Heavy flavor measurements in small systems

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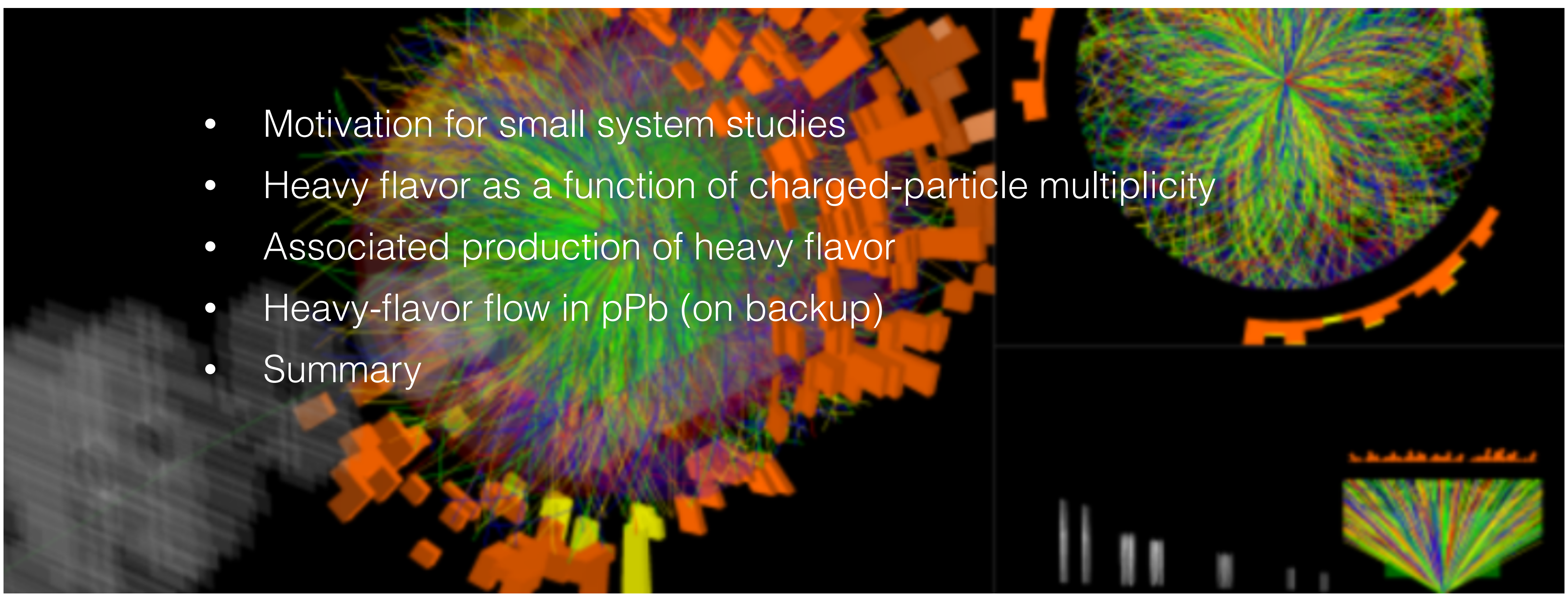
ECT Trento — QGP characterisation with HF — 15-18 November 2021



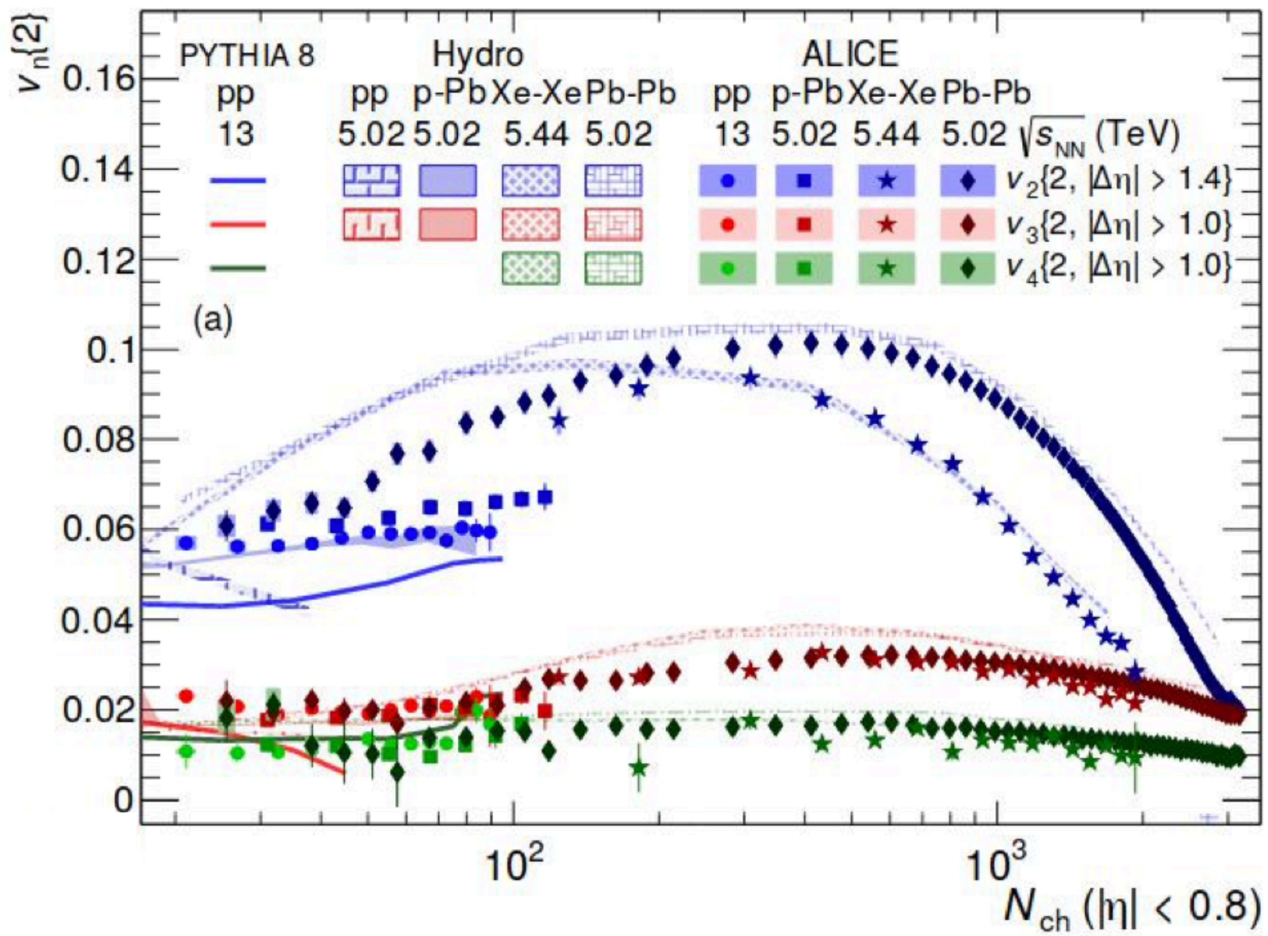
- Motivation for small system studies
- Heavy flavor as a function of charged-particle multiplicity
- Associated production of heavy flavor
- Heavy-flavor flow in pPb (on backup)
- Summary

Observation of collective behaviour in few-particle systems

- Unexpected similar values of v_n in pp, p-Pb and heavy-ion collisions at low multiplicity.

- **In small (few-particle) systems,**
  - **pp measurements can not be explained by models without collective effects** (PYTHIA 8).
  - **model description in pp and p—Pb not satisfactory** (PYTHIA 8, IP-GLASMA+MUSIC+UrQMD).

- **Observation at the origin of new research directions to address the physics of small systems and the transition from small to large systems** (initial state of the collision, possible sub-nucleon structure, origin of collectivity…)



ALICE, Phys. Rev. Lett. 123, 142301 (2019)
arXiv:1903.01790

Small system physics at the LHC

Table prepared by the WG small systems from the HL/E-LHC working group (~140 refs)
arXiv:1812.06772 arXiv:1602.09138

Observable of effect	Pb-Pb	pPb (high mult)	pp (high mult)
SOFT Probes			
low p_T spectra ("radial flow")	yes	yes	yes
Intermediate p_T ("recombination")	yes	yes	yes
HBT radii	R_{out}/R_{side}~1	$R_{out}/R_{side} \leq 1$	$R_{out}/R_{side} \leq 1$
Azimuthal anisotropy (v_n) (2 prt. correlations)	v_1-v_7	v_1-v_5	v_2-v_4
Characteristic mass dependence	v_2-v_5	v_2-v_3	v_2
Higher order cumulants	"4~6~8 " + higher harmonics	"4~6~8 " + higher harmonics	"4~6 "+ higher harmonics
Event by event v_n distributions	n=2-4	Not measured	Not measured
Event plane and v_n correlations	yes	yes	yes
HARD Probes			
Direct photons at low p_T	yes	Not measured	Not measured
Jet Quenching	yes	Not observed	Not measured
Quarkonia Nuclear Modification Factor	J/ψ regeneration / Υ suppression	suppressed	Not measured
Heavy-flavor anisotropy	yes	yes	Not measured

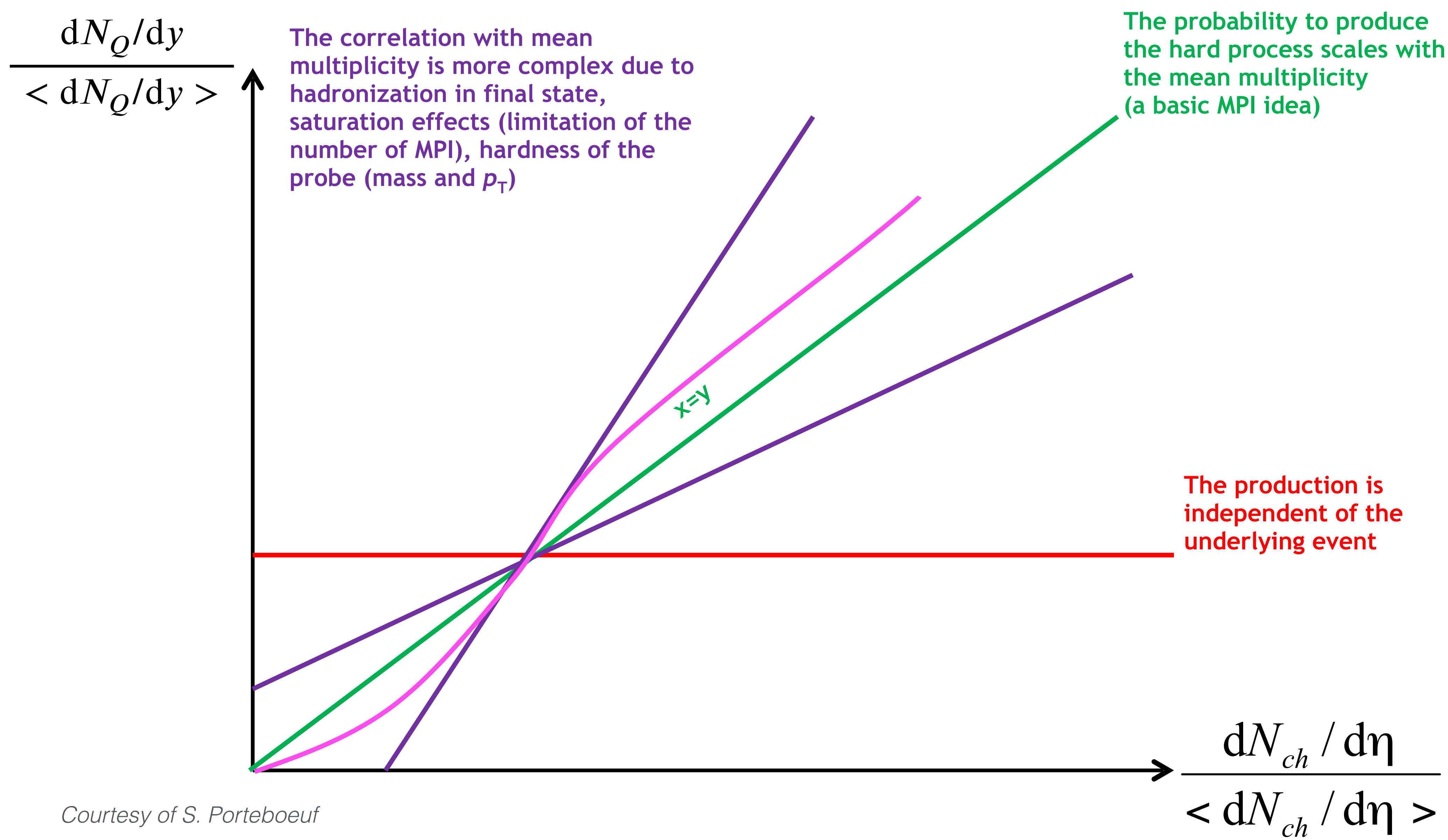
Physics of the transition from small to large systems

- Which is the origin of the collectivity in small systems?
  Hydrodynamics requires Reynolds number $R_e \gg 1 \rightarrow$ small η/s
- Do we observe QGP droplets in small systems?
  Collectivity ≠ QGP
- How do hard probes interact with the QGP droplets?
  Energy loss ∝ system size → small system; small effect
- Which mechanism (in the initial state) could allow to reach the energy density required for a phase transition in small systems?
  Initial state, possible sub nucleon structure,… ?
- .. is it the same for all systems ?
- Can all high energy hadronic collisions be described within the same formalism, from small to large systems?

- **(THIS TALK) Focus on signals of multiple parton interaction processes in the heavy flavor sector**

Measurements vs. charged-particle multiplicity

(Too) Simple expectations, discussions



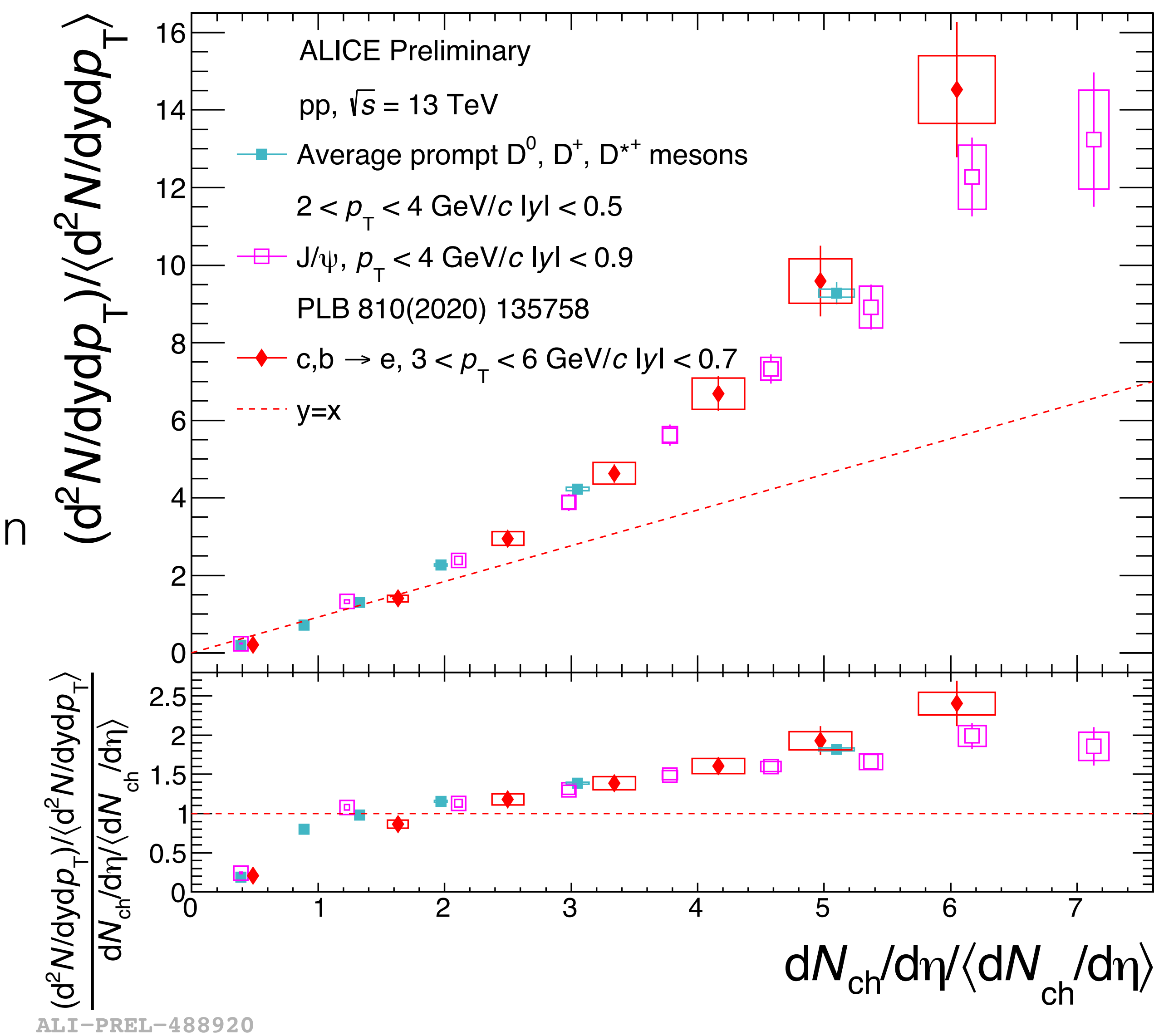
Courtesy of S. Porteboeuf

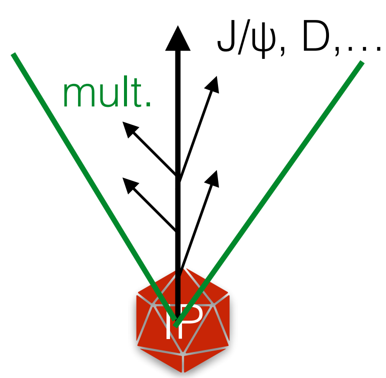
Charm yields vs. multiplicity in pp

ALICE, JHEP 09 (2015) 148

ALICE, arXiv:2005.11123; PLB 810 (2020) 135758

- **Rapid increase with charged-particle multiplicity at mid-rapidity (D, D_s, J/Ψ, non-prompt J/Ψ)**
  - suggesting common origin,
  - trend described by models including some ‘sort of’ **multiple-parton interactions**
    - all models show a departure from linearity;
    - described by initial state model with modified gluon distribution or percolation models;
    - PYTHIA and EPOS do not reproduce quantitatively the trend.





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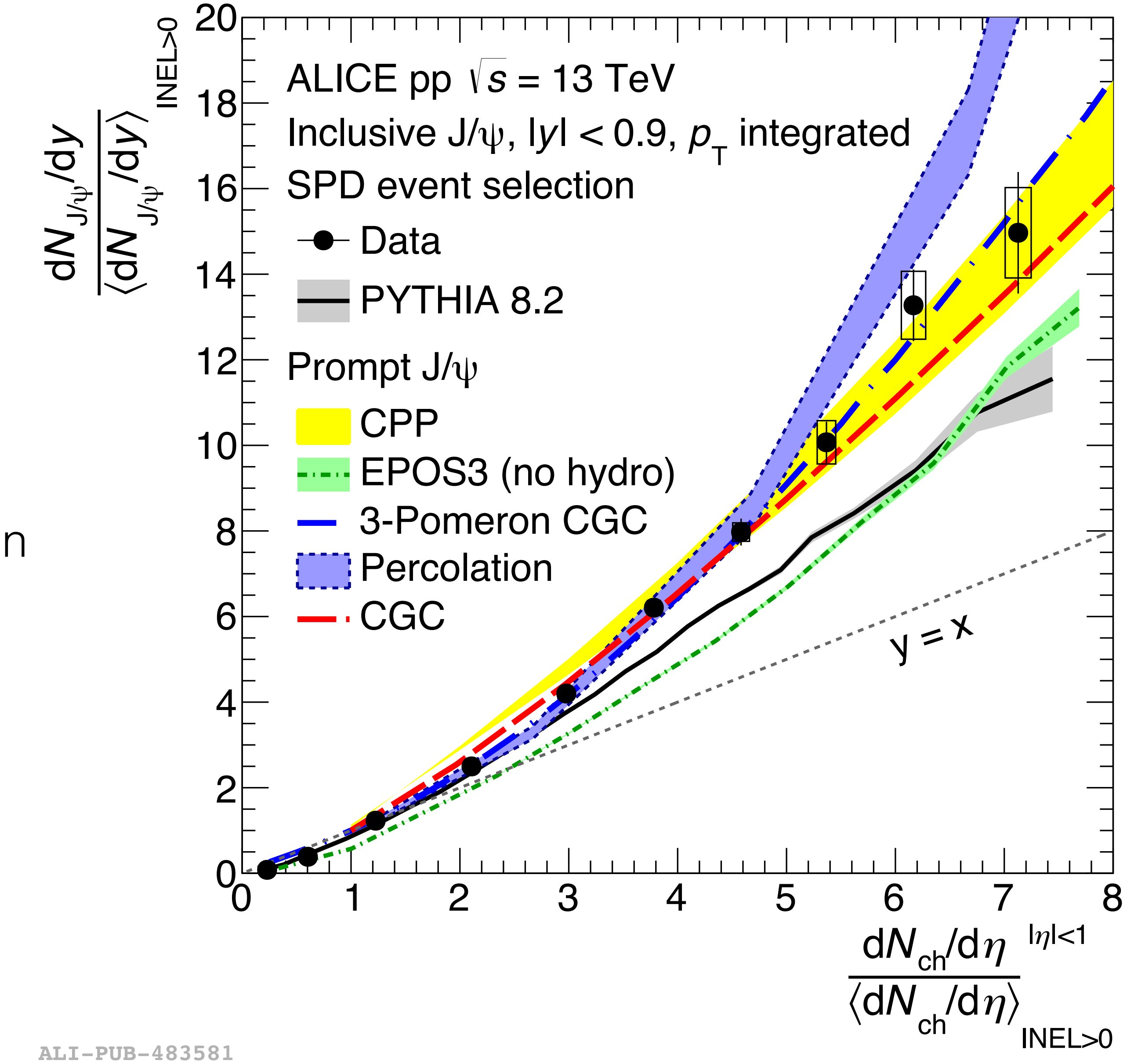
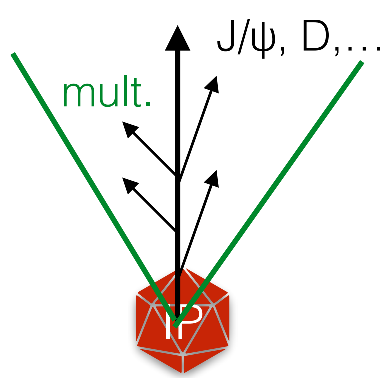


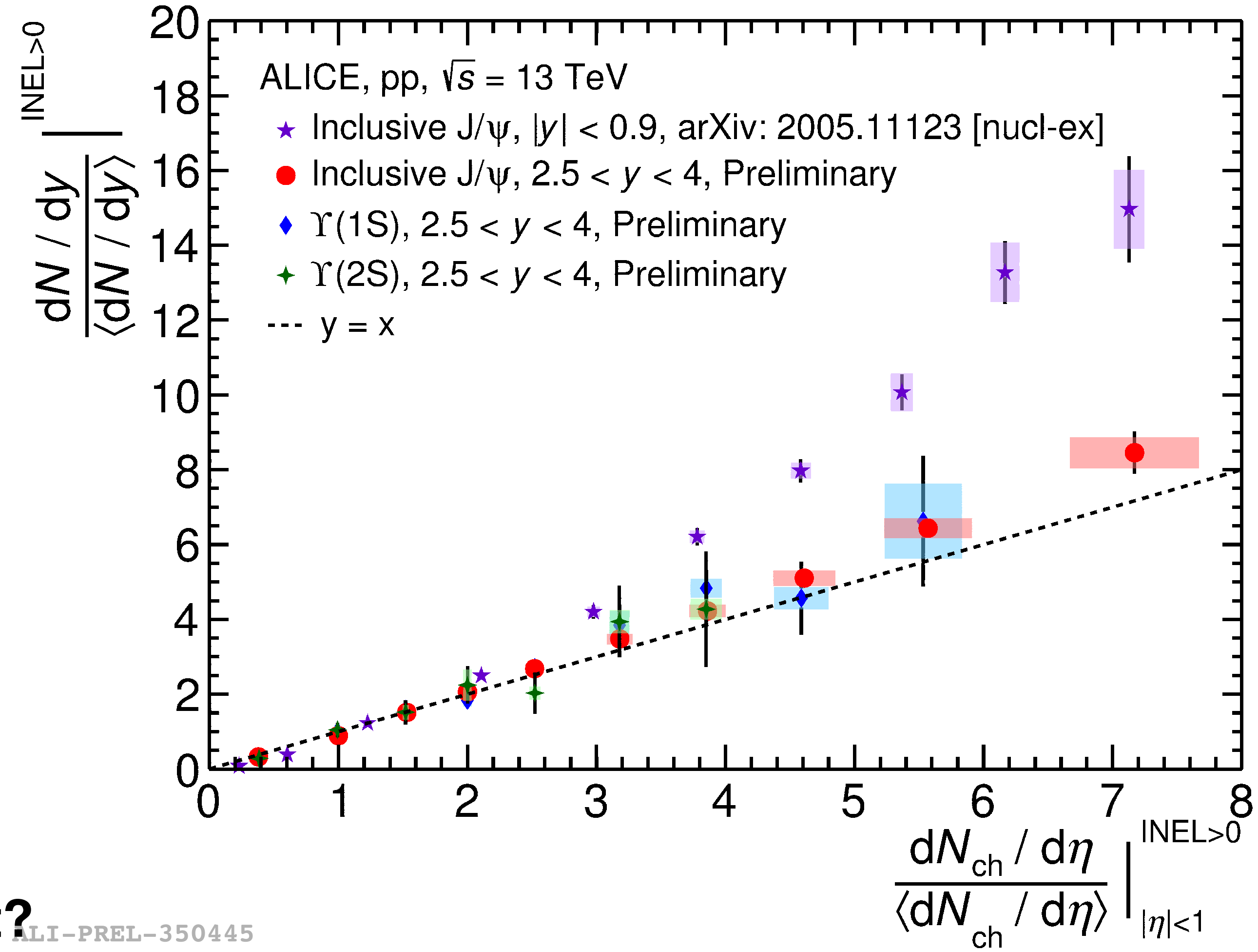


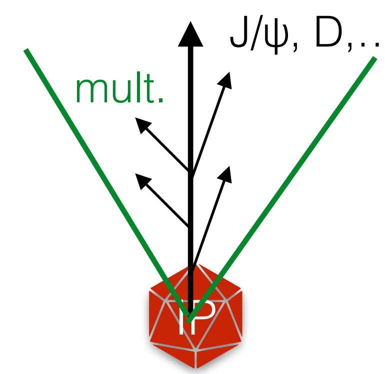
Heavy flavor yields vs. multiplicity in pp

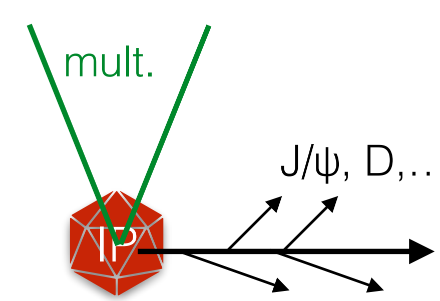
- **Rapid increase with charged-particle multiplicity at mid-rapidity (D, D_s, J/Ψ, non-prompt J/Ψ)**
    - suggesting common origin
    - trend described by models including some 'sort of' multiple-parton interactions

- **but preliminary J/Ψ and ϒ results at forward-y suggest a slower increase** (than mid-y ones)
    - **hadronisation?**
      D-meson measurements disfavour this hypothesis
    - **fragmentation?**
      Study particle species (kinematic dep.), also particle production in jets / isolated.
    - **associated production? underlying event?**
      Multi-differential studies:
      yields at different y,
      vs multiplicity at different y,
      in sphericity intervals
      or vs angle (event classifier).
    - **final state effects ?**

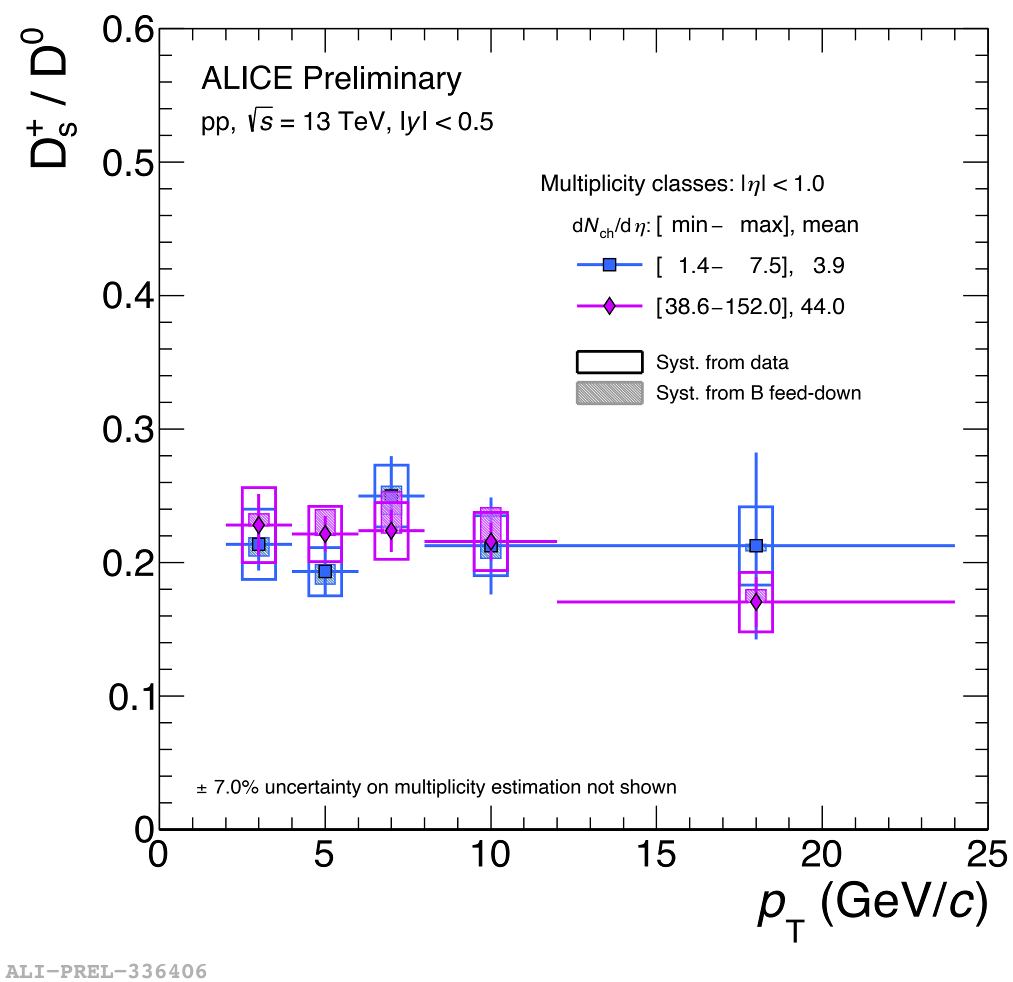
ALICE, JHEP 09 (2015) 148
ALICE, arXiv:2005.11123; PLB 810 (2020) 135758

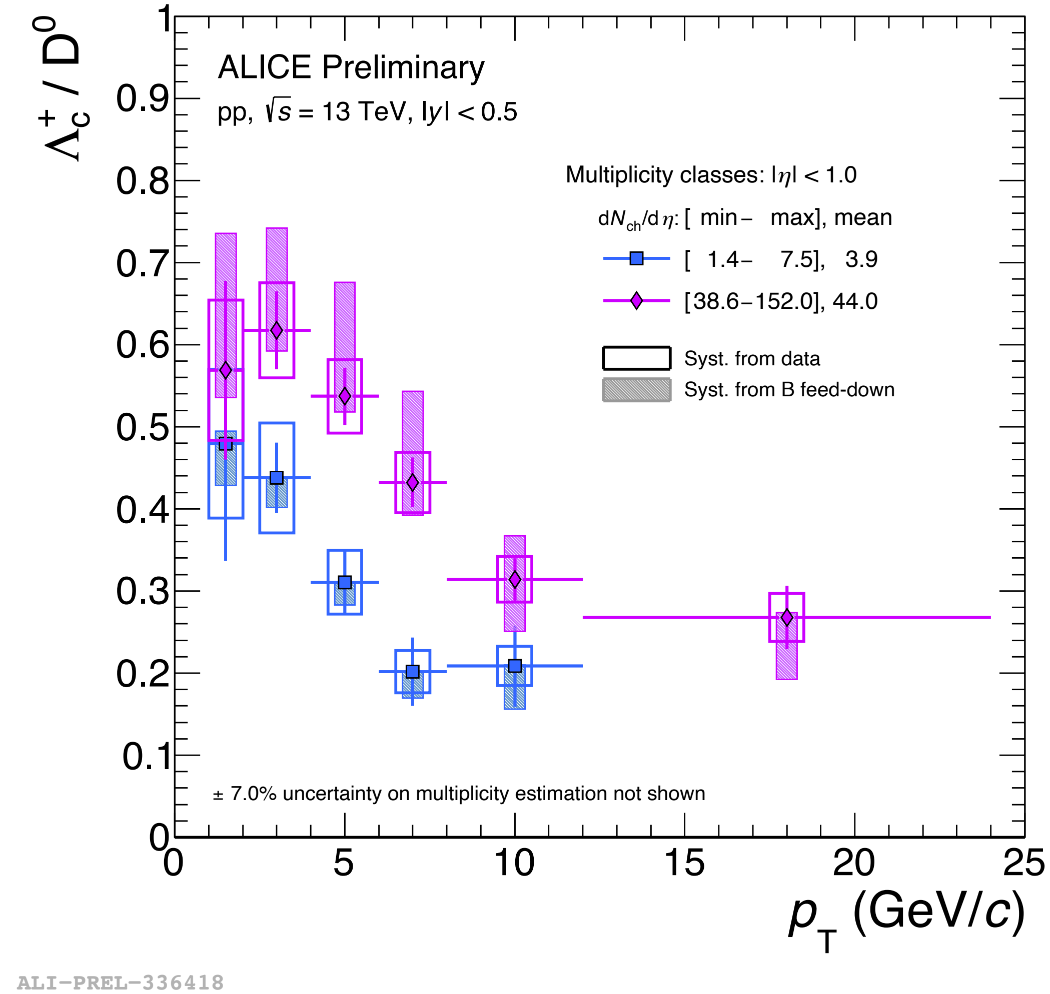






... hadronization / fragmentation ?





- **No indication of modification of D_s/D^0 ratio** as a function of multiplicity within uncertainties.
- **Significant dependence of Λ_c/D^0 with charged-particle multiplicity.**
- Charm baryon yields at the LHC have revealed unexpected features that are currently under scrutiny from the experimental and theoretical points of view.

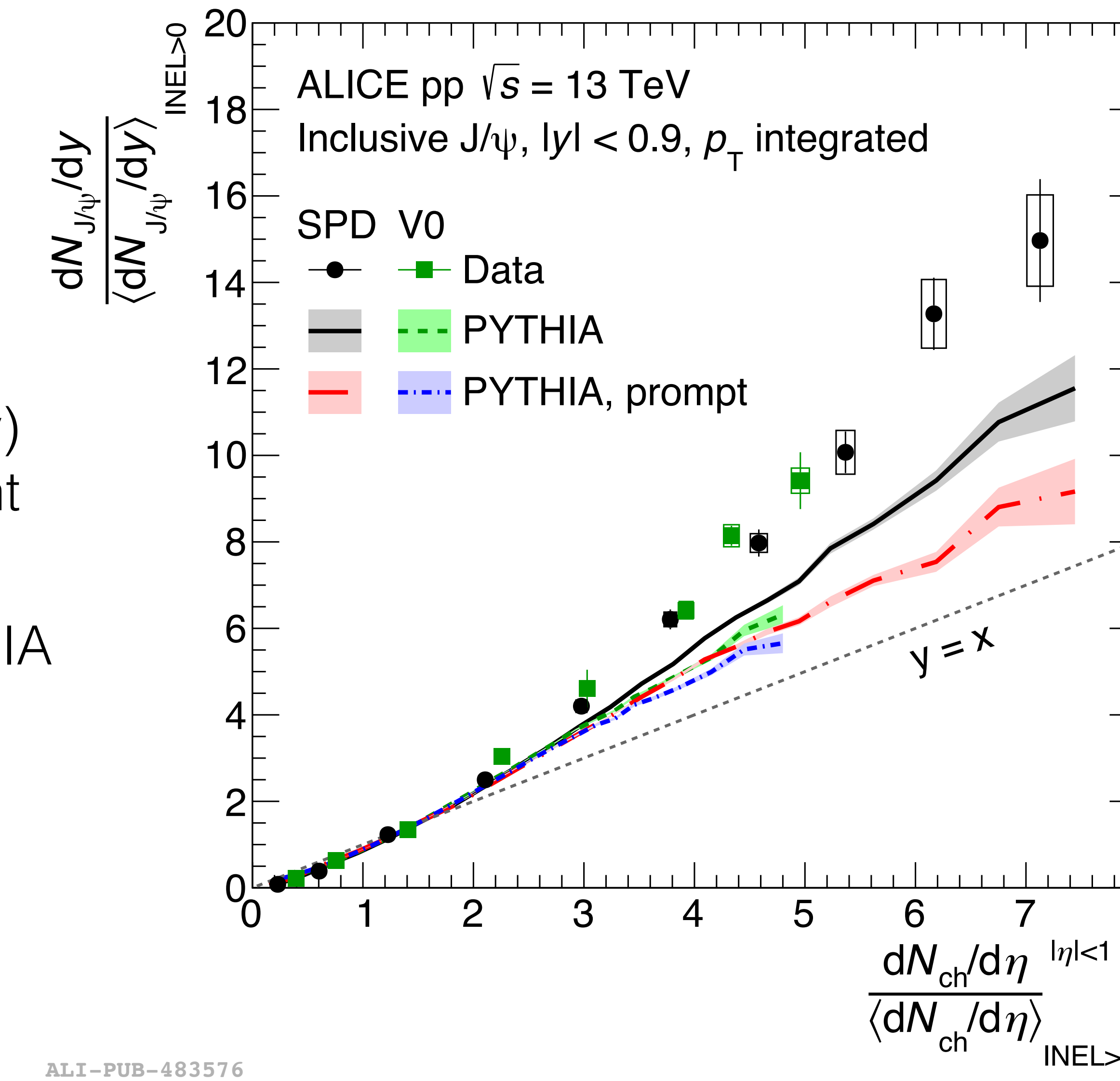
  Follow other talks during this workshop!

A. Rossi
A. Palasciano
M. Faggin

S. Plumari
F. Prino

… associated production ?

- J/Ψ at midrapidity
- Multiplicity estimator either at central or large rapidity.
- Rapid increase of J/Ψ yield (larger than x=y) independent of the multiplicity measurement interval.
- Observed correlation stronger than in PYTHIA



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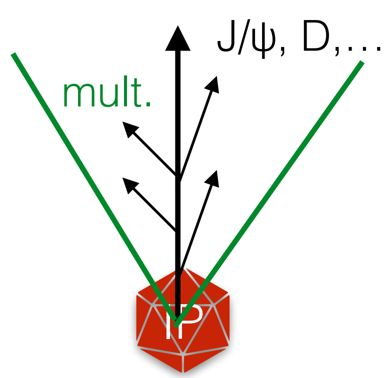
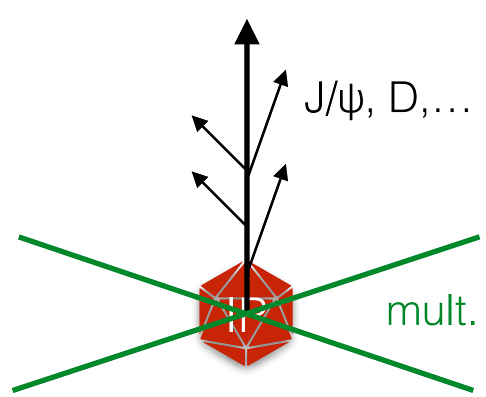
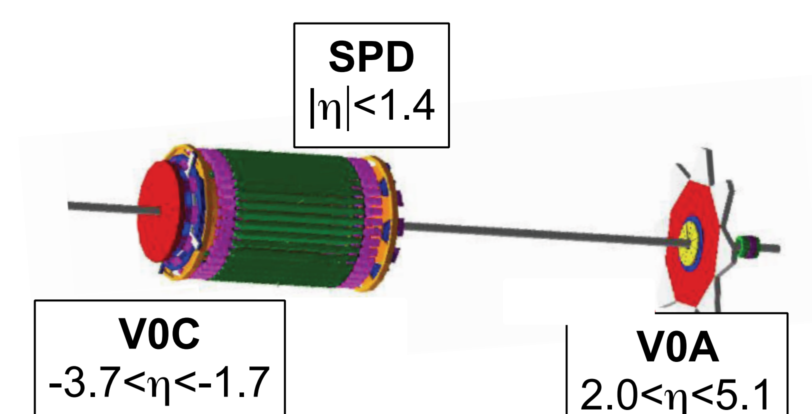
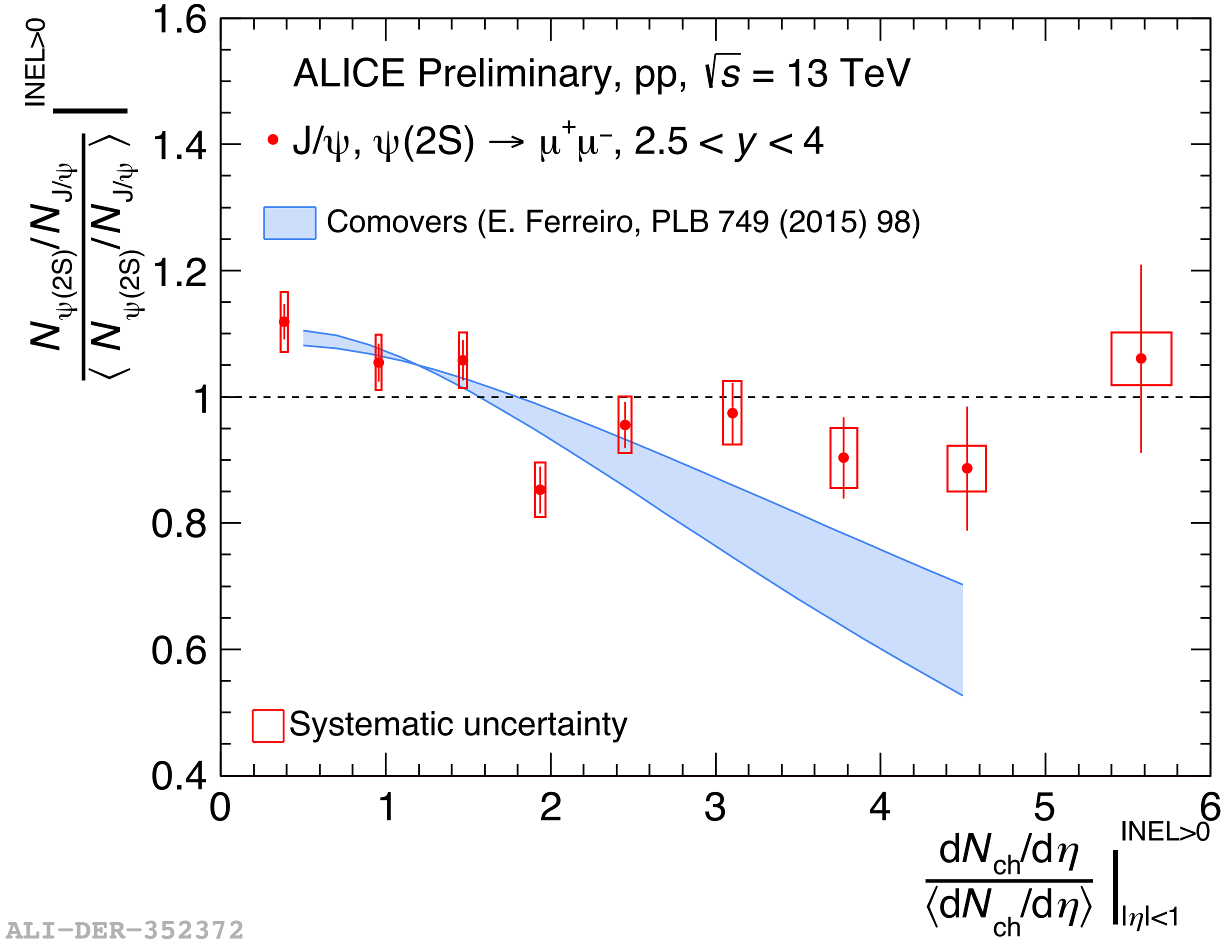
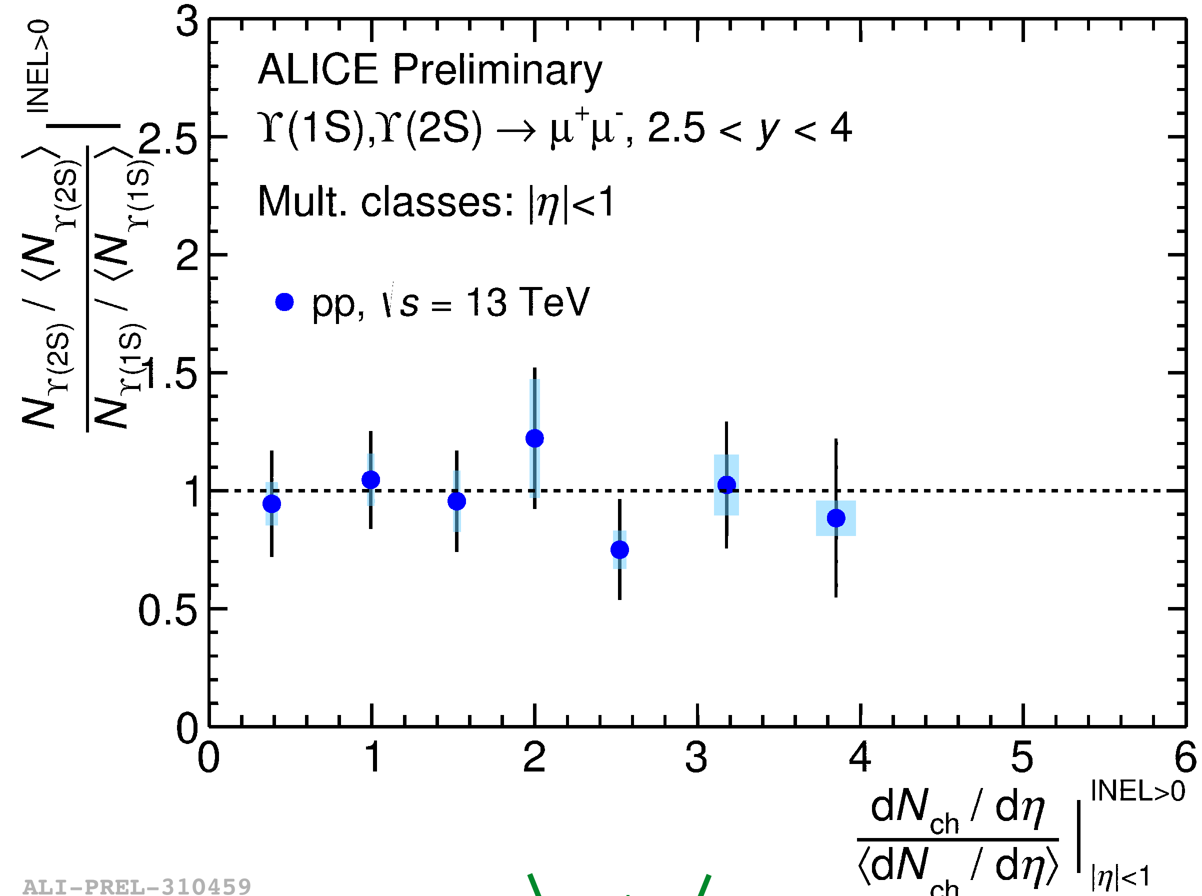


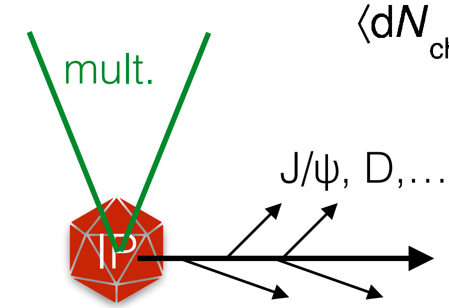




… possible final-state effects ?

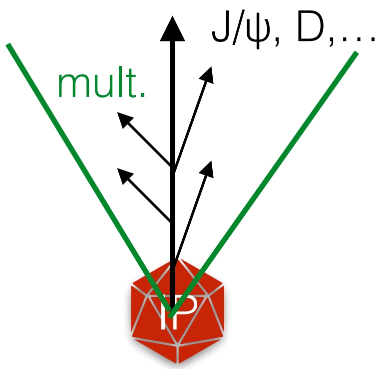


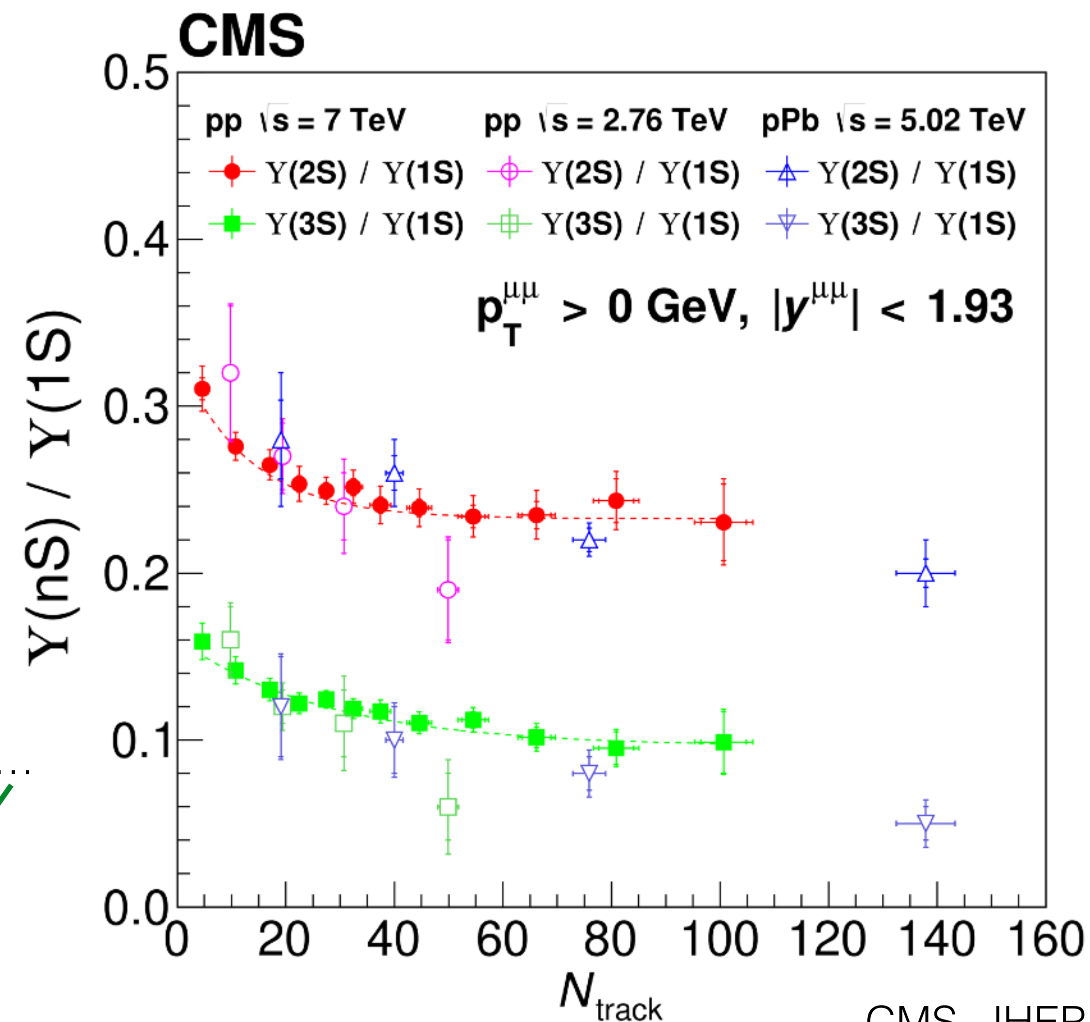


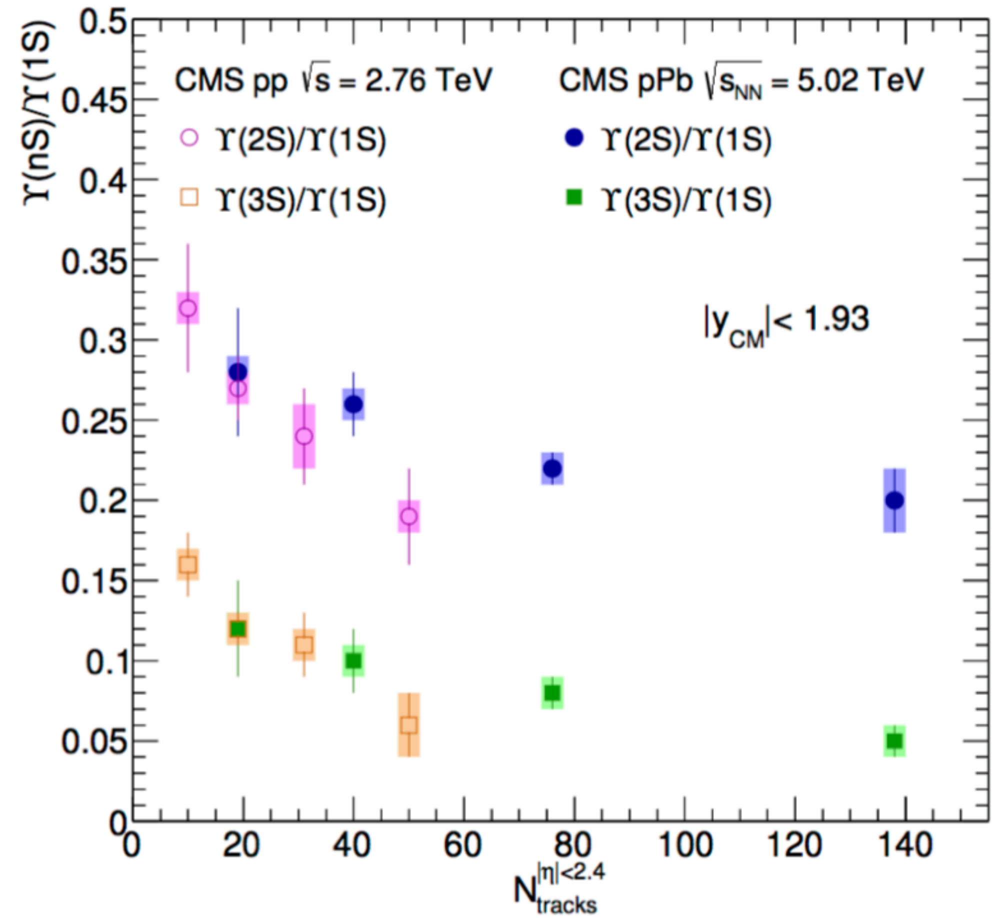


- Excited-to-ground state ratios at large rapidity consistent with a flat behavior within uncertainties.
- Comover scenario: expects a decrease of the excited-to-ground state ratios due to the high density final state environment. Bound state dissociation depending on their binding energies.

… possible final-state effects ?



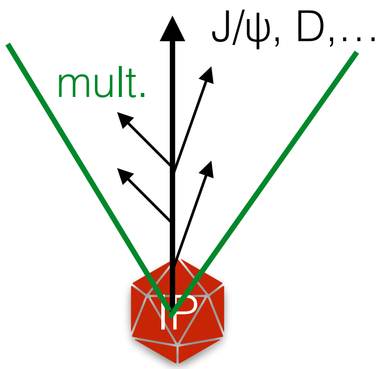


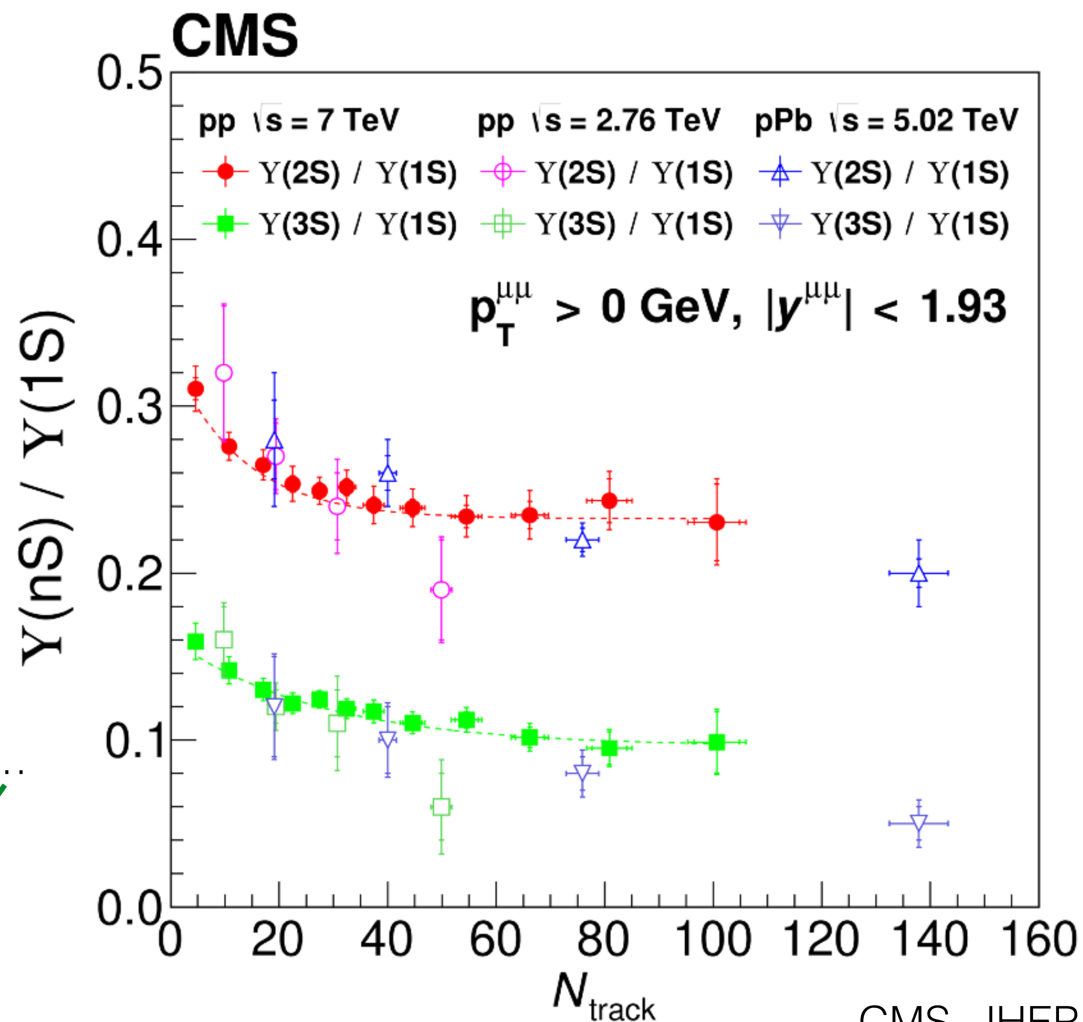


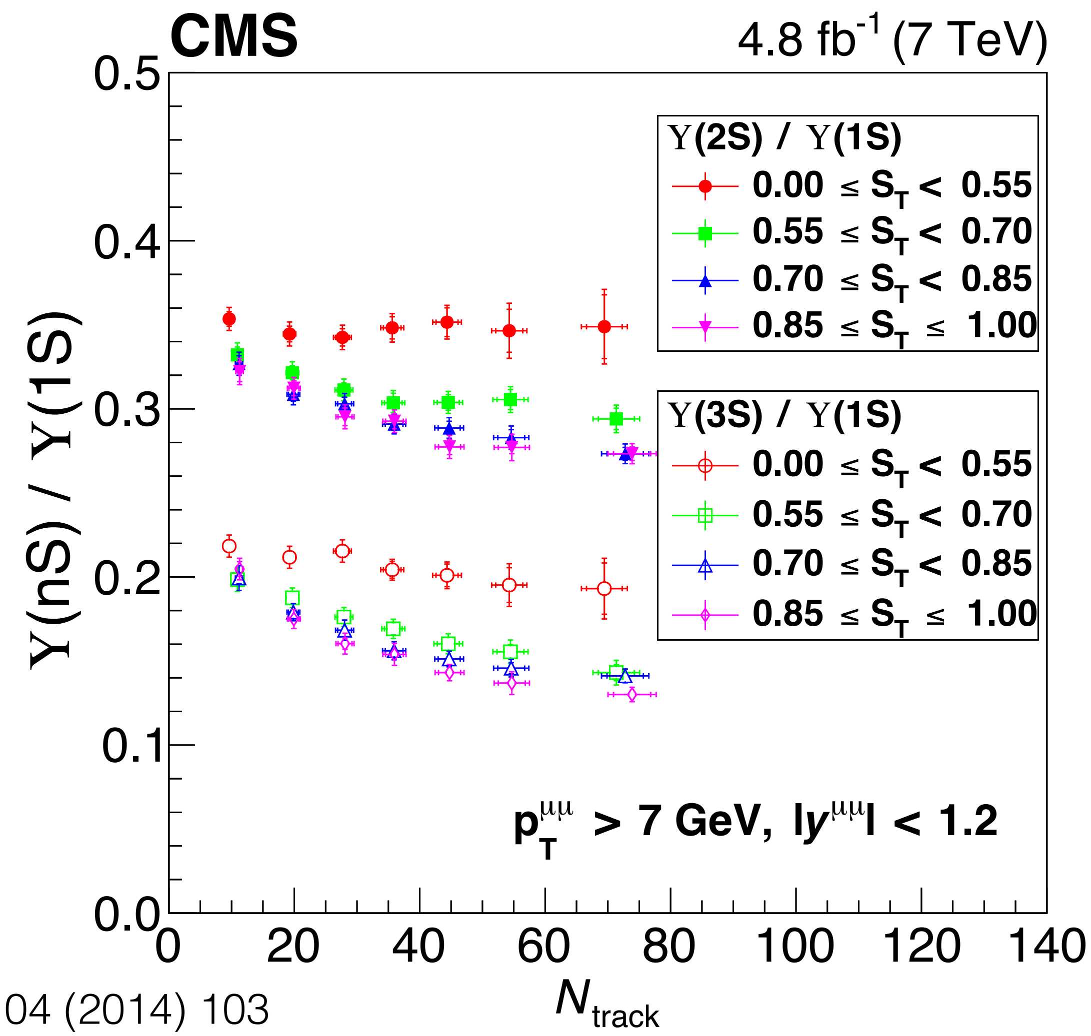
CMS, JHEP 04 (2014) 103
CMS, arXiv:2007.04277, JHEP 11 (2020) 001

- **Reduction of excited-to-ground state Υ ratios with increasing charged-particle multiplicity** (the effect decreases with increasing momentum).
- No influence of the azimuthal angle separation between charged particles and Υ momentum direction, nor of the variation of number of tracks in a restricted cone around Υ.
- **The ratios are multiplicity independent for jet-like events.**
- Require improved model description of quarkonium production in pp.

… possible final-state effects ?





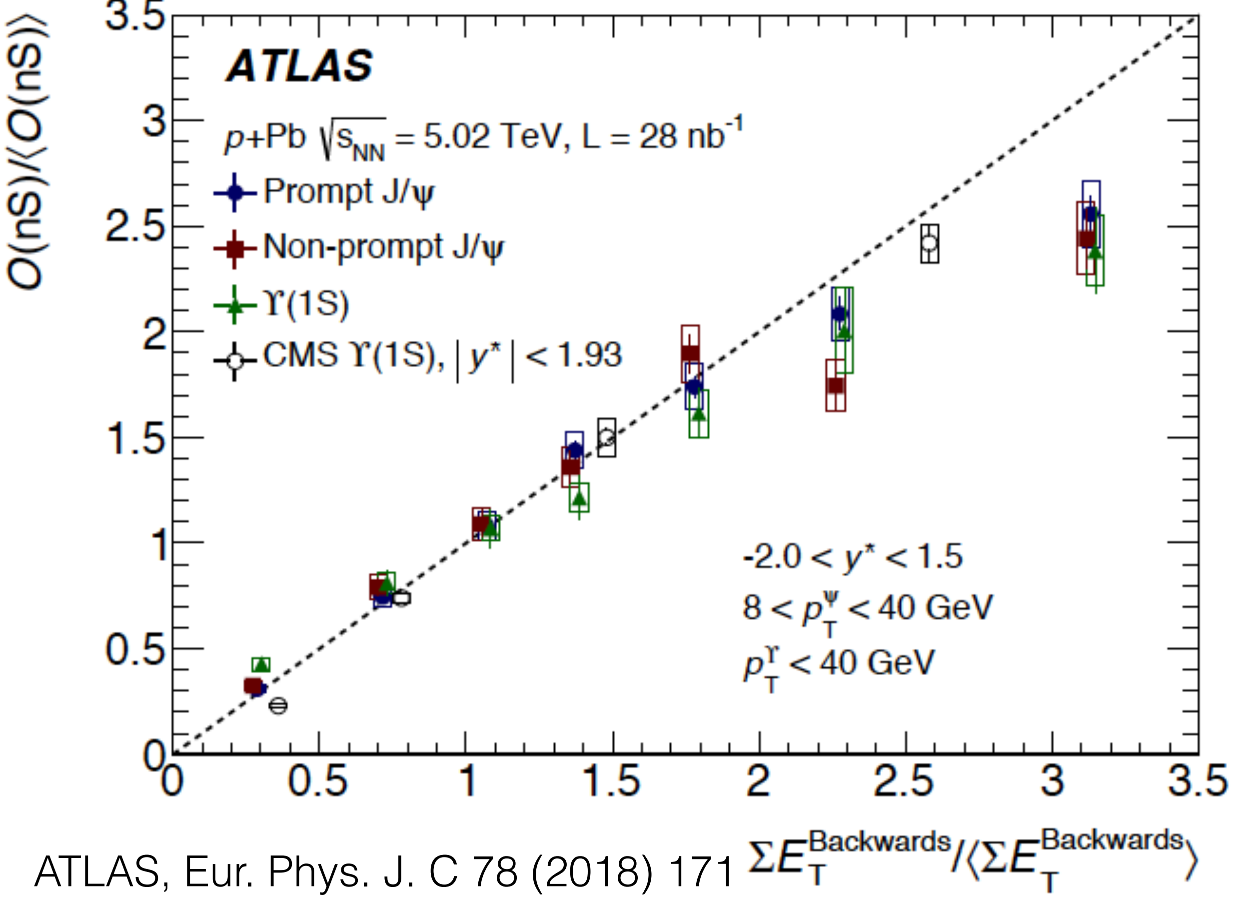


CMS, JHEP 04 (2014) 103
CMS, arXiv:2007.04277, JHEP 11 (2020) 001

- **Reduction of excited-to-ground state ϒ ratios with increasing charged-particle multiplicity** (the effect decreases with increasing momentum).
- No influence of the azimuthal angle separation between charged particles and ϒ momentum direction, nor of the variation of number of tracks in a restricted cone around ϒ.
- **The ratios are multiplicity independent for jet-like events.**
- Require improved model description of quarkonium production in pp.

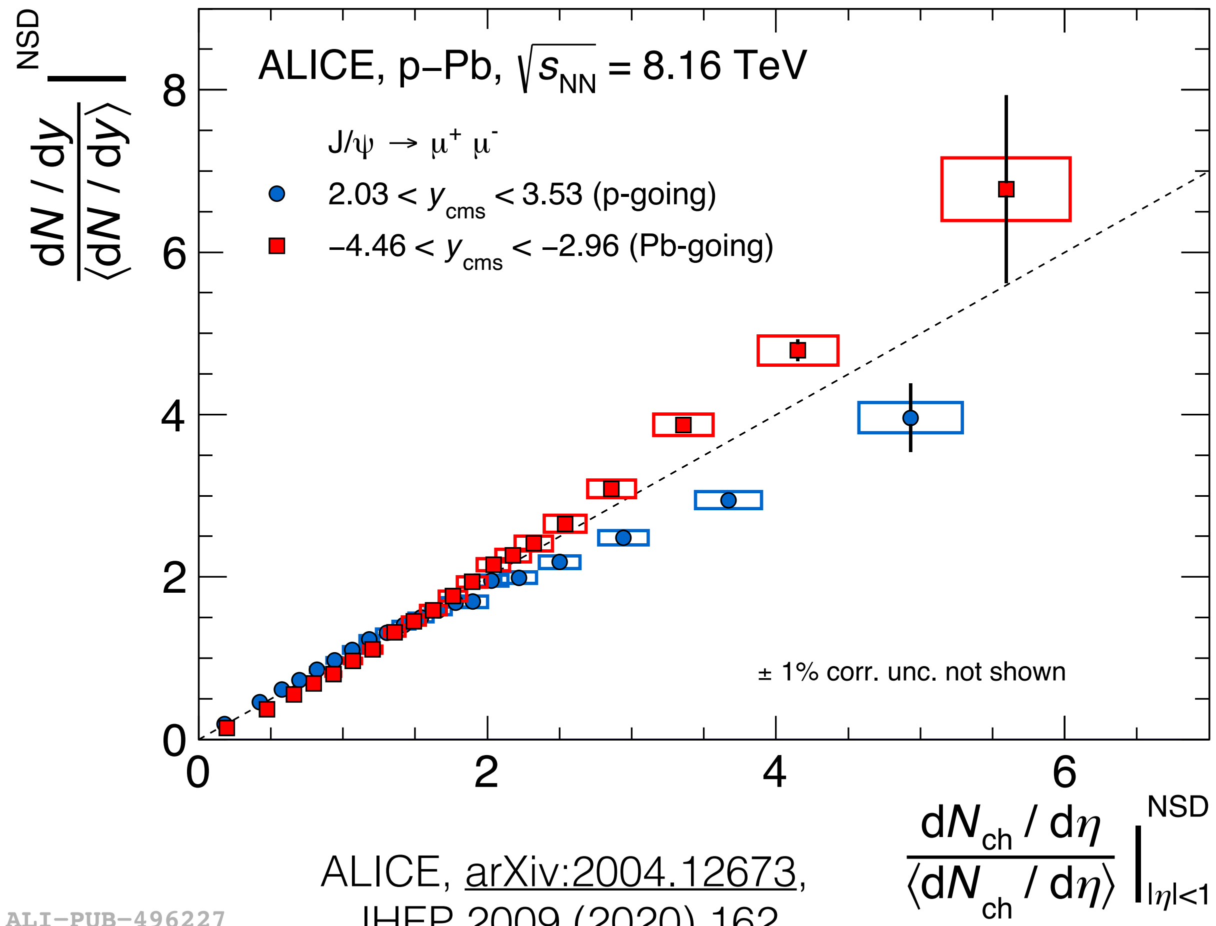
Quarkonia yield vs. multiplicity in p-Pb

Quarkonia at central rapidity, multiplicity at large rapidity



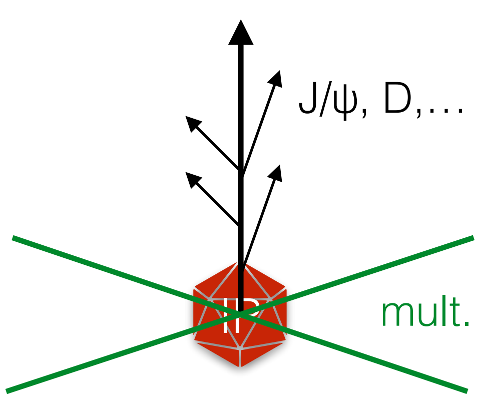
ATLAS, Eur. Phys. J. C 78 (2018) 171
CMS, JHEP 04 (2014) 103,

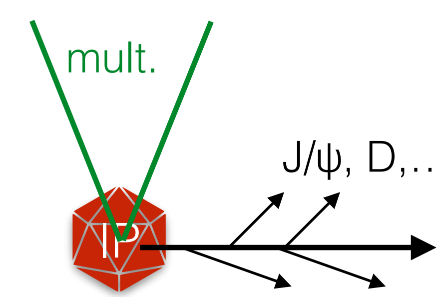
Quarkonia at large rapidity, multiplicity at central rapidity



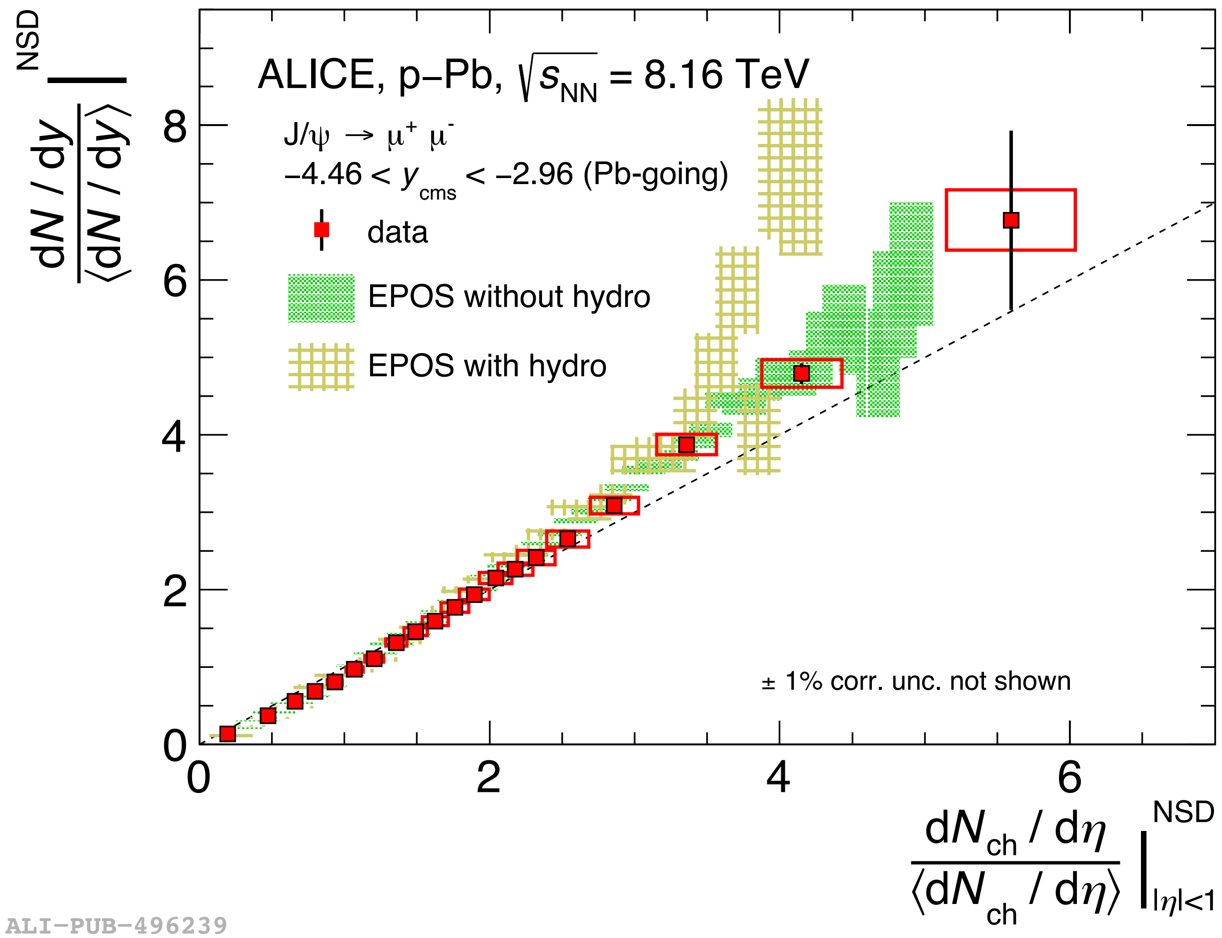
ALICE, arXiv:2004.12673, JHEP 2009 (2020) 162

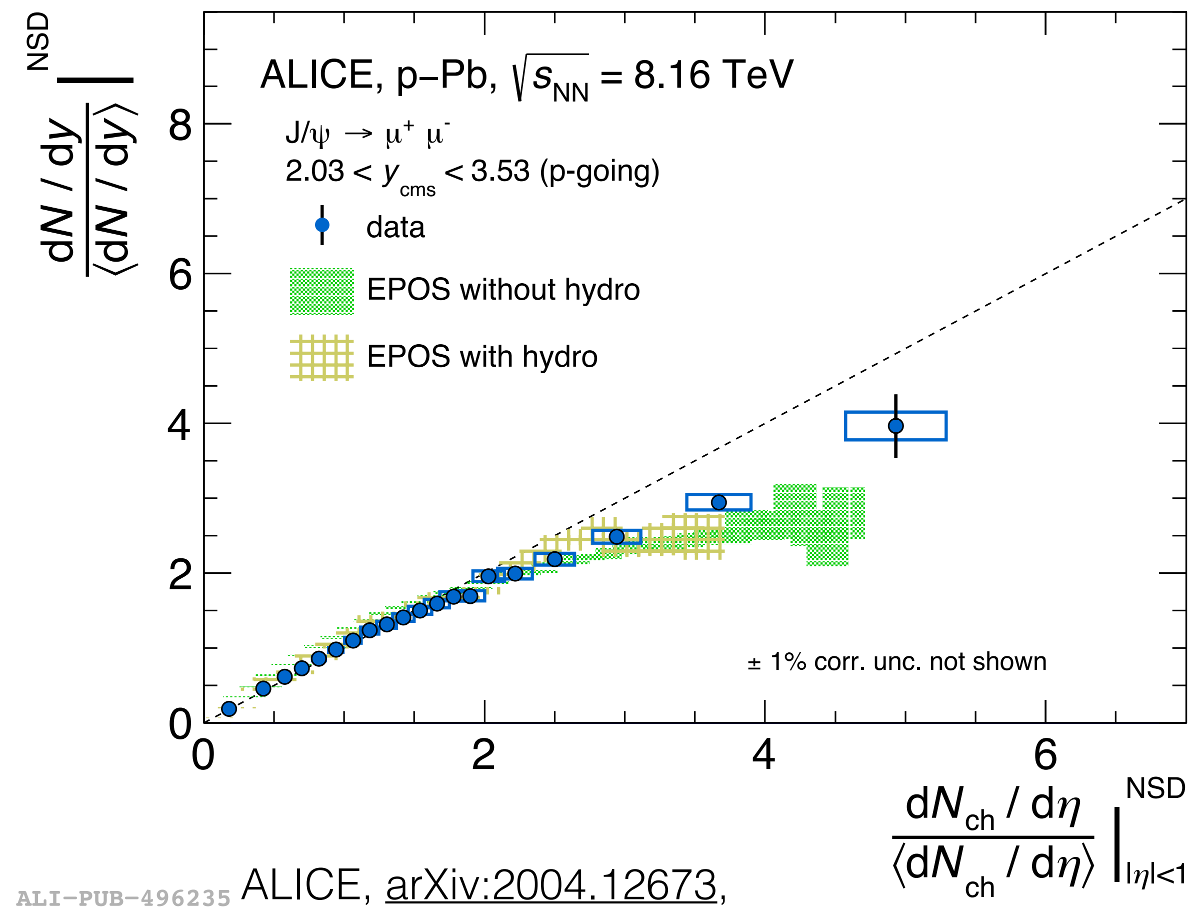
- At mid-rapidity and the p-going direction (x_{Pb}~10^{-5}), slower-than-linear increase of quarkonia yields; whereas in the Pb-going direction (x_{Pb}~10^{-2}), stronger-than-linear increase.
  - independent of collision energy (at the LHC),
  - no or small dependence on particle species,
  - **mechanism whose effect evolves quickly with y but slowly with energy**
    multiple binary collisions? shadowing / saturation?





J/ψ yield vs. multiplicity in p-Pb





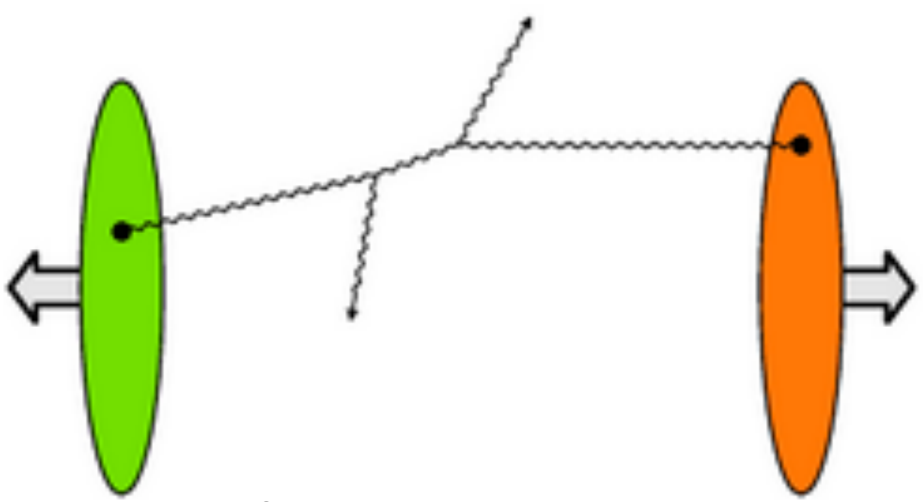
ALICE, arXiv:2004.12673, JHEP 2009 (2020) 162

- Good description of data by EPOS 3
- Origin of the different trend vs. rapidity:
  - influence of the bulk of particles larger in the Pb-going direction? study azimuthal anisotropy?
  - asymmetric collision geometry playing a role? different core-corona effect?
  - saturation?

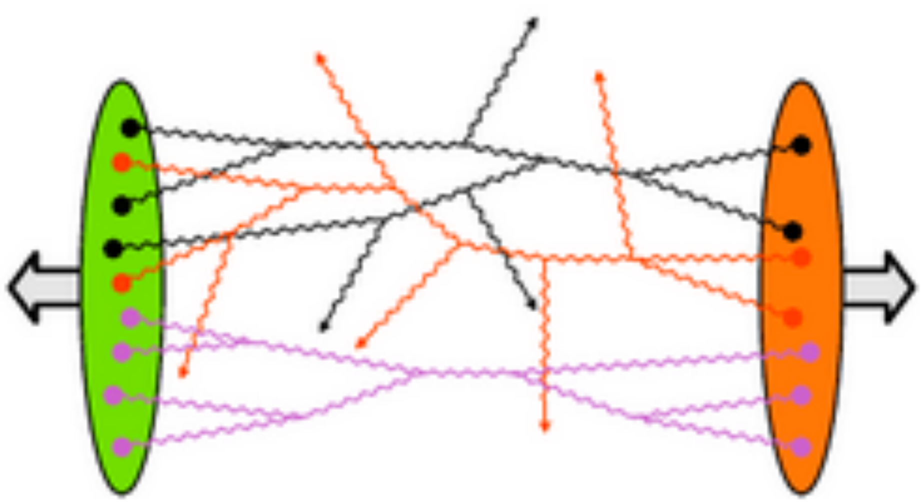
H. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, and K. Werner, Phys.Rept. 350 (2001) 93–289
K. Werner, B. Guiot, I. Karpenko, and T. Pierog, Phys.Rev. C89 (2014) 064903

Associated particle production measurements

- **Double and triple parton scatterings**
  ➜ production of two or three charm/beauty particles, be it D^0, J/ψ, ϒ,…
  - Generalized PDFs (x,Q^2,b) of the proton, including the unknown energy evolution of the proton transverse profile. And by extent the nPDFs in nuclei.
  - Role of partonic correlations in the wave functions (x, p, flavor, spin, color,…).
  - Constrain heavy-flavor production modelling.
  - Background for other studies (e.g. BSM resonance decays of multiple heavy particles).



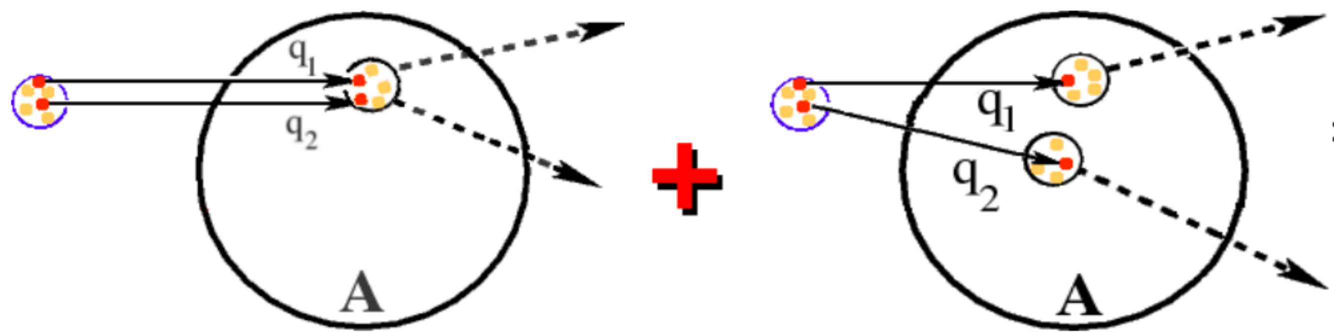
Single parton scattering



Multiple parton scattering

Double parton scattering (DPS) in pA

d'Enterria, Snigirev, PLB 727 (2013) 157



$$\Rightarrow \quad \sigma^{DPS}_{(pA)} = \sigma^{DPS,1}_{(pA)} + \sigma^{DPS,2}_{(pA)}$$

$$\sigma^{DPS,1}_{(pA\to ab)} = A \cdot \sigma^{DPS}_{(pN\to ab)} \;+\; \sigma^{DPS,2}_{(pA\to ab)} = \sigma^{DPS}_{(pN\to ab)} \cdot \sigma_{\mathrm{eff,pp}} \cdot F_{pA}$$

p-A overlap function:

$$F_{pA} = \int d^2r\, T^2_{pA}(\mathbf{r}) = 30.4\ \mathrm{mb}^{-1}$$

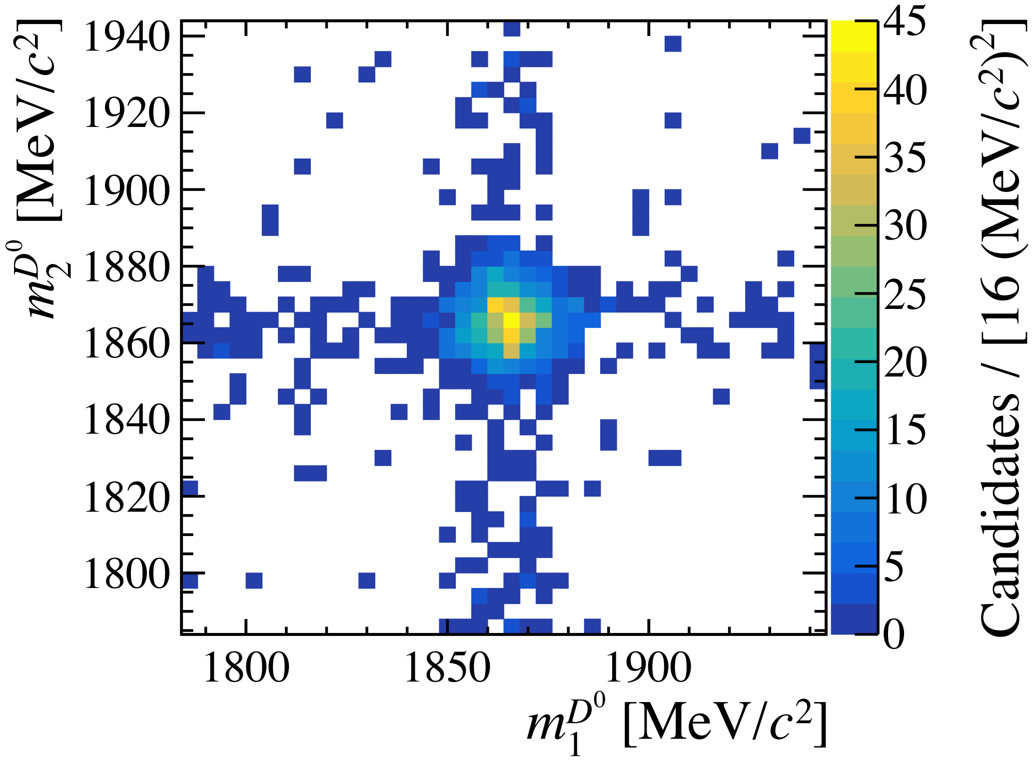
Pb Woods-Saxon density (r=6.62 fm, a=0.546 fm)

- Two contributions to DPS cross section in pA
  - relative weight $\sigma^{DPS,1} : \sigma^{DPS,2}$ = 0.7 : 0.3 (small A), 0.33 : 0.66 (large A)
- "pocket formula"

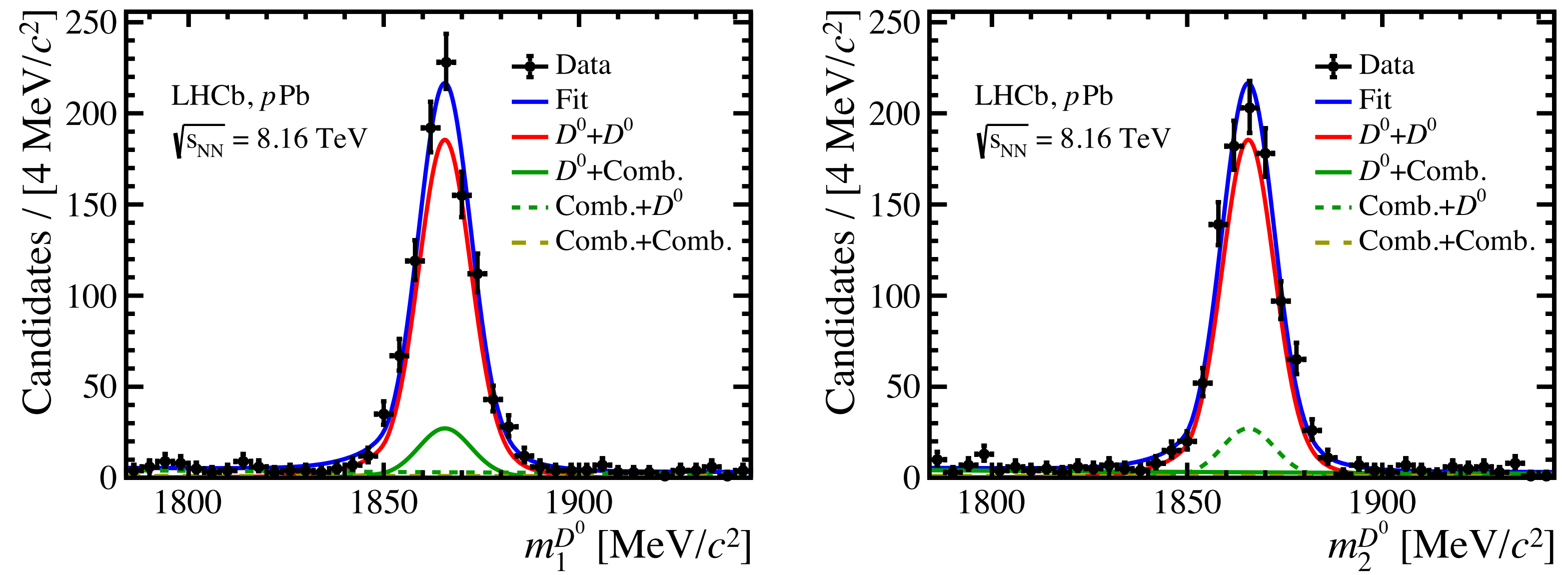
$$\sigma^{DPS}_{pA\to ab} = \left(\frac{m}{2}\right) \frac{\sigma^{SPS}_{pN\to a} \cdot \sigma^{SPS}_{pN\to b}}{\sigma_{\mathrm{eff,pA}}}\,; \qquad \sigma_{\mathrm{eff,pA}} = \frac{\sigma_{\mathrm{eff,pp}}}{A + \sigma_{\mathrm{eff,pp}} F_{pA}}$$

- **Ratio of DPS / SPS large in pA/pp**: $\sigma_{\mathrm{eff,pA}} / \sigma_{\mathrm{eff,pp}} \propto (A + A^{4/3}/\pi) \sim 600$ (not 208!)
- Tranverse density (F_{pA}) well known ➜ **alternative to extract $\sigma_{\mathrm{eff,pp}}$**

Double charm production in pPb

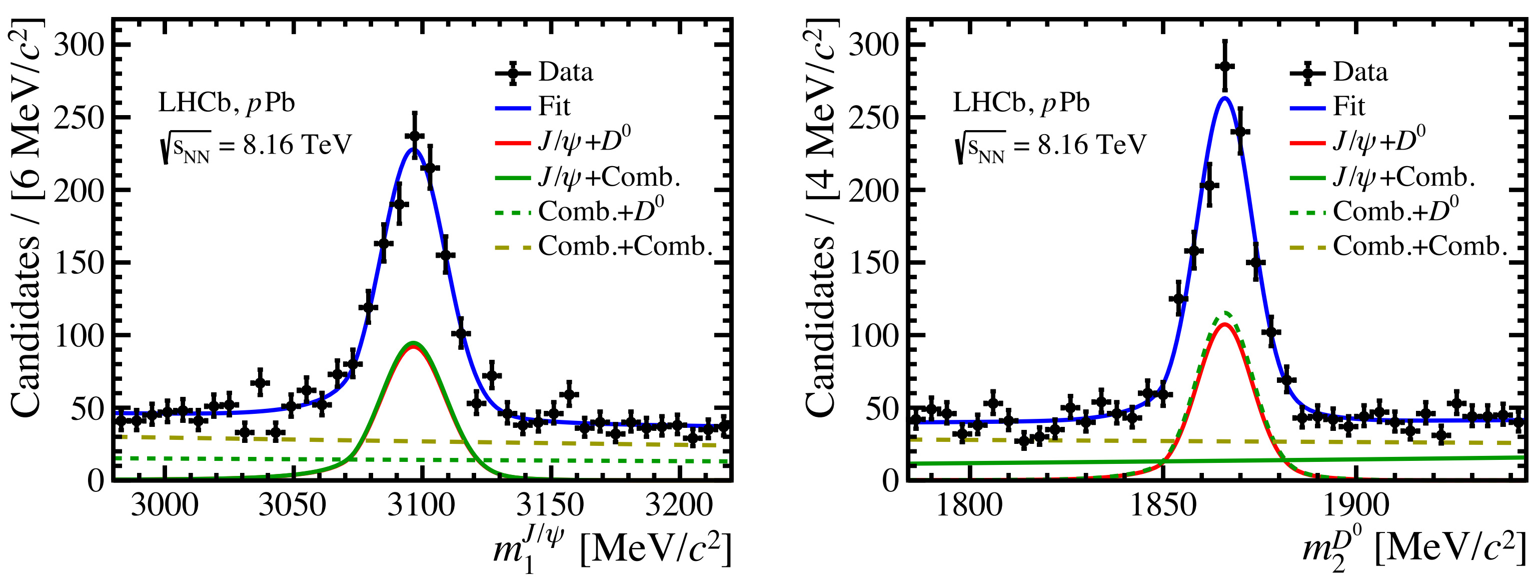


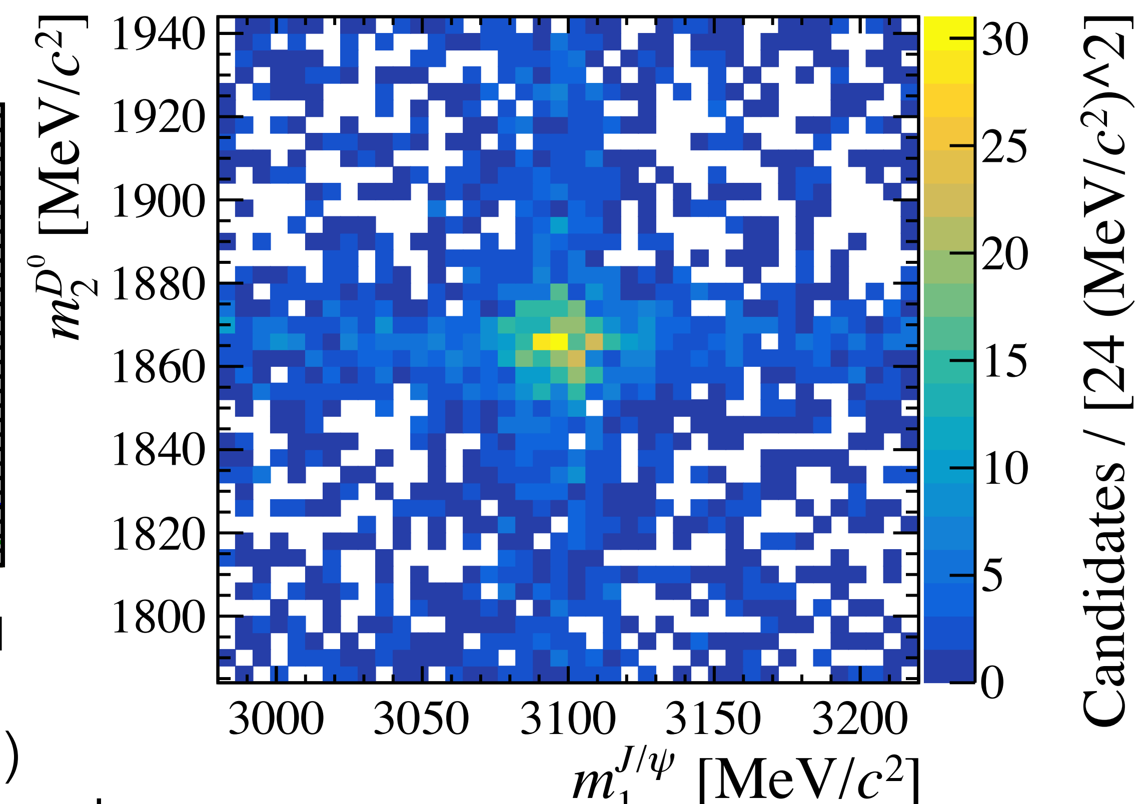
D^0+D^0 production in pPb collisions



LHCb, arXiv:2007.06945; Phys.Rev.Lett. 125 (2020) 212001

$J/\psi + D^0$ in pPb

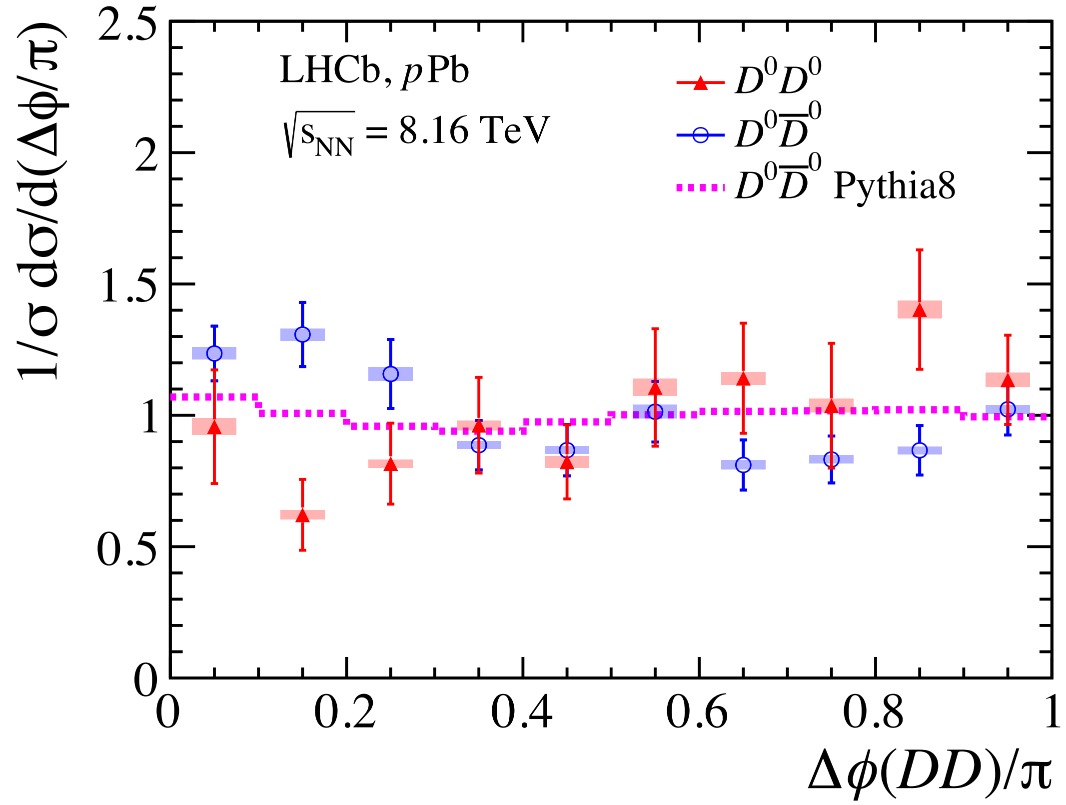


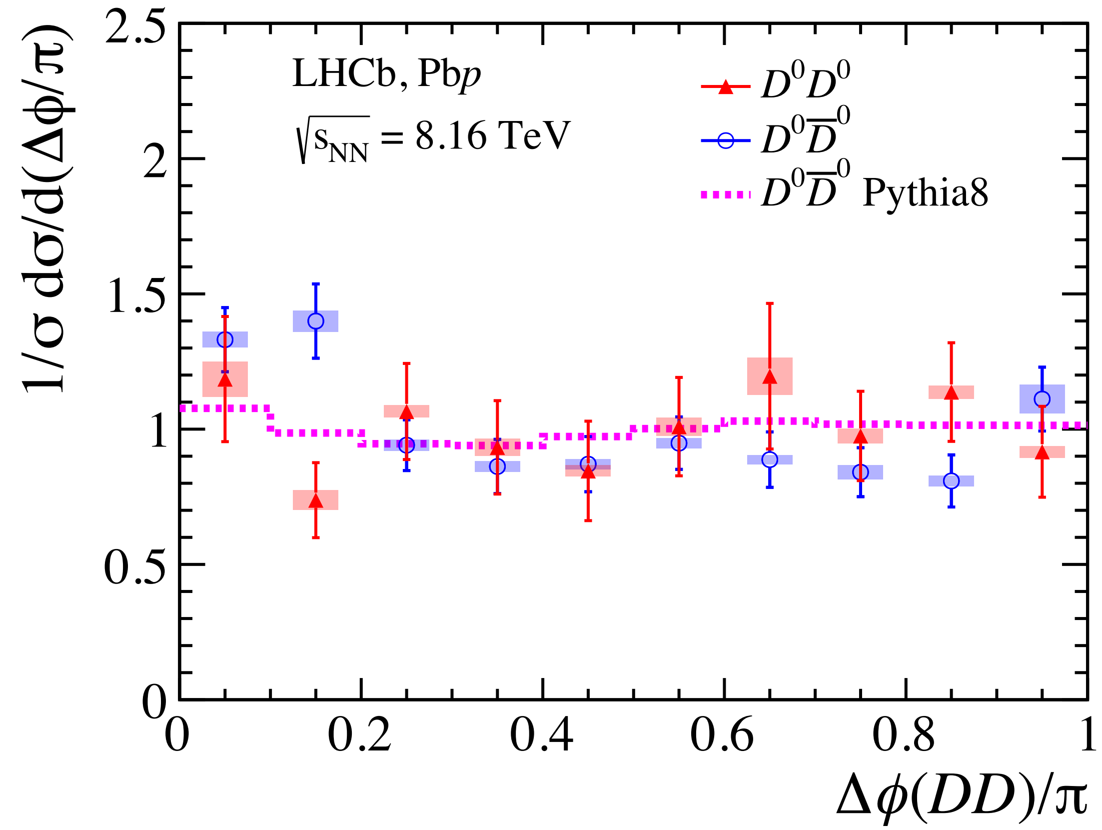


- Prompt D^0+D^0 (and c.c.) as well as $J/\psi+D^0$ (and cc.) production measured in pPb collisions for the first time !

Double charm production in pPb

LHCb, arXiv:2007.06945; Phys.Rev.Lett. 125 (2020) 212001

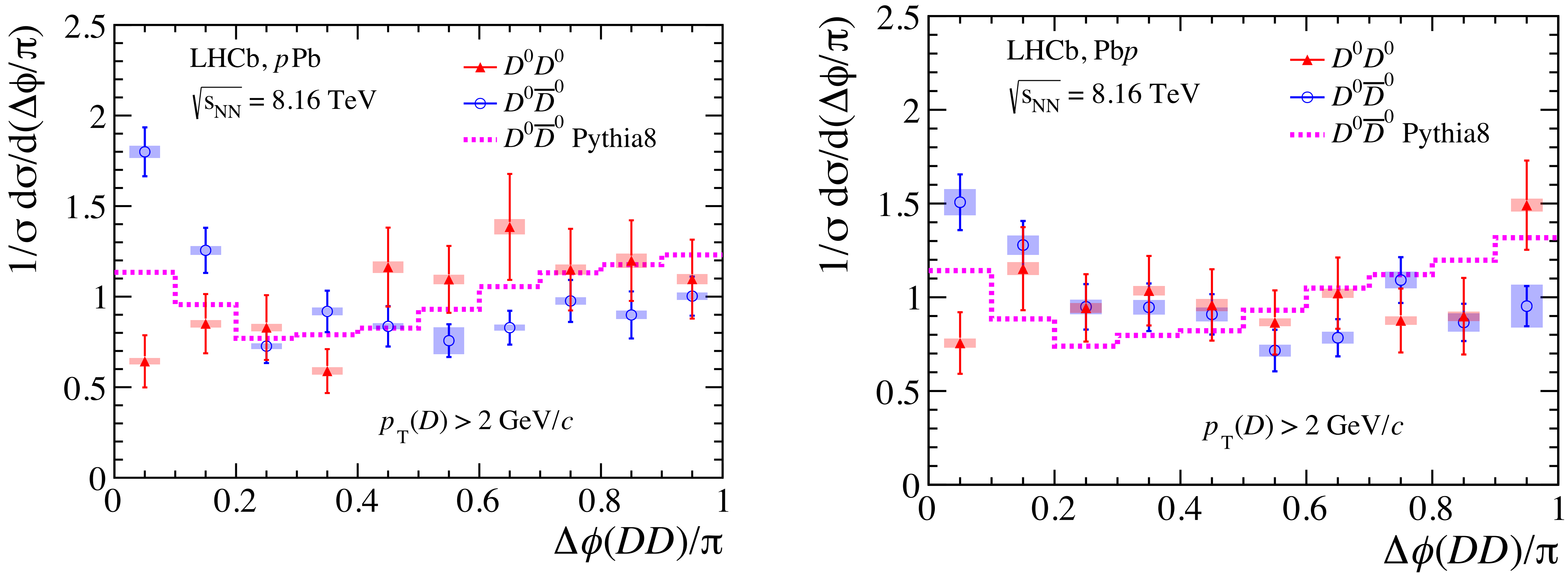




- Kinematic correlation of the two charm pairs via the relative azimuthal angle:
  - close to uniform for both LS and OS pairs for the p_T-integrated case,
  - for p_T>2 GeV, OS favors Δϕ~0 while LS distribution is compatible with flat.
- Azimuthal angle correlation **inconsistent with PYTHIA8 simulation.**
- **The flat Δϕ distribution is consistent with a large DPS contribution in LS pair production.**

Double charm production in pPb

LHCb, arXiv:2007.06945; Phys.Rev.Lett. 125 (2020) 212001



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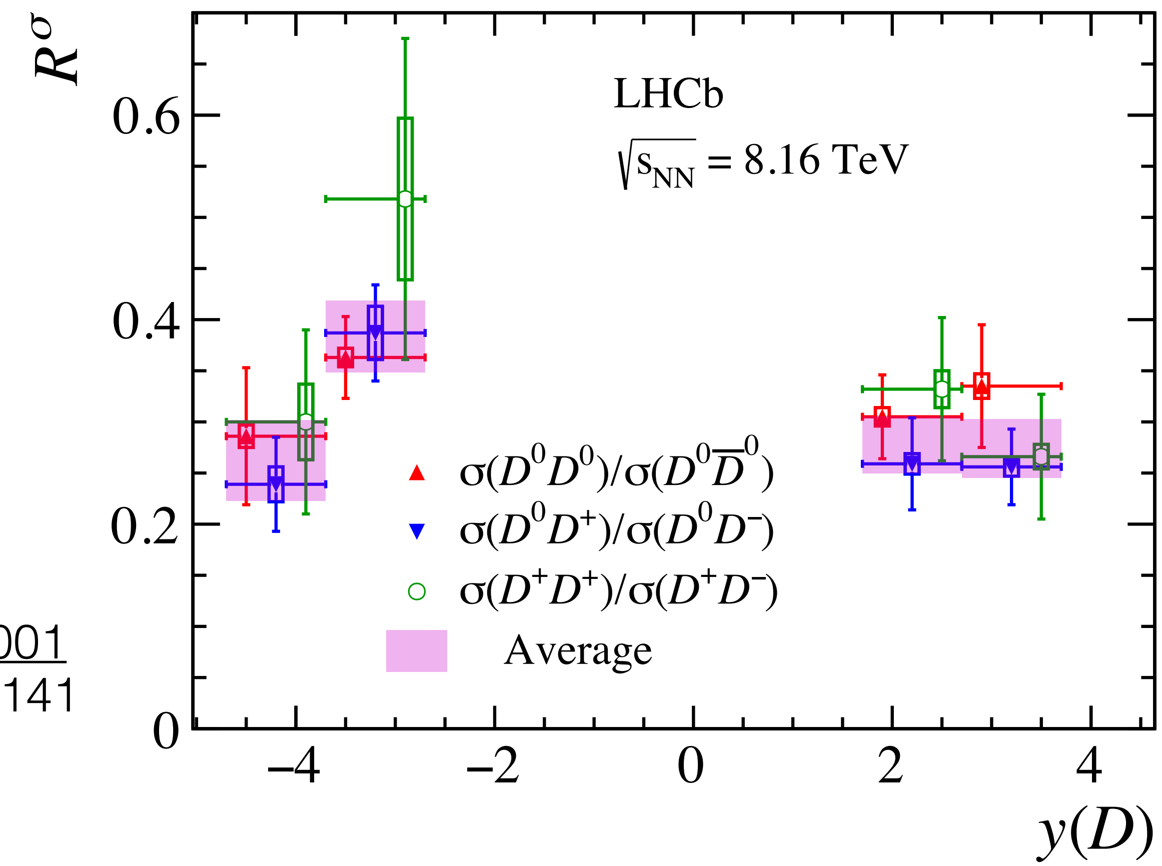
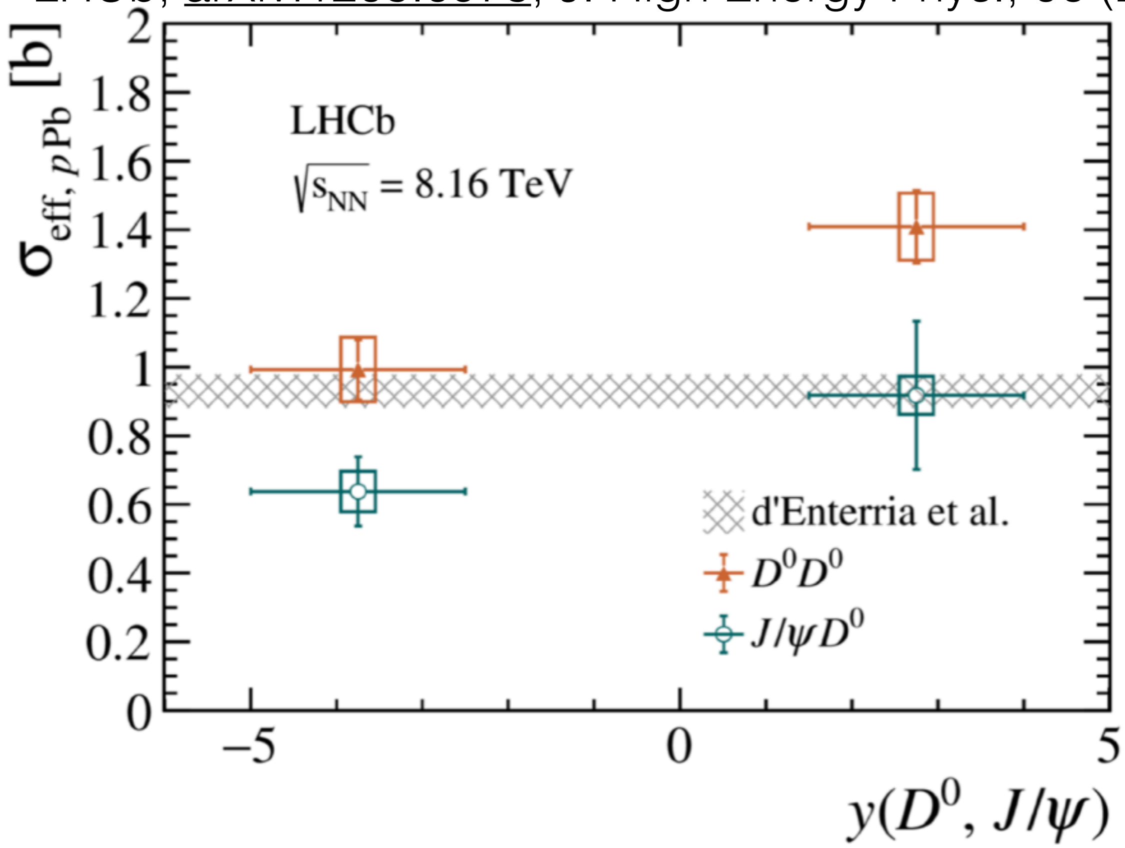
Double charm production in pPb

- Ratio of LS pair production over OS pairs significantly larger (~ factor 3) than in pp collisions $R(D^0D^0, pp) = 0.109 \pm 0.008$
- Evaluation of the effective cross section results in values ~1b.
- **Suggesting DPS/SPS enhanced by a factor of ~3 in pPb compared to pp !**



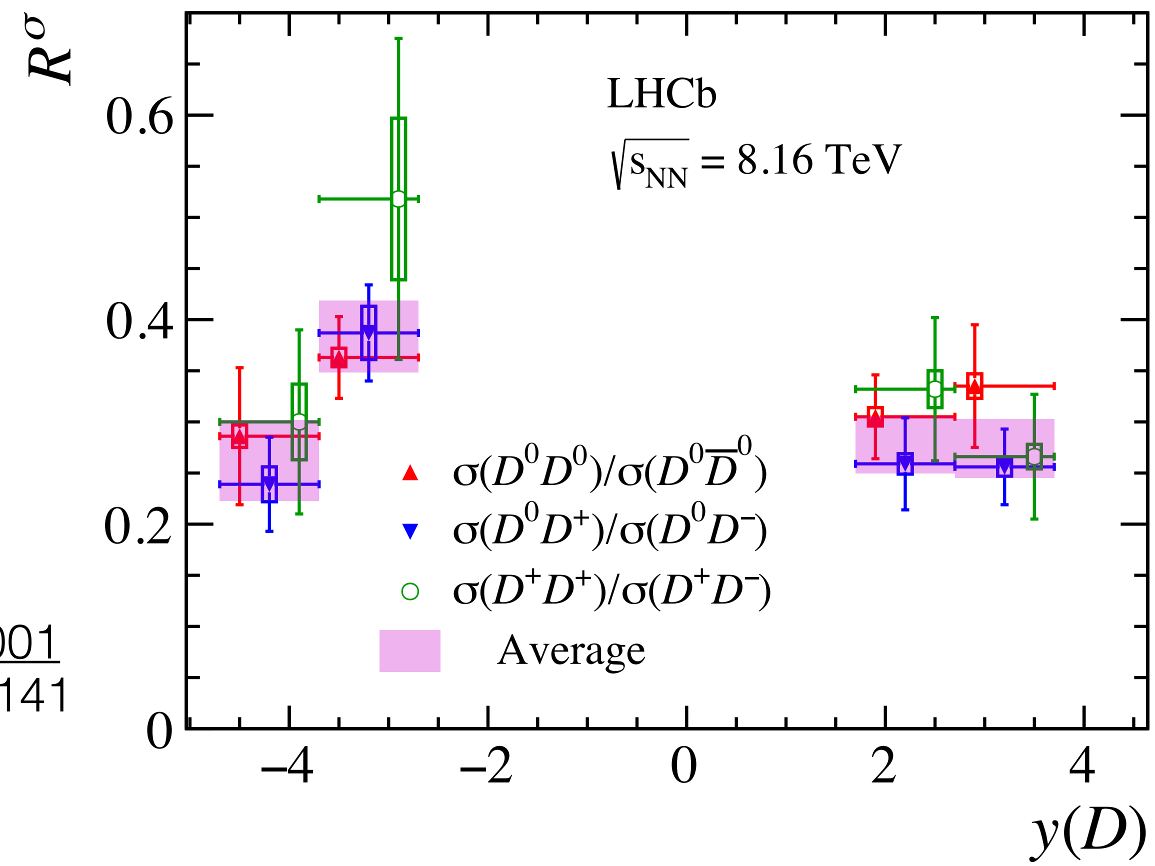
LHCb, arXiv:2007.06945; Phys.Rev.Lett. 125 (2020) 212001
LHCb, arXiv:1205.0975; J. High Energy Phys., 06 (2012) 141



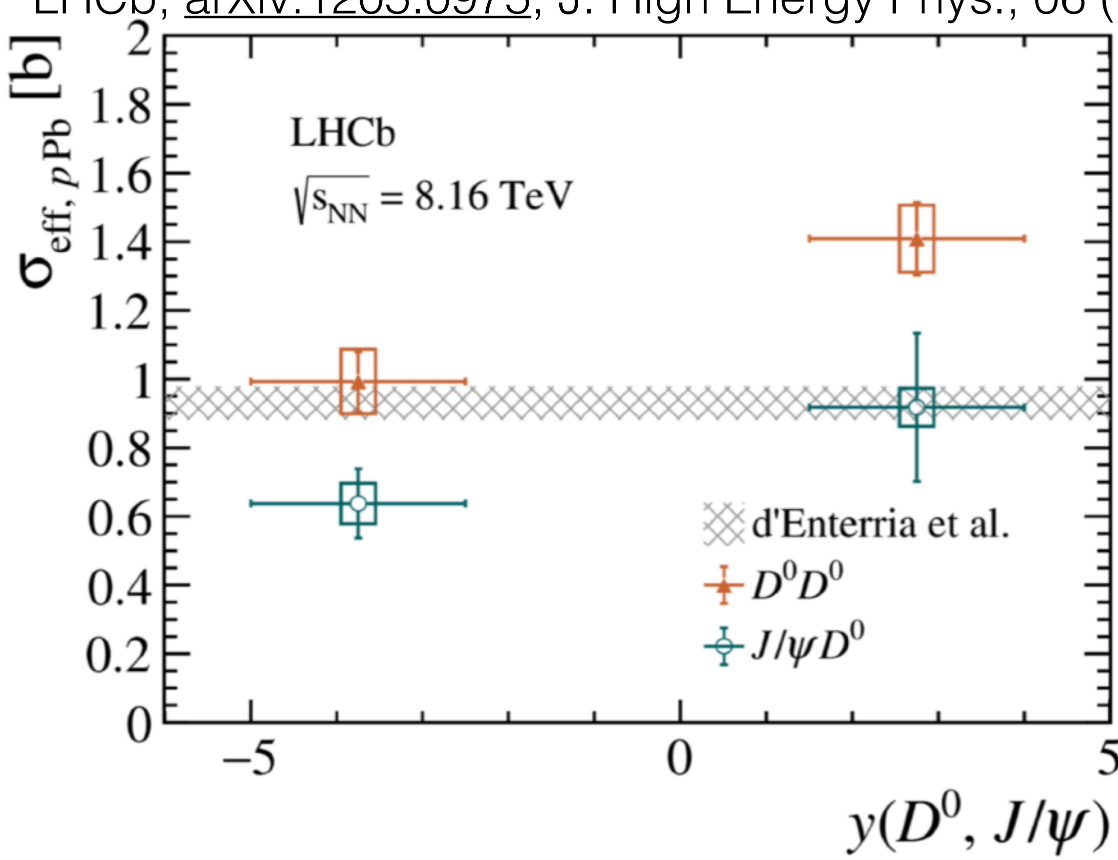
$$\sigma^{AB}_{DPS} = \frac{1}{1+\delta^{AB}} \frac{\sigma^A \sigma^B}{\sigma_{\mathrm{eff}}}; \qquad \delta^{AB} = 1(0) \text{ if } A = (\neq) B$$

Double charm production in pPb

- Ratio of LS pair production over OS pairs significantly larger (~ factor 3) than in pp collisions R(D^0D^0,pp) = 0.109 ± 0.008
- Evaluation of the effective cross section results in values ~1b.
- **Suggesting DPS/SPS enhanced by a factor of ~3 in pPb compared to pp !**



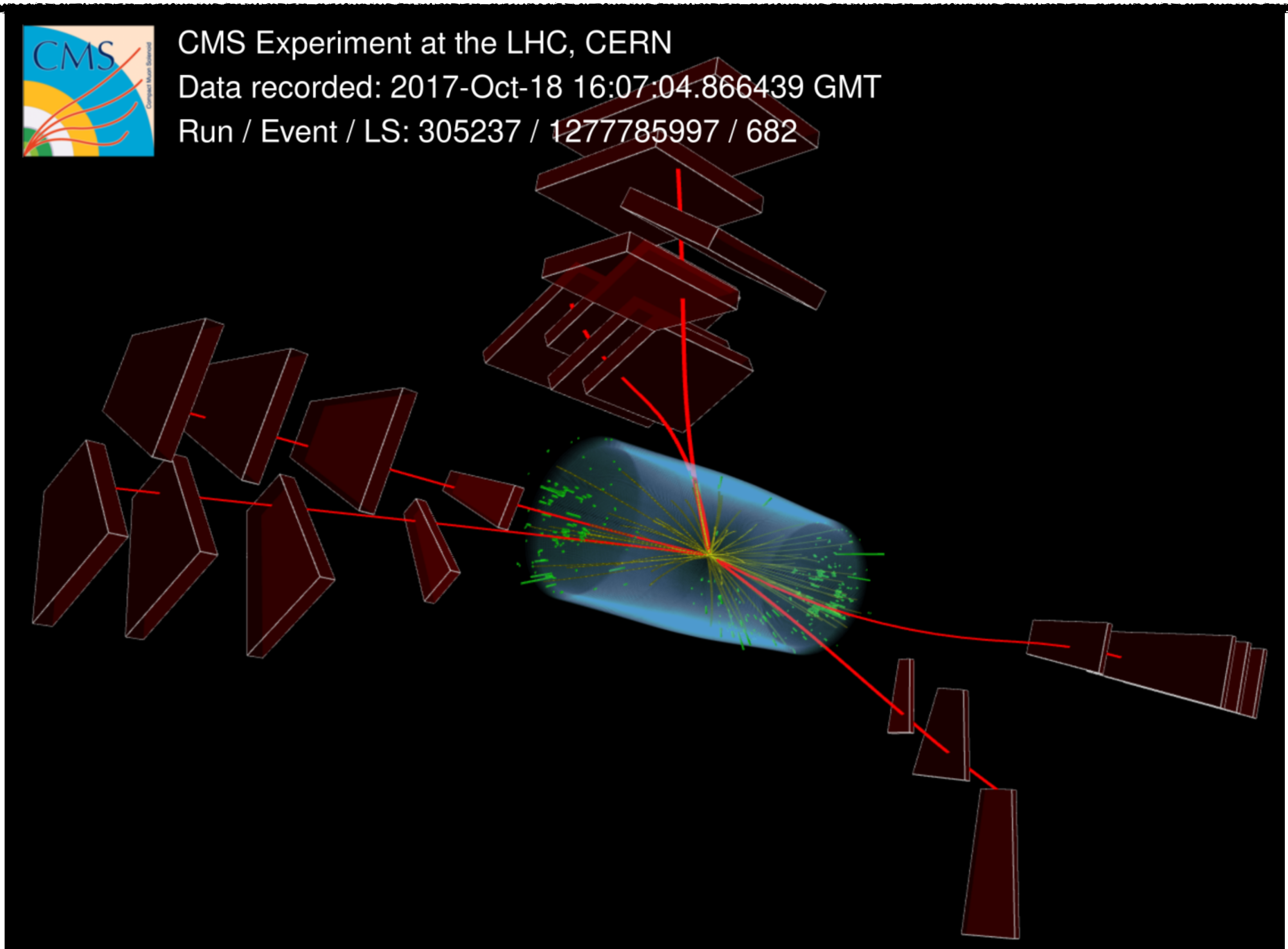
LHCb, arXiv:2007.06945; Phys.Rev.Lett. 125 (2020) 212001
LHCb, arXiv:1205.0975; J. High Energy Phys., 06 (2012) 141



- Larger values for J/ψ+D than D+D as observed in pp possibly due to SPS contamination or DPS enhancement.
- **Effective cross section values in pPb (positive y) results higher than Pbp ones, may suggest a complicated structure of nPDF (impact parameter dependence)**
  ➜ DPS nuclear modification factor to pin down the spatial distribution of nPDFs

H.-S. Shao, arXiv:2001.04256; Phys. Rev. D 101, 054036 (2020)

Triple J/ψ production in pp at 13 TeV



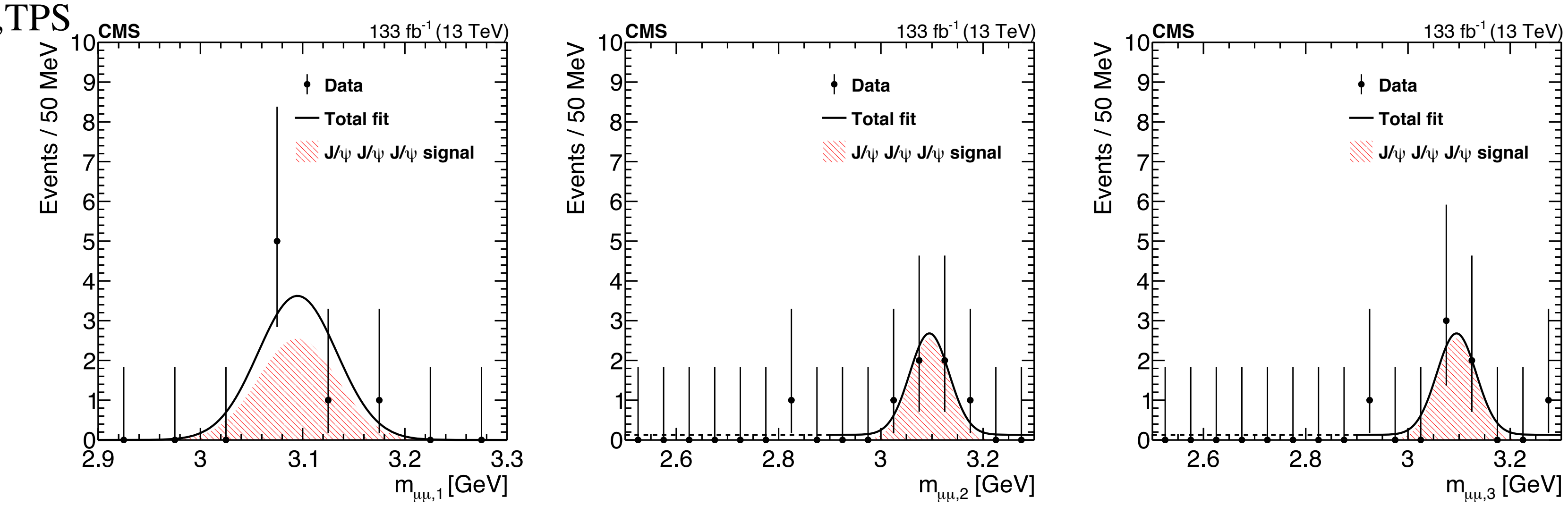
Triple J/ψ production in pp at 13 TeV

- **Triple parton scattering cross section as alternative to extract $\sigma_{\rm eff,DPS}$**

$$\sigma^{\rm TPS}_{hh'\to a_1 a_2 a_3} = \left(\frac{m}{3!}\right) \frac{\sigma^{\rm SPS}_{hh'\to a_1}\cdot\sigma^{\rm SPS}_{hh'\to a_2}\cdot\sigma^{\rm SPS}_{hh'\to a_3}}{\sigma^2_{\rm eff,TPS}}\,; \qquad \sigma_{\rm eff,TPS} = (0.82\pm0.11)\,\sigma_{\rm eff,DPS}$$

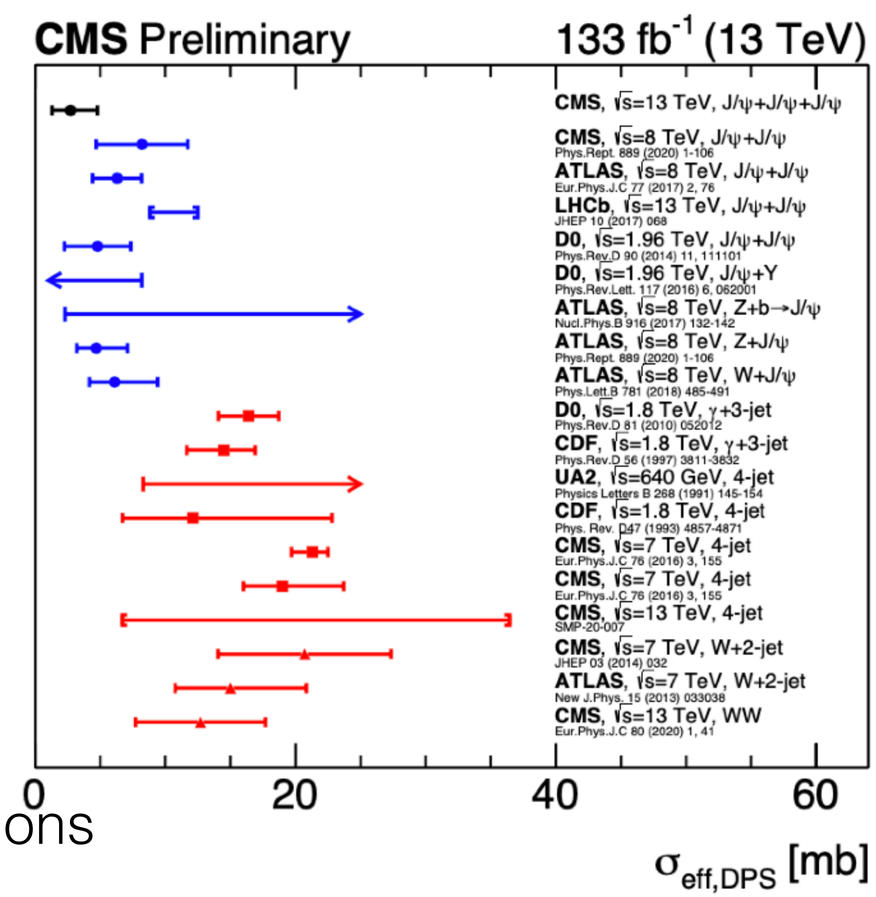
d'Enterria, Snigirev, arxiv:1612.05582;
Phys. Rev. Lett. 118, 122001 (2017)

CMS, CMS-BPH-21-004 ; CERN-EP-2021-215



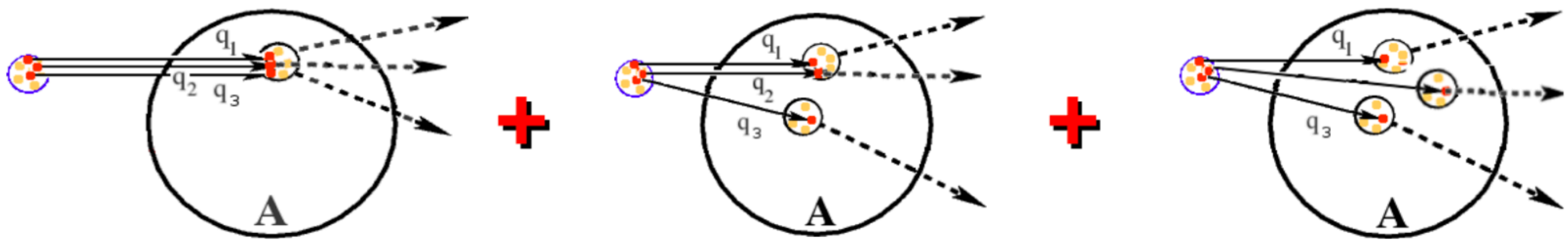
- **First observation of triple J/ψ production** by CMS exploiting 133 fb^{-1} in pp at 13 TeV:
  σ(pp→3J/ψ) = 272 $^{+141}_{-104}$ (stat) ±17 (syst) fb

- With the pocket formula with (N)NLO single-, double-, triple-J/ψ SPS:
  - **Triple-J/ψ fractions:**
    ~6% SPS, ~74% DPS, ~20% TPS
  - **$\sigma_{\rm eff,DPS}$ = 2.7$^{+1.4}_{-1.0}$ (exp) $^{+1.5}_{-1.0}$ (theo) mb consistent with di-quarkonia**
    (lower than jet/γ/W/Z DPS results)
    - q/g x-dependence transverse profile & correlations



Triple parton scattering in pPb

d'Enterria, Snigirev, arXiv:1612.08112; EPJC 78 (2018)359



$$\sigma^{\rm TPS,1}_{\rm pA\to abc} = A \cdot \sigma^{\rm TPS}_{\rm pN\to abc}$$

$$\sigma^{\rm TPS,2}_{\rm pA\to abc} = \sigma^{\rm TPS}_{\rm pN\to abc} \cdot 3\, \frac{\sigma^2_{\rm eff,TPS}}{\sigma_{\rm eff,DPS}}\, F_{\rm pA},$$

$$\sigma^{\rm TPS,3}_{\rm pA\to abc} = \sigma^{\rm TPS}_{\rm pN\to abc} \cdot \sigma^2_{\rm eff,TPS} \cdot C_{\rm pA}, \quad \text{with}$$

$$C_{\rm pA} = \frac{(A-1)(A-2)}{A^2} \int d^2b\, T^3_{\rm pA}(\mathbf{b}),$$

Relative weight of TPS terms: $\sigma^{\rm TPS,1}_{\rm pA\to abc} : \sigma^{\rm TPS,2}_{\rm pA\to abc} : \sigma^{\rm TPS,3}_{\rm pA\to abc} = 1 : 4.54 : 3.56$

(TPS yields in pPb: 10% "genuine", 50% involve 2 nucleons, 40% involve 3 different Pb nucleons)

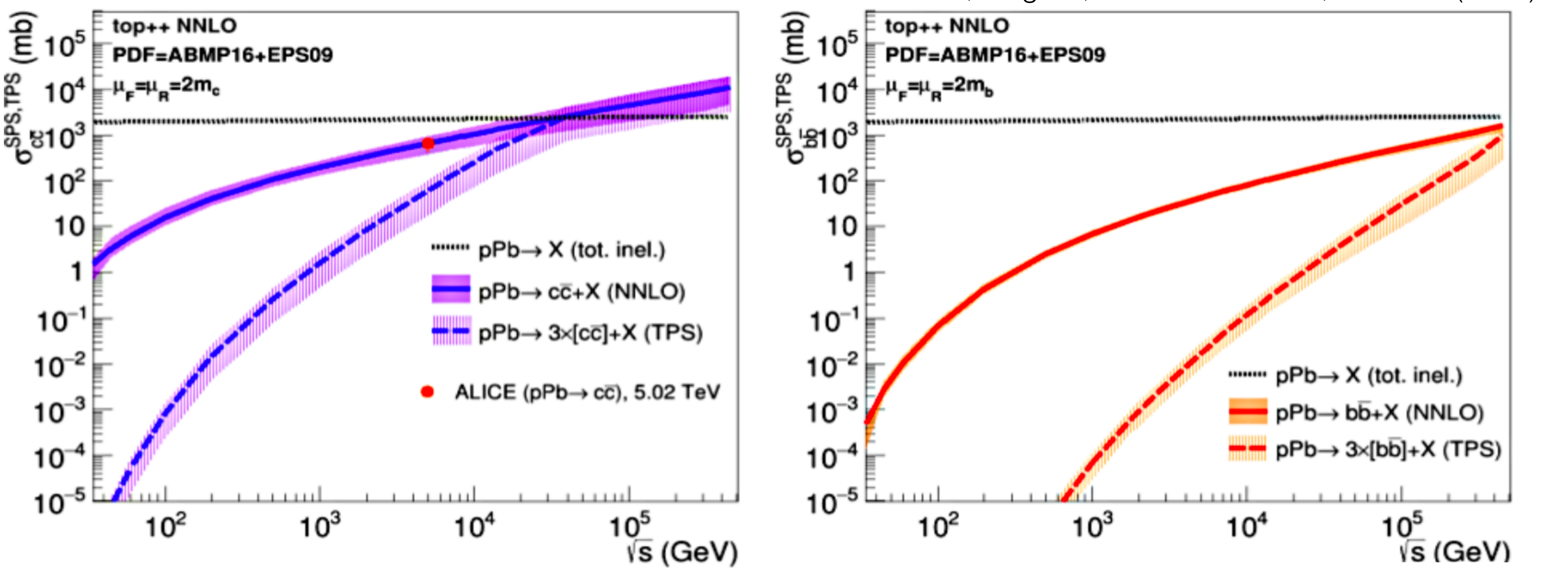
- Three contributions to TPS cross section in pA
- "pocket formula"

$$\sigma^{\rm TPS}_{\rm pA\to abc} = \left(\frac{m}{3!}\right) \frac{\sigma^{\rm SPS}_{\rm pN\to a} \cdot \sigma^{\rm SPS}_{\rm pN\to b} \cdot \sigma^{\rm SPS}_{\rm pN\to c}}{\sigma^2_{\rm eff,TPS,pA}}; \qquad \sigma_{\rm eff,TPS,pA} = \left(\frac{A}{\sigma^2_{\rm eff,TPS}} + \frac{3F_{\rm pA}[mb^{-1}]}{\sigma_{\rm eff,DPS}} + C_{\rm pA}[mb^{-2}] \right)^{-1/2}$$

- **Triple cross sections are large in pA**: a factor x45 for pPb compared to pp.
- Pb transverse density well known (F_{pA}, C_{pA}) ➜ **alternative to extract $\sigma_{\rm eff,pp}$**

Triple parton scattering in pPb

d'Enterria, Snigirev, arXiv:1612.08112; EPJC 78 (2018)359



- **Charm and beauty have very large contribution from TPS at the LHC and above**
  - triple charm amounts to ~20% (~100%) of inclusive charm at the LHC (FCC)
  - triple beauty amounts to ~3% of inclusive beauty cross sections at FCC.
- Opportunities with Run 3 & 4 and FCC.

TABLE I: Total charm and bottom SPS (NNLO) and TPS cross sections (in mb) in pPb at LHC and FCC with scales, PDF, and total (quadratically added, including $\sigma_{\mathrm{eff,TPS}}$) uncertainties. The asterisk indicates that the theoretical prediction of the TPS charm cross section is "unphysical" (see text).

Final state	$\sqrt{s_{\mathrm{NN}}} = 8.8$ TeV	$\sqrt{s_{\mathrm{NN}}} = 63$ TeV
$\sigma(c\bar{c} + X)$	$960 \pm 450_{\mathrm{sc}} \pm 100_{\mathrm{pdf}}$	$3400 \pm 1900_{\mathrm{sc}} \pm 380_{\mathrm{pdf}}$
$\sigma(c\bar{c}\, c\bar{c}\, c\bar{c} + X)$	$200 \pm 140_{\mathrm{tot}}$	$8700^{*} \pm 6200_{\mathrm{tot}}$
$\sigma(b\bar{b} + X)$	$72 \pm 12_{\mathrm{sc}} \pm 5_{\mathrm{pdf}}$	$370 \pm 75_{\mathrm{sc}} \pm 30_{\mathrm{pdf}}$
$\sigma(b\bar{b}\, b\bar{b}\, b\bar{b} + X)$	$0.084 \pm 0.045_{\mathrm{tot}}$	$11 \pm 7_{\mathrm{tot}}$

Summary

- Rich ongoing studies in small systems (not a comprehensive talk!).

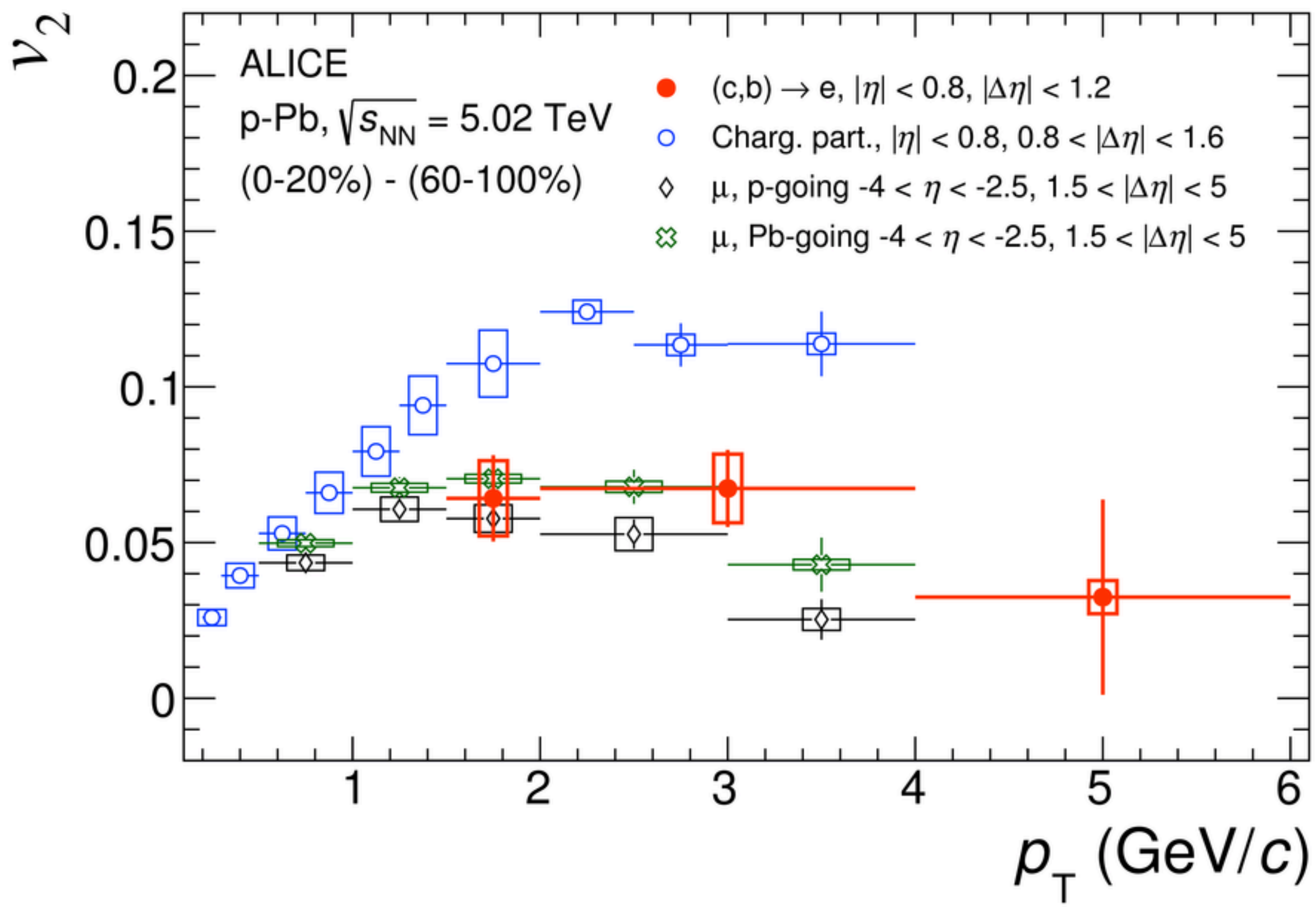
- Multiplicity dependence of heavy flavors:
  - Increase of the yields with charged-particle multiplicity (with a more or less steep trend depending on the y and the collision system).
    Models including some 'multiple parton interactions' describe data within uncertainties.
  - Bottomonia excited-to-ground state ratios decrease with multiplicity (but for jet-like events!).
    Improved description of quarkonium production, hadronization and fragmentation is crucial.

- Associated particle production measurements emerging:
  - Triple J/ψ production in pp observed for the first time.
  - Double charm production observed for the first time in pPb data.
  - Non-negligible DPS/TPS cross sections in pA and AA; opportunities in Run 3, 4 & FCC.

- **Multiple parton interaction studies important to constrain particle production models, test possible modifications of hadronization/fragmentation and understand measurements in small systems.**

- Further theoretical developments also required.

Open heavy-flavor flow in p-Pb



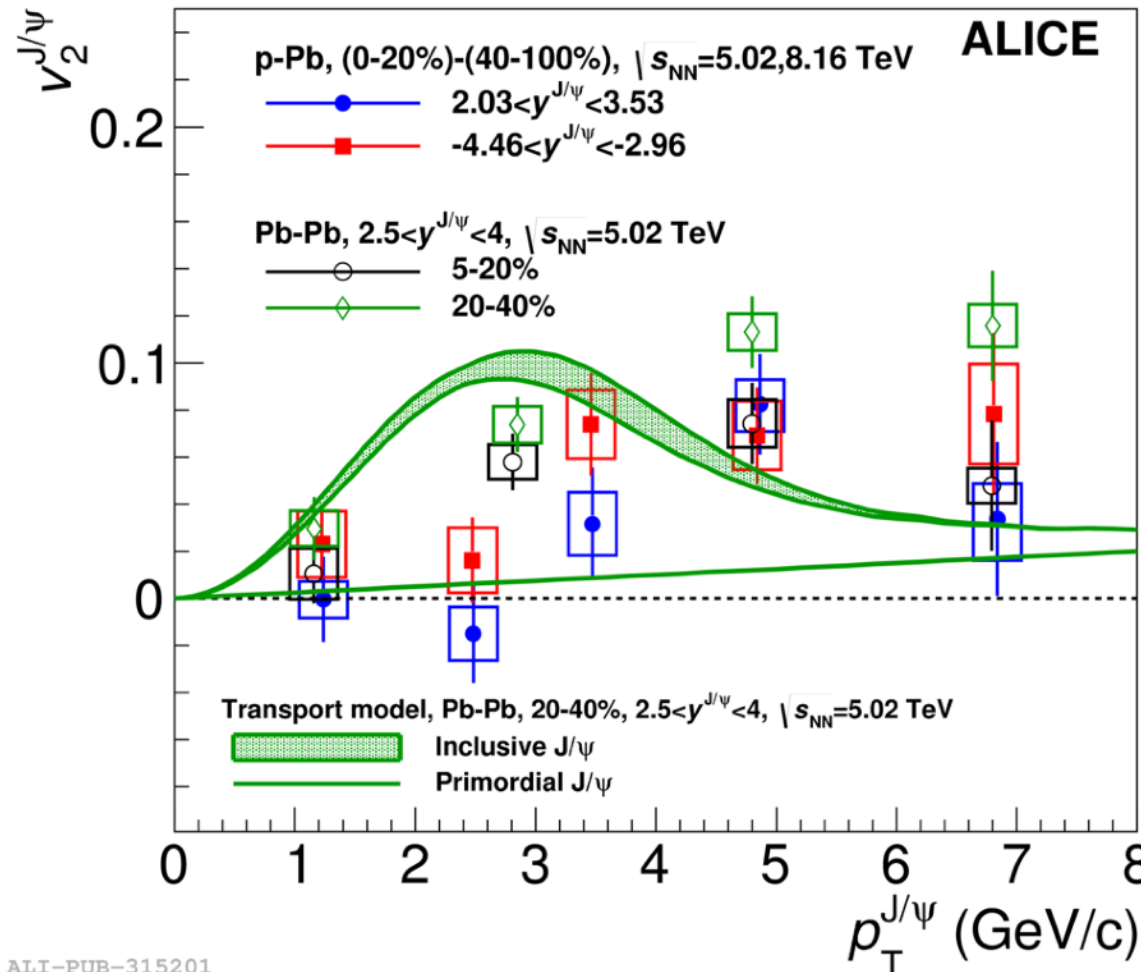
ALICE, PRL122, 072301 (2019)
ALICE, PLB 726, 164 (2013)
ALICE, PLB 753, 126 (2016)

- **Positive v_2 of heavy-flavor decay electrons (HFE) in high multiplicity events.**
  - 4.6σ (6σ) in $2<p_T<4$ GeV/c ($1.5<p_T<4$ GeV/c)
- For $2<p_T<4$ GeV/c v_2(HFE) ~ v_2(inclusive muons) < v_2(ch.particles)

- **Collective effects reminiscent to those in A-A, where they are interpreted as a sign of QGP fluid dynamics**
  → is sort of mini-QGP created in small collision systems?
- Need models

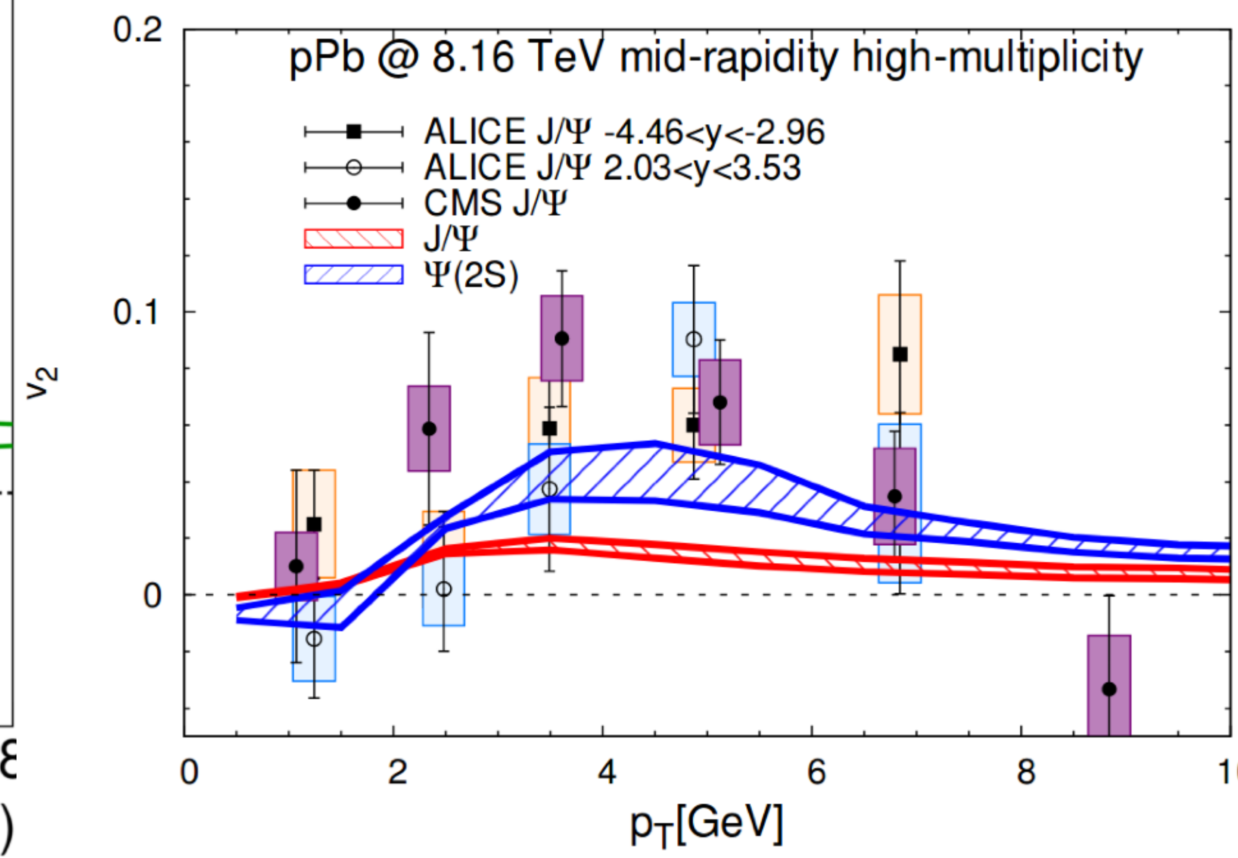
J/Ψ flow in p-Pb

Combined 5.02 + 8.16 TeV



ALICE, PLB 780 (2018) 7-20

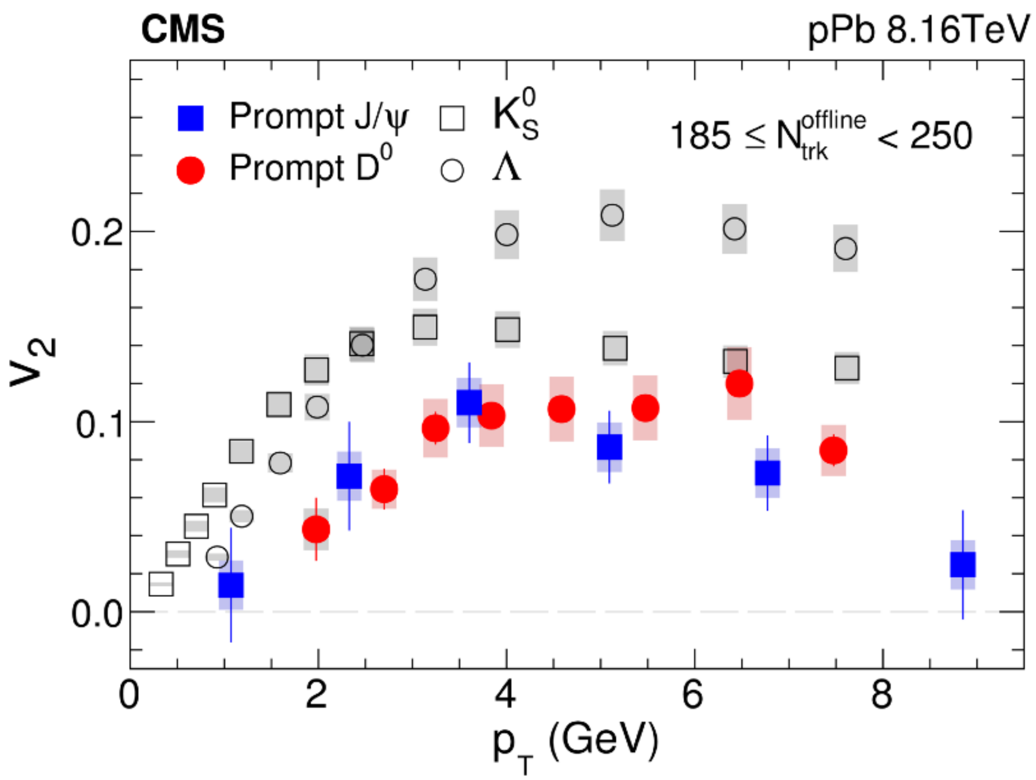
Comparison to CMS and transport model (JHEP 1903 (2019) 015)



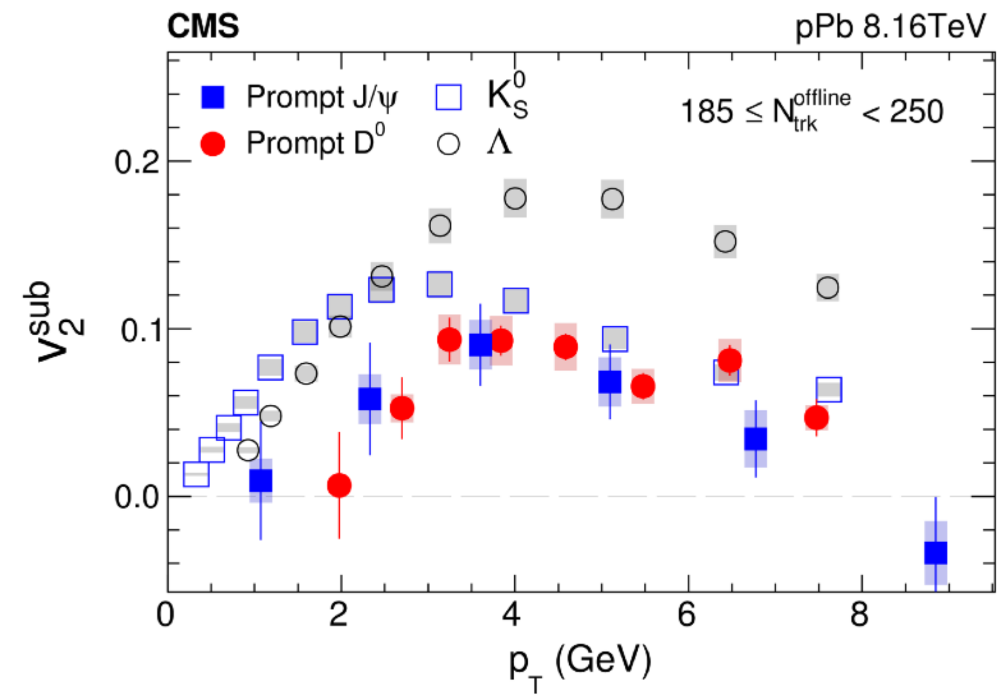
C. Cheskov — CERN seminar July 2019

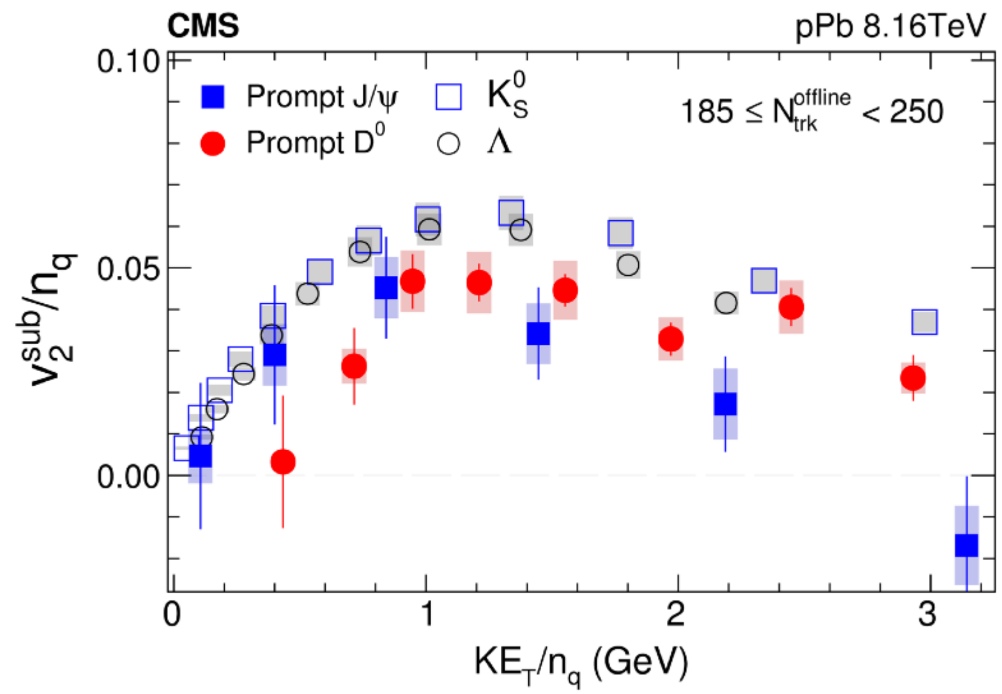
- **Observation of positive J/ψ v_2 (5σ), confirmed by CMS for prompt J/ψ at mid-rapidity**
- Values similar to semi-central (5-20%) Pb-Pb
- Do not really fit into the picture of transport models
  – Small system size → negligible path-length dependent effects
  – Small amount of available charm quarks → negligible regeneration
- Similar v_2 independently of the J/ψ measurement rapidity interval (within unc.).
- Missing mechanism in models? Initial-state effects in CGC proposed in PRL 122 (2019) 172302.

Particle flow in pPb



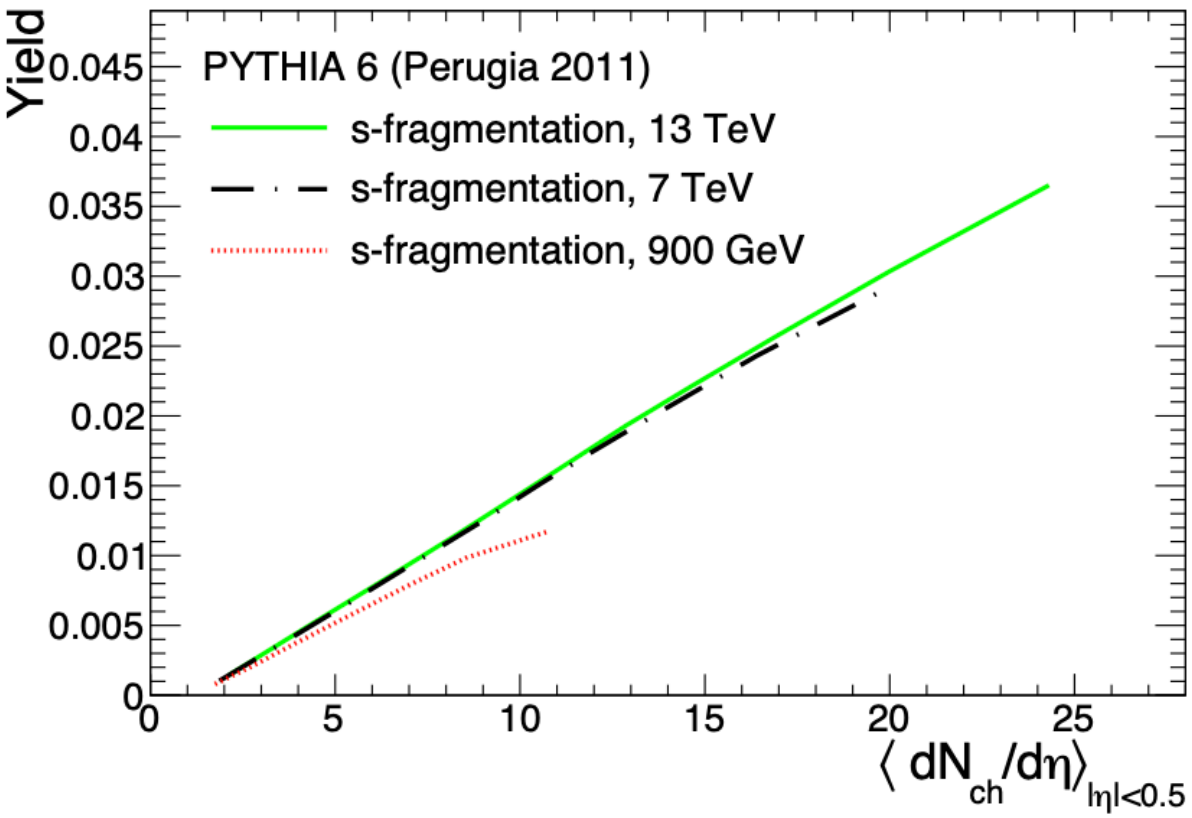
CMS, PAS HIN-18-010
PLB 791 (2019) 172

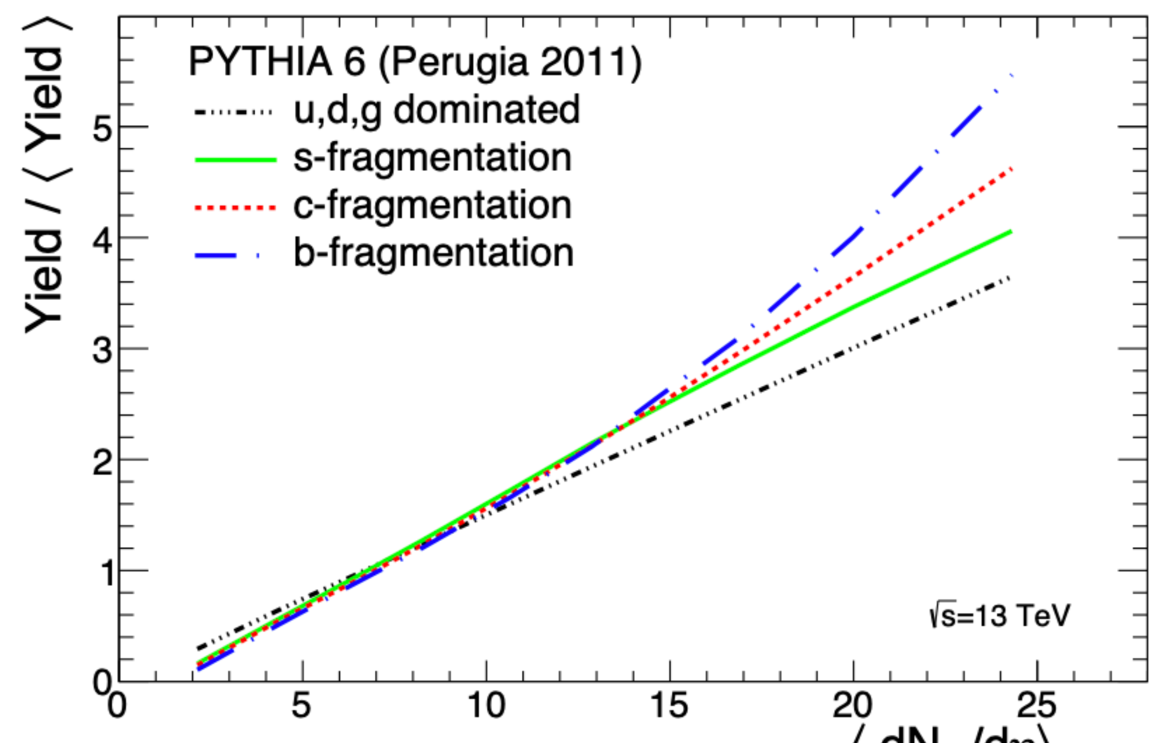




- **Charm flows (v_2>0) in p-Pb collisions**
- At low p_T < ~4-5 GeV/c → v_2(ch.particles) > v_2(D) ≈ v_2(J/ψ)
- At high p_T > ~6 GeV/c need more stats to conclude

Understanding strange yields: pp, PYTHIA & MPI





C. Loizides, A. Morsch, arXiv:2109.05181

- Relevance of modelling the pp impact parameter dependence of MPIs!
- The **energy independence of strange-particle yields** at 7 TeV and above is reproduced in PYTHIA simulations of the s-fragmentation contribution
  ➜ can not be interpreted as a consequence of final-state effects
- Quark-flavor evolution:
  - **Smooth evolution from linear to quadratic from the udg-hadronization and s-fragmentation components to the c- and b-fragmentation contributions. ➜ unified approach for all species**
  - As a result of the significant contribution of associated particle production to the measured charged-particle multiplicity (auto-correlation bias).