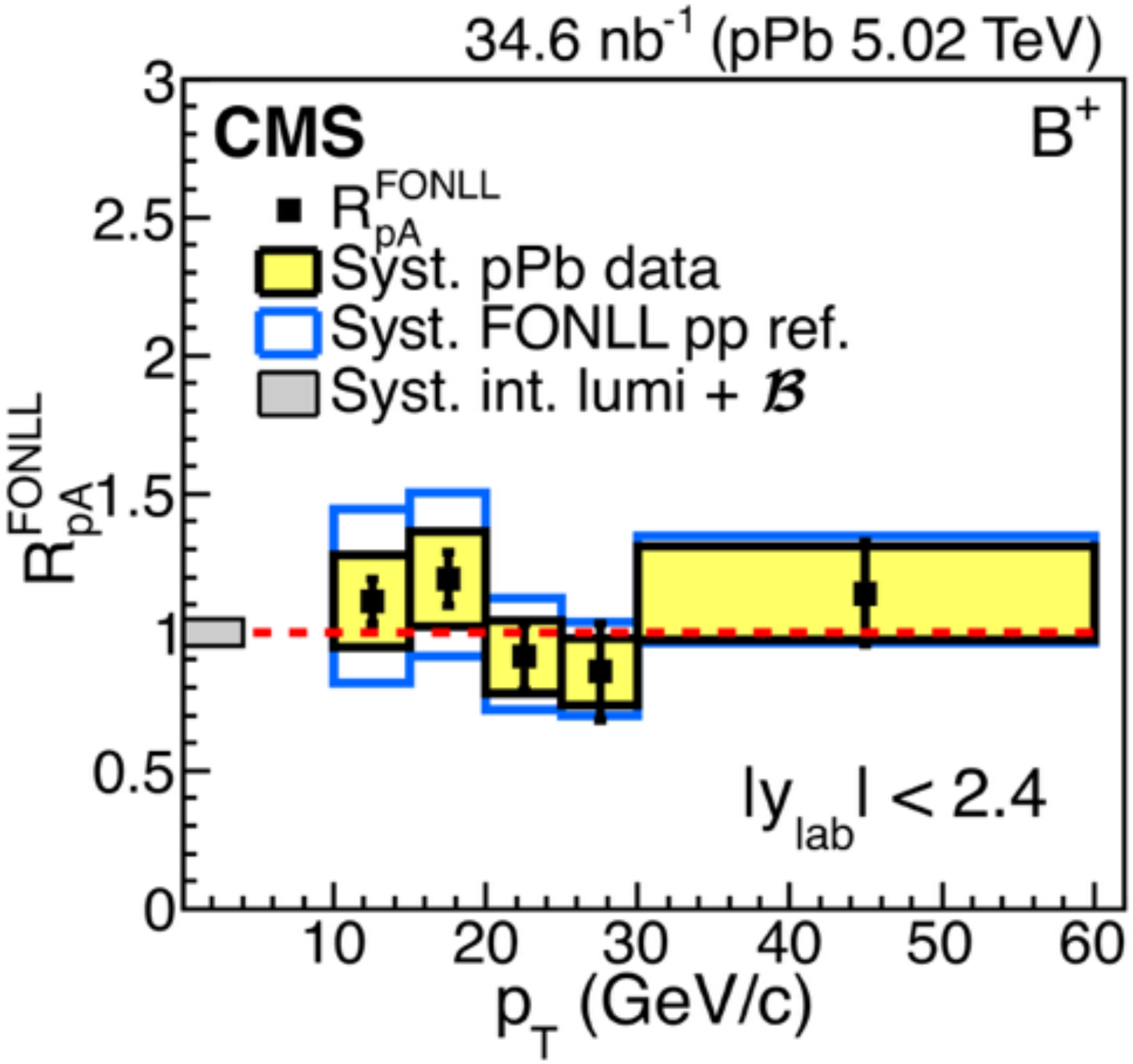
Phys. Rev. Lett. 113, 132301 (2014)

Exclusive B meson measurements

PRL 116 (2016) 032301



- $J/\psi \rightarrow \mu^+\mu^-$ reconstruction
- Tracks are associated to J/ψ candidate to build B-meson candidates



Measured in pPb collisions only:

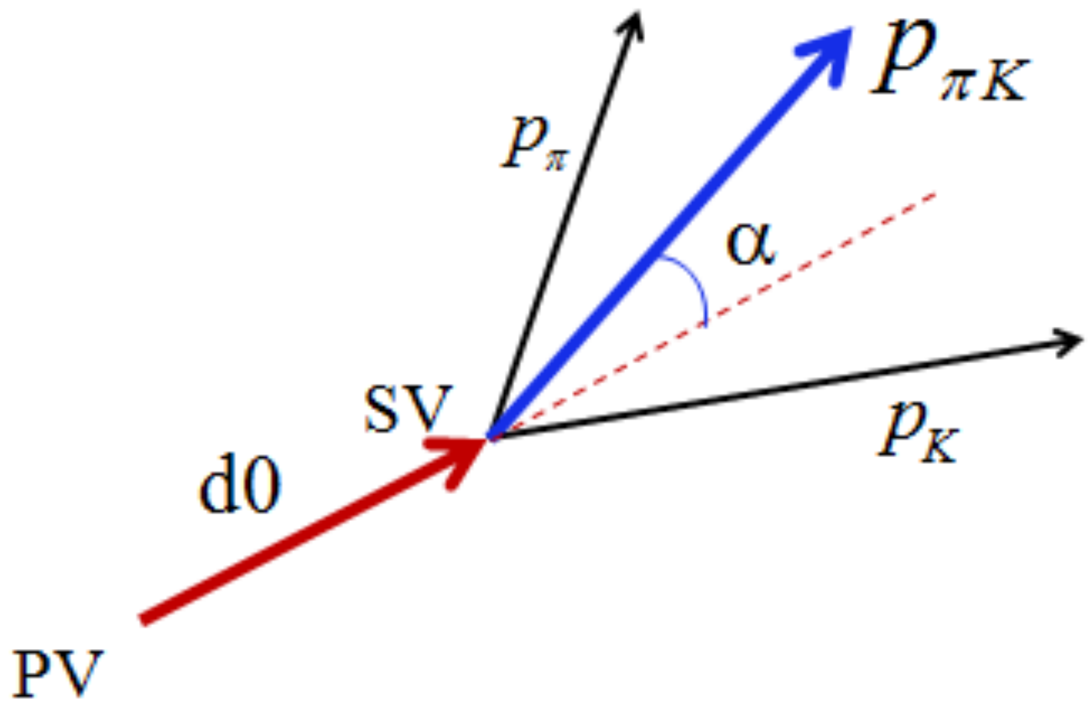
- R^{FONLL}_{pA} consistent to unity

PbPb measurement coming soon!

First Run II heavy flavour analysis!

CMS-PAS-HIN-16-001

D^0 measurements in pp and PbPb collisions



$D^0 \rightarrow K^- \pi^+$ in pp and PbPb collisions
(0-10% and 0-100%) at 5.02 TeV in |y|<1.0

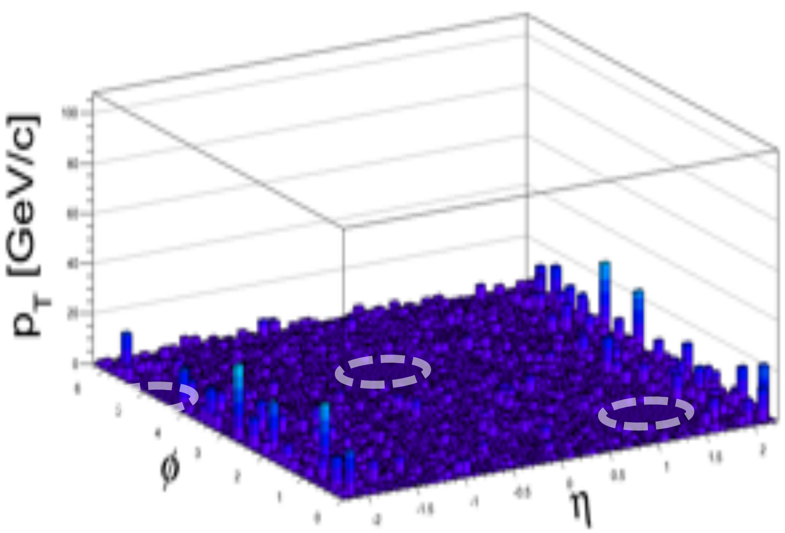
Analysis strategy:
- Primary and D^0 vertex reconstruction
- D^0 candidate reconstruction
- D meson selection**:**
  - pointing angle **(α)**
  - decay length normalised to its error **(d_0)**
  - D^0 vertex probability

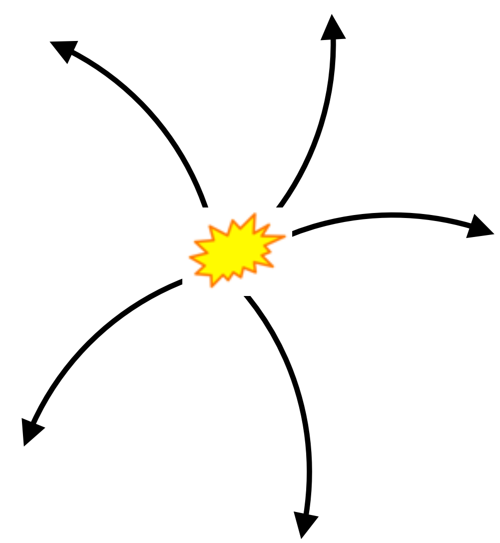
↓

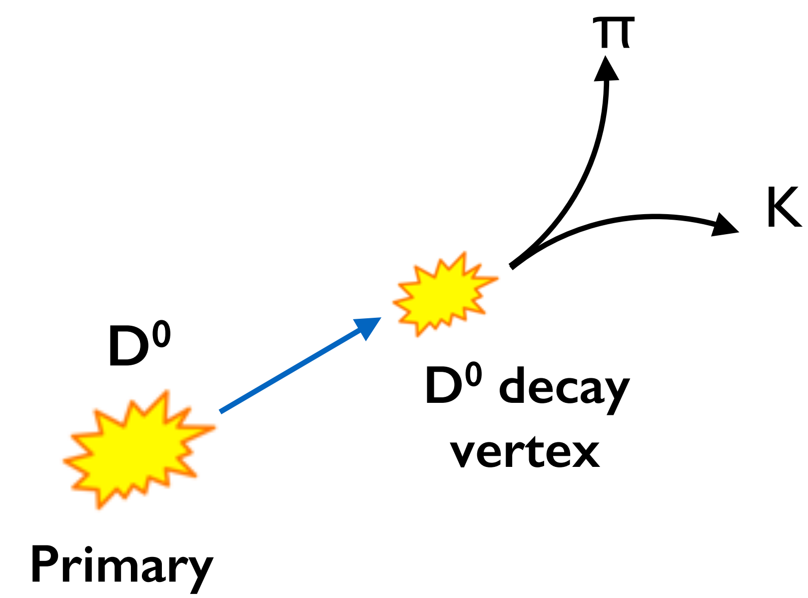
Invariant mass analysis

Data samples:
- **2 billion pp MB events** in pp and **150 million PbPb MB** for low p_T analysis (<20 GeV/c)
- **Triggered sample** selected with dedicated HLT D^0 filters to enhance the statistics up to very high p_T (p_T>20 GeV/c)

D^0 triggers at High-Level-Trigger (HLT)







Events firing hardware jet triggers (Level-1) are selected

- L1 jet algorithm with online background subtraction

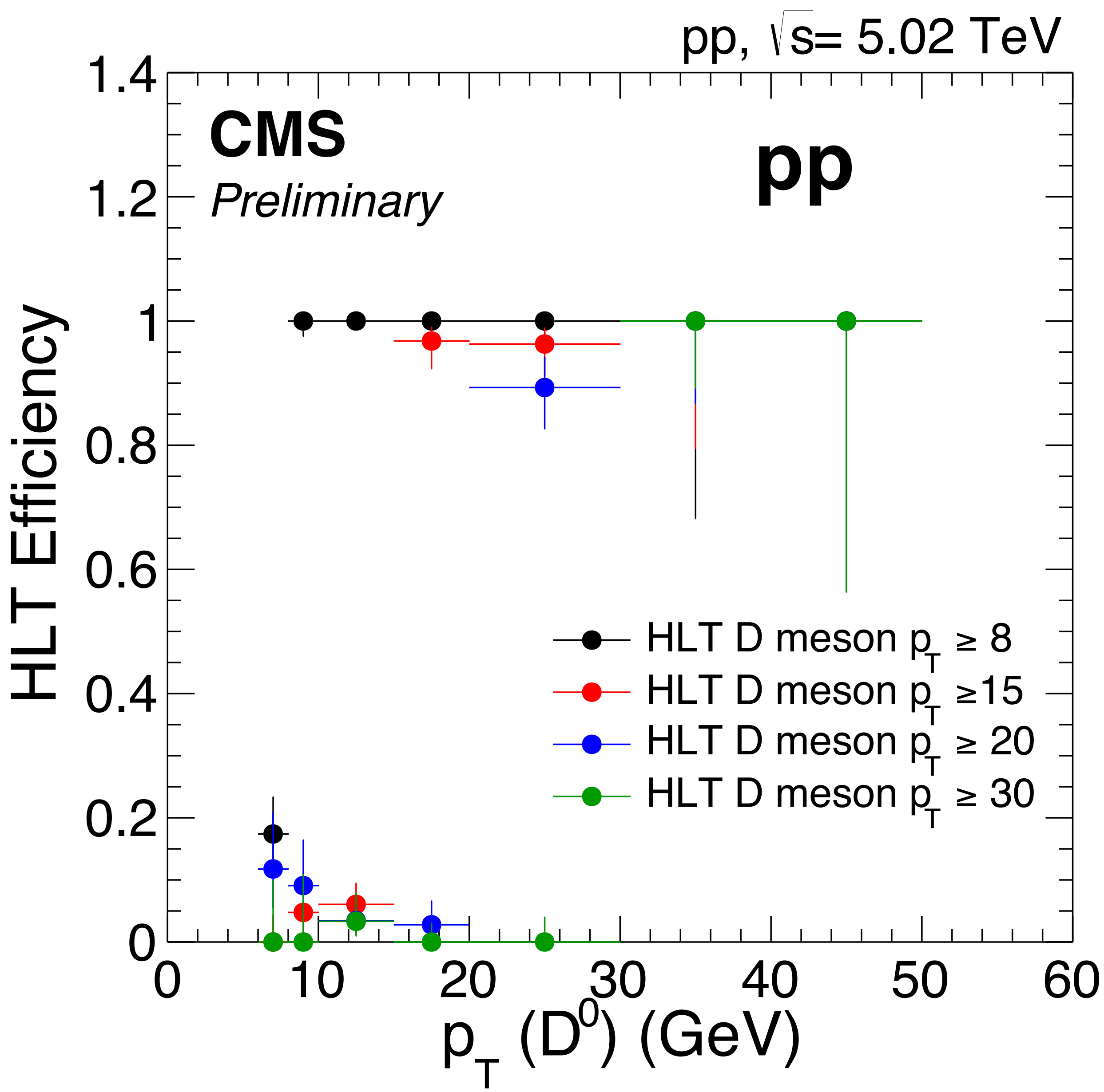
Tracks are reconstructed in software trigger system (HLT) for selected events

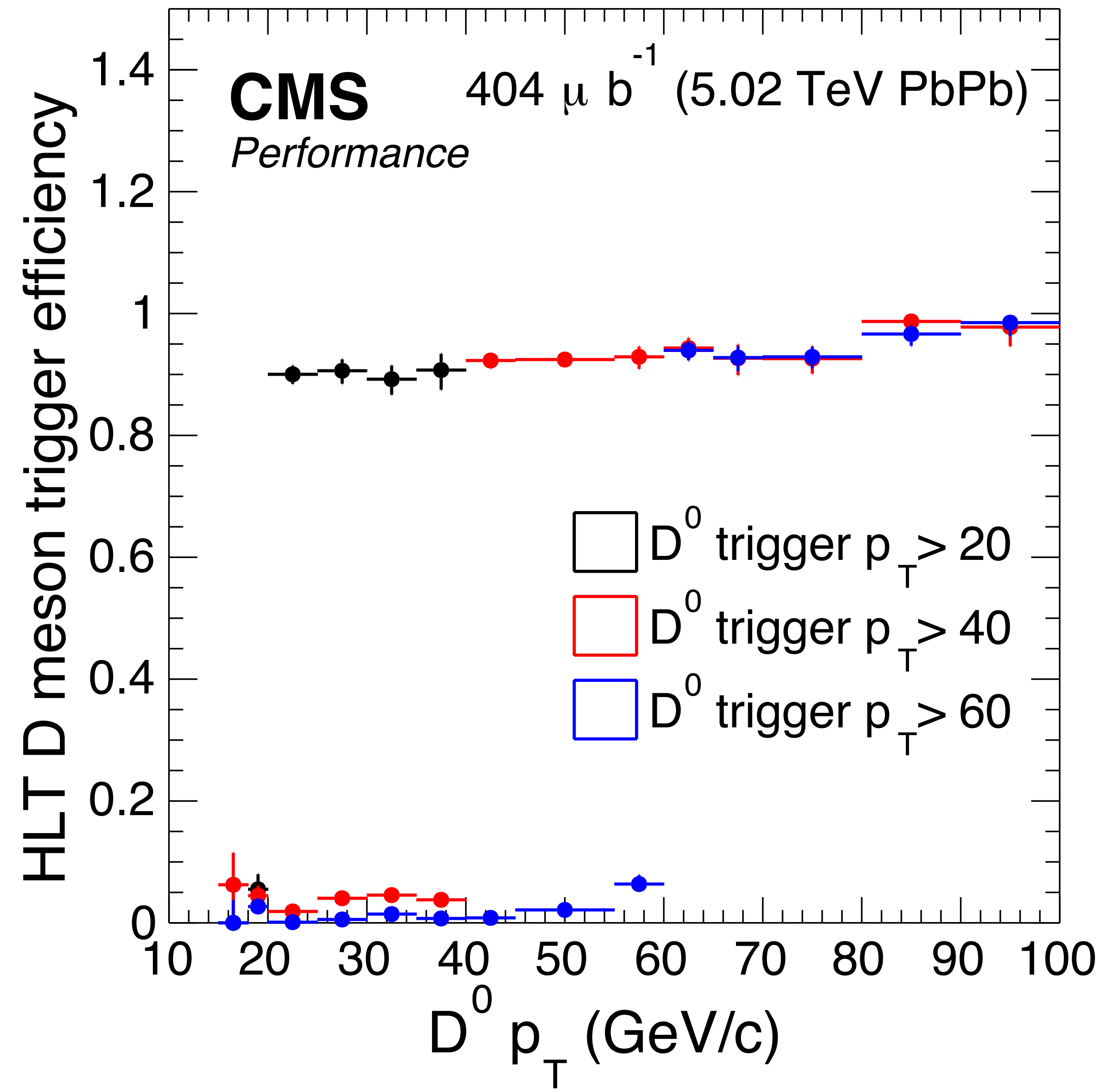
Track seed p_T cut applied:
- $p_T > 2$ GeV for pp
- $p_T > 8$ GeV for PbPb

D^0 meson are reconstructed

- Online D^0 reconstruction
- loose selection to reduce the rates based on D^0 vertex displacement

Performances of D^0 triggers





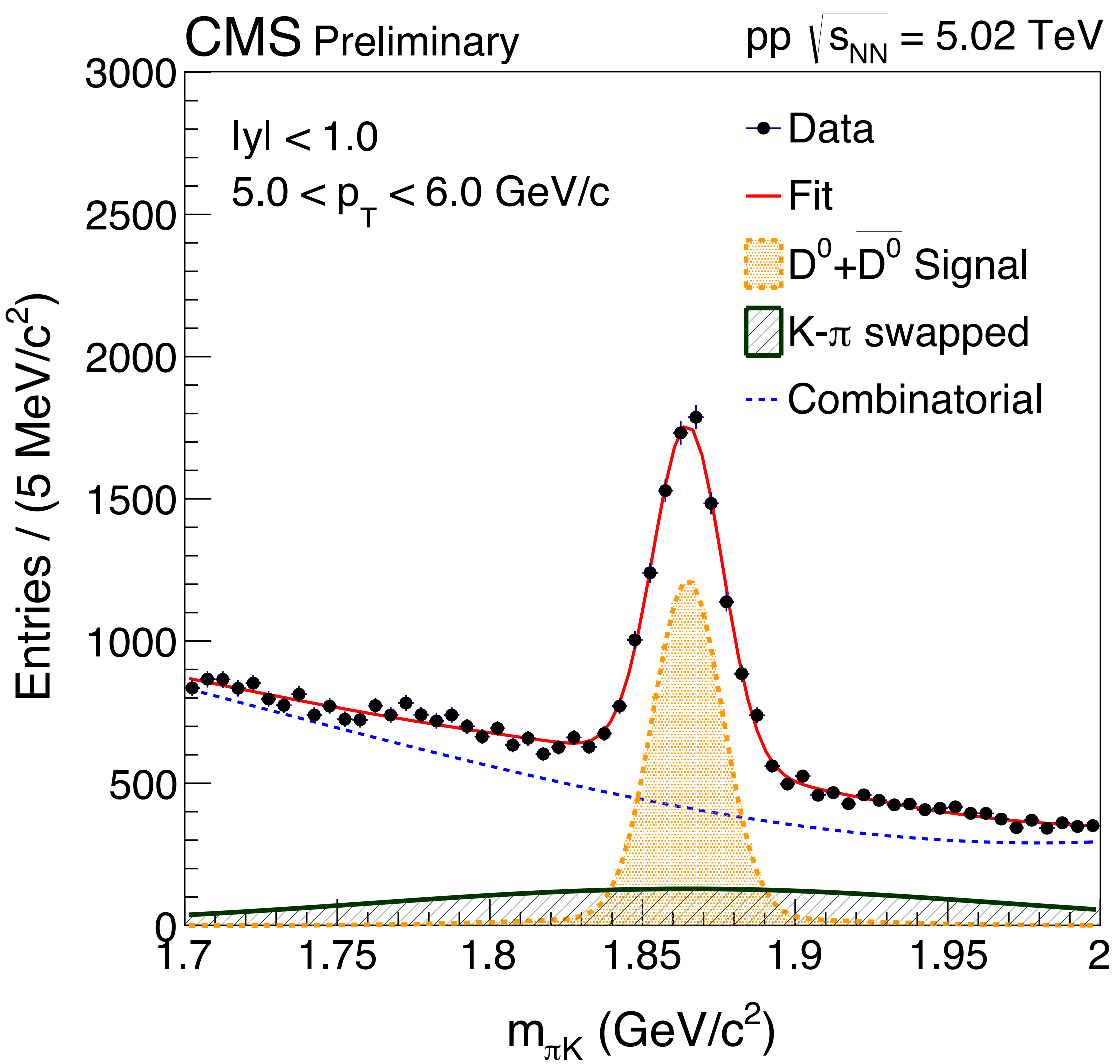
→ pp efficiency reaches 100% right above its D^0 p_T threshold

→ PbPb efficiency goes from ~90 to 100% depending on p_T

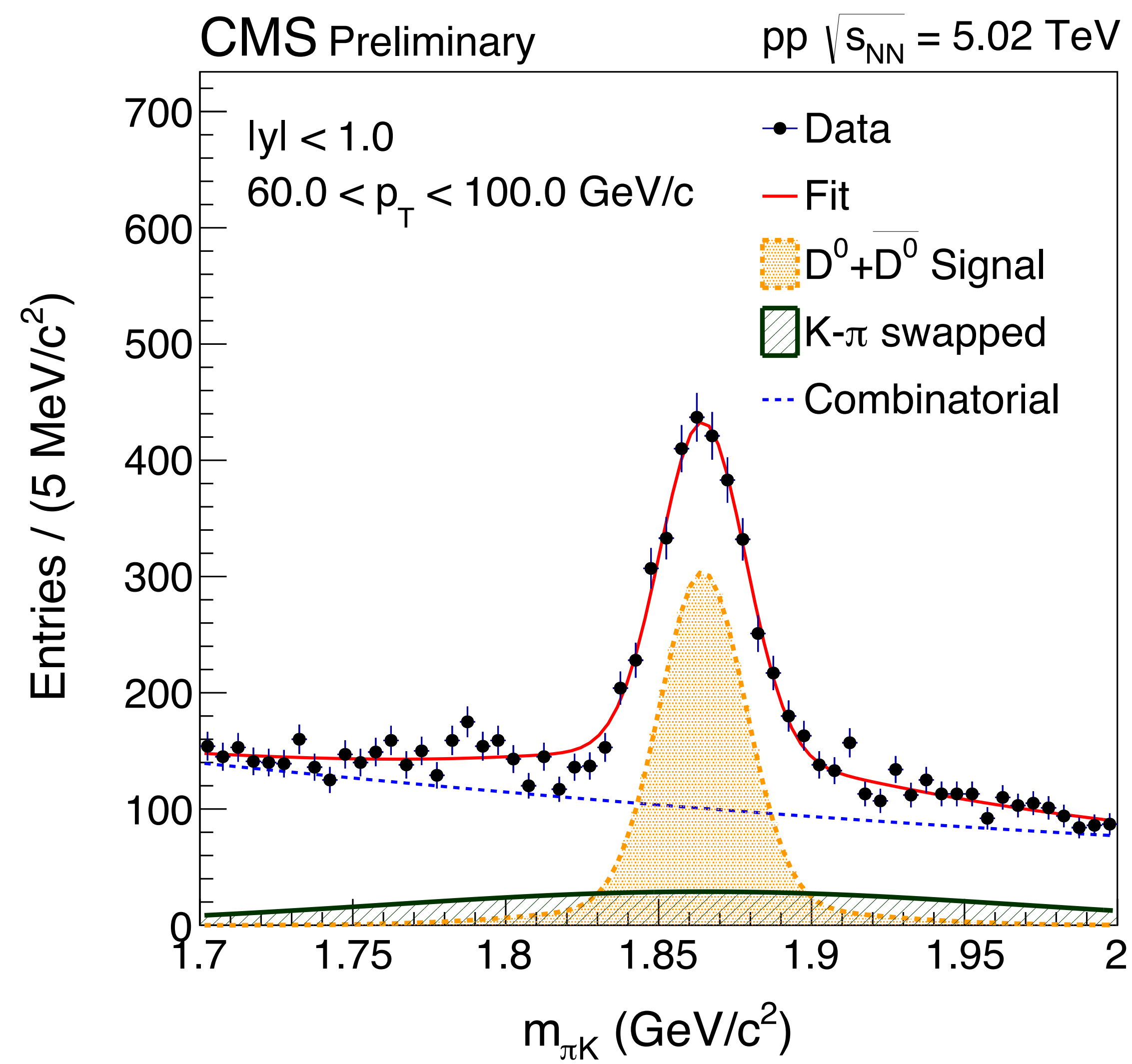
proton-proton spectra at 5.02 TeV

- Invariant mass spectra of D^0 mesons in pp collisions at 5.02 TeV

$5<p_T<6$ GeV/c



$60<p_T<100$ GeV/c



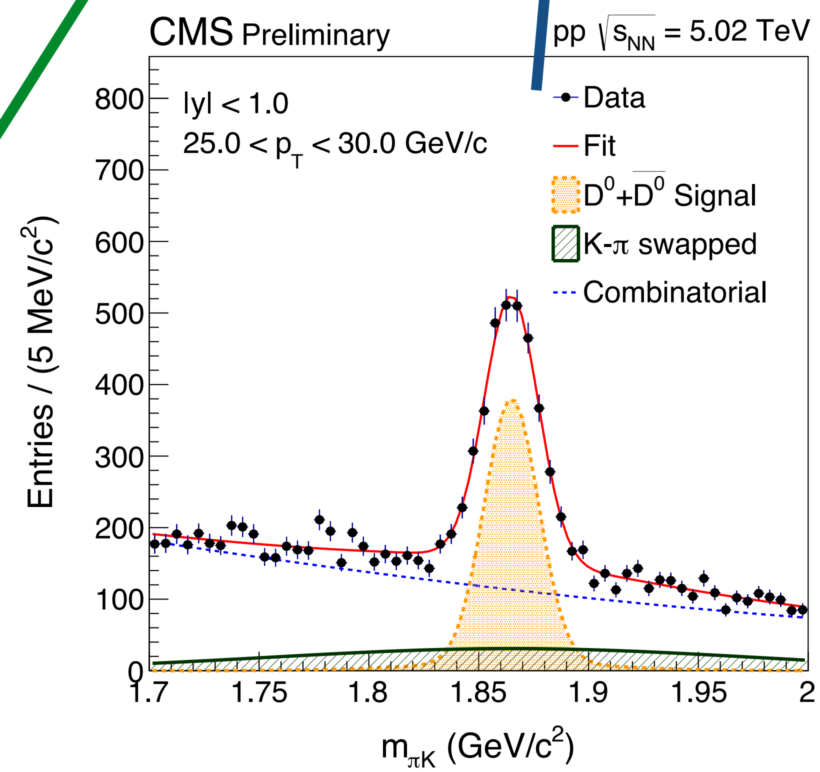
Mass distributions fitted with:

- 3rd order polynomial fit for **combinatorial background**
- Double gaussian to **model the signal**
- Gaussian shape to model **the candidates with swapped mass hypothesis**

From raw yields to cross sections

$$\left.\frac{d\sigma^{D^0}}{dp_T}\right|_{|y|<1.0} = \frac{1}{2}\frac{f_{prompt}}{\Delta p_T}\frac{\left.N^{D^0}\right|_{|y|<1.0}}{(Acc\times\epsilon)_{prompt}\cdot BR\cdot\alpha_{prescale}\cdot\epsilon_{trigger}\cdot\mathcal{L}}$$

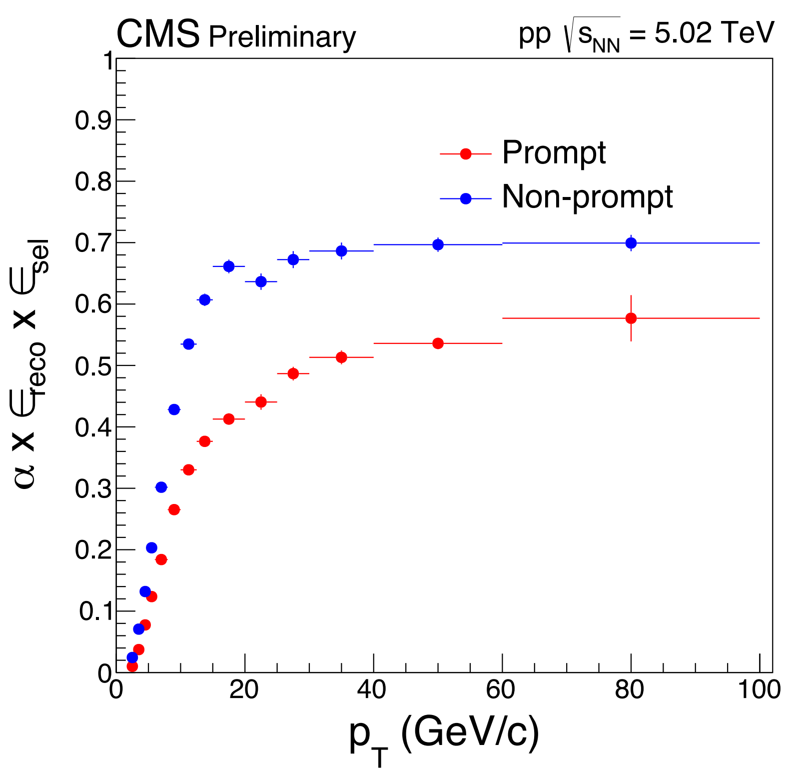
fraction of prompt D^0: fully data driven for the first time in heavy ions



raw yields extracted via fits to invariant mass distributions

For triggered data:

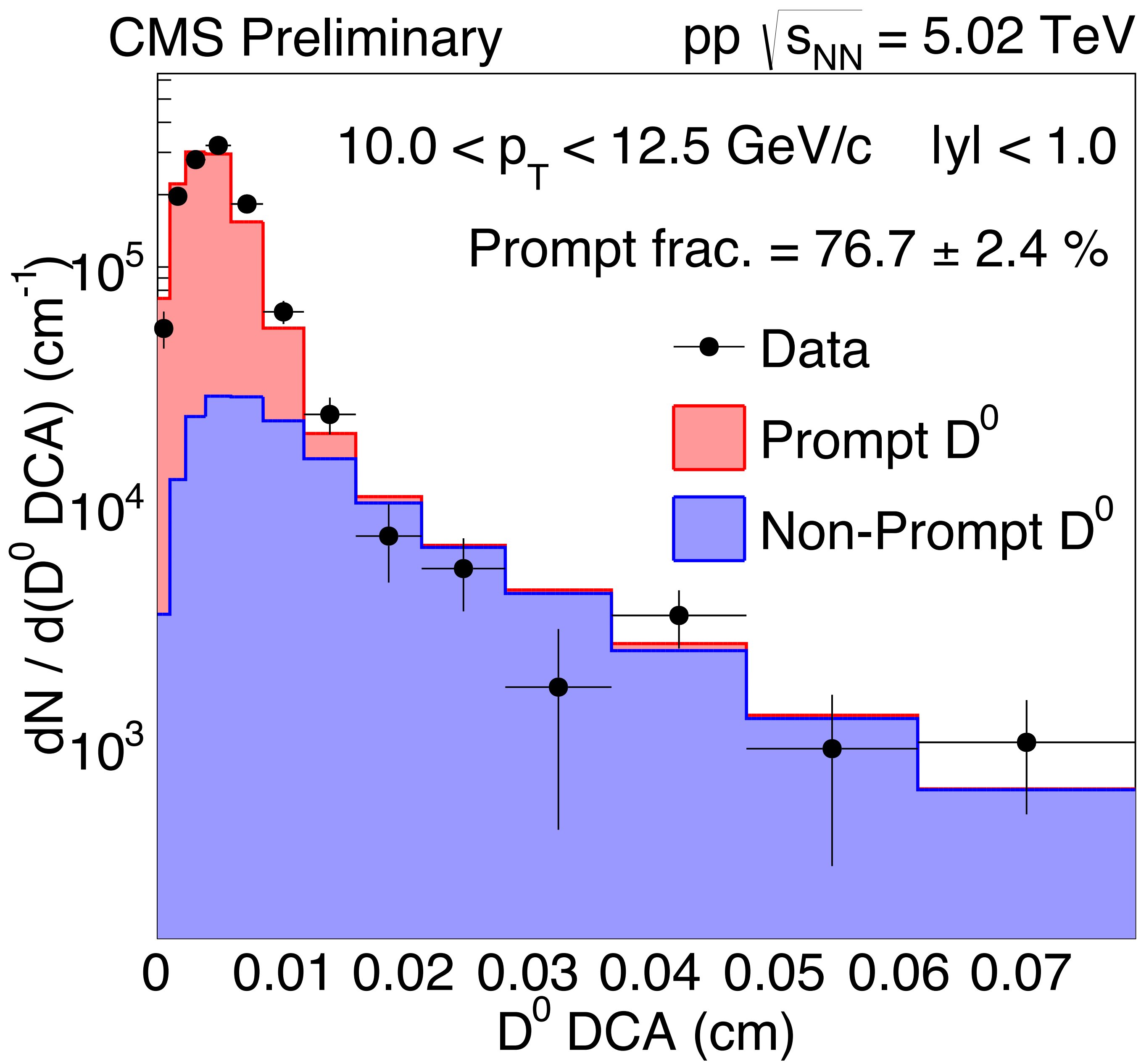
- Needs to correct for trigger selection efficiency



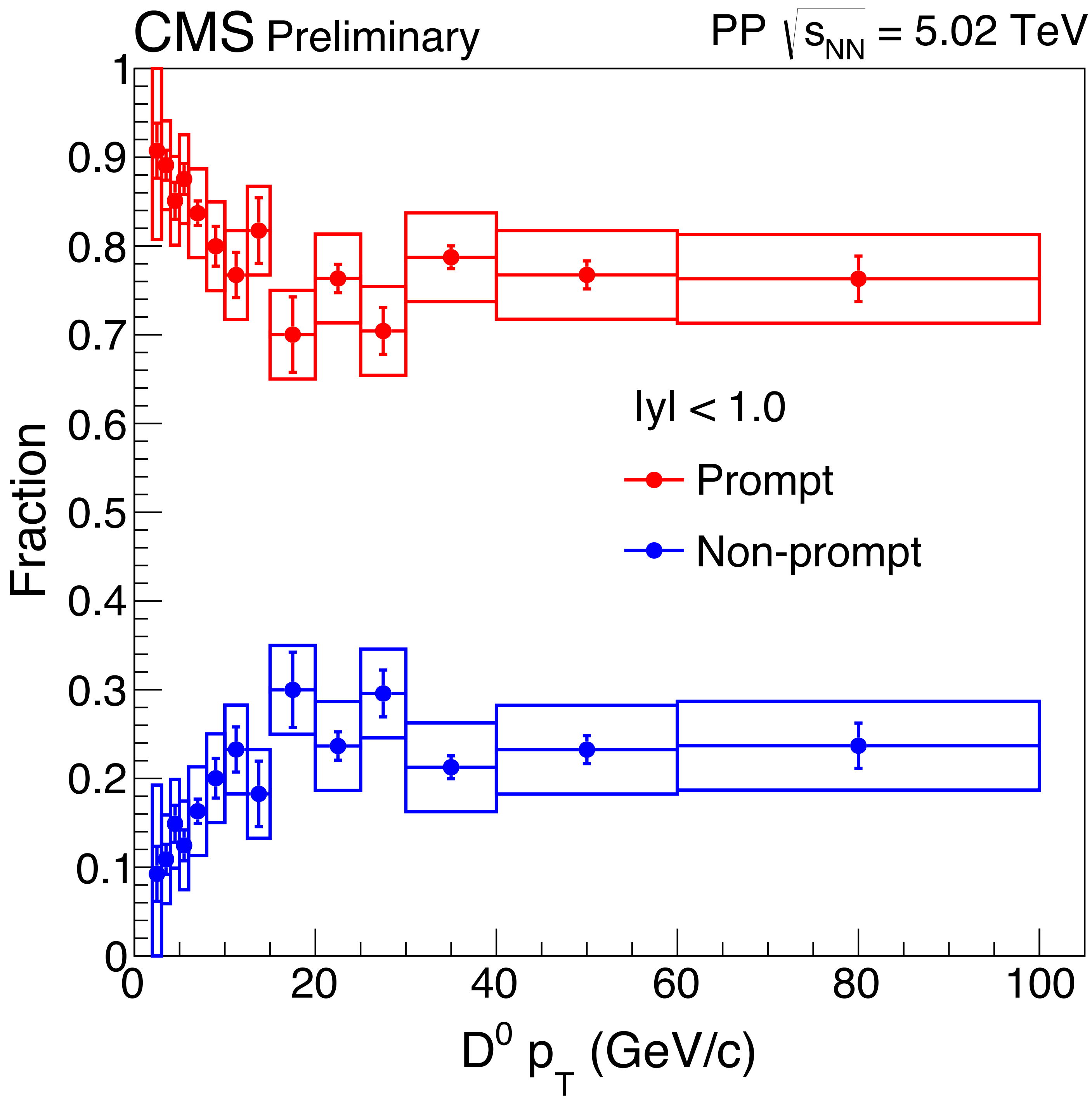
b-feed subtraction in pp collisions

- **f_{prompt}** = fraction of D^0 mesons coming from c-quark fragmentation

f_{prompt} estimated **fully data driven** by exploiting the different shapes of distance of closest approach (DCA) distributions of prompt and non prompt D^0 mesons

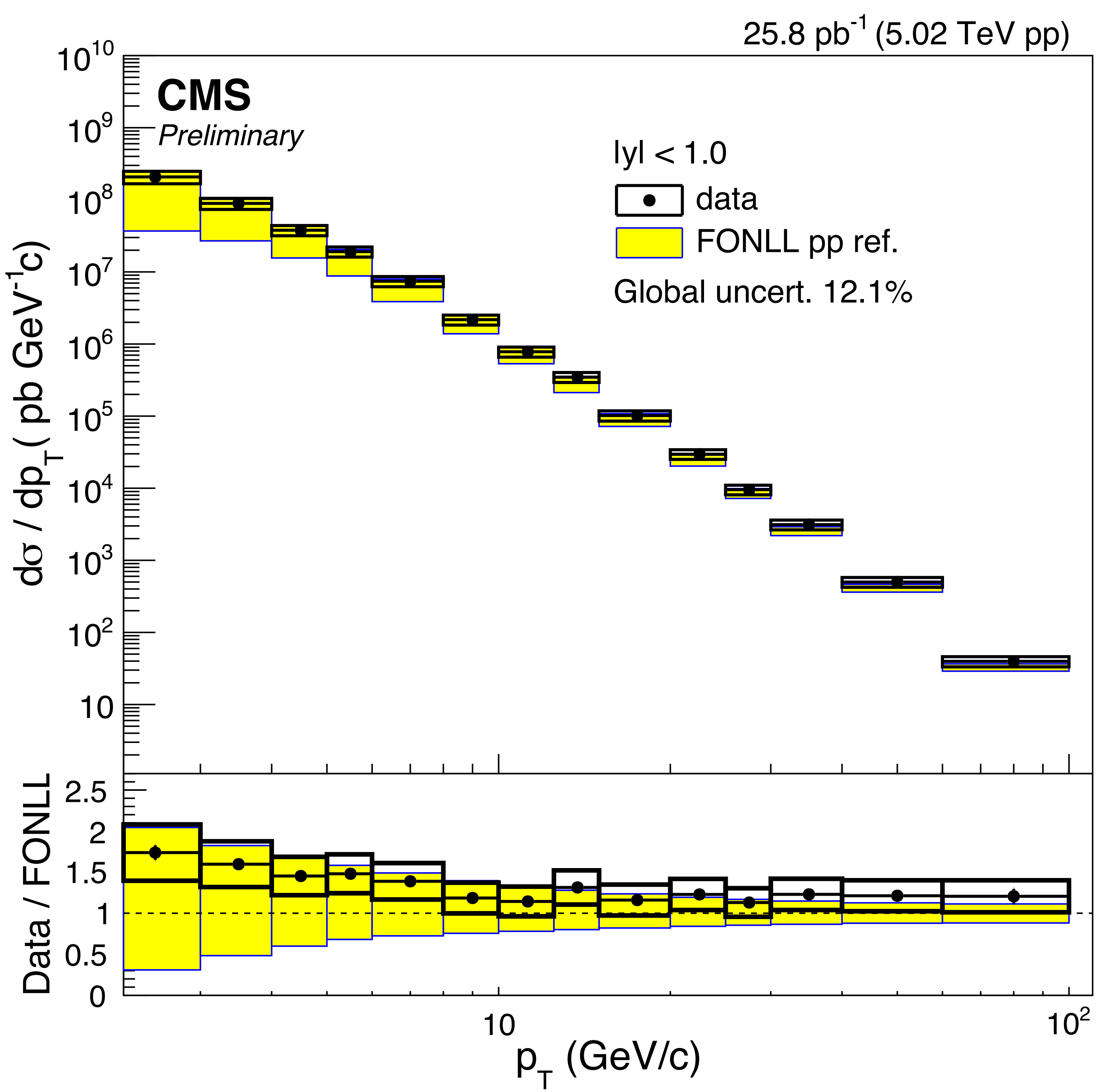


f_{prompt} fraction in pp collisions



p_T-differential cross section in pp

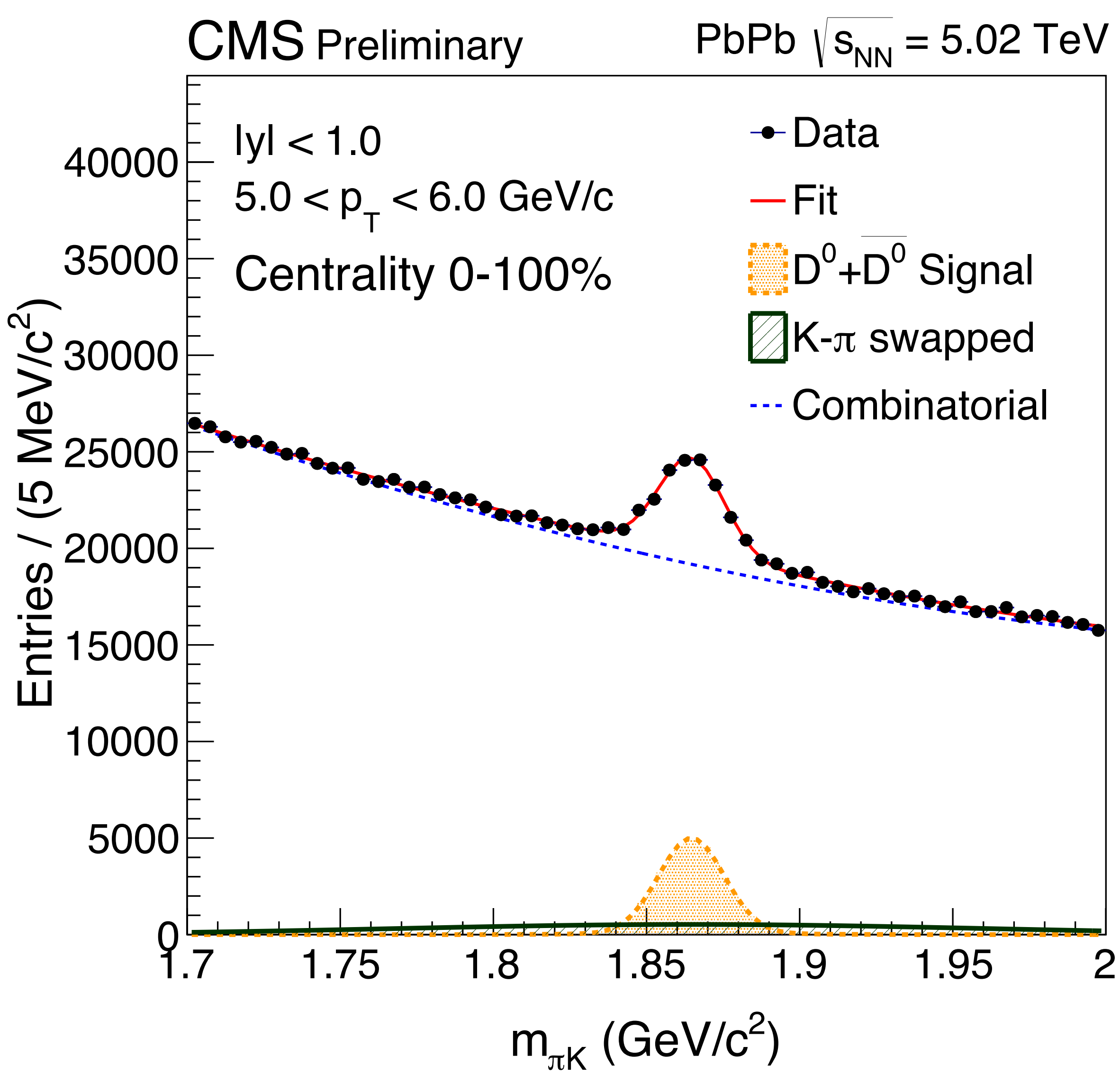
CMS-PAS-HIN-16-001



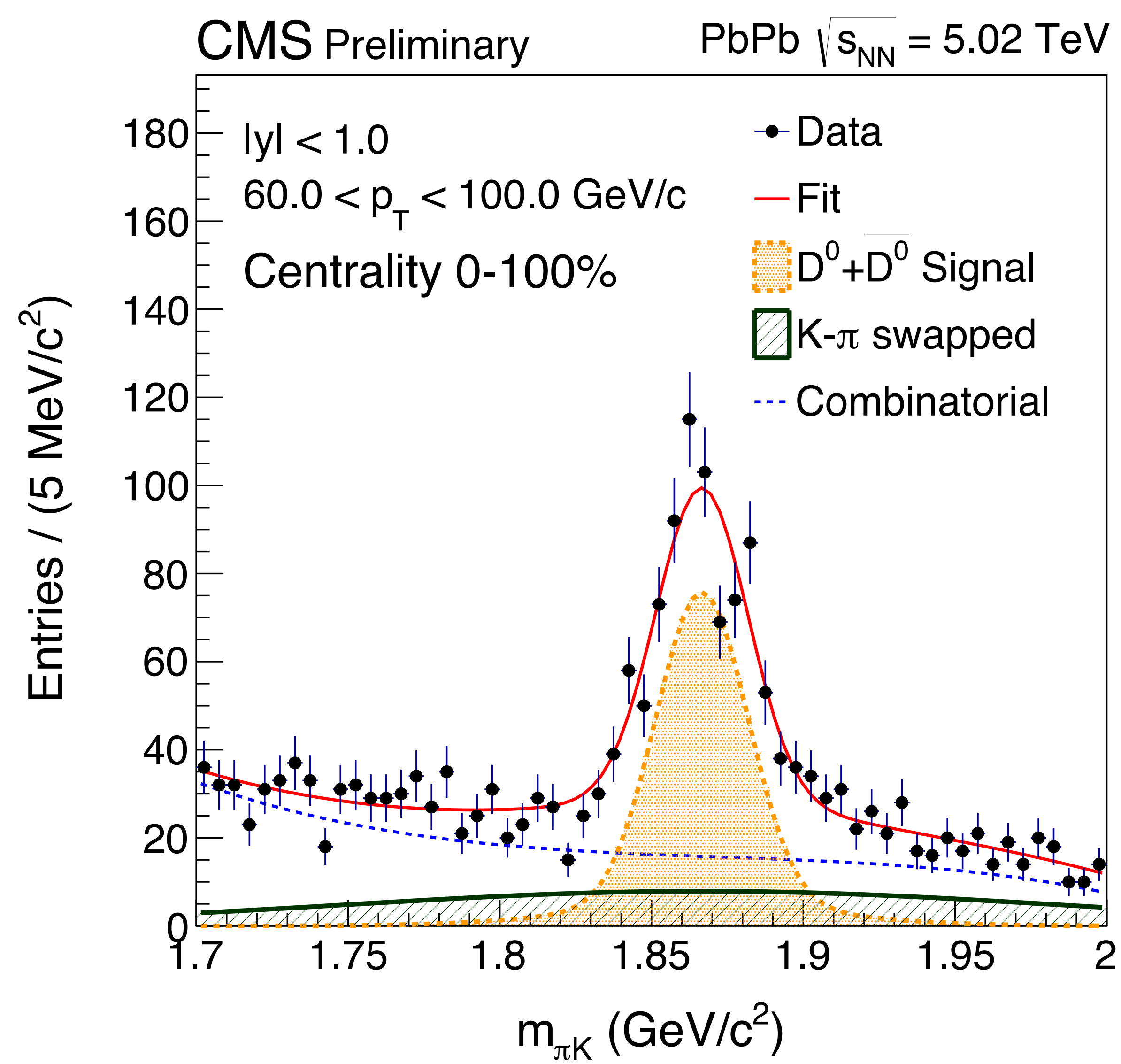
- First measurement of pp D^0 cross section at 5.02 TeV
- p_T coverage from 2 to 100 GeV/c in $|y|<1.0$

- **Consistent with upper bound of FONLL calculations!**

PbPb analysis at 5.02 TeV in 0-100%

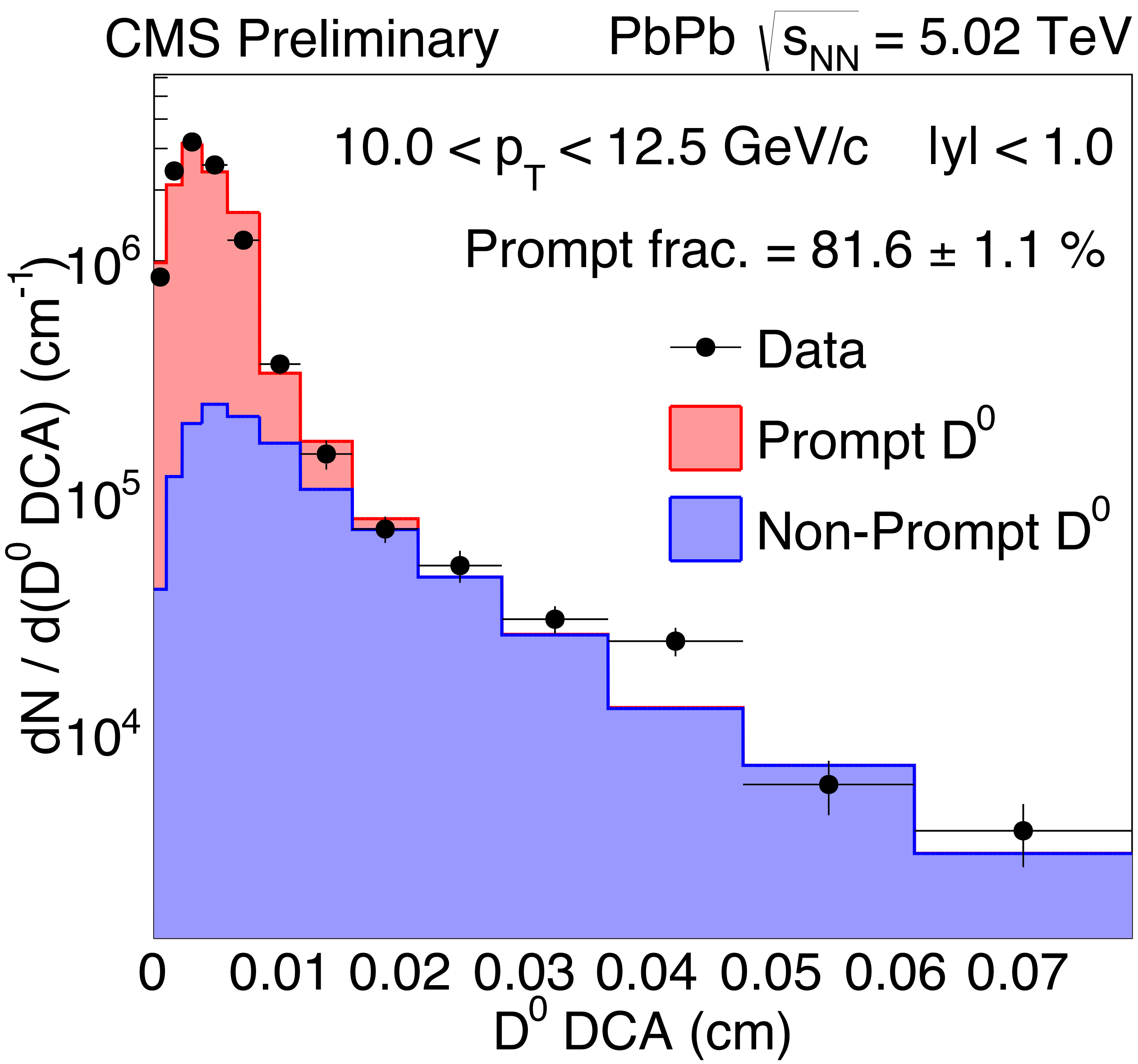


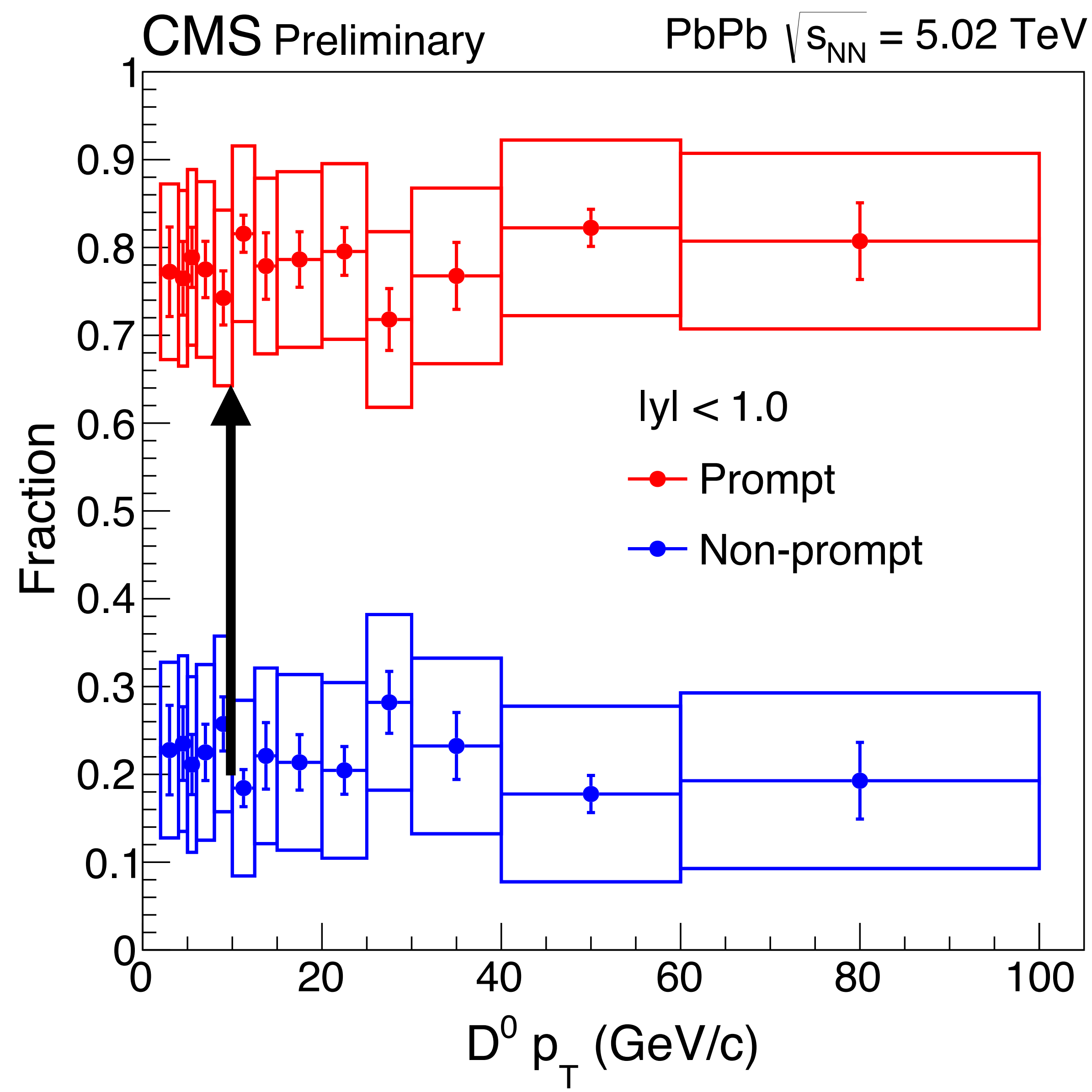
5<p_T<6 GeV/c



60<p_T<100 GeV/c

b-feed subtraction in PbPb collisions



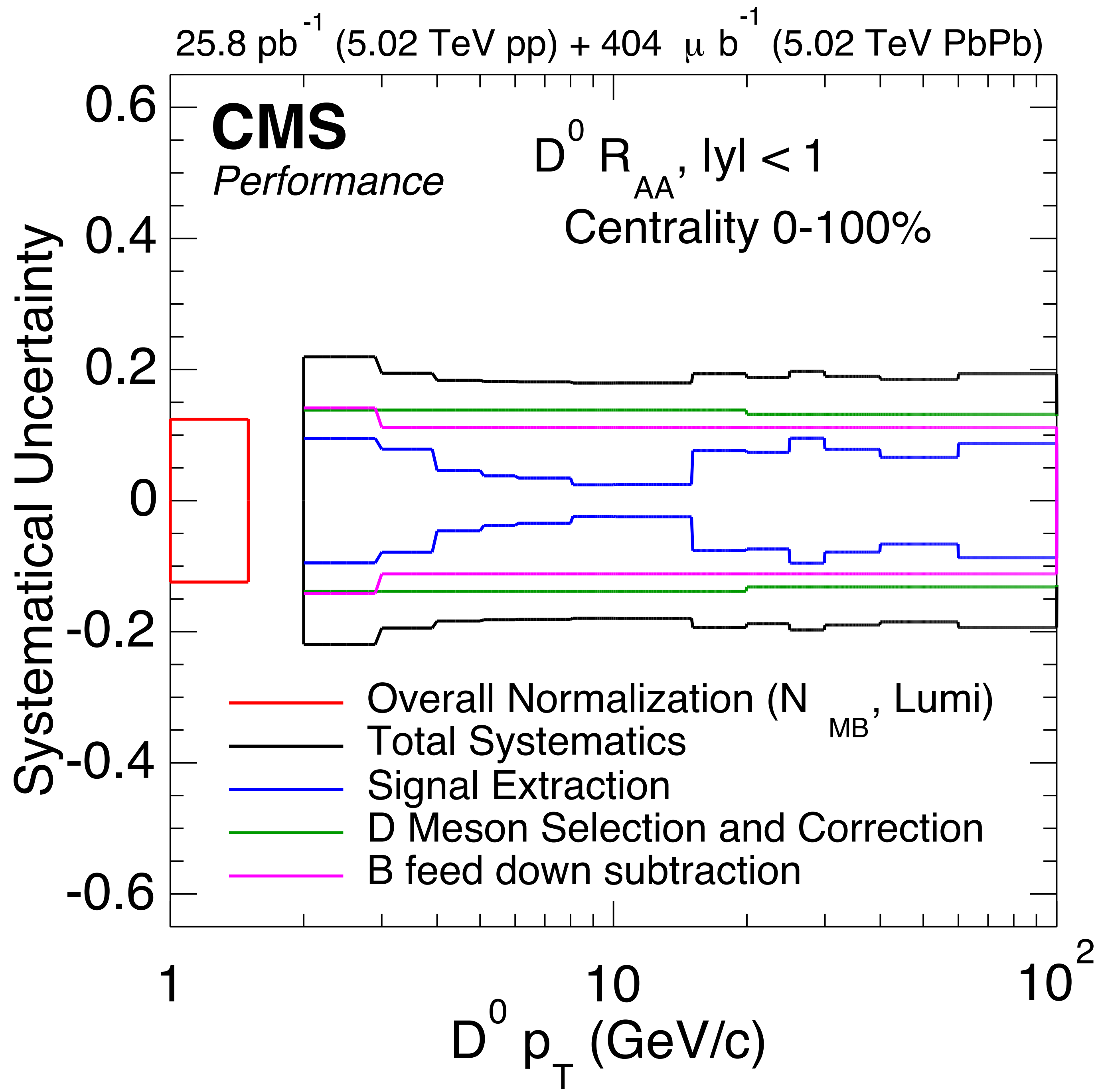


strong separation power also in PbPb!
first data-driven extraction in heavy-ion collision!

f_{prompt} is ~ flat as a function of p_T
→ conservative systematic uncertainties

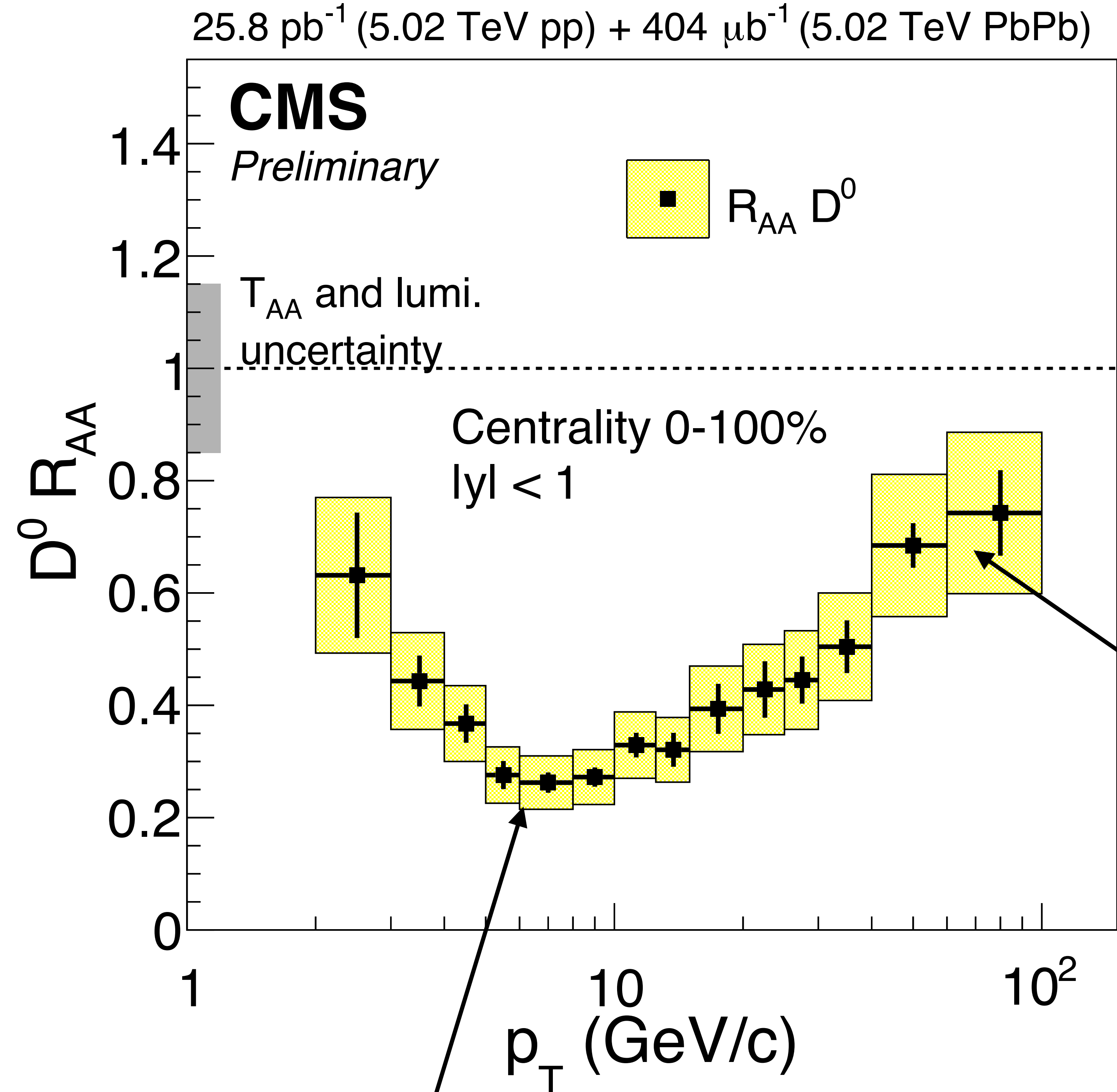
Systematic uncertainty summary

- **Signal extraction systematics**
  - Varying signal and background fit functions
- **D meson selection:**
  - Comparing data and MC data driven efficiencies of the different cut selections
  - Systematic on trigger efficiency
  - Tracking efficiency systematic: (evaluated data driven with 2 and 4 prongs D^0 decays!)
- **B-feed down uncertainty**
  - Obtained by comparing f_{prompt} estimation with alternative method based on decay length and with FONLL-based predictions



D^0 R_{AA} in PbPb collisions at 5.02 TeV in 0-100%

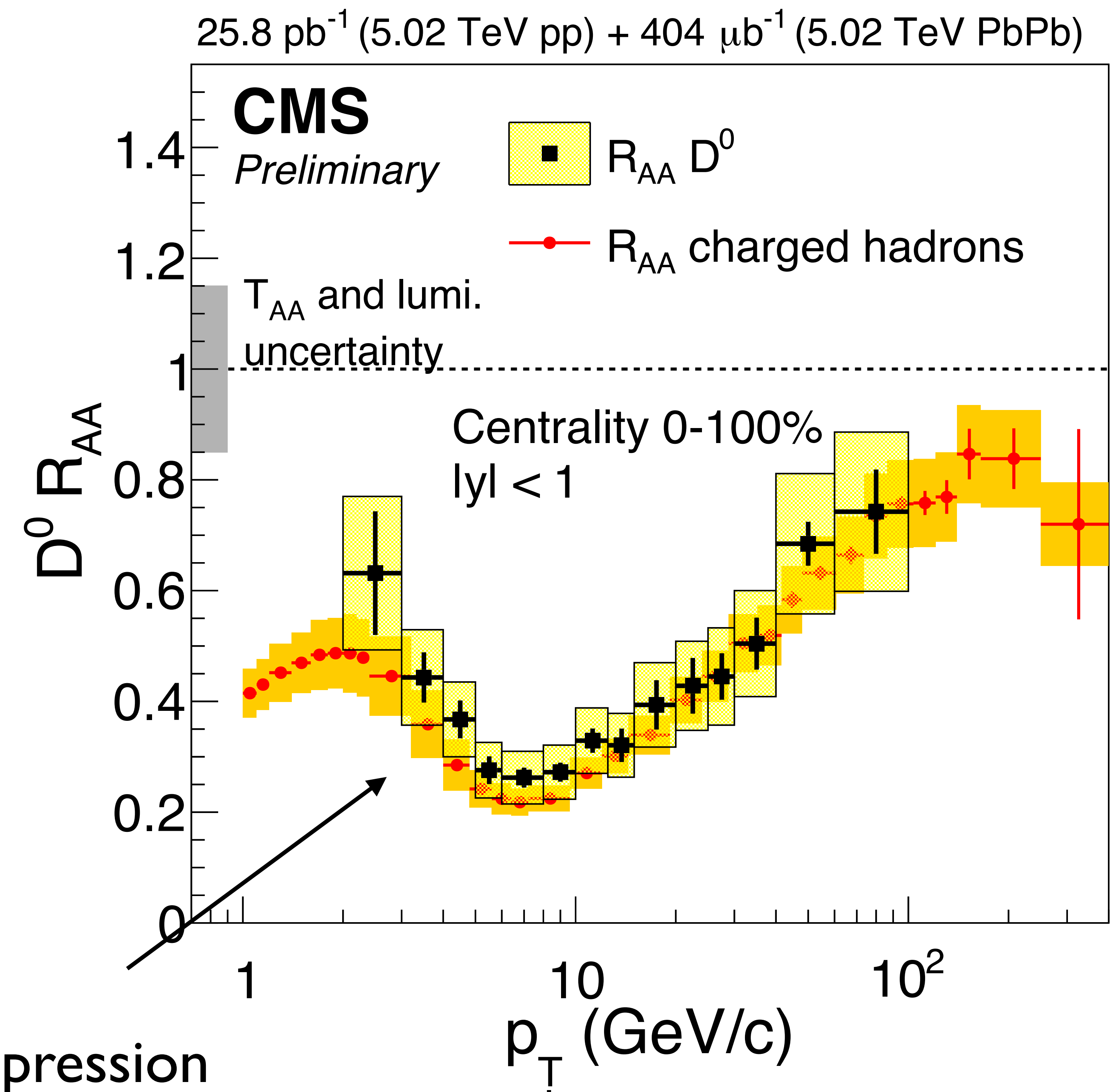
CMS-PAS-HIN-16-001



RAA~0.7-0.8 at very high pT

strong suppression (~4-5) at 5-8 GeV/c

Comparison with charged particle R_{AA} in 0-100%

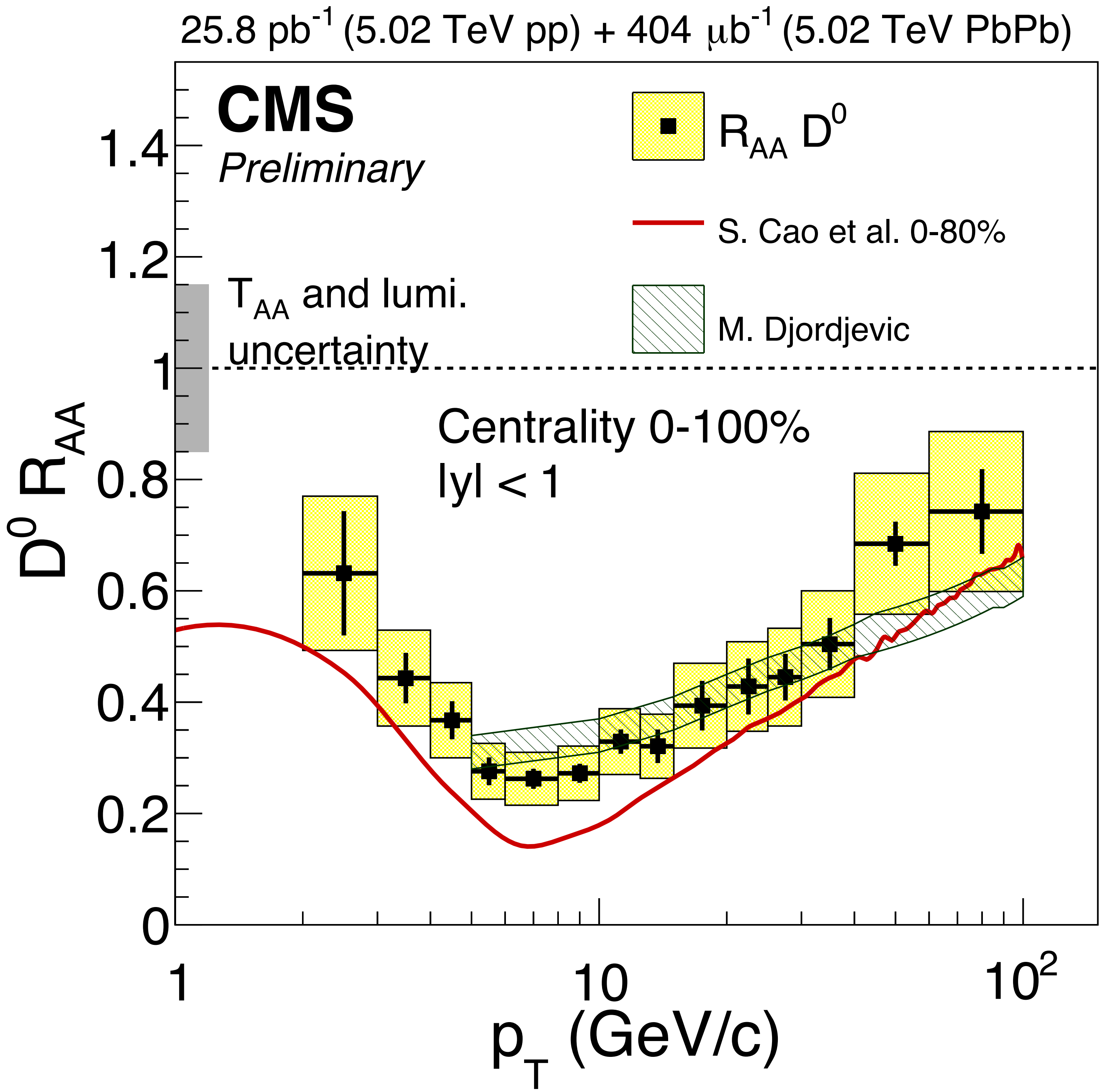


CMS-PAS-HIN-15-015

See Austin Baty's talk

similar suppression observed up to very high p_T

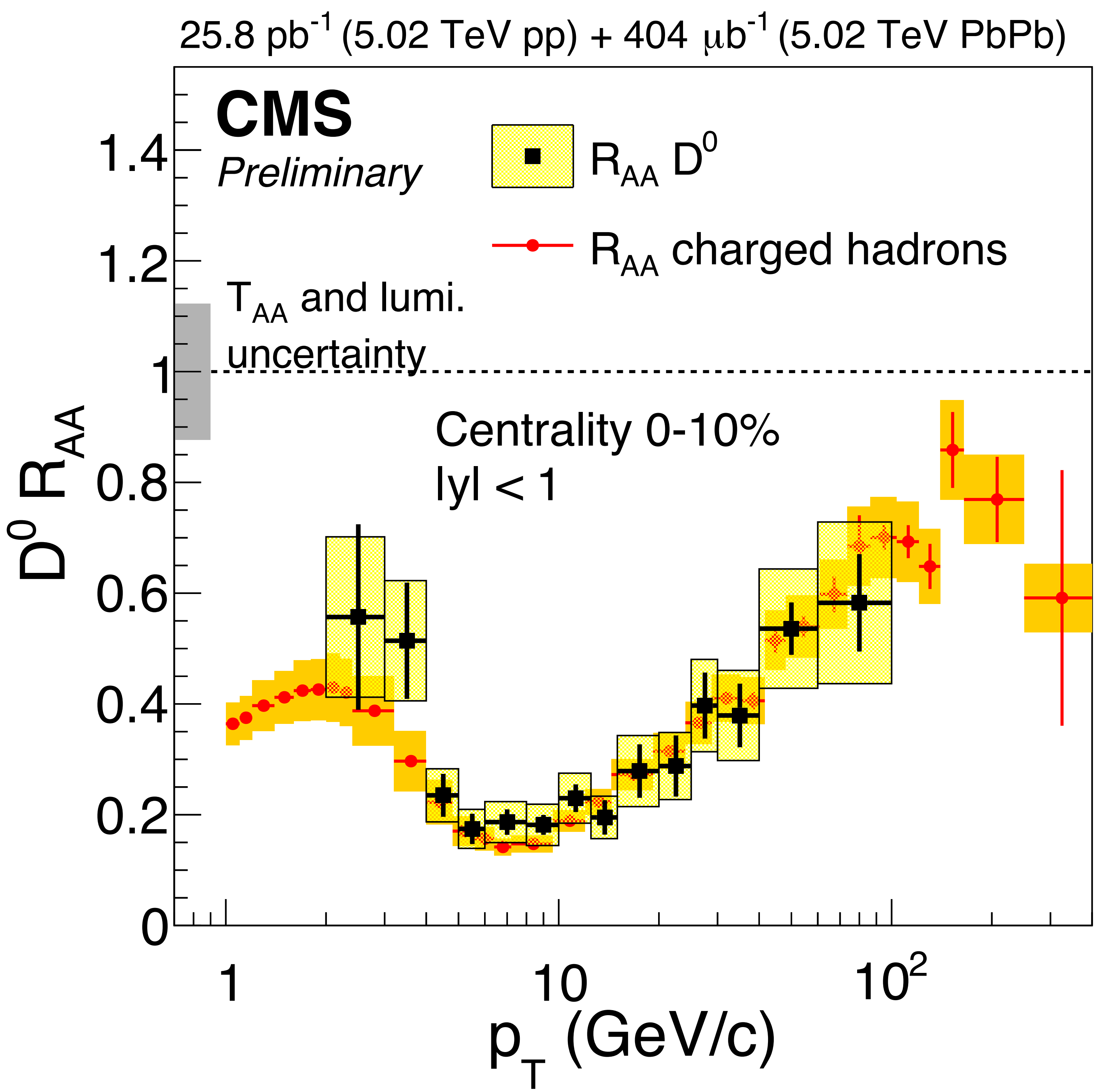
Comparison with theoretical calculations



[1] arXiv:1605.06447v1.
[2] Phys. Rev. C 92 (Aug, 2015) 024918

- **S.Cao et al**. (Linearized Boltzmann transport model + hydro [1])
- **M. Djordjevic** (QCD medium of finite size with dynamical scattering centers with collisional and radiative energy loss [2])

Comparison with charged particle R_{AA} in 0-10%

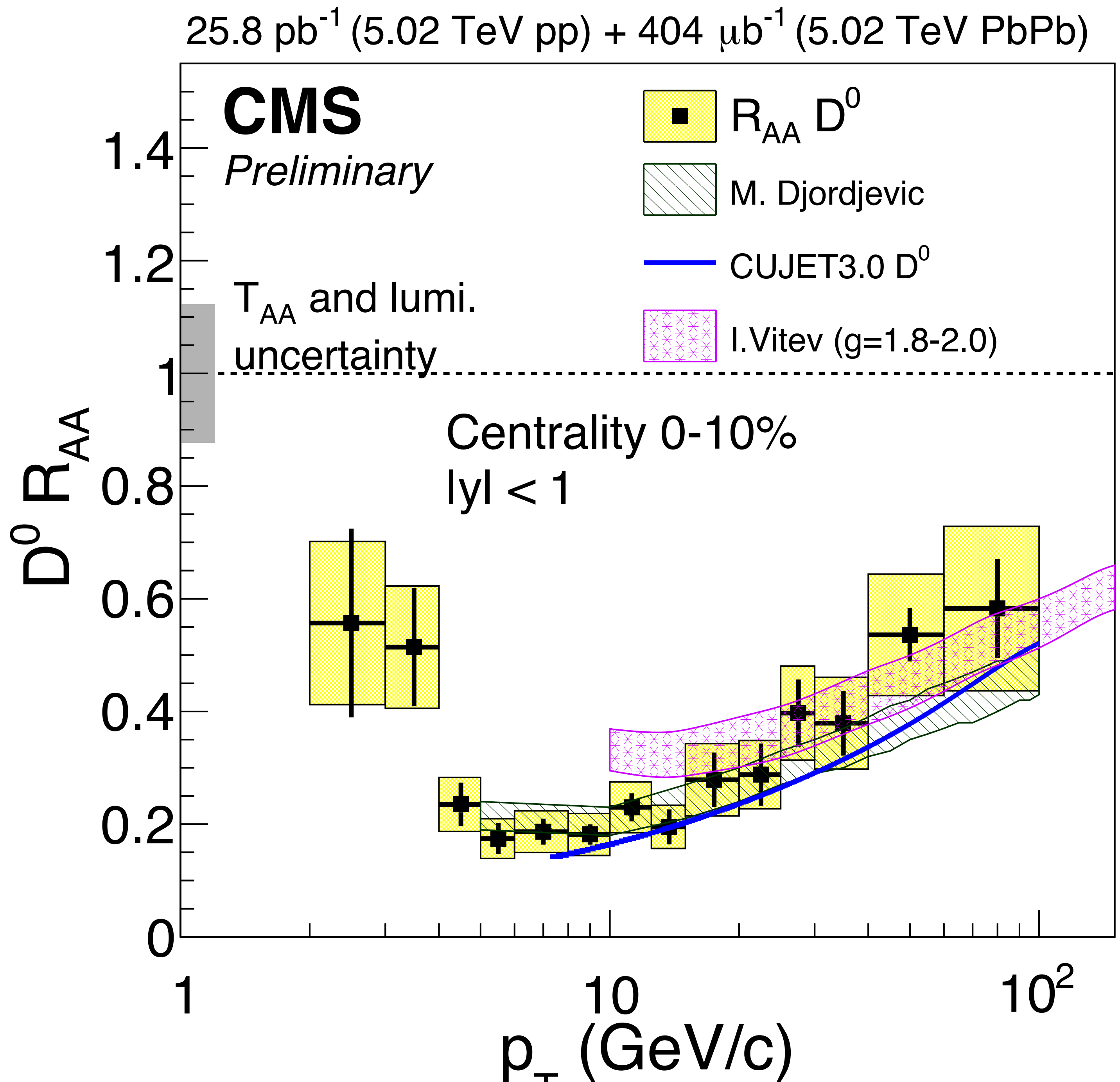


→Similar behaviour observed in central collisions 0-10%

→No indication of sizeable difference between D^0 and charged particle R_{AA}

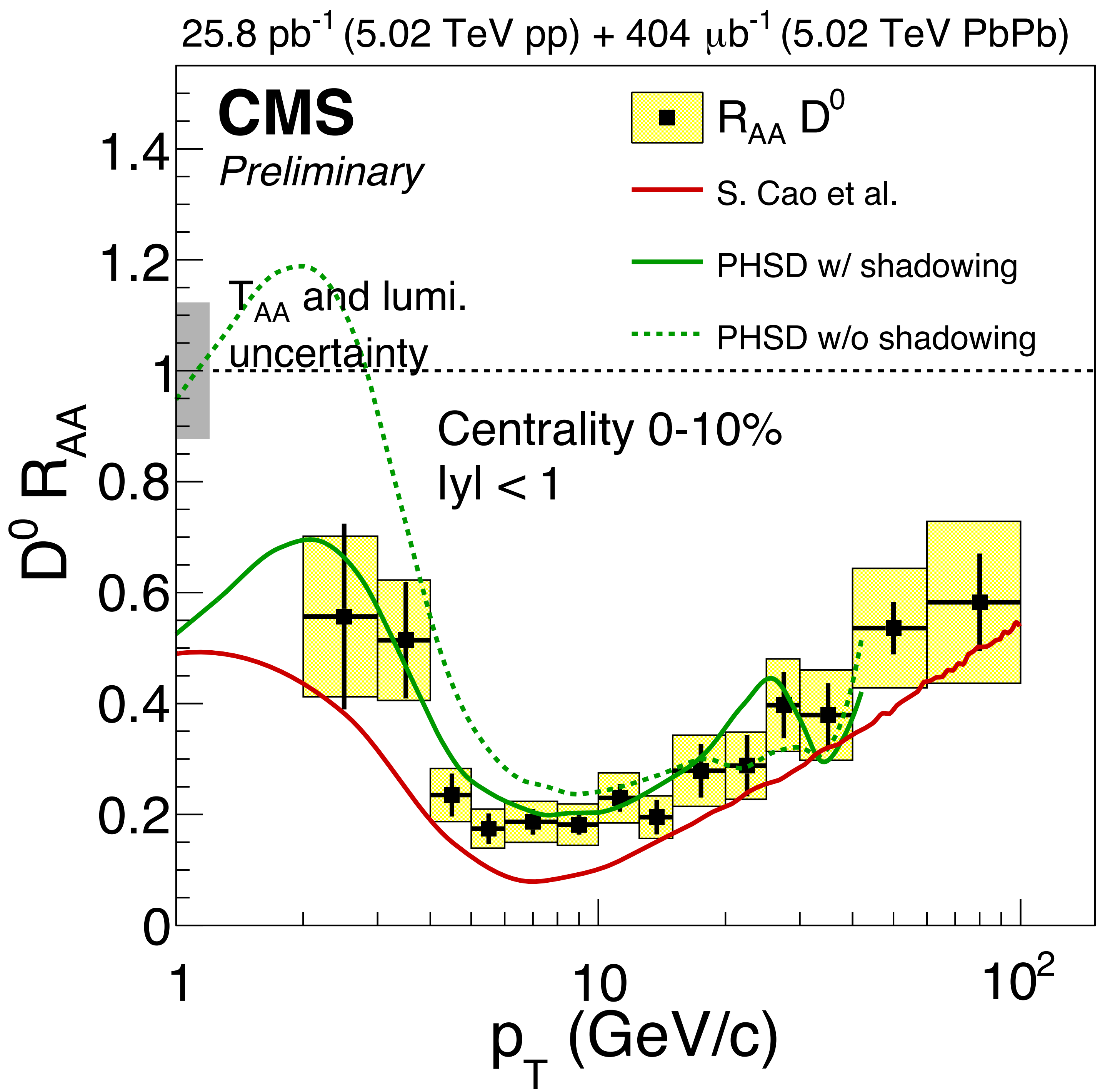
Comparison with charged particle R_{AA} in 0-10%

[1] JHEP 02 (2016) 169
[2] Phys. Rev. C 92 (Aug, 2015) 024918
[3] Phys. Rev. D 93 (Apr, 2016)



- **CUJET3.0** (jet quenching model based on DGLV opacity expansion theory [1])
- **M. Djordjevic** (QCD medium of finite size with dynamical scattering centers with collisional and radiative energy loss [2])
- **I.Vitev** jet propagation in matter, soft-collinear effective theory with Glauber gluons (SCETG)[3]

Comparison with theoretical calculations

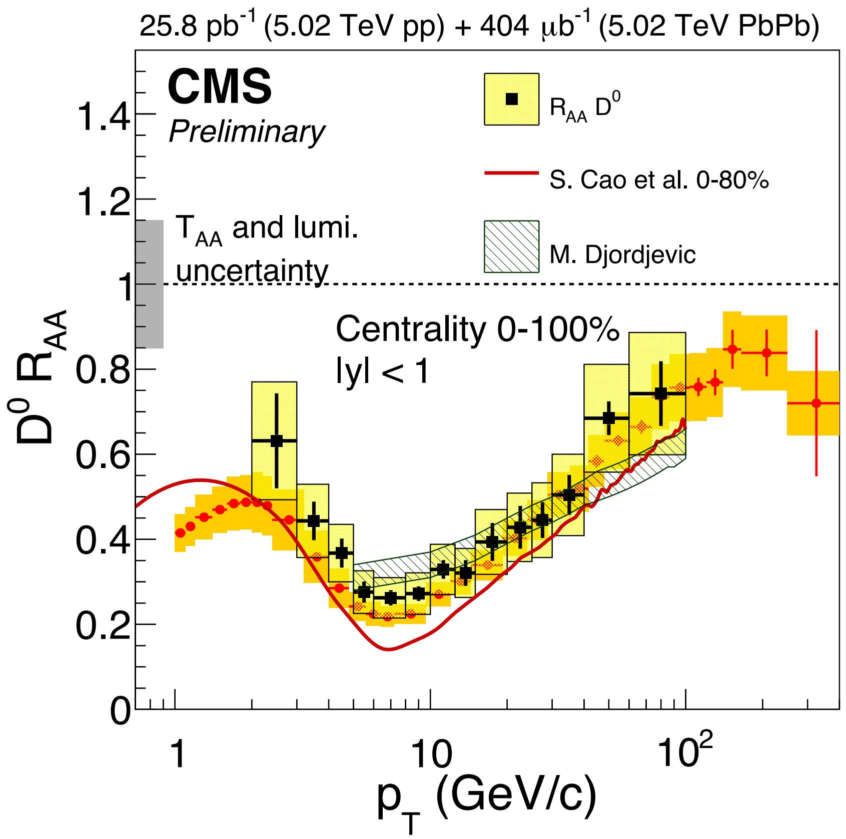


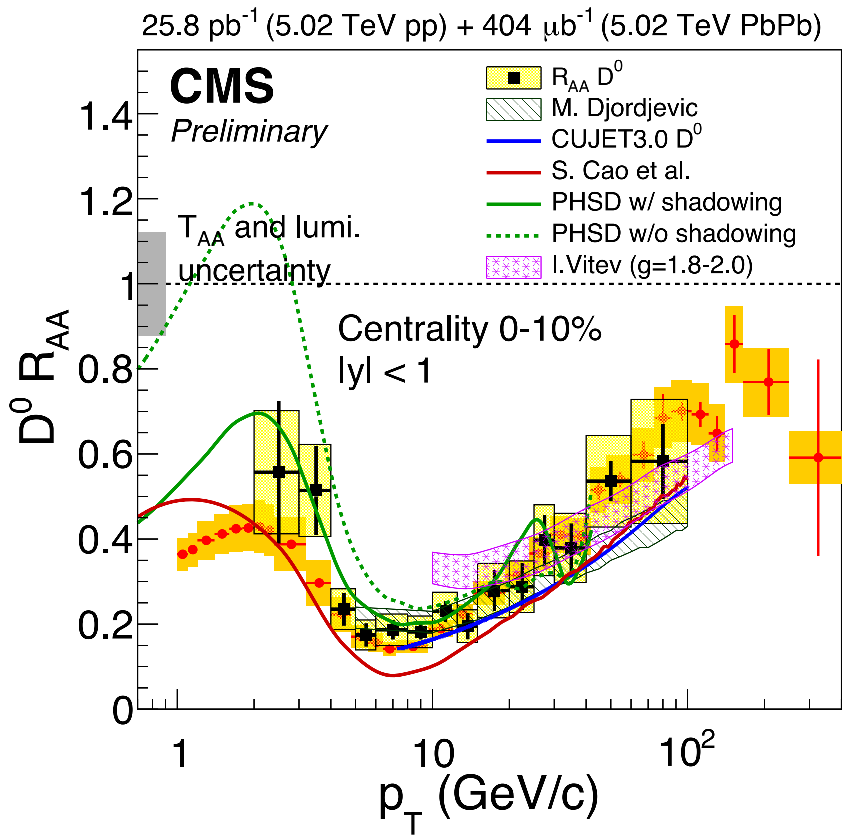
- **S.Cao et al**. (Linearized Boltzmann transport model + hydro [1])
- **PHSD** (Parton-Hadron-String Dynamics model[2])

[1] arXiv:1605.06447v1.
[2] Phys. Rev. C 93 (Mar, 2016) 034906

Conclusions

- **Hints of different suppression of J/ψ←B and D mesons at low p_T**
- **At higher p_T (>100 GeV/c) inclusive jets and b-jets are well in agreement**
- **D and charged particle RAA agree up to very high p_T!**
  - putting stronger constraints on theoretical calculations
  - forcing theoretical to describe HF measurements in a much wider kinematic range where different processes (e.g. radiative vs collisional) have a different relevance





Outlook

- **More precise measurements of B production are getting urgent:**
  - with Run2 data, CMS can measure with good precision the b-production via $J/\psi \leftarrow B$, b-jets and **exclusive B measurements**

  → complete picture of the HF energy loss

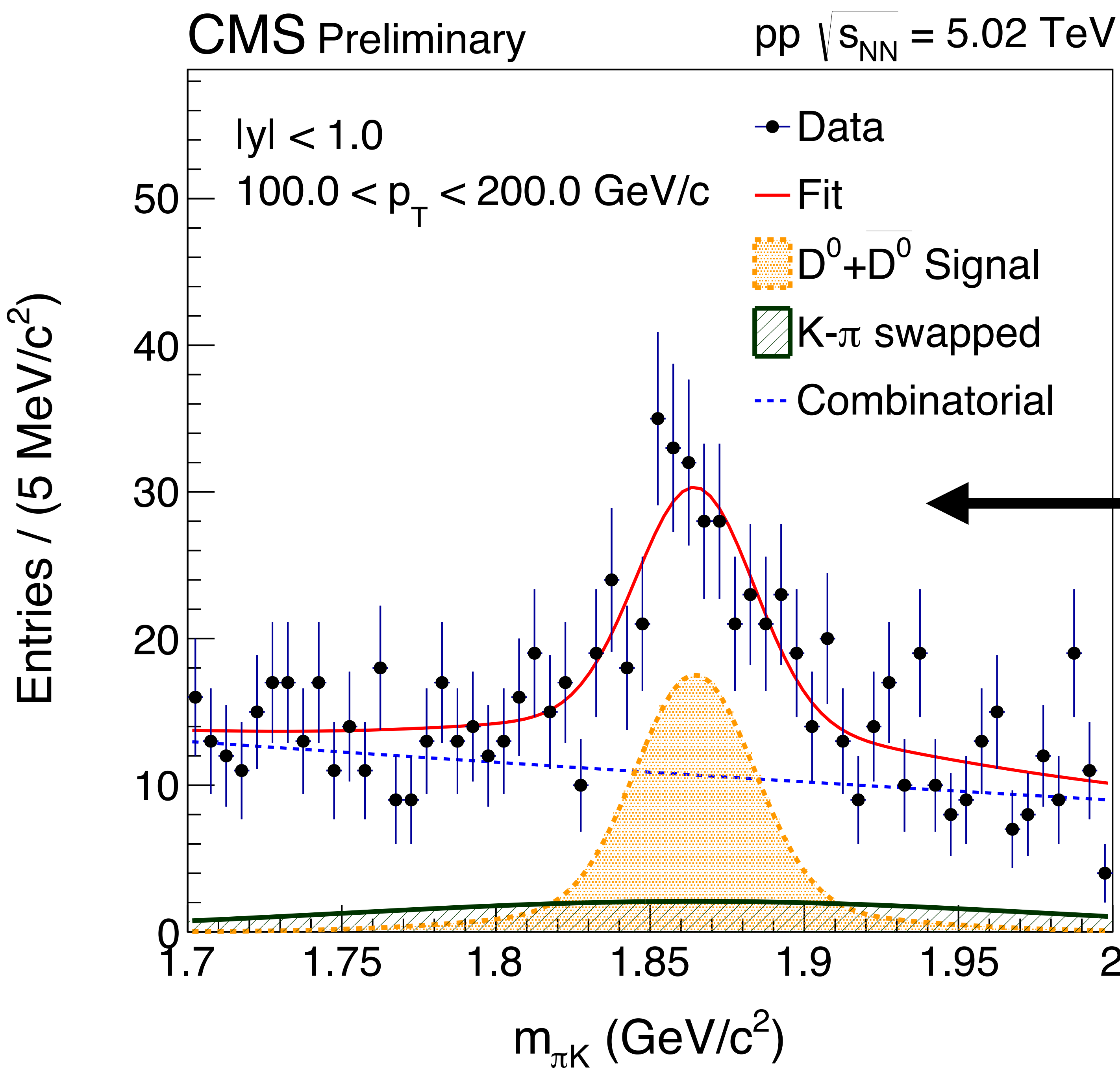
- **D-meson production at low p_T**
  - measure D meson production in PbPb (and pPb) down to ~1 GeV to further constrain the mechanisms of productions (e.g. recombination) and relevance of cold nuclear effects

- **D and B v_n measurements**
  - fundamental to understand collective behaviour of HF quarks and to constraint theoretical calculations

- **Gluon splitting?**
  - the relevance of soft and hard gluon splitting processes still needs to be addressed. Are we always measuring gluon energy loss?
  - More differential measurement (HF/photon, D-hadron correlations) are needed

BACKUP

D^0 triggers at High-Level-Trigger

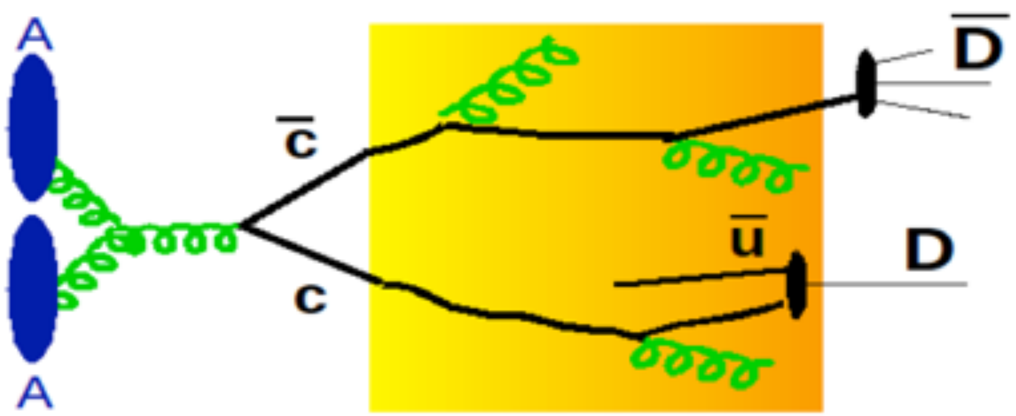


pp collisions at 5.02 TeV

extending the high p_T reach of D^0 analysis up to 200 GeV!

Why studying heavy flavours in HI?

Heavy quarks produced in hard scatterings (described by pQCD) at the early stages of the collisions **interact with medium and lose energy!**

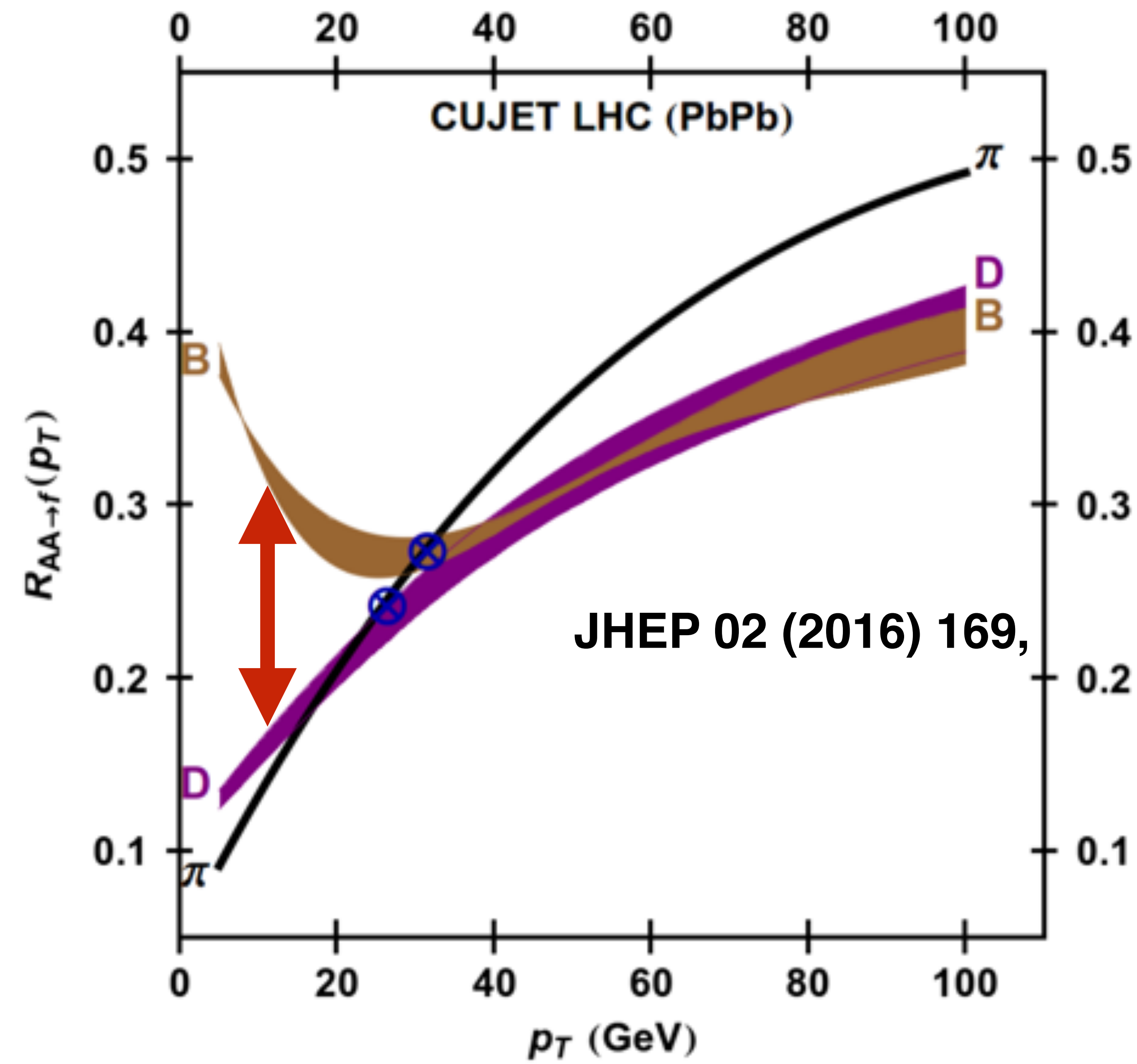


$R^{\text{light particle}}_{AA} < R^{D}_{AA} < R^{B}_{AA}$?

Does energy loss depends on the flavour?

Expected $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ due to:

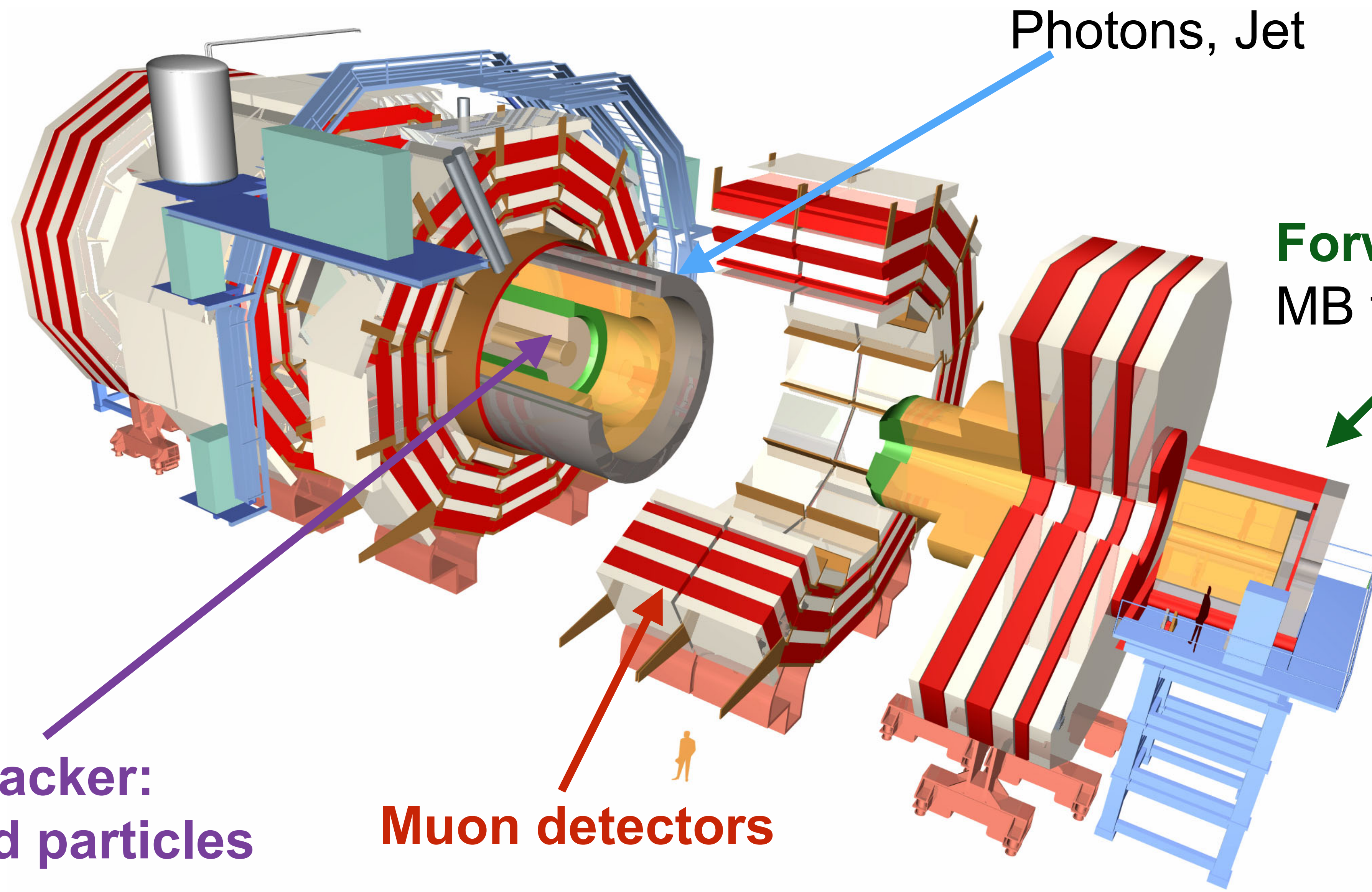
- Casimir factor= <ΔE> ∝ C_R
- **Dead cone effect** (radiation suppressed at small angles)



CMS detector

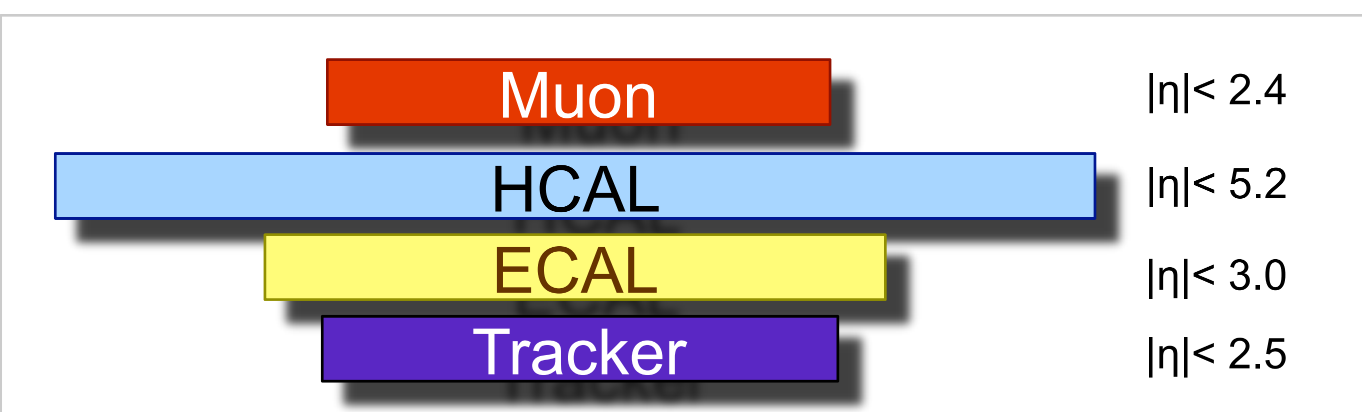
EM and hadronic calorimeters
Photons, Jet

Forward Calorimeter:
MB triggers, centrality

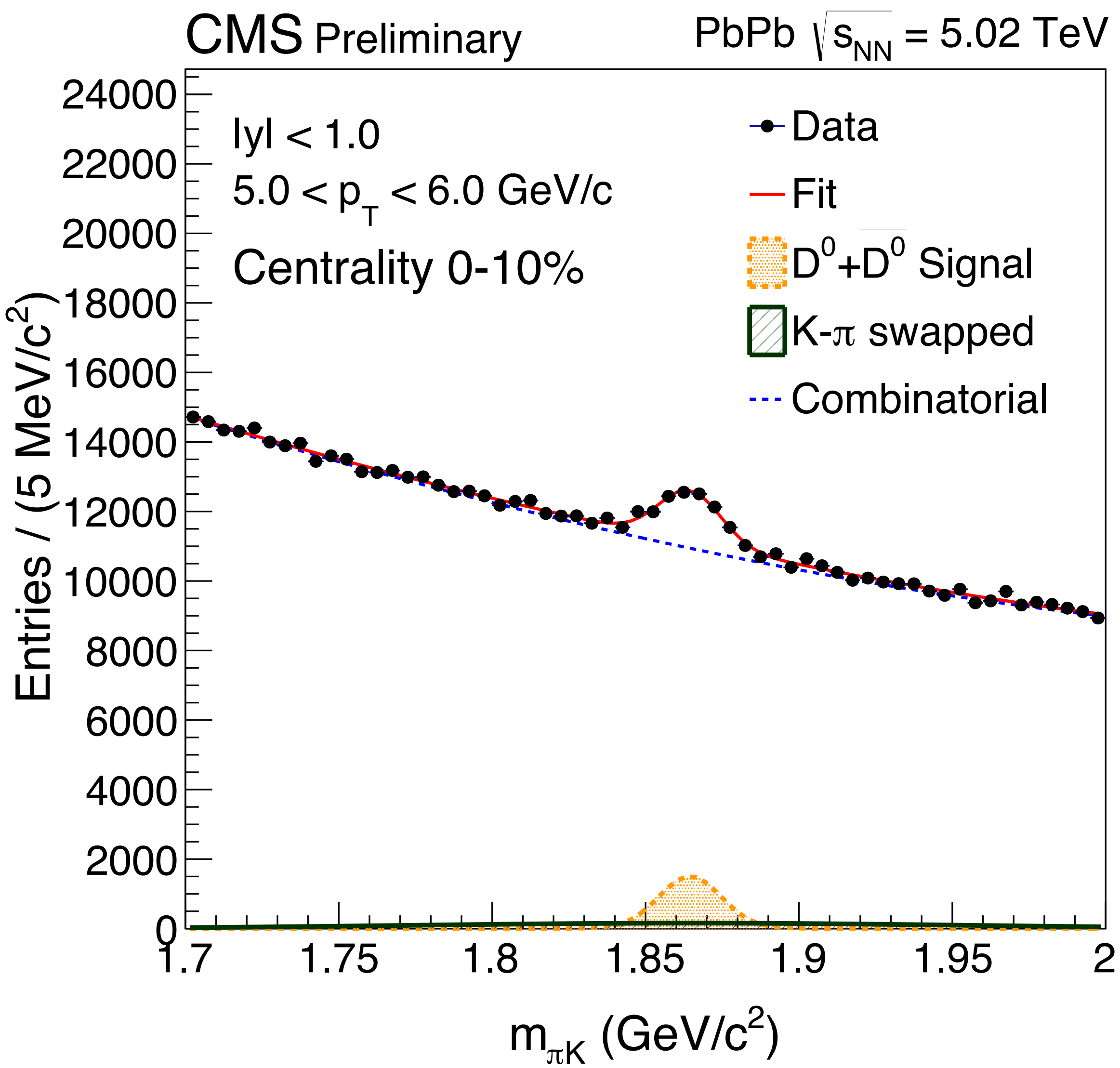


Inner tracker:
charged particles

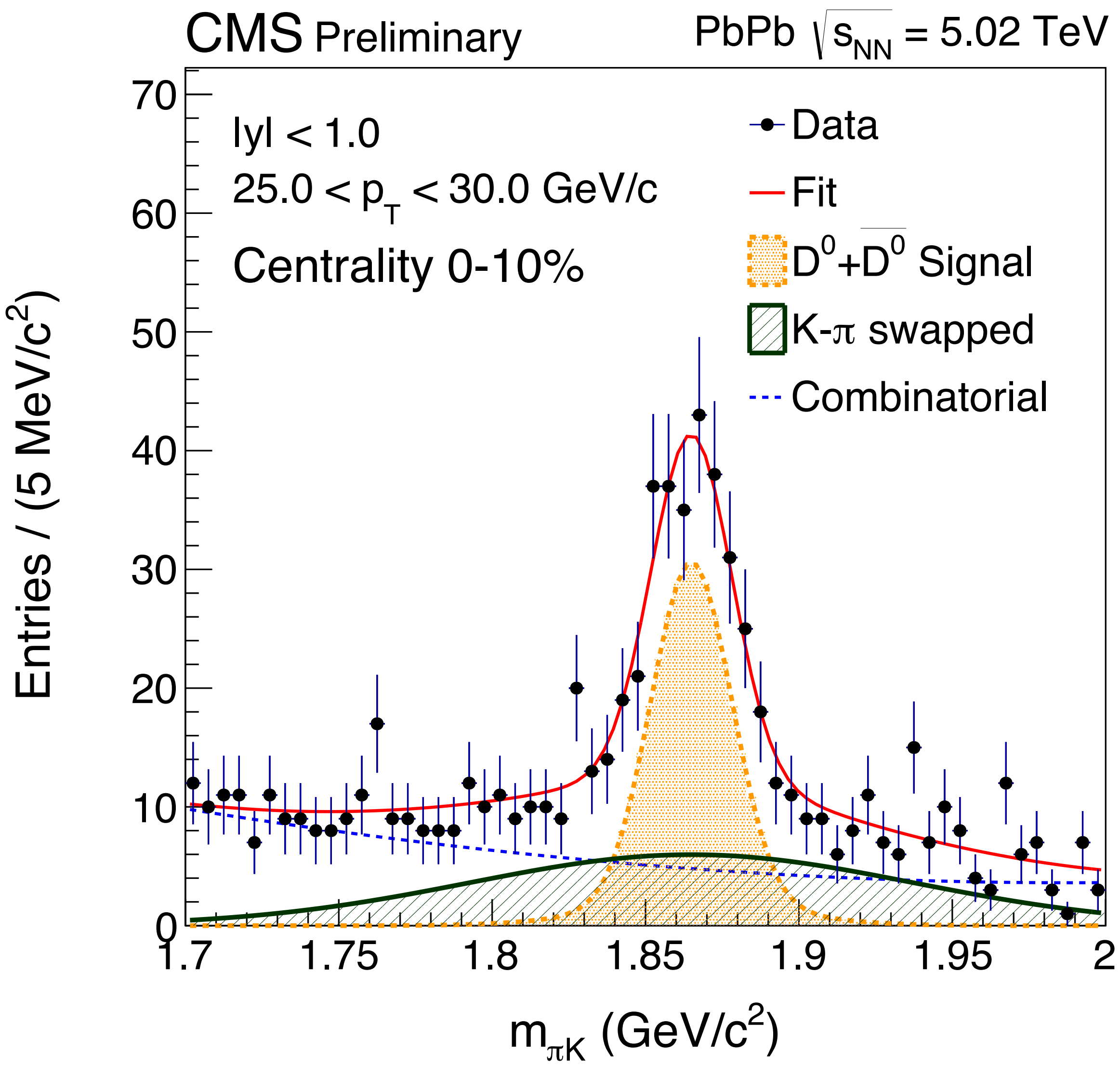
Muon detectors



PbPb analysis at 5.02 TeV in 0-10%

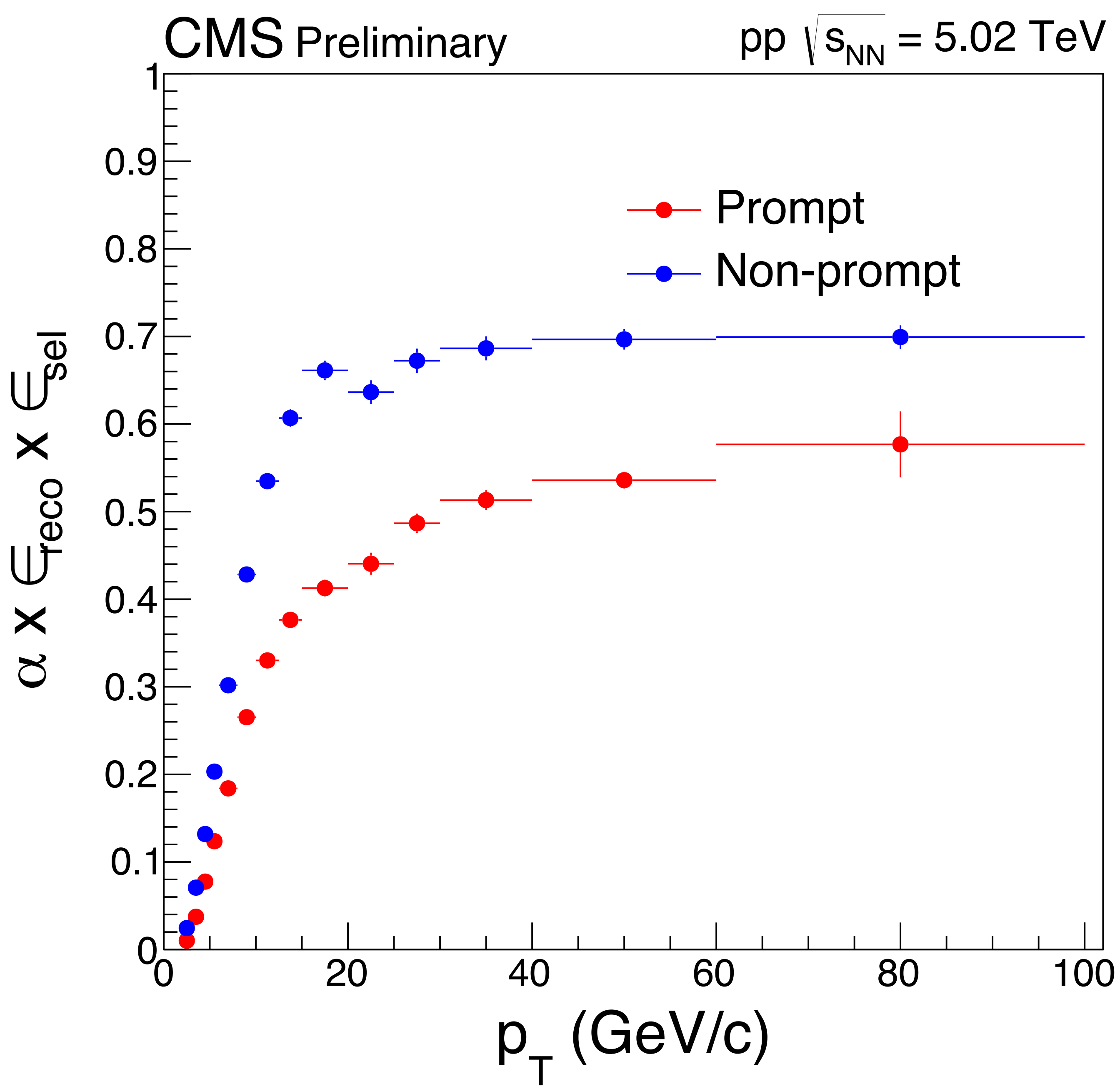


5<p_T<6 GeV/c

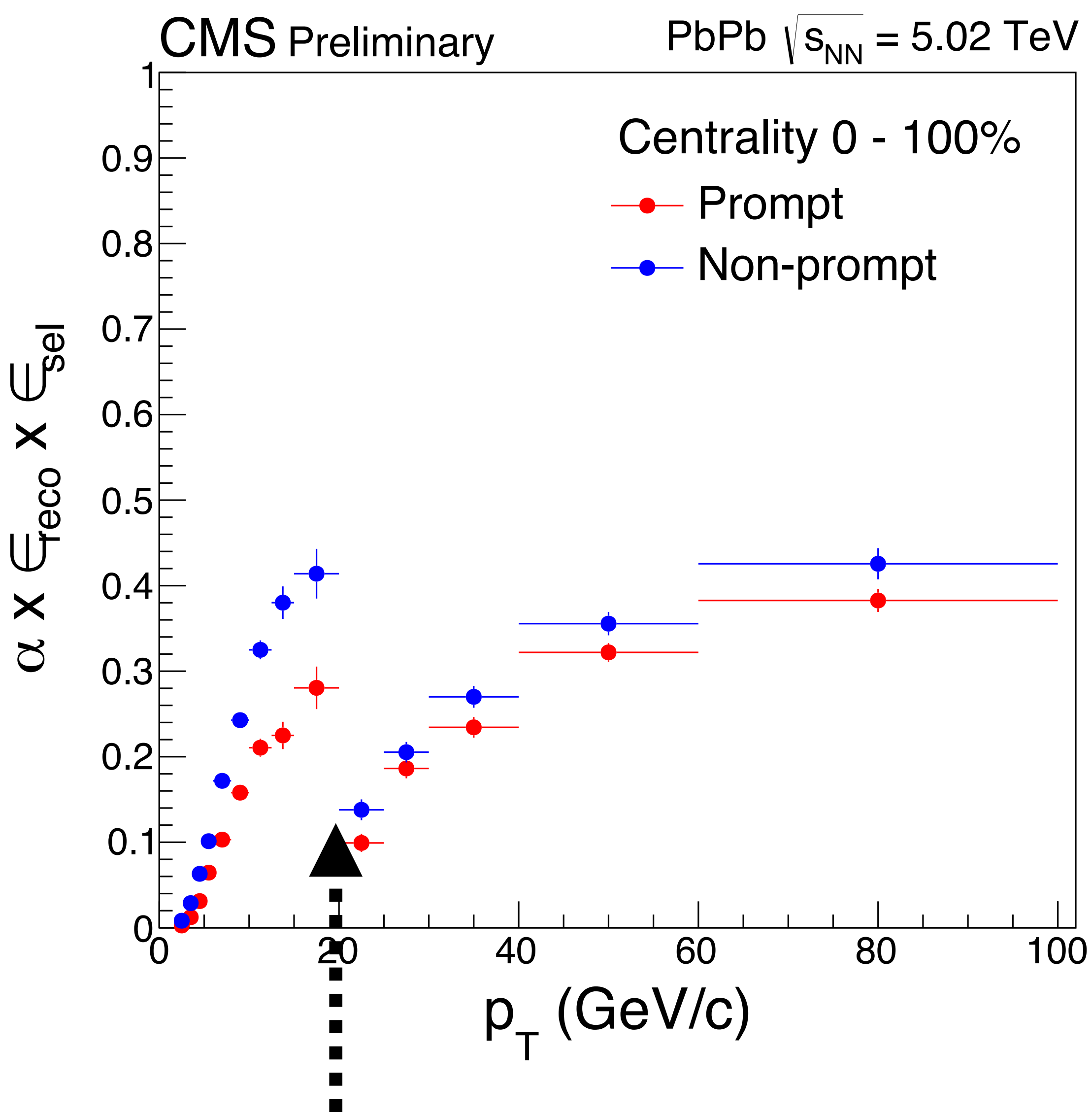


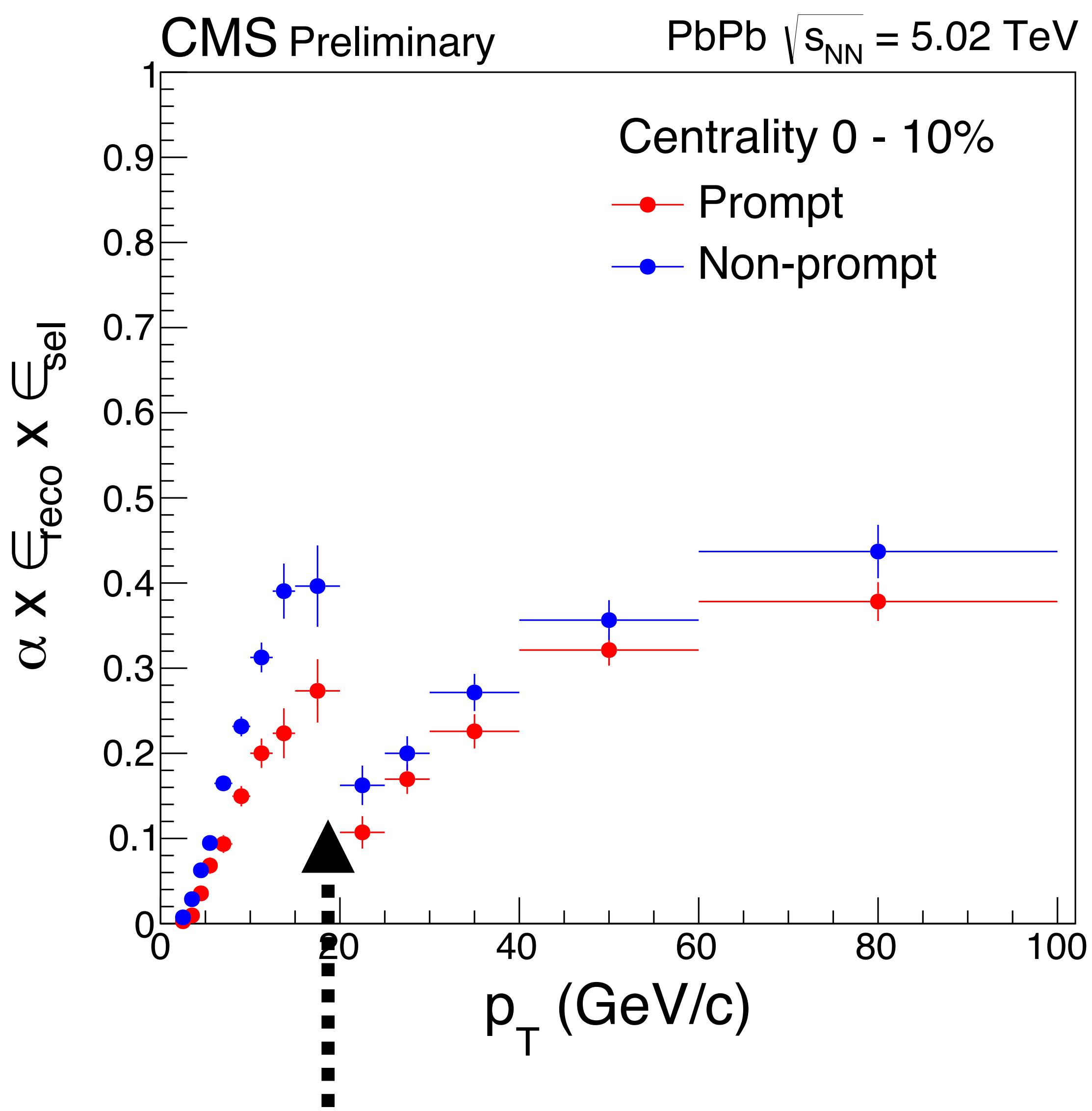
60<p_T<100 GeV/c

Acceptance x efficiency in pp collisions



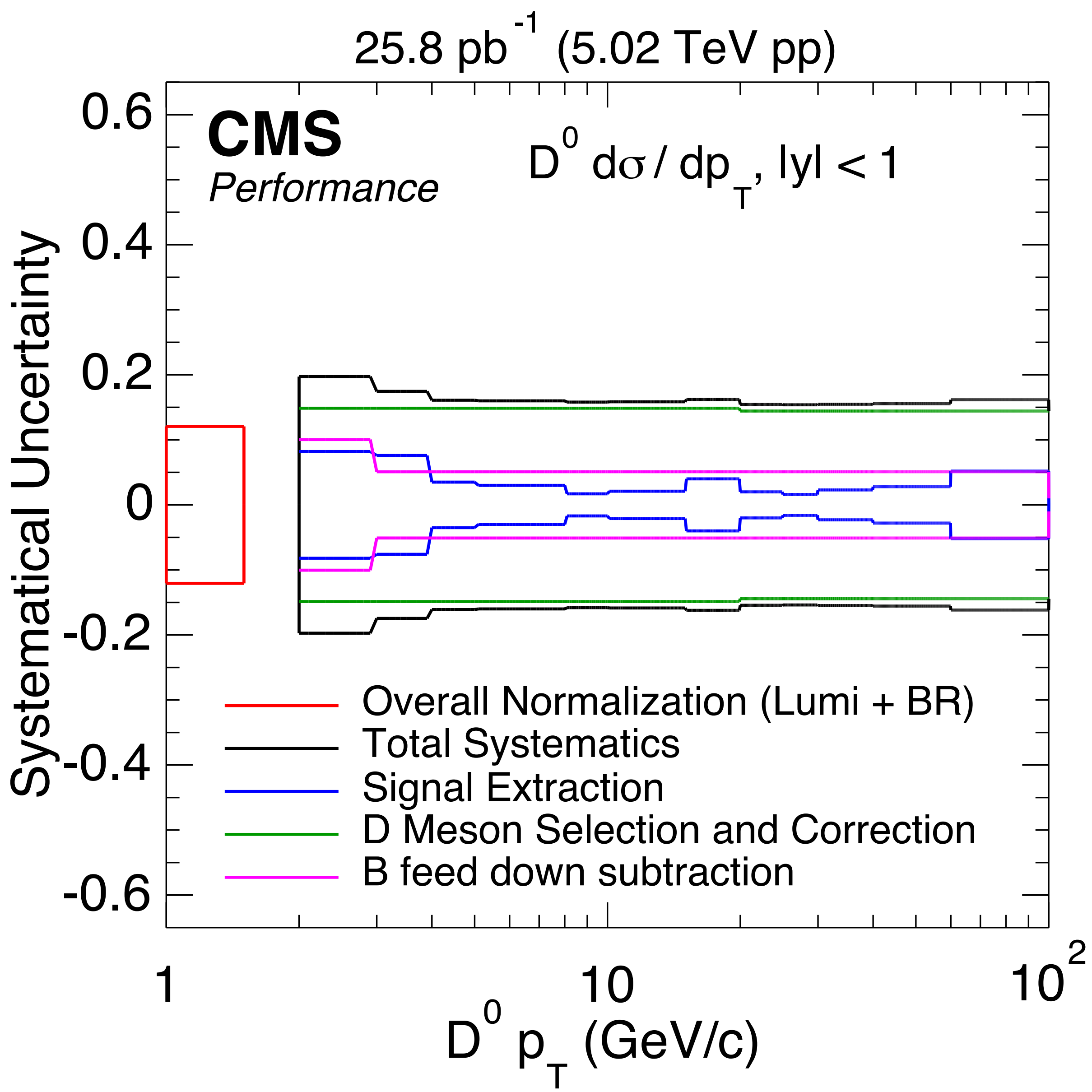
Acceptance x efficiency in PbPb collisions



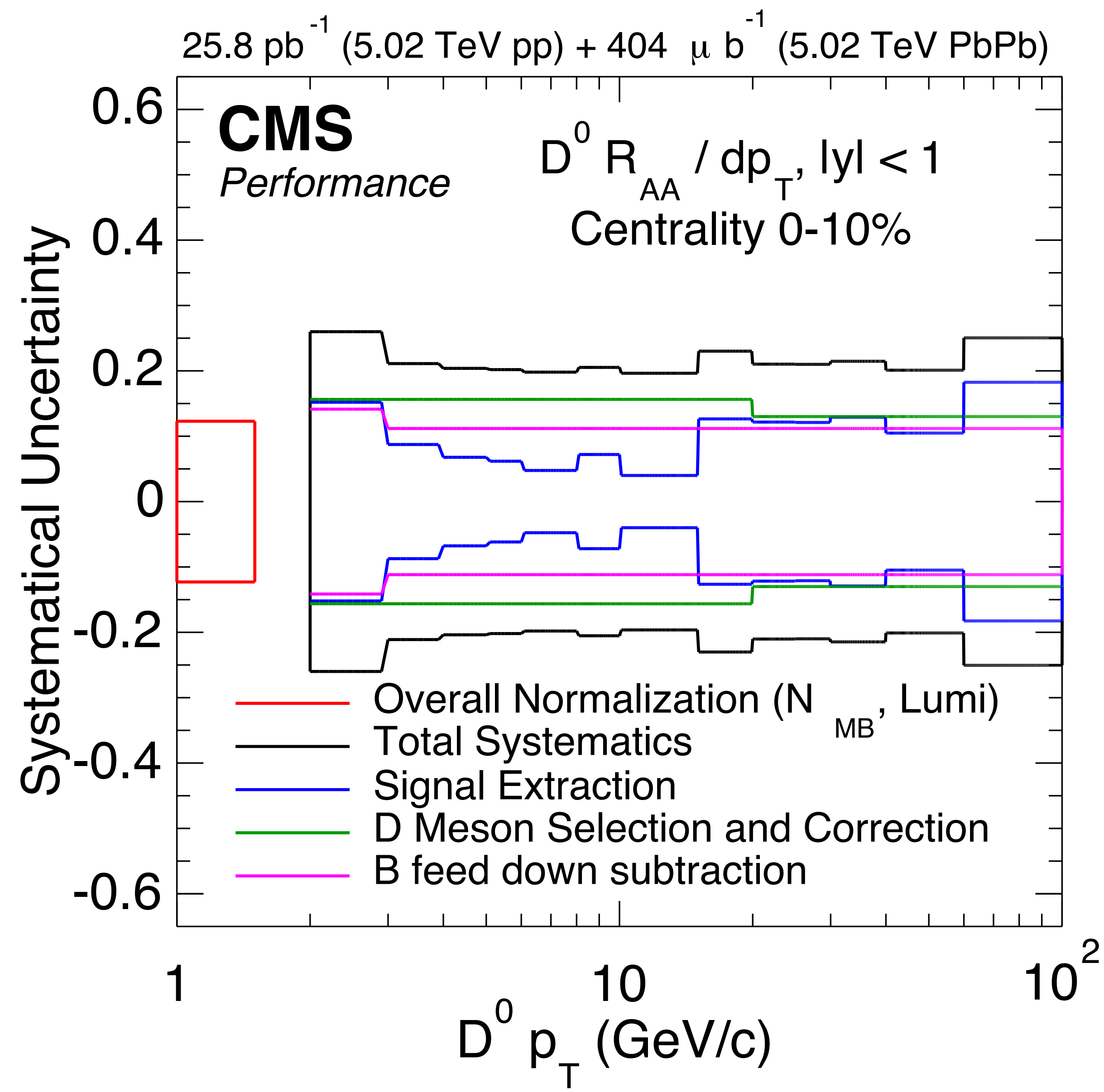


Drop in the efficiency is due to the tracking selection applied in the HLT tracking that requires a tight selection in the offline analysis

Summary of systematic uncertainties

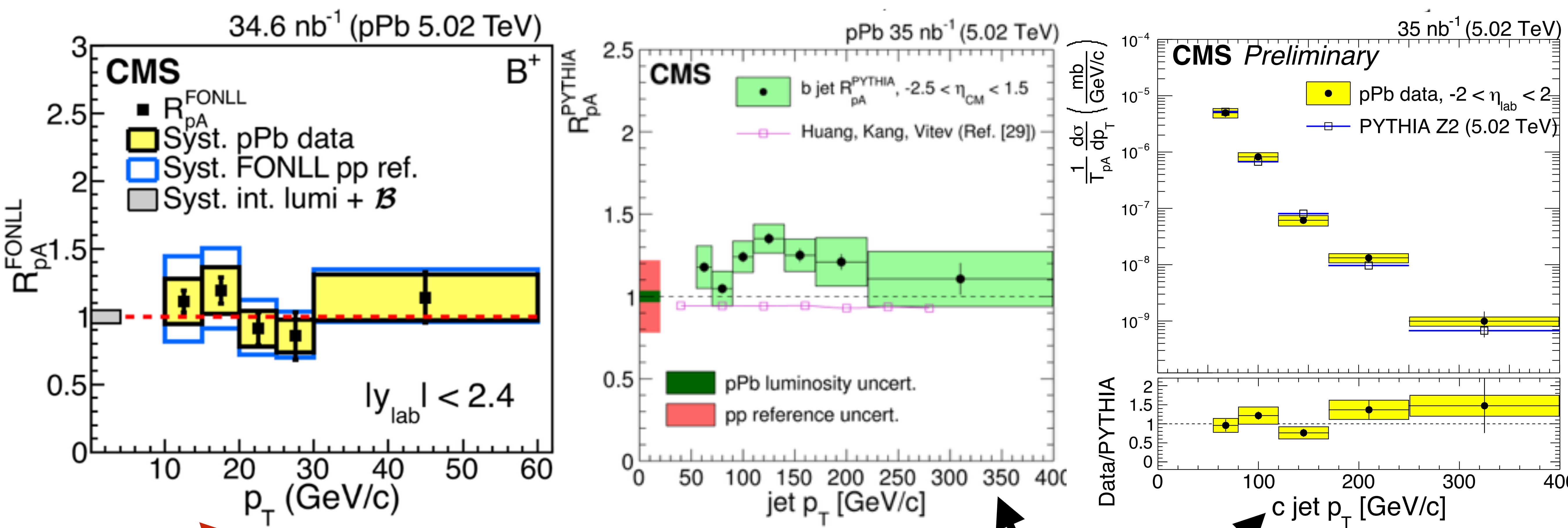


pp 5.02 TeV



PbPb 5.02 TeV Centrality 0-10%

Heavy-Flavour production in pPb



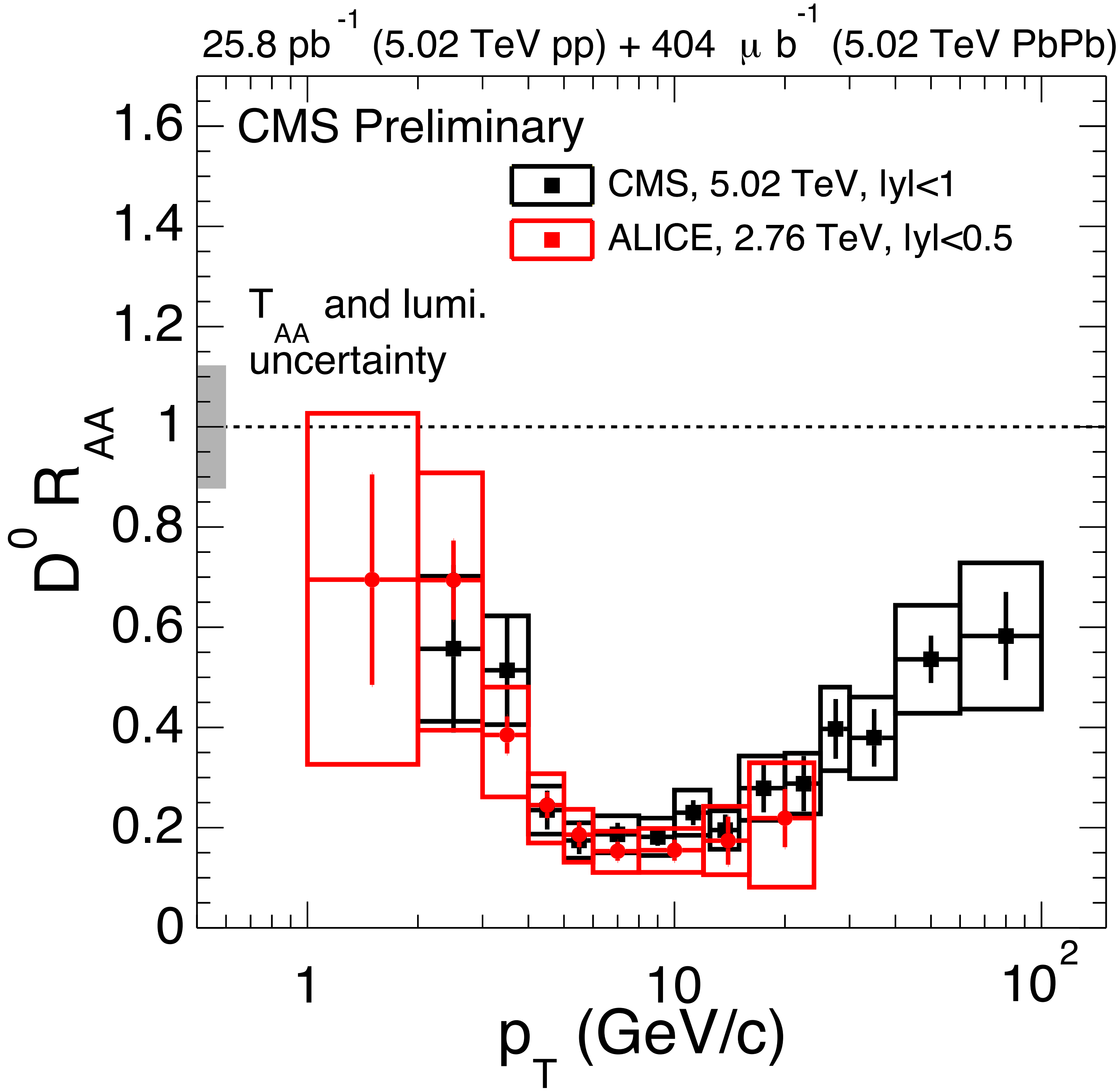
B$^+$ production in pPb
→ compatible with predictions from FONLL scaled by A=208

tagged c and b-jet production
→ compatible with predictions from PYTHIA scaled by A=208

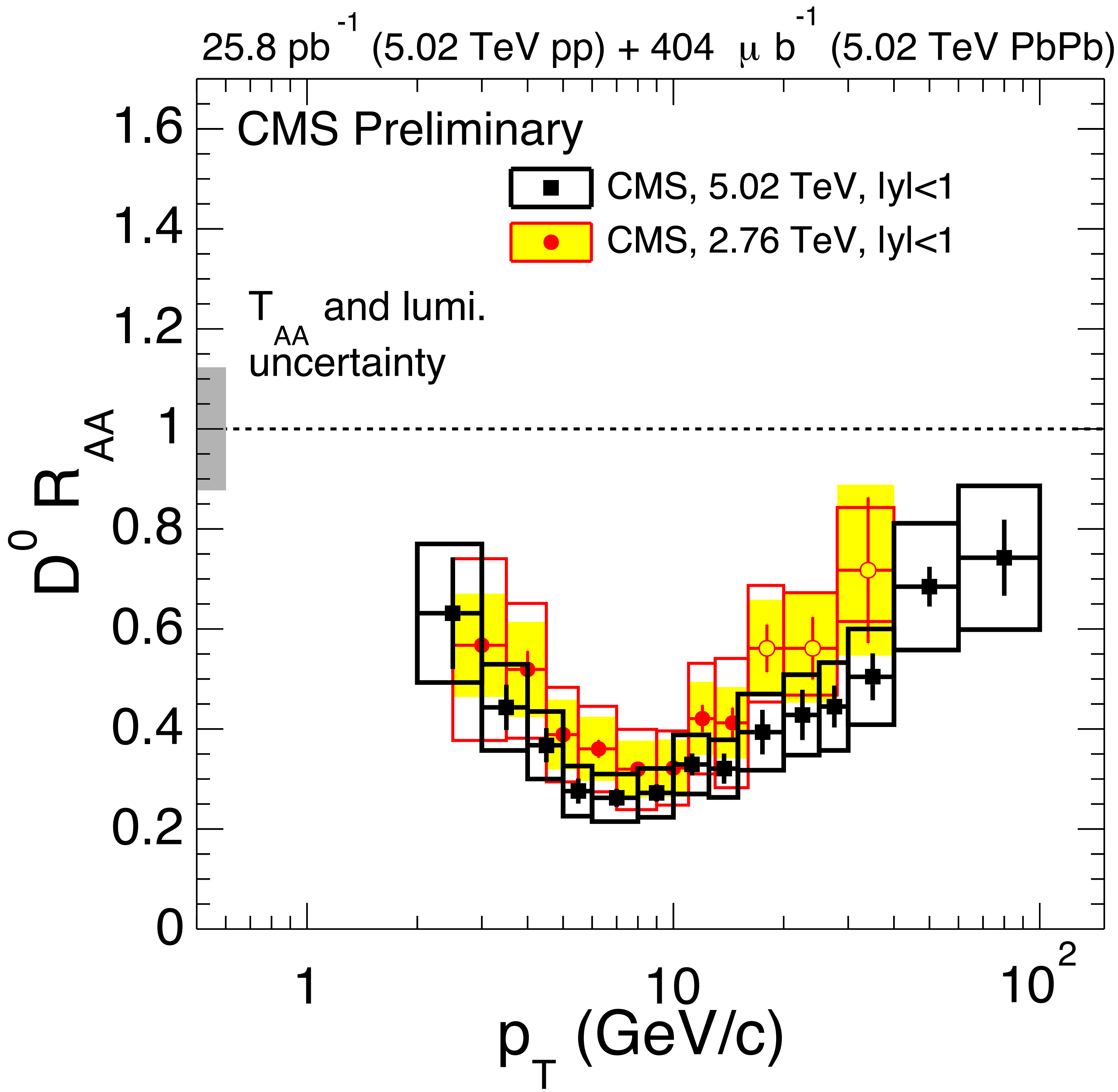
HF pPb production not significantly modified by cold nuclear matter effects (e.g. PDF modification in nuclei)

PRL 116 (2016) 032301, CMS-HIN-15-012 ,PLB 754 (2016) 59

D^0 R_{AA} comparison with ALICE



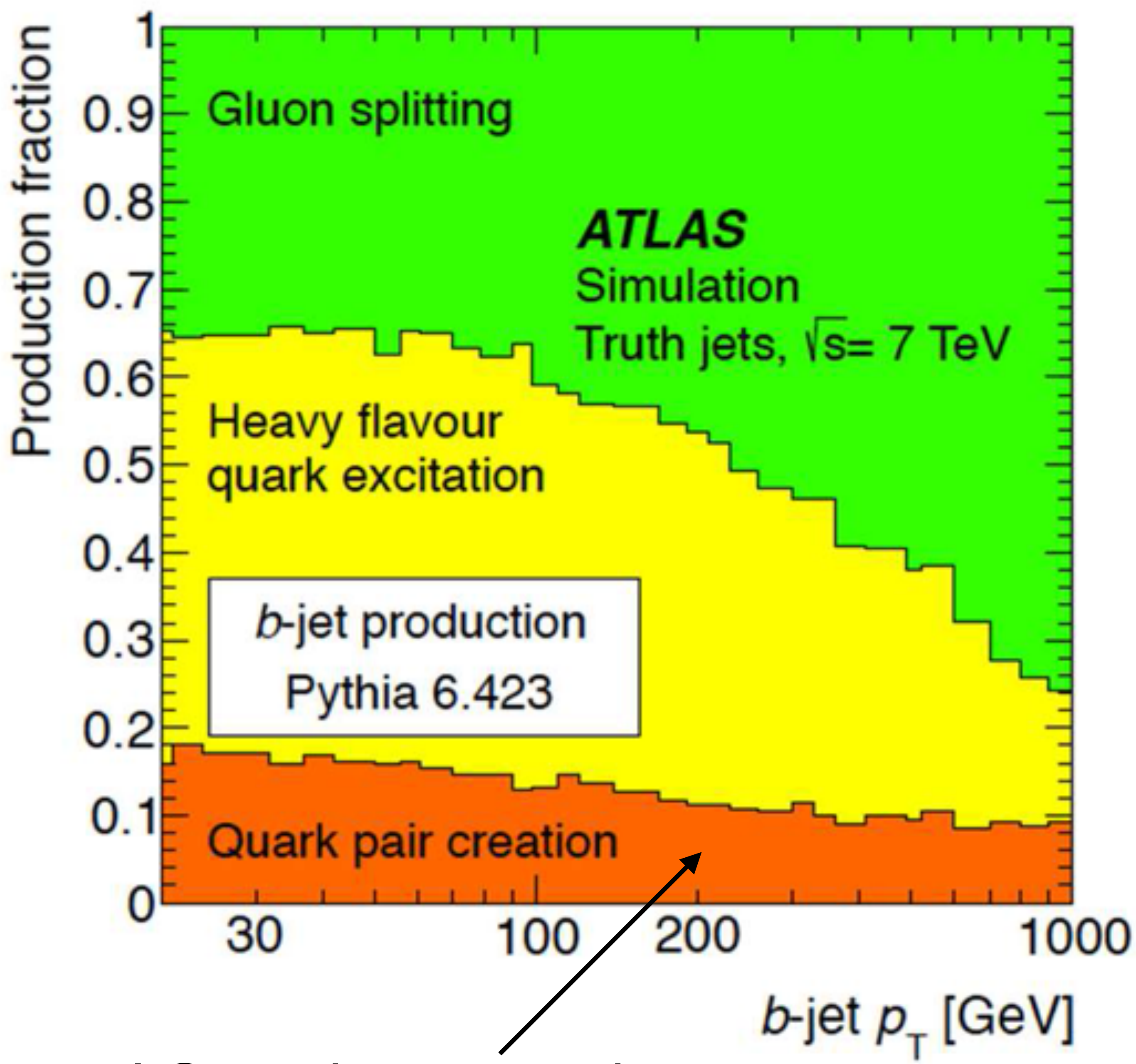
D^0 R_{AA} comparison with CMS 2.76 TeV



2.76 TeV pp reference was done by extrapolating ALICE measurement via FONLL

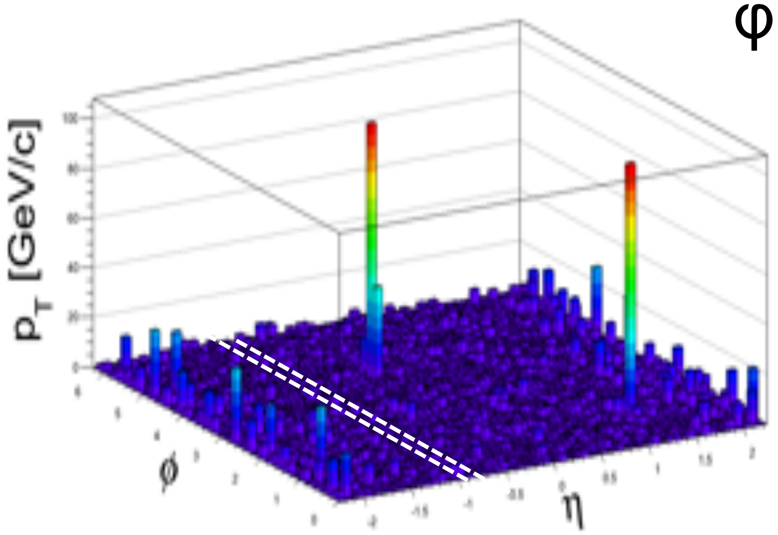
HF production mechanisms in pp

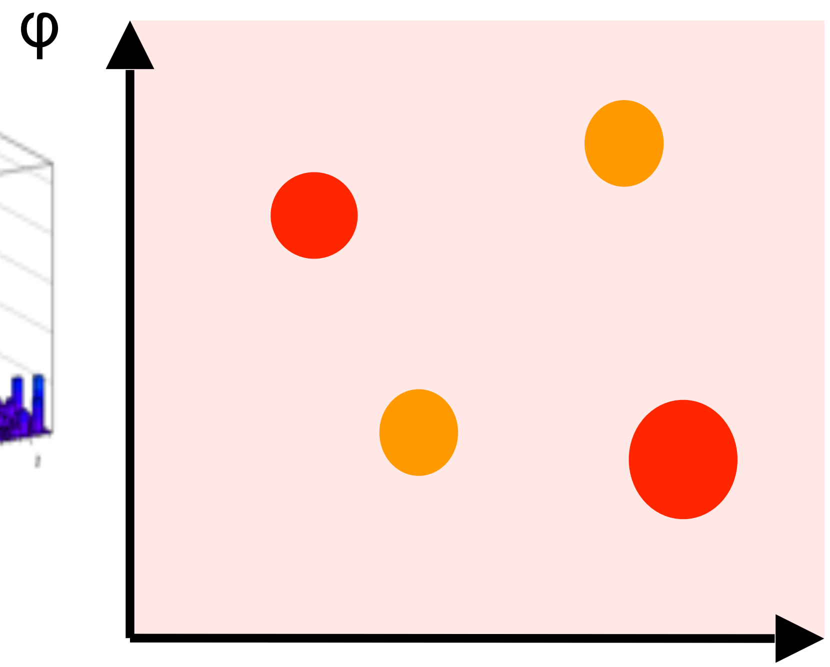
EPJC 73 (2013) 2301



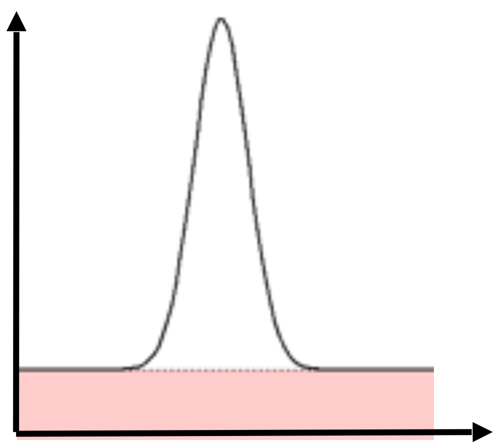
LO production mechanisms are not dominant at the LHC energies

Background subtraction





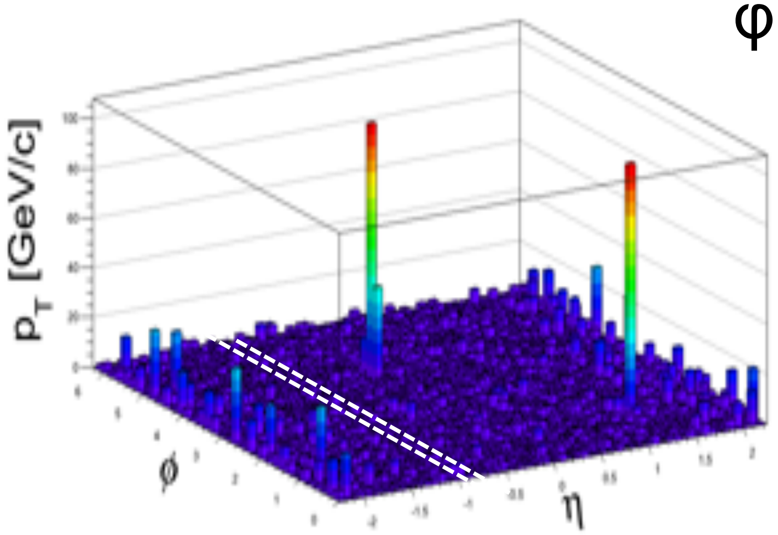
1)Background energy per tower calculated in strips of η. Pedestal subtraction

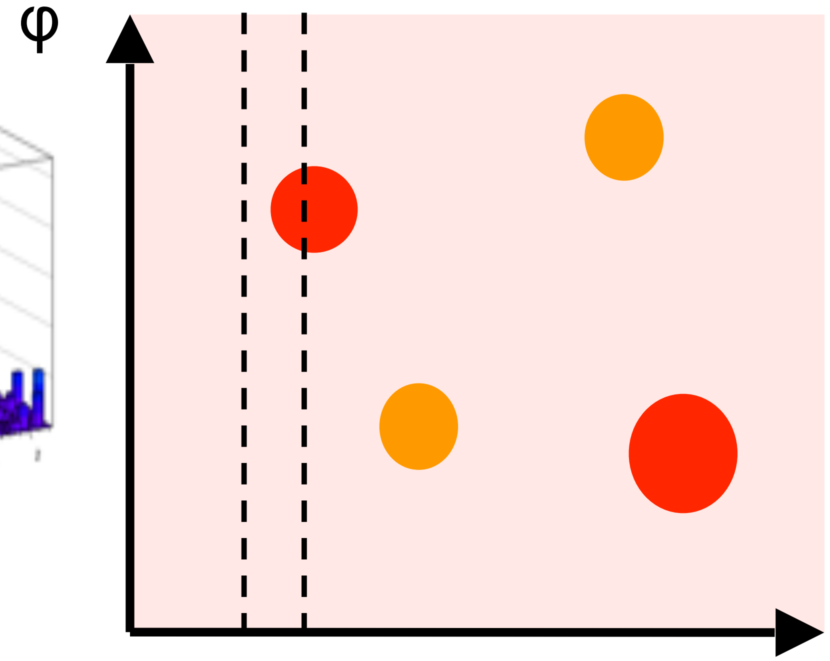


Estimate background
for each tower ring of constant η
estimated background = $\langle p_T \rangle + \sigma(p_T)$

- Captures dN/dη of background
- Misses ϕ modulation – to be improved

Background subtraction





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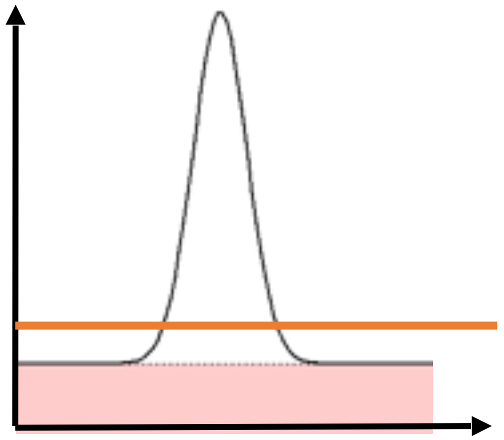
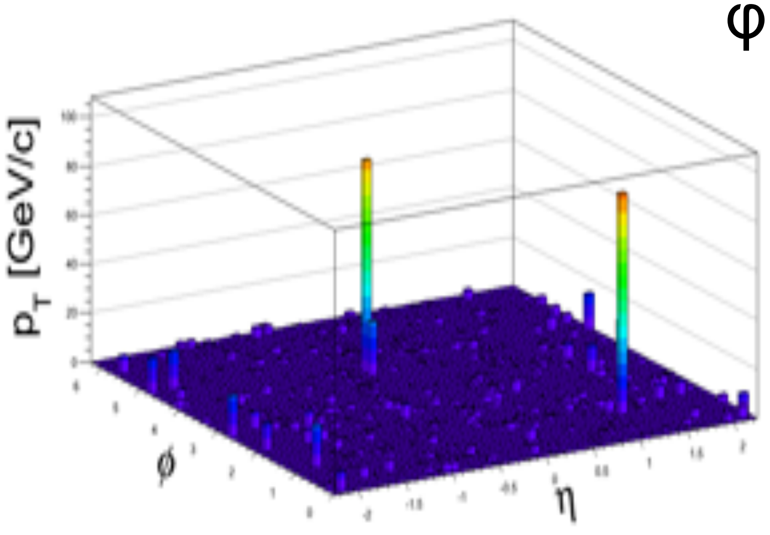
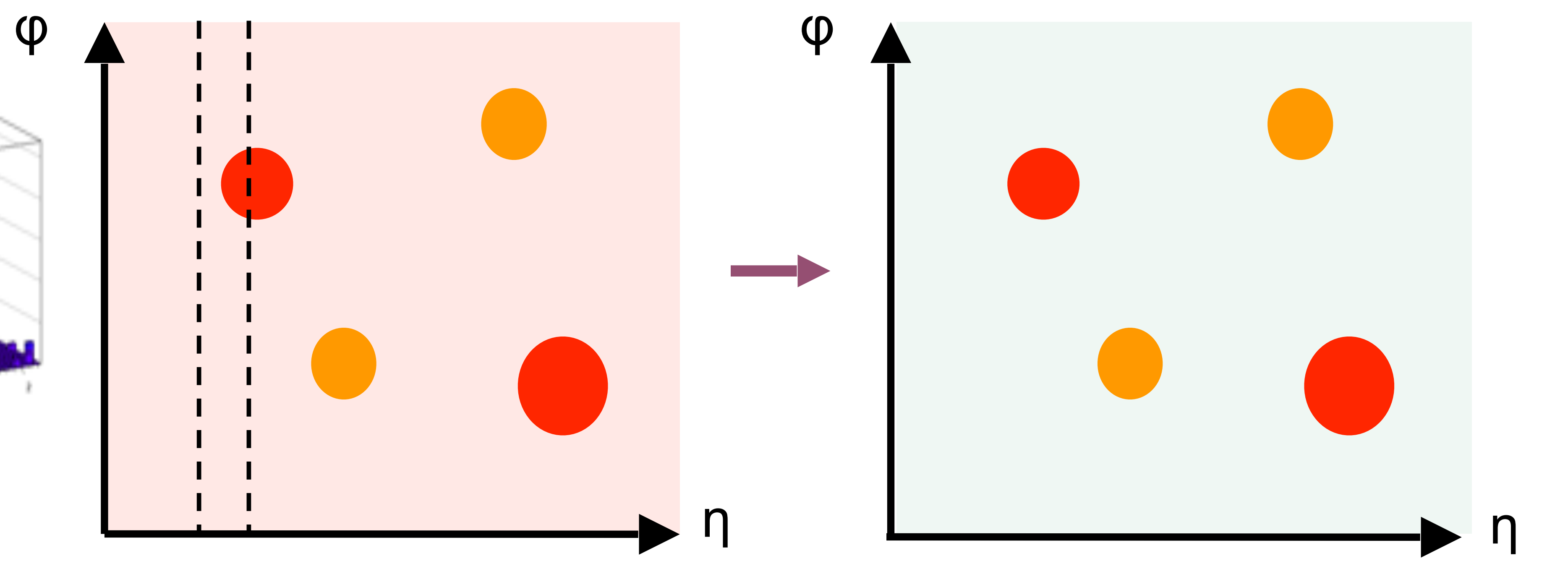


Background level

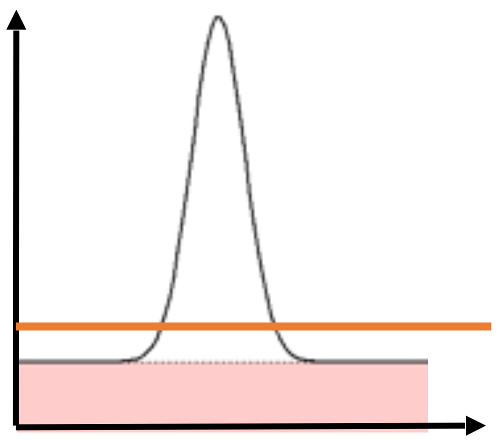
Background subtraction





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

2) Run anti k_T algorithm on background subtracted towers



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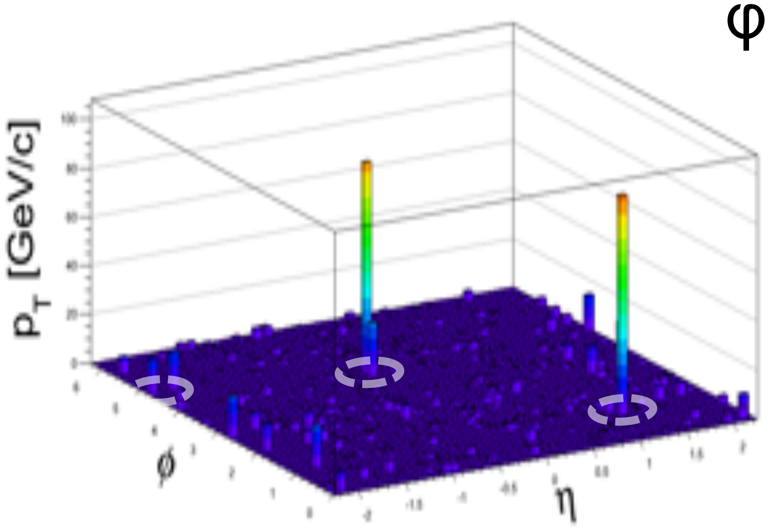
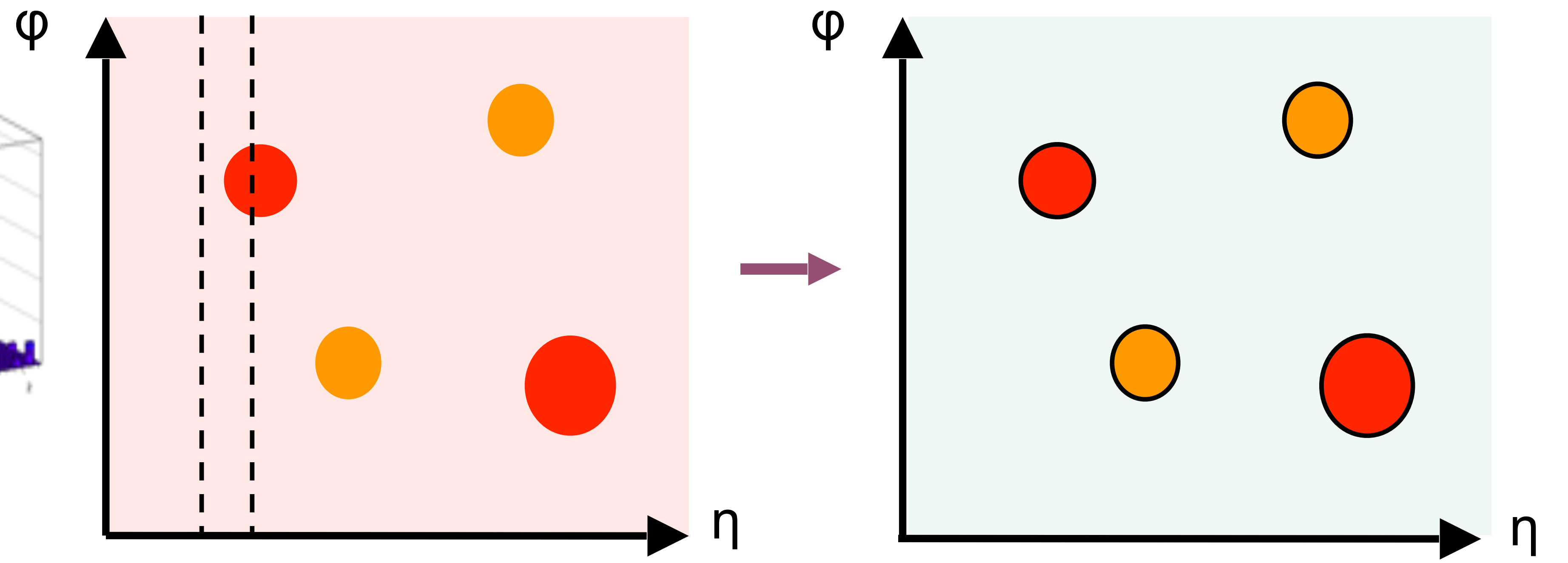
Background subtraction





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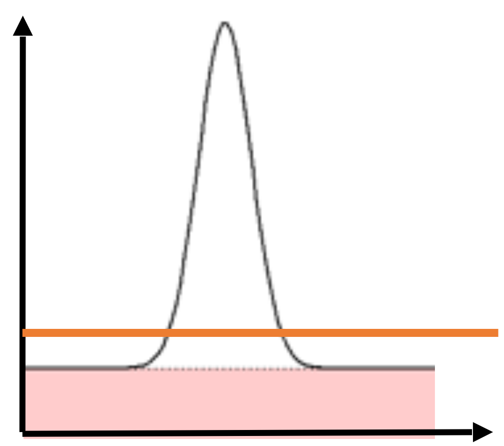
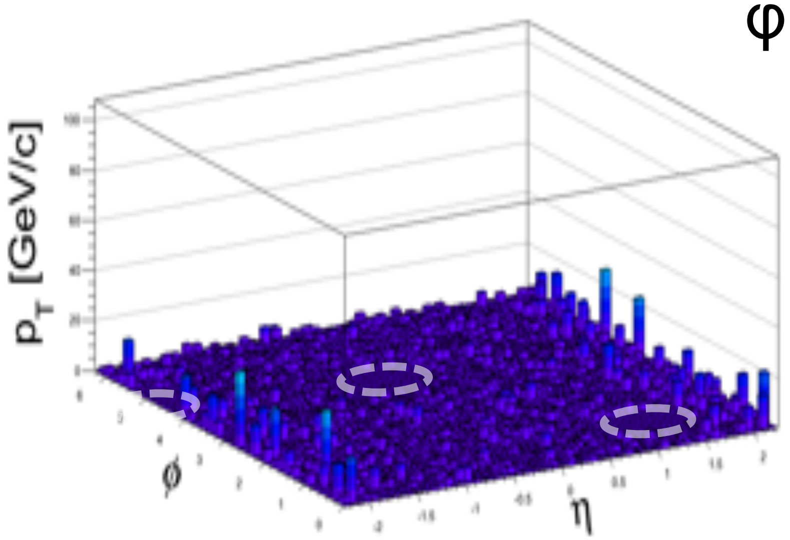
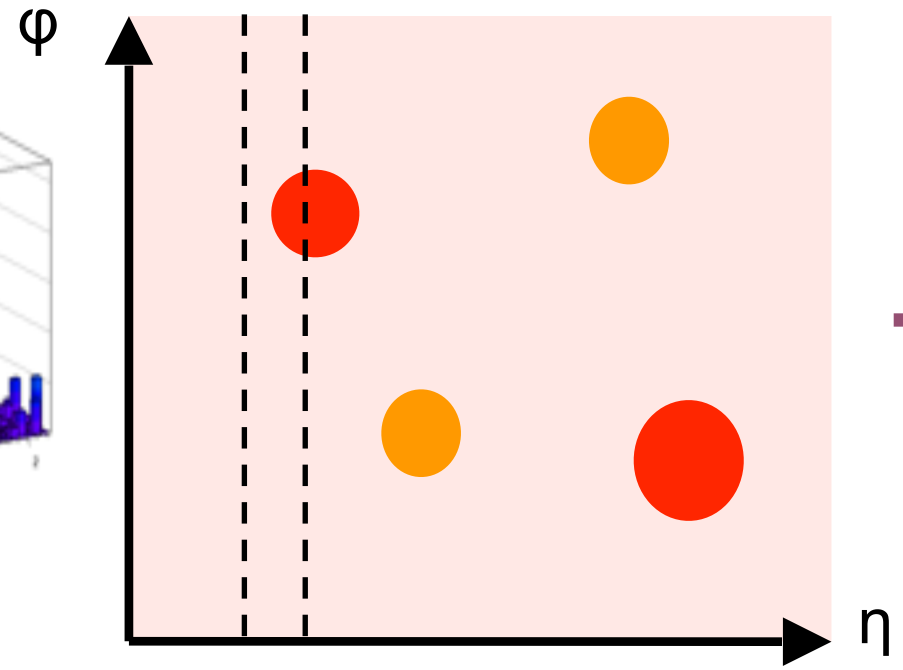


Background level

Background subtraction





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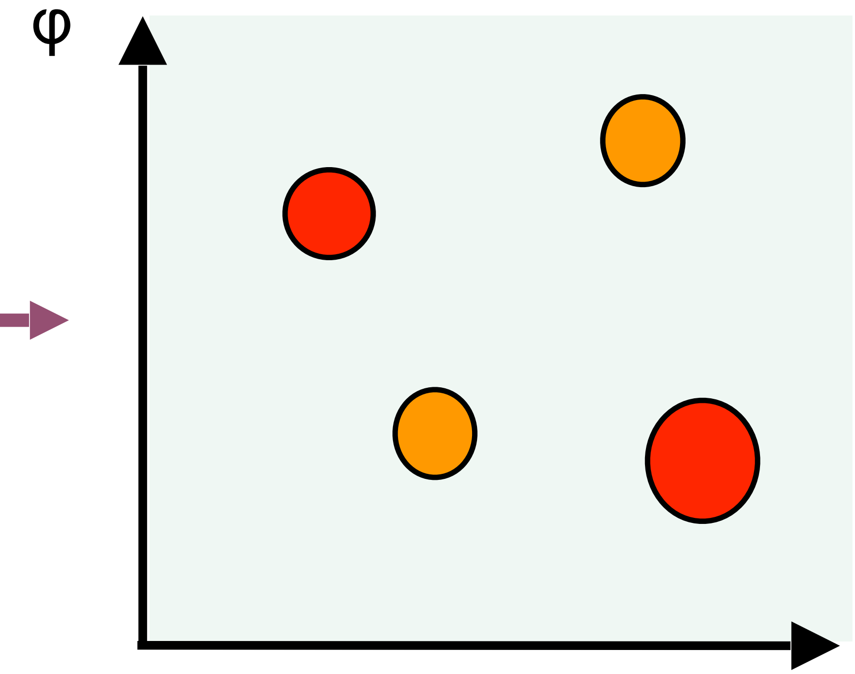

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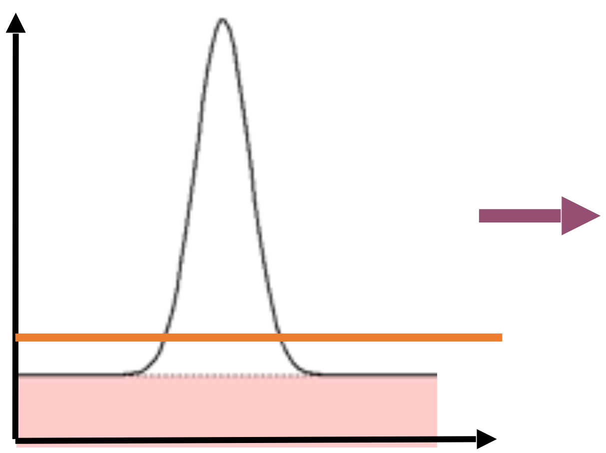
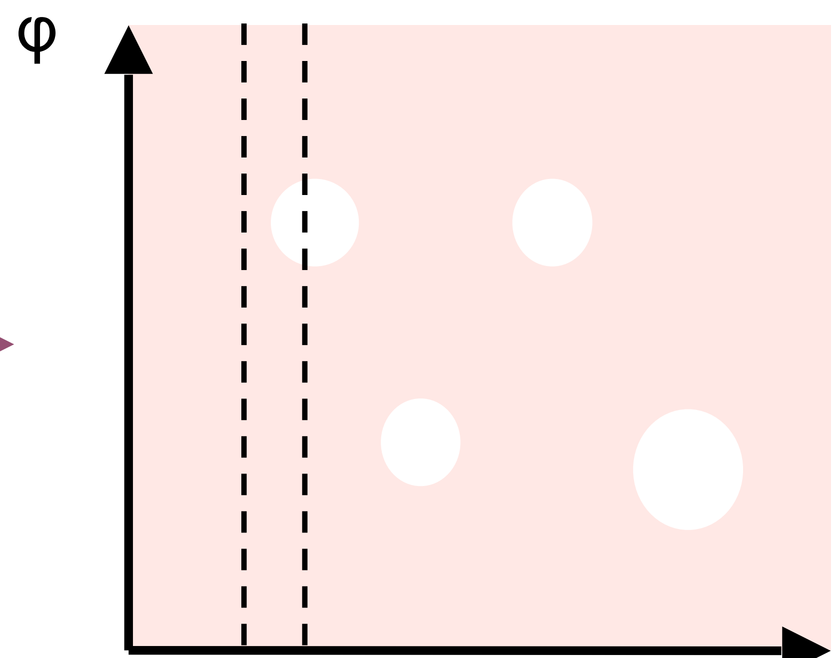
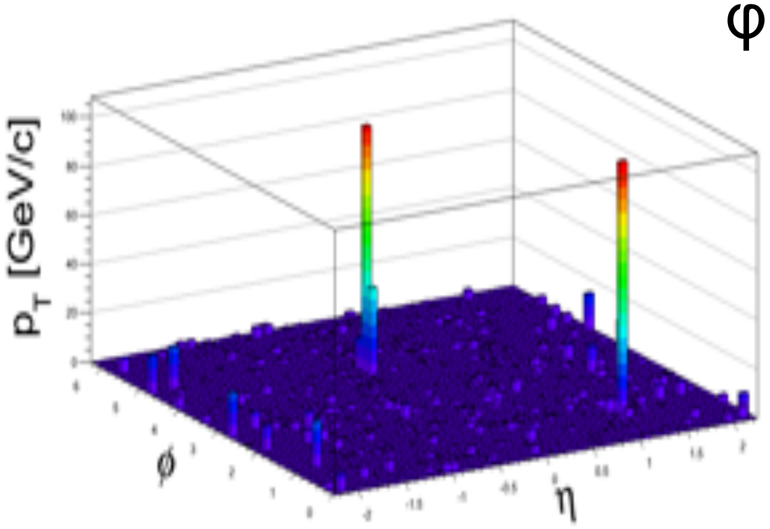


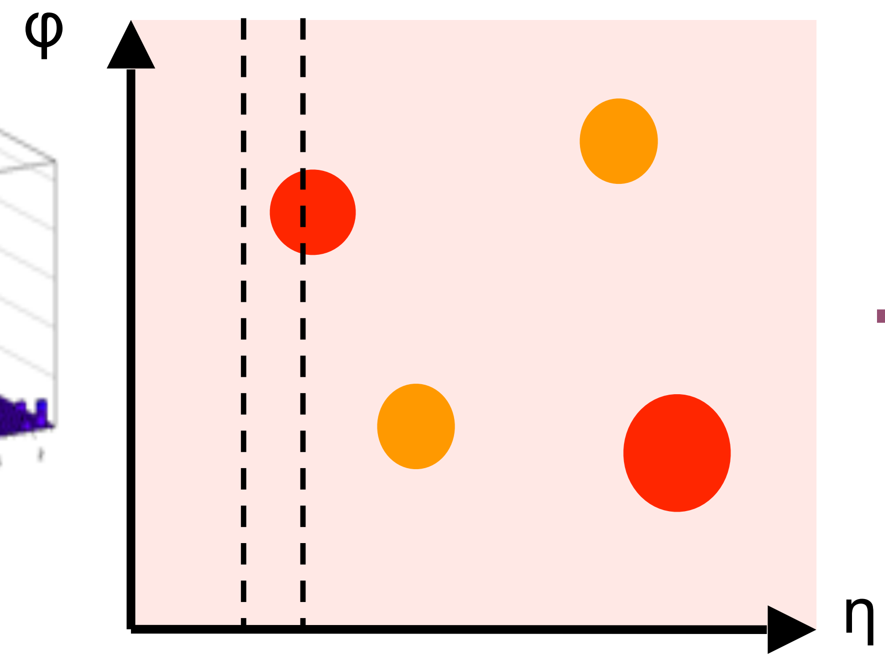
Background level

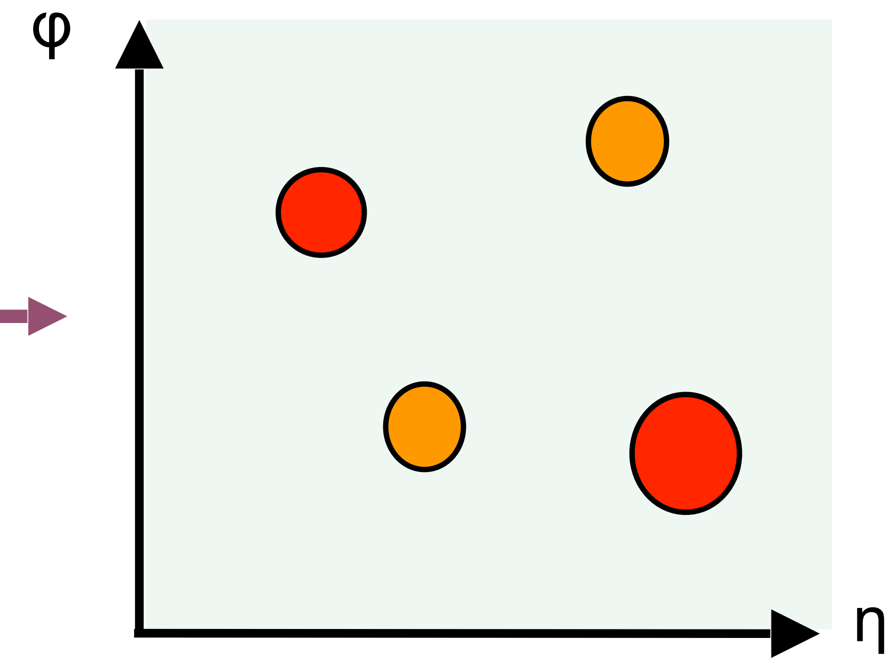


3) Exclude reconstructed jets

Background subtraction







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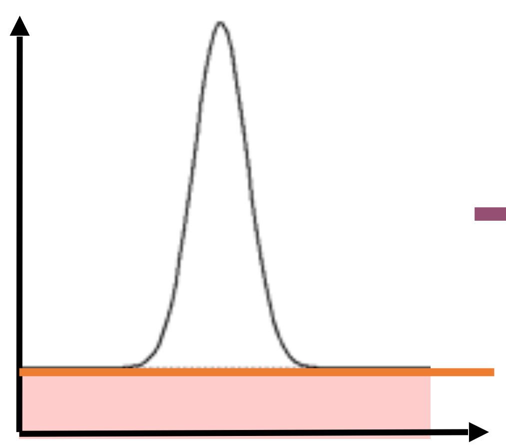
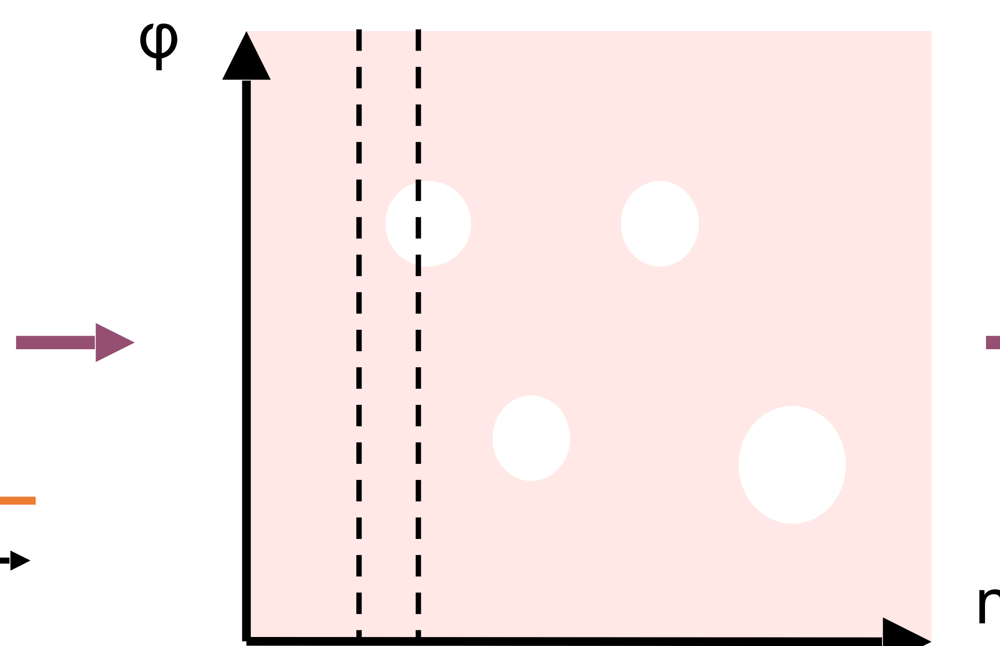
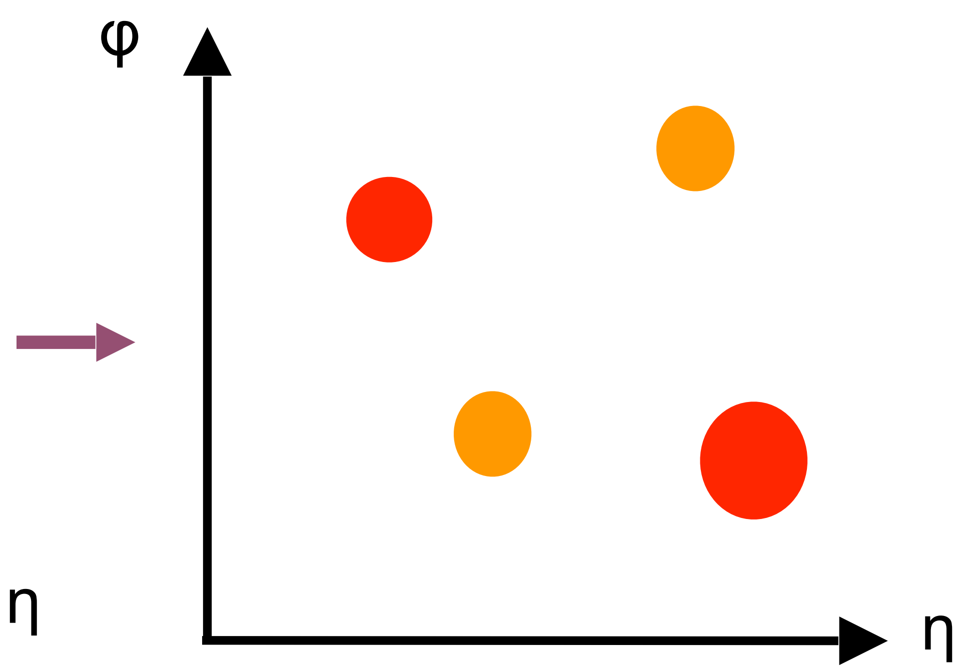


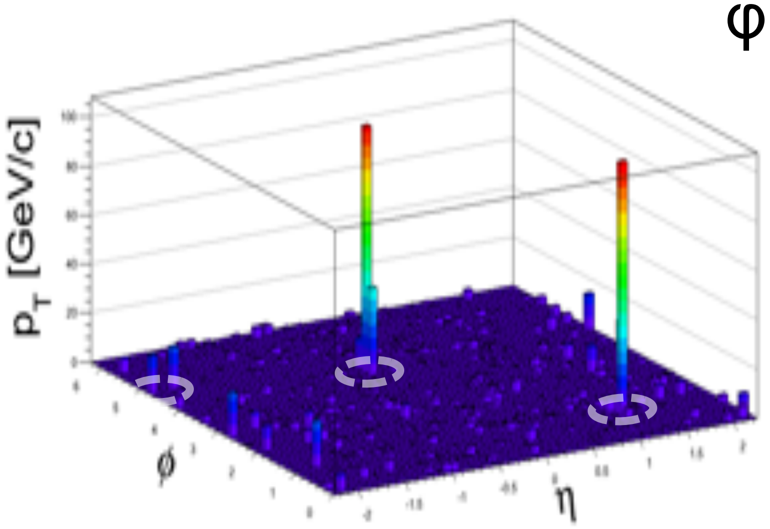
Background level

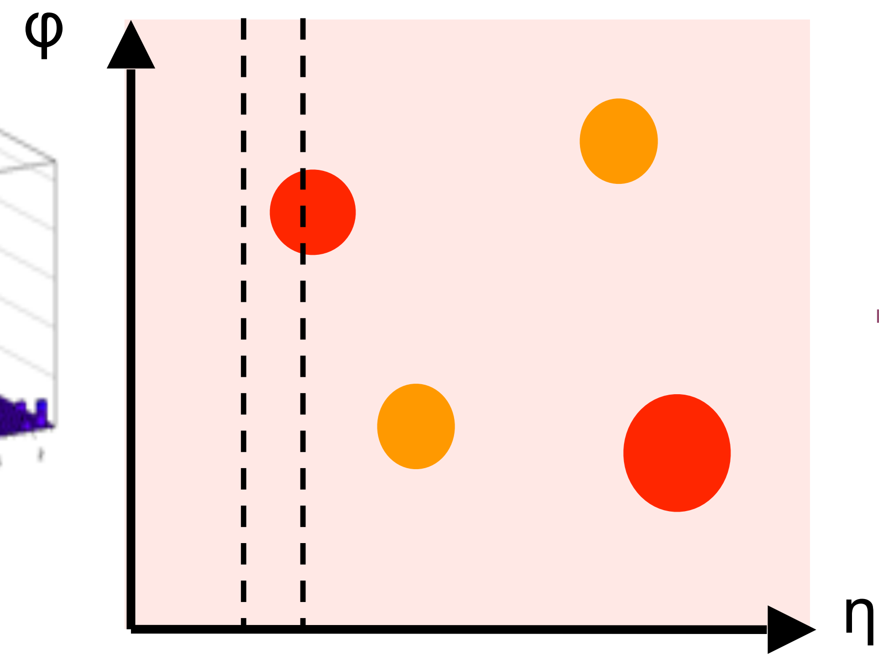


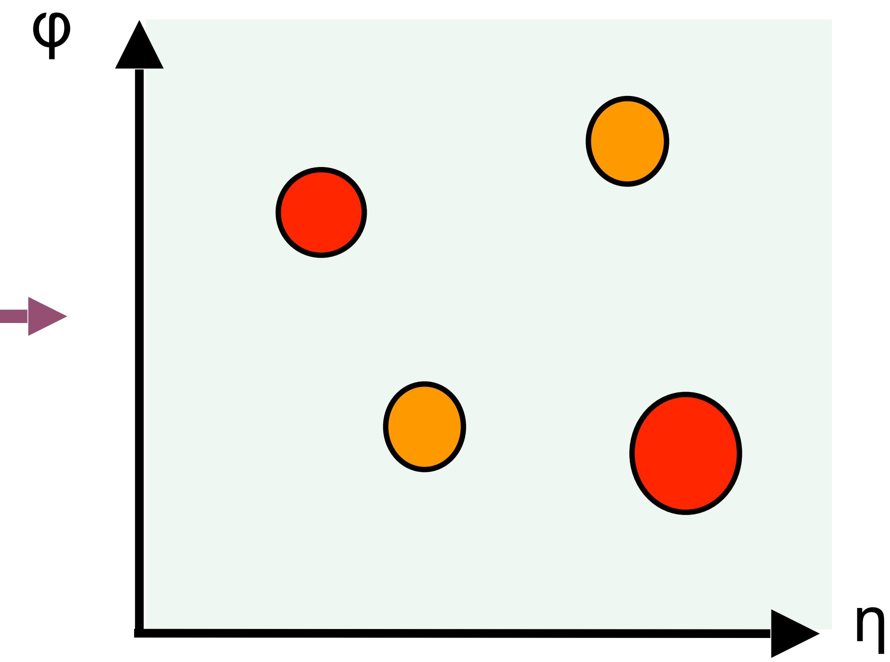


3) Exclude reconstructed jets. Recalculate the background energy

Background subtraction







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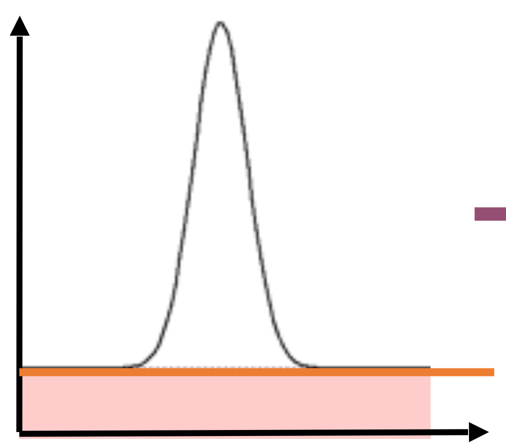
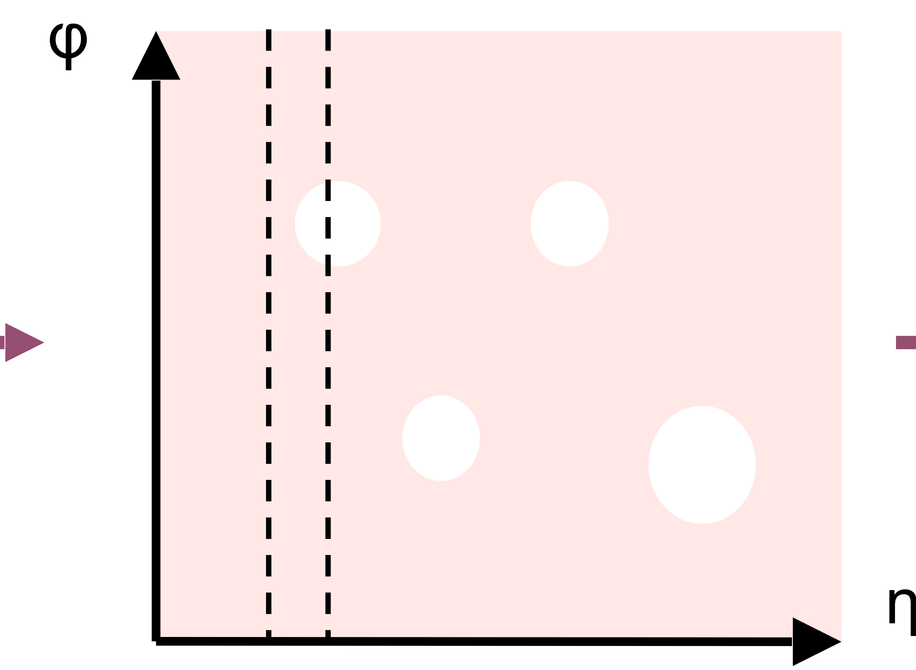
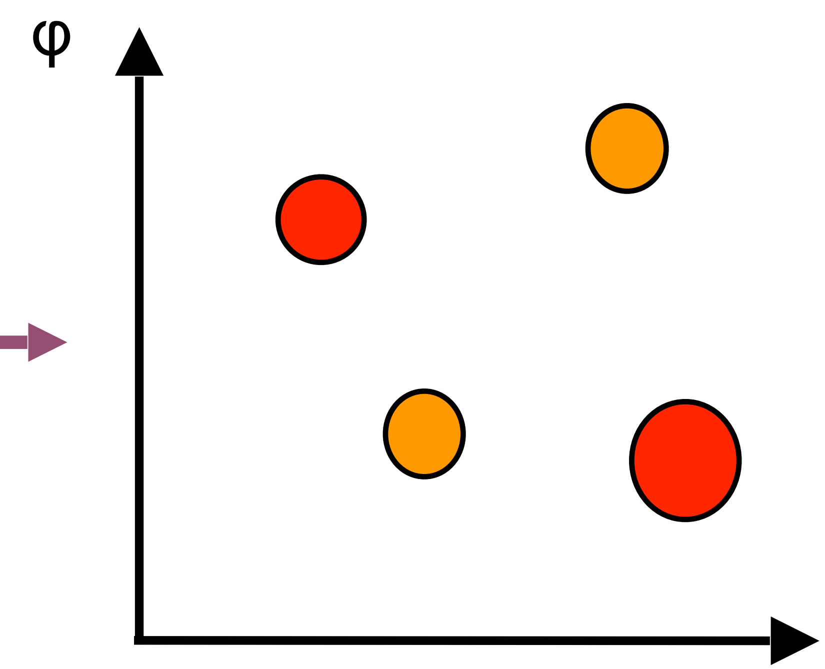


Background level

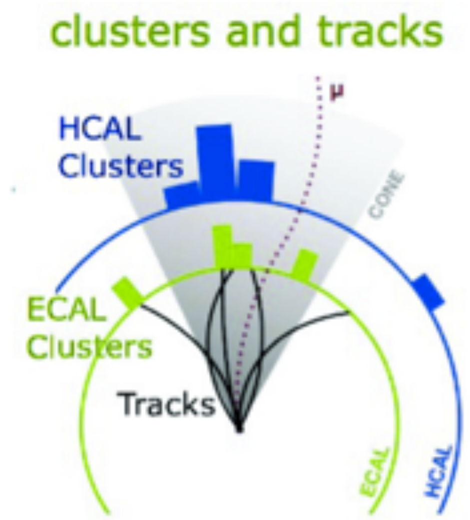


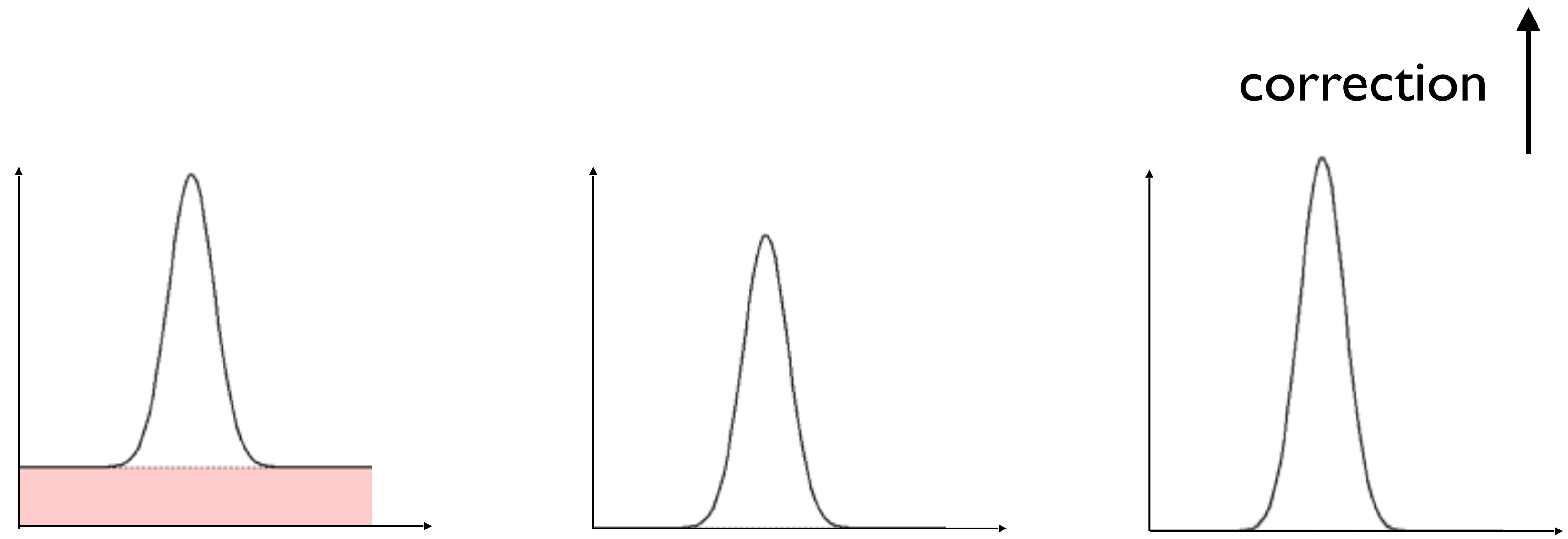


3) Exclude reconstructed jets. Recalculate the background energy

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

Jet analysis workflow





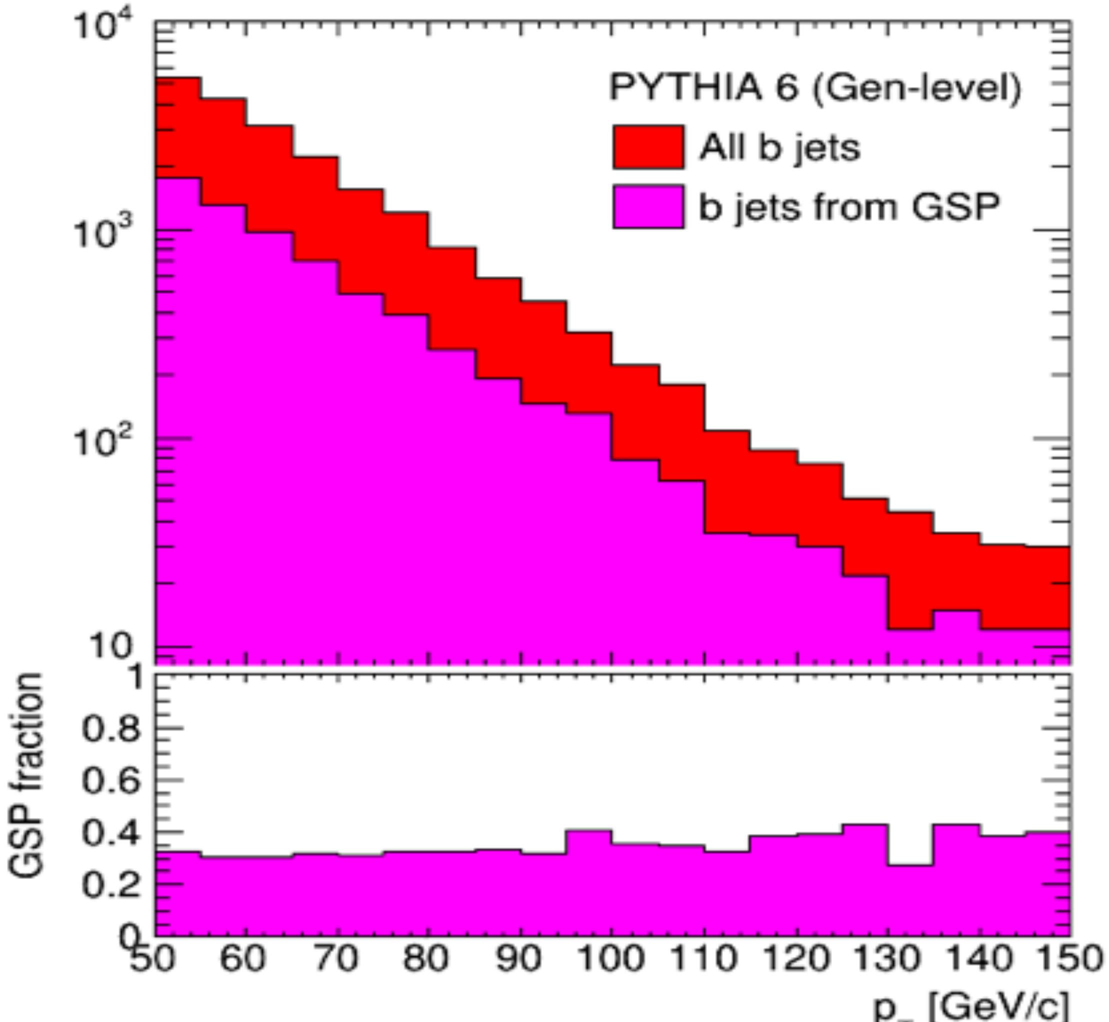
Raw jet energy → Background subtraction → Jet energy correction → Jet energy

Background subtraction: Remove underlying events contribution

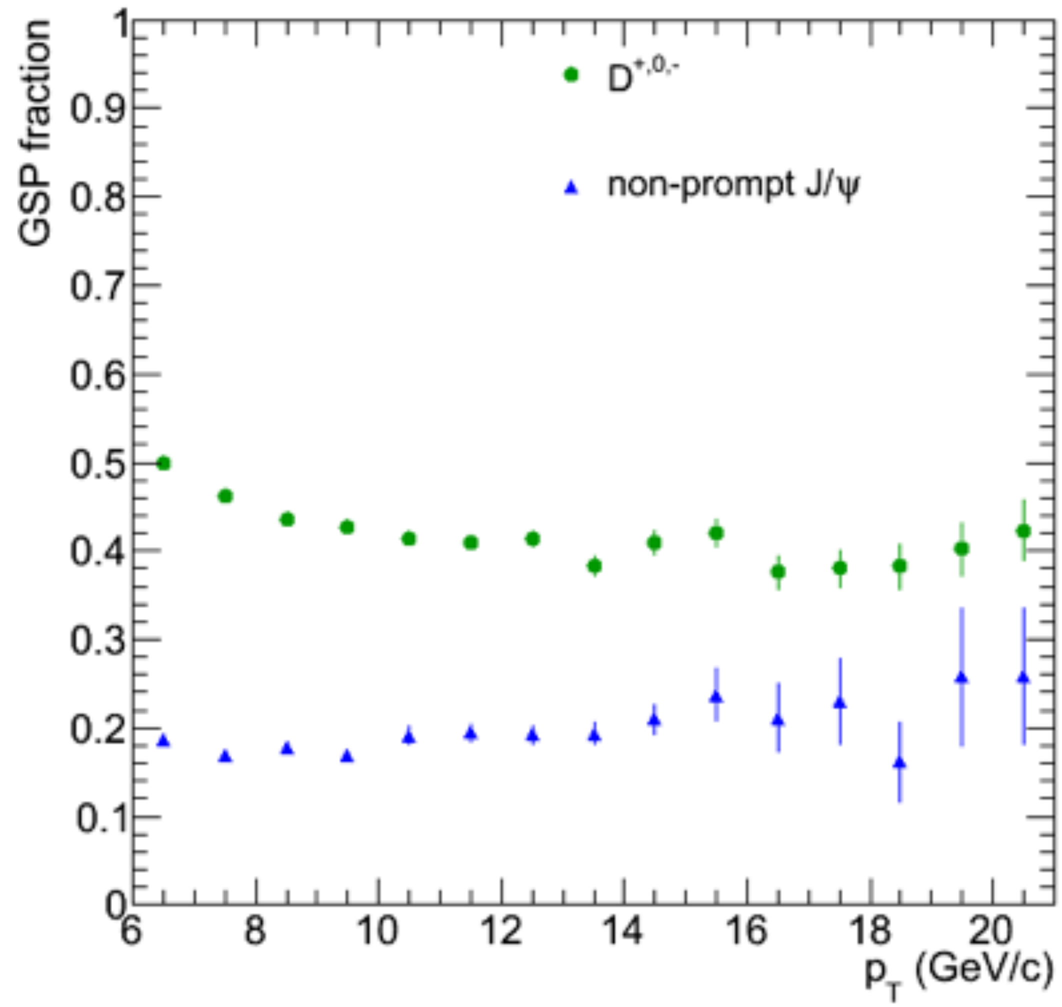
Jet energy correction: MC Simulation PYTHIA

Gluon splitting matters!

b jets



D mesons, non-prompt J/ψ

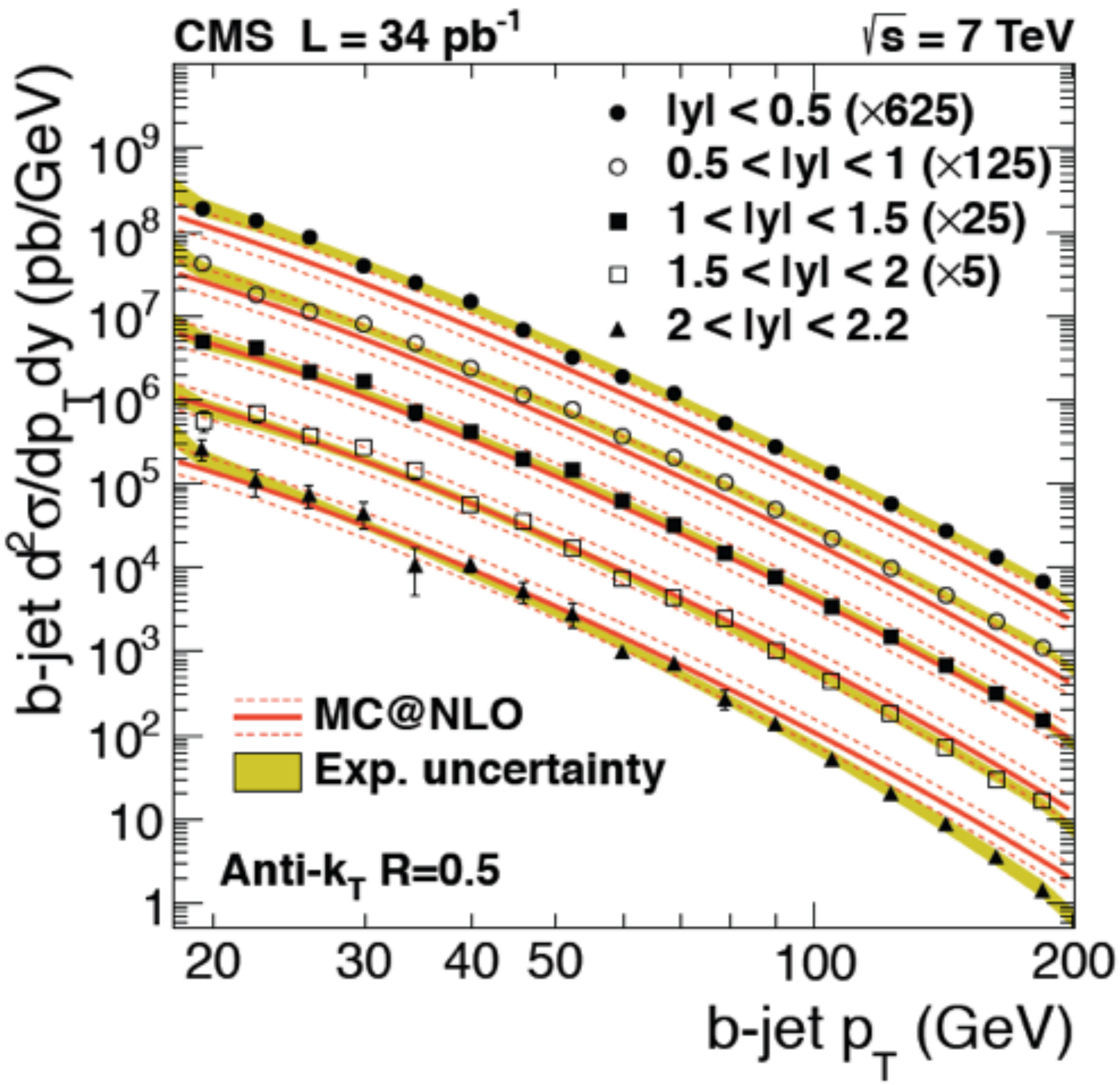


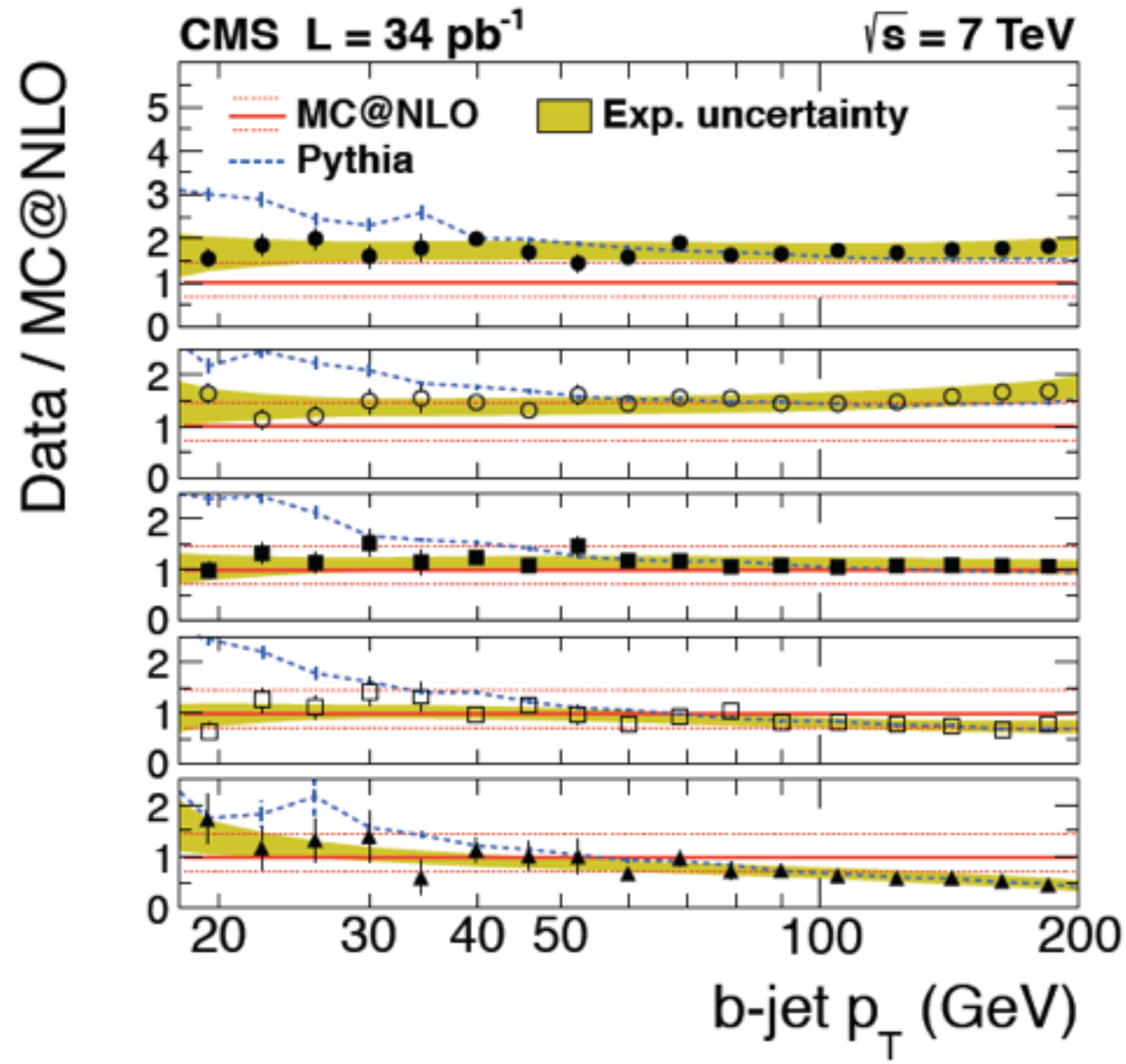
Plots from Matthew Nguyen

- A non negligible fraction of b-jets at the LHC come from gluon splitting
- Even more important for charm than for bottom at LHC energy!

b-jet cross section

Double differential cross section (y and pT)

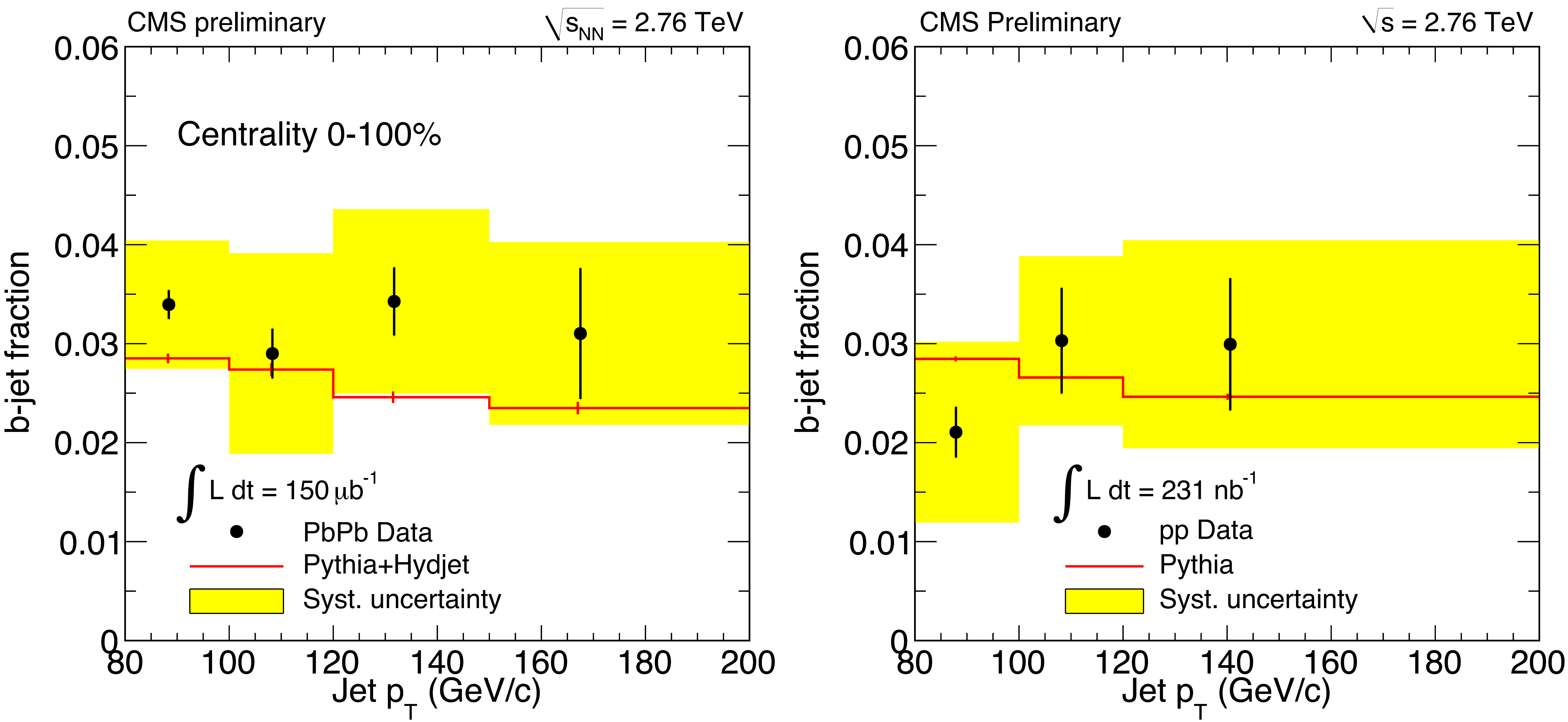




- MC@NLO agreement at the edge of uncertainties
- Pythia overshoots at low pT, agrees well at high pT

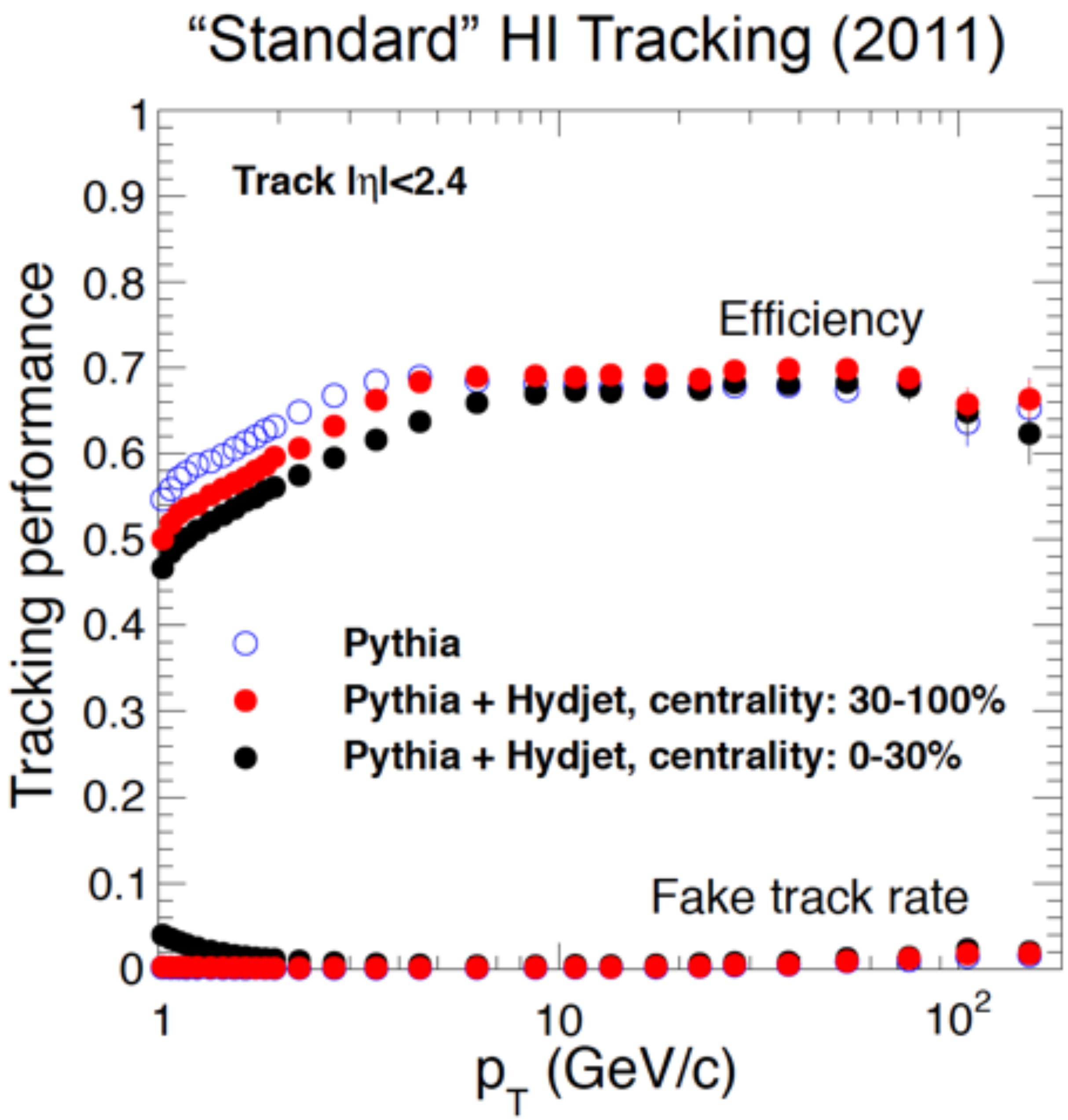
b-jet to inclusive jet ratio

b-jet fraction = # of tagged jets * purity / efficiency



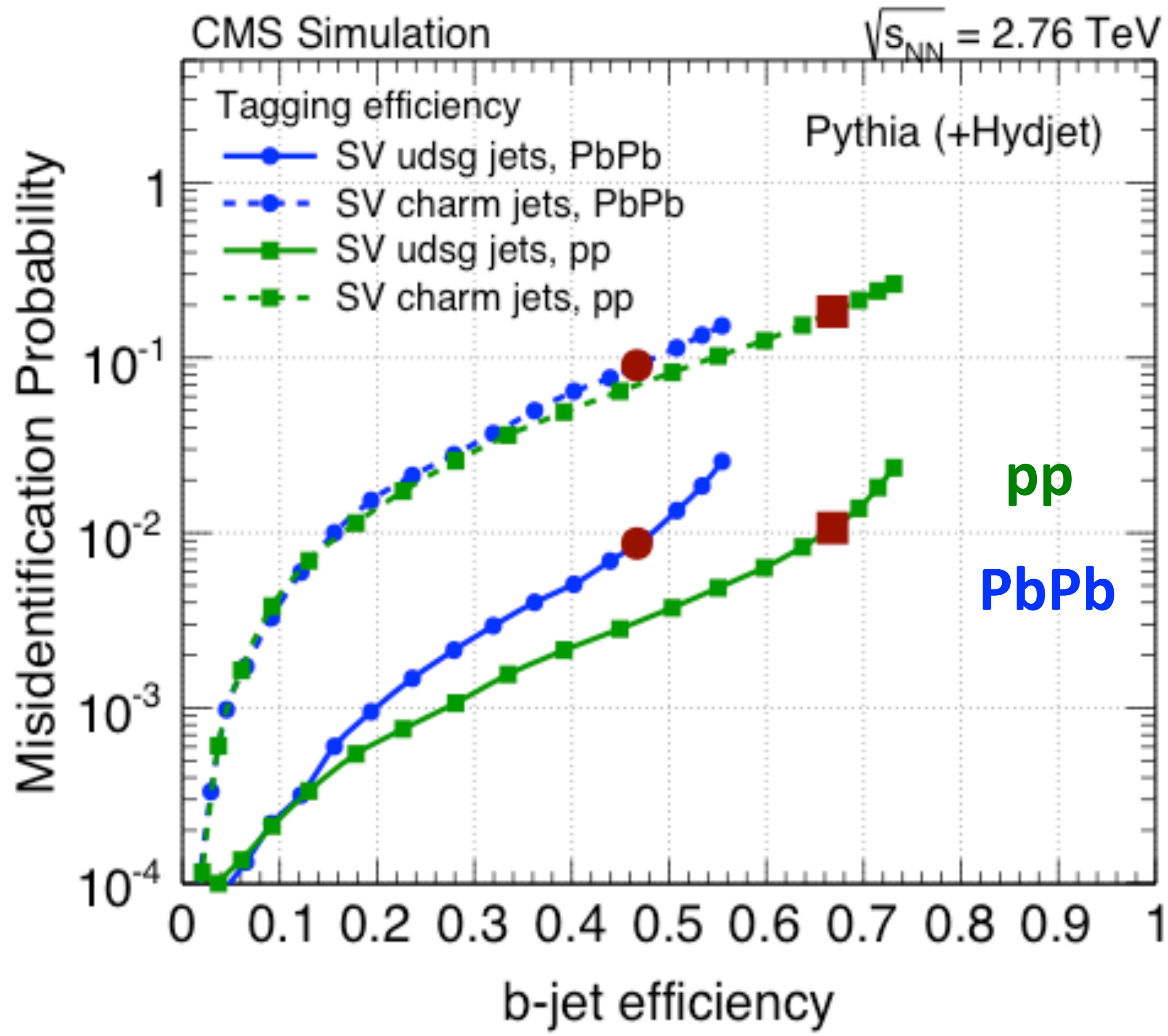
- b-jet fraction consistent within pp and PbPb within uncertainty
- Both measurements consistent with MC predictions

Tracking in heavy-ion collisions



CMS-PAS-HIN-12-013

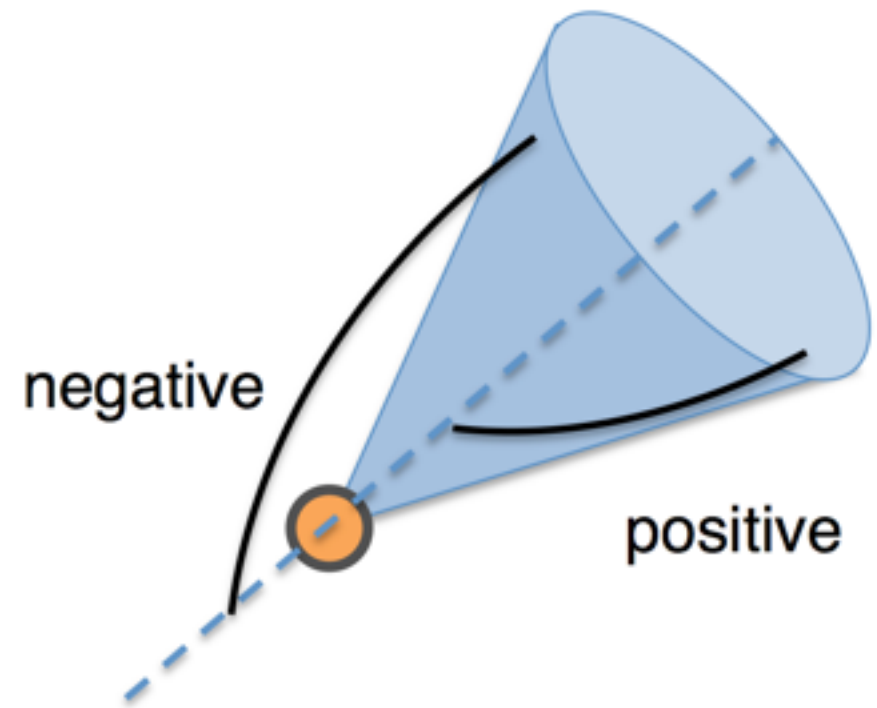
b-jet efficiency vs misidentification



jet probability tagger

- Alternative tagger used as a cross-check on SSV
- Each track assigned a probability to be from primary vertex
- Determined separately for Data and MC using negative IP tracks
- JP= probability that all tracks originate from primary vertex

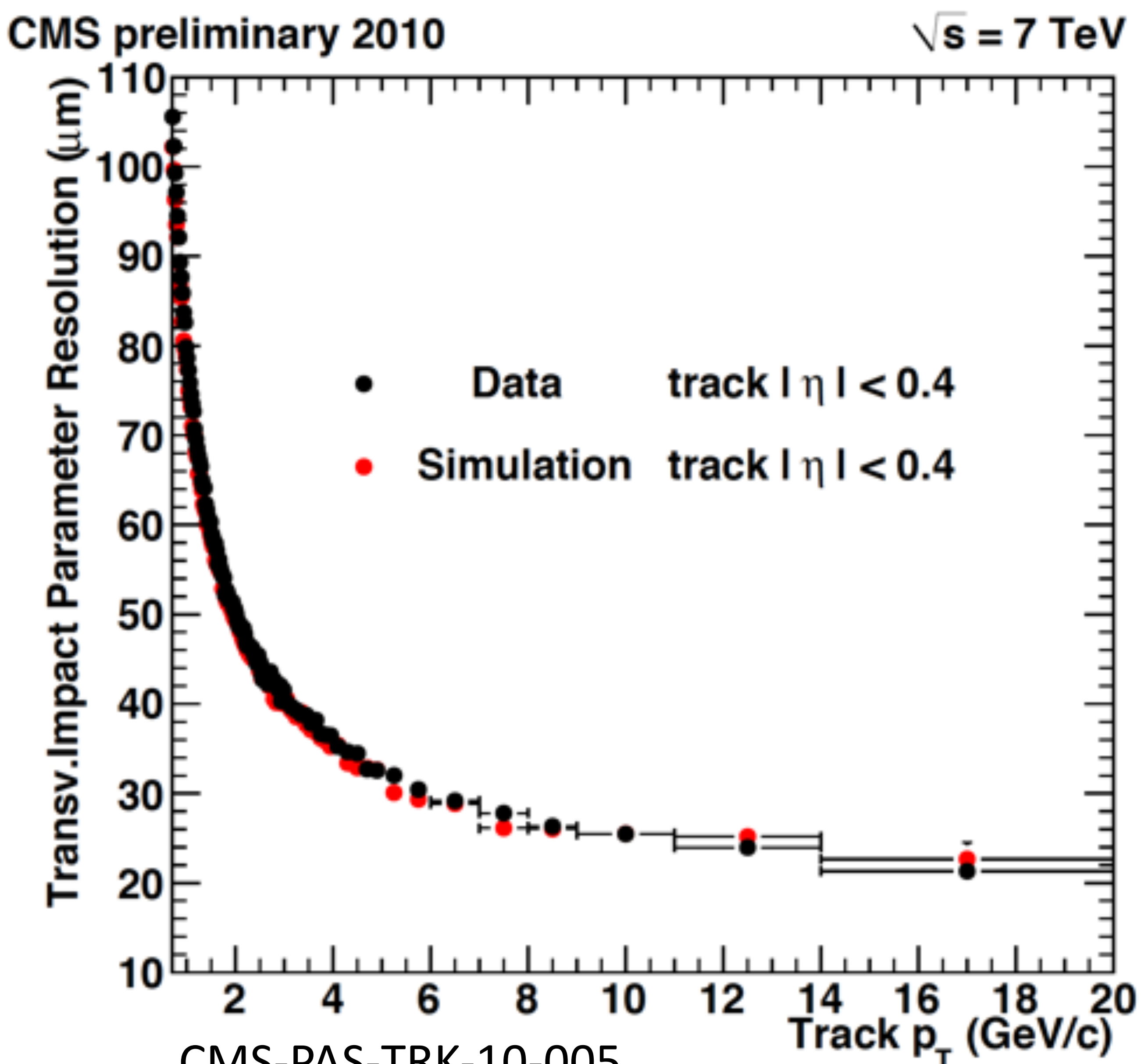
Signed impact parameter



$$P_N = \Pi \cdot \sum_{j=0}^{N-1} \frac{-\log \Pi}{j!}$$

with $\Pi = \prod_{i=1}^{N} P(S^i)$

Tracking performances

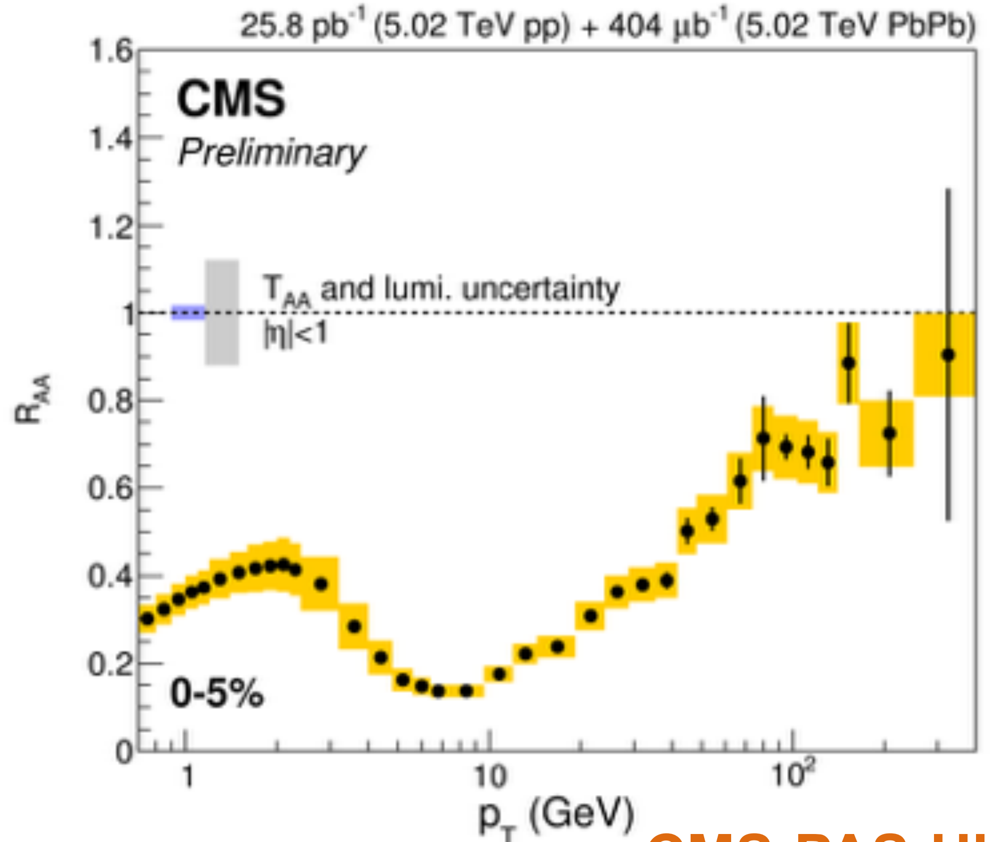


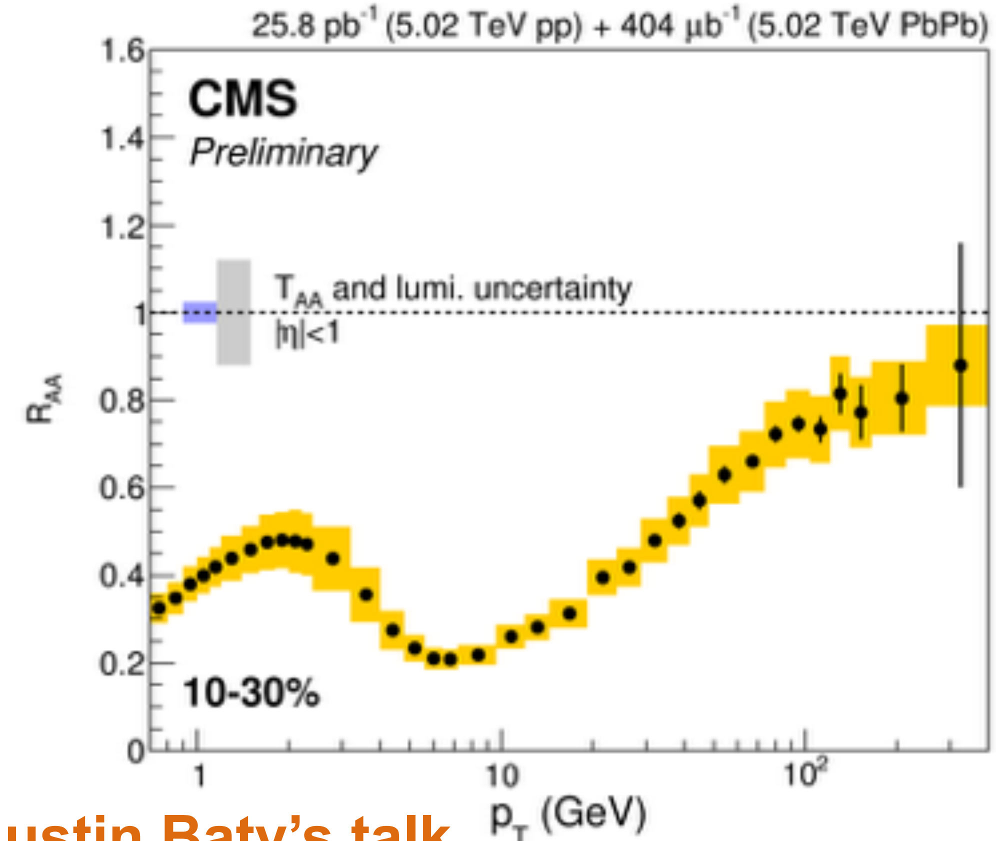
CMS-PAS-TRK-10-005

Excellent pixel spacial resolution

- ≈100 μm at 1 GeV/c, 20 μm at 20 GeV/c
- well described by MC simulations based on GEANT

Charged particle R_{AA} at 5.02 TeV





CMS-PAS-HIN-15-015, See Austin Baty's talk