Soft QCD Measurements

Jan Fiete Grosse-Oetringhaus, CERN

27th International Symposium on
Lepton Photon Interactions at High Energies

18.07.15

Soft QCD

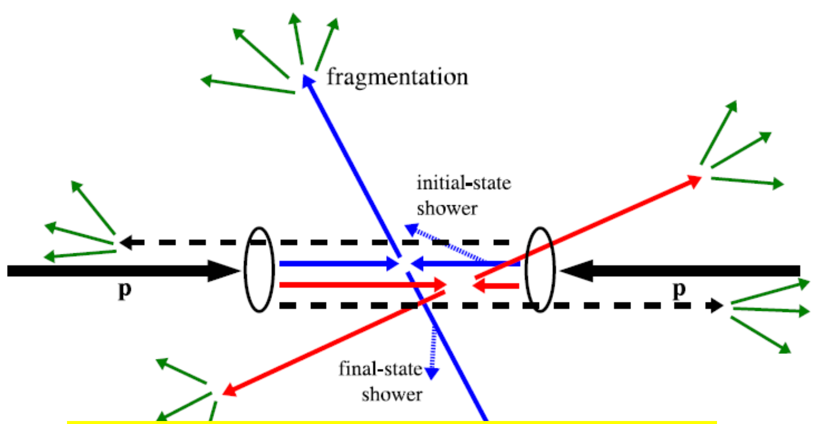
- QCD in the non-perturbative regime
  - Poorly understood theoretically
  - Phenomenology and MC tuning unavoidable
- Crucial to model backgrounds for measurements of rare probes (SM & BSM)
  - Precondition for precision measurements and discoveries

PDFs

ISR

FSR

Hadronisation
Fragmentation



Most of the event is soft
Pile up contribution is soft

Multiple parton interaction

Low Q^2 scattering

Diffraction

Color reconnection

Today’s Menu

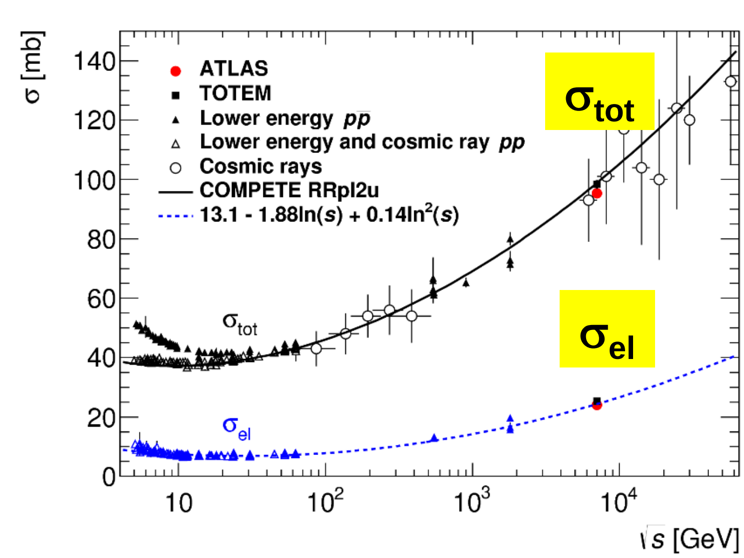
- Cross-sections
- Charged-particle distributions
- Underlying event
- Multiple parton interactions
- Identified particles
- The ridge(s)

Tremendous amount of soft QCD results from LHC !

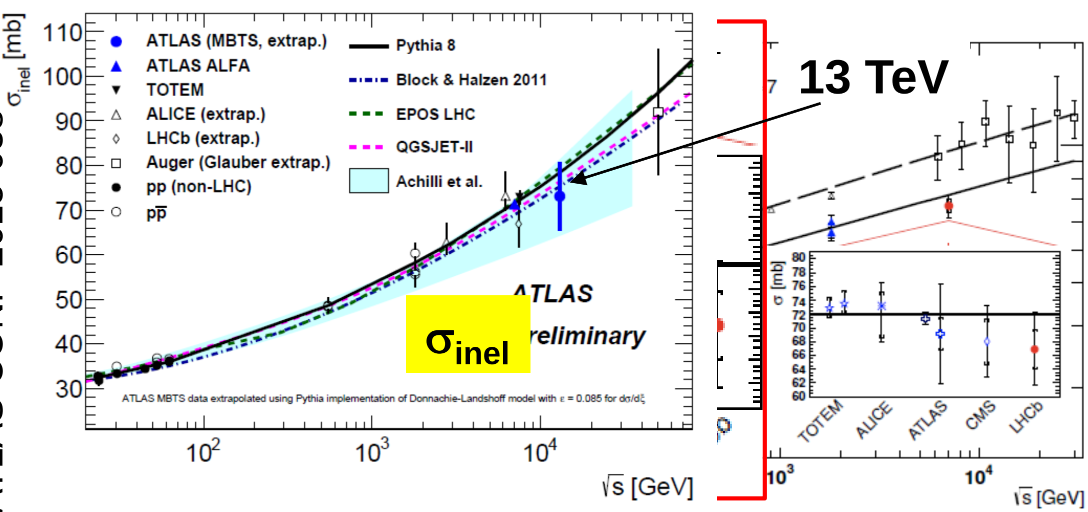
Links to public results pages:
ALICE ATLAS CMS LHCb LHCf TOTEM

Cross sections

- Total σ from $d\sigma_{el}/dt$ by optical theorem
  - ALFA (ATLAS) and TOTEM
- Sensitivity to inelastic σ by all exps
  - First measurement at 13 TeV !
- Diffractive σ
  - Definition experimentally tricky (high-mass diffraction w/o rapidity gap)
  - MC tuning best with rapidity gaps

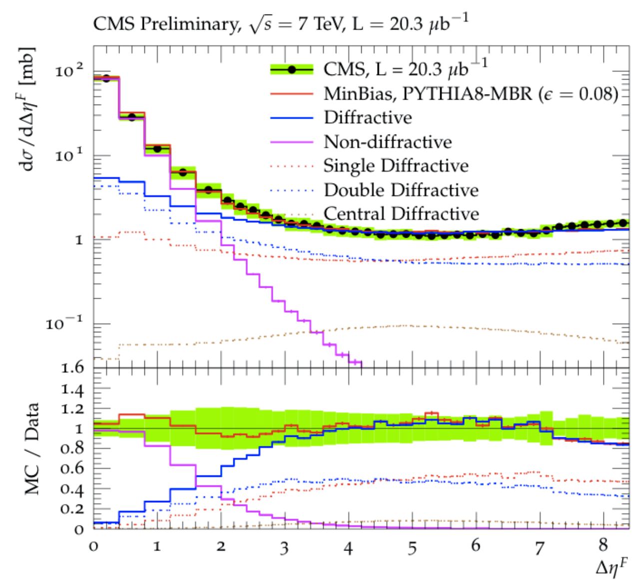


NPB(2014)486



ATLAS-CONF-2015-038

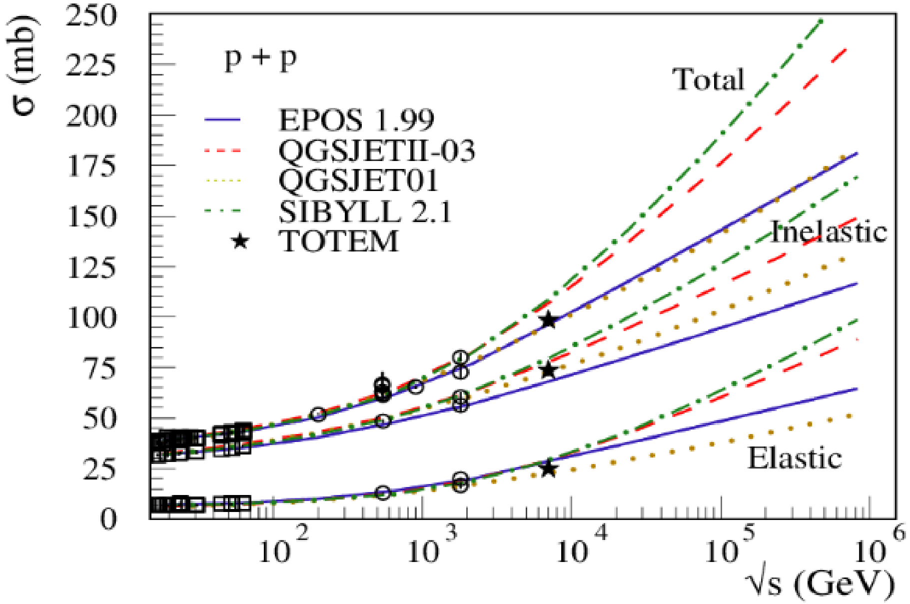
JHEP02(2015)129



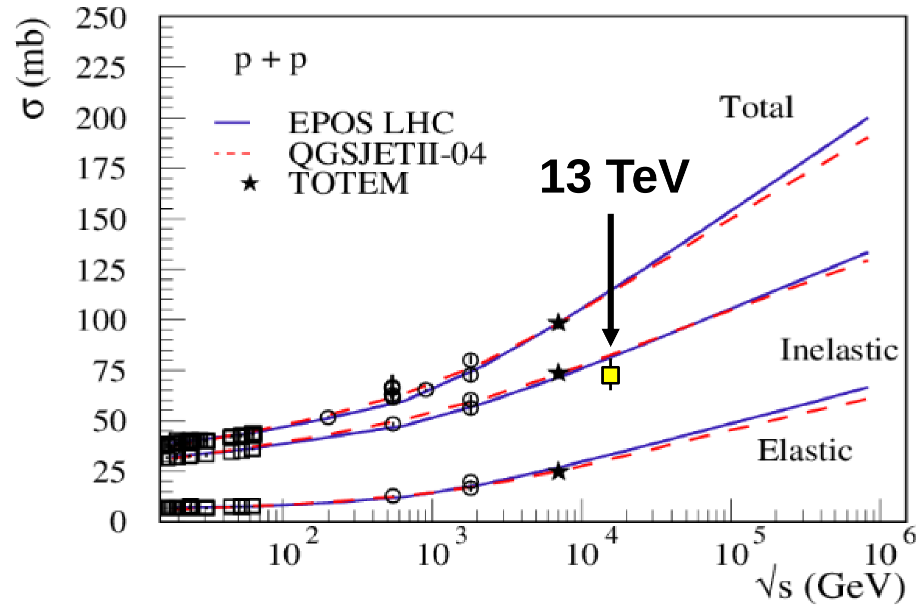
PAS-FSQ-12-005

Relevance for Cosmic-Ray Physics

Pre - LHC



Post - LHC



T. Pierog, ISVHECRI 2014

Significant reduction of extrapolation uncertainty

Particle Multiplicities

- Elementary characterization of collisions
  - Charged primary particles (mostly hadrons)
  - First test of MCs, tunes and models

Event classes

- **Inelastic collisions**
- **Non-single diffractive, defined by**
  - **Diffractive mass, e.g. $\xi < 0.05$**
  - **"MC flag"**
- **Particle-level (events with at least one track above some p_T)**

Phase space

- **Within η acceptance**
- **Above $p_{T,min}$ (→ p_T resolution uncertainty)**
- **Extrapolated to $p_T = 0$ (→ extrapolation uncertainty)**

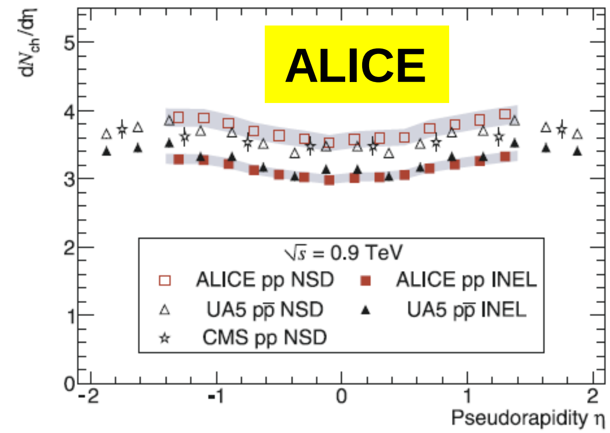
Primary particle definition

- **Typical definition (@ LHC): $\tau > 0.3 \cdot 10^{-10}$ s (or $c\tau > 1$ cm)**
- **In 13 TeV, ATLAS has removed strange baryons from their definition (as they are mostly insensitive to them)**

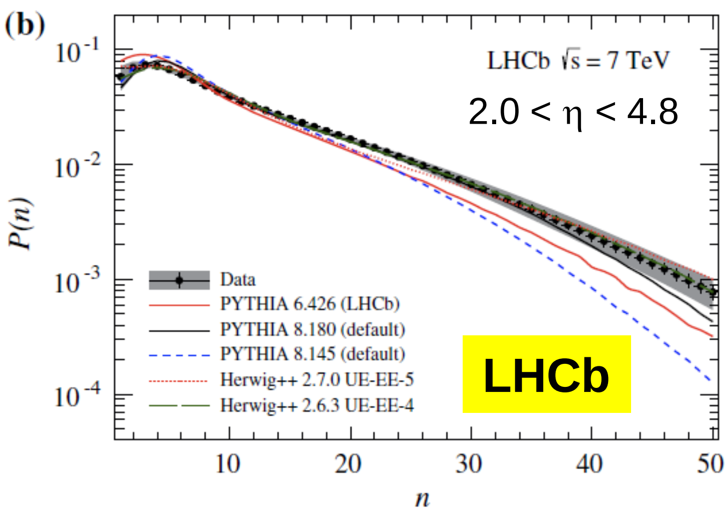
→ Let's try not to deviate too much from each other in definitions (facilitates direct comparisons between experiments and with basic models)

Particle Multiplicities (2)

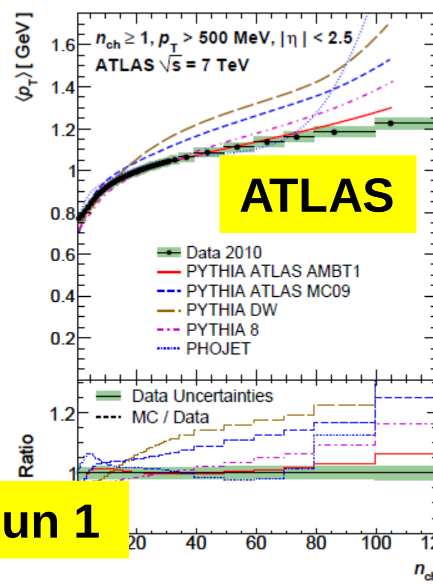
- Pseudorapidity density $dN_{ch}/d\eta$
- Multiplicity distribution $P(N_{ch})$
- p_T distribution dN_{ch}/dp_T
- Average-p_T vs N_{ch}

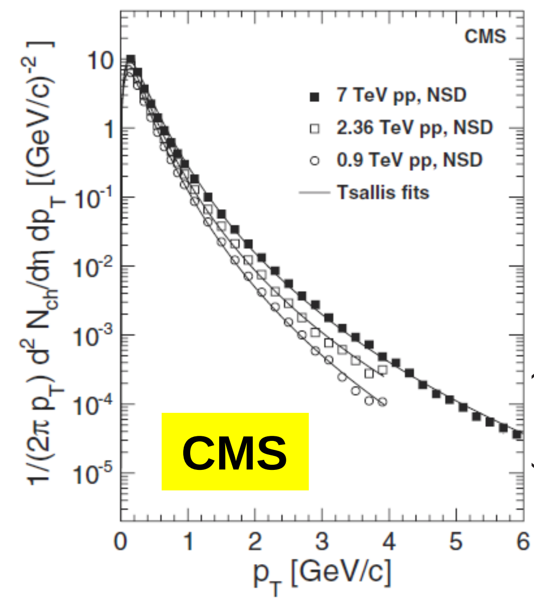


EPJC (2010) 68,89



EPJC (2014) 74,2888





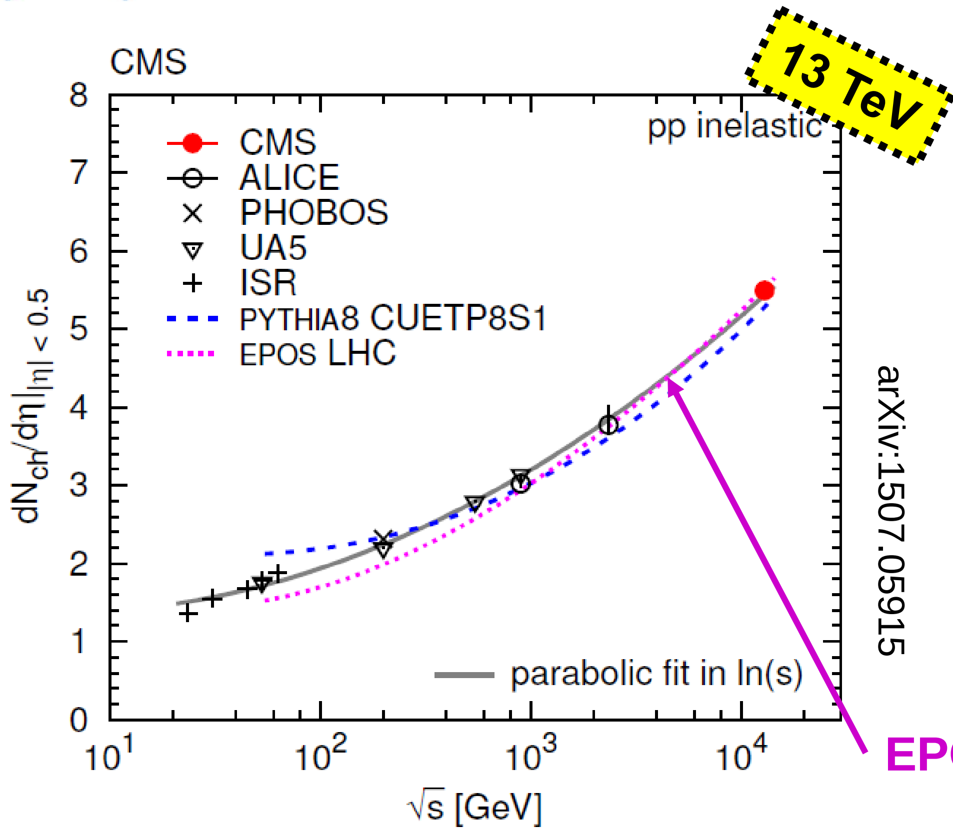
PRL 105, 022002 (2010)

Significant amount of results from Run 1

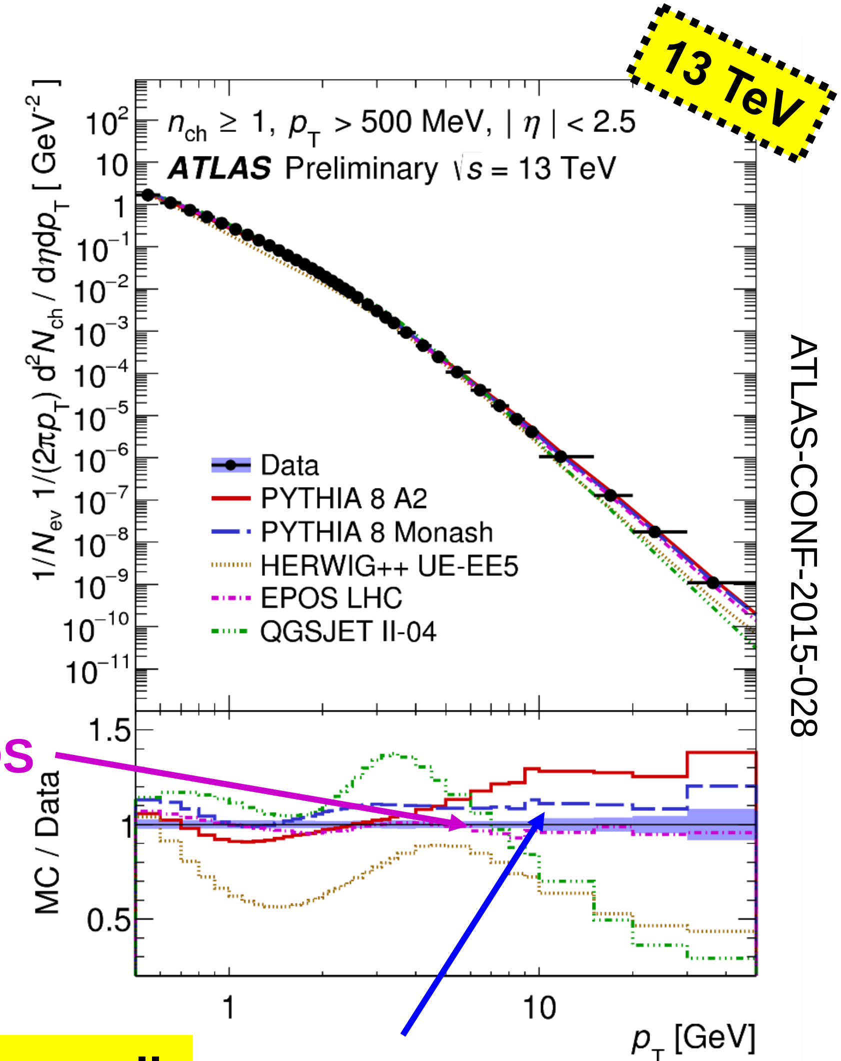
NJP13:053033,2011

LHC-wide WG on MB&UE: LINK

13 TeV !



EPOS



measured with B = 0
($p_T \rightarrow 0$ extrapolation minimal)

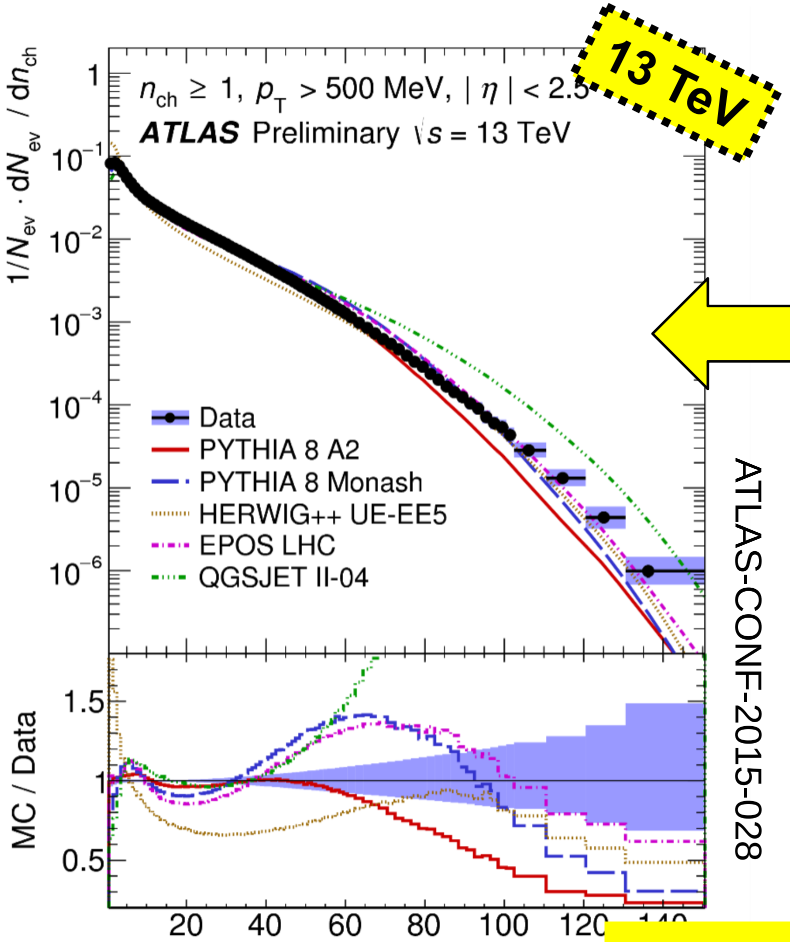
P8 Monash

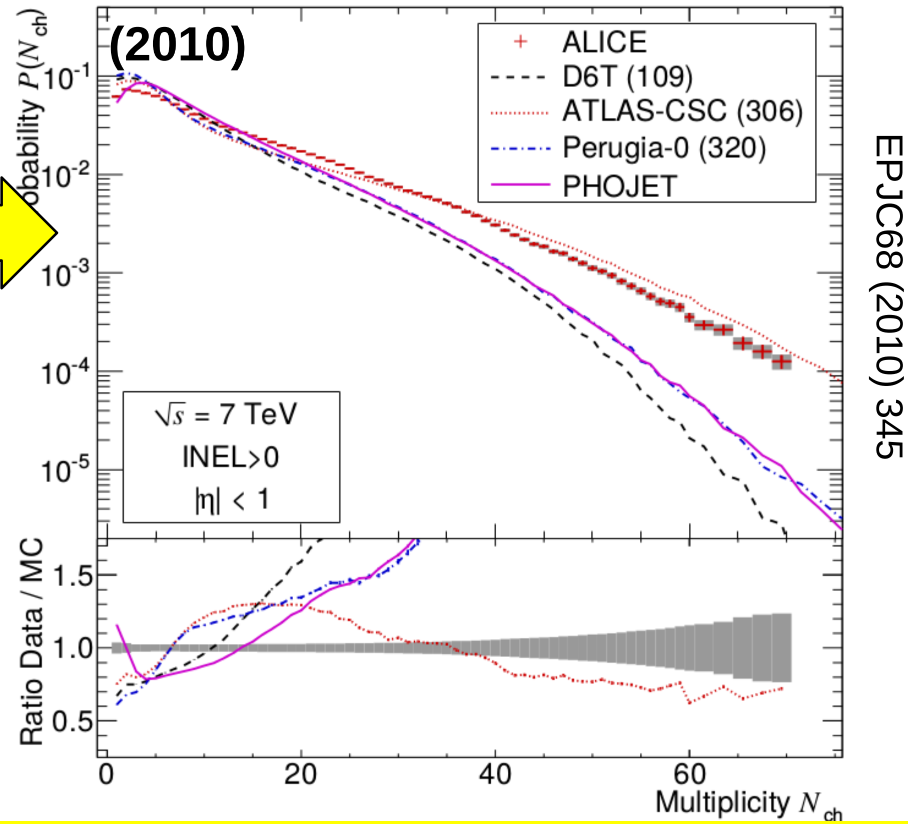
EPOS LHC and Pythia8 Monash doing very well

13 TeV !

13 TeV predictions (tuned with 7-8 TeV)

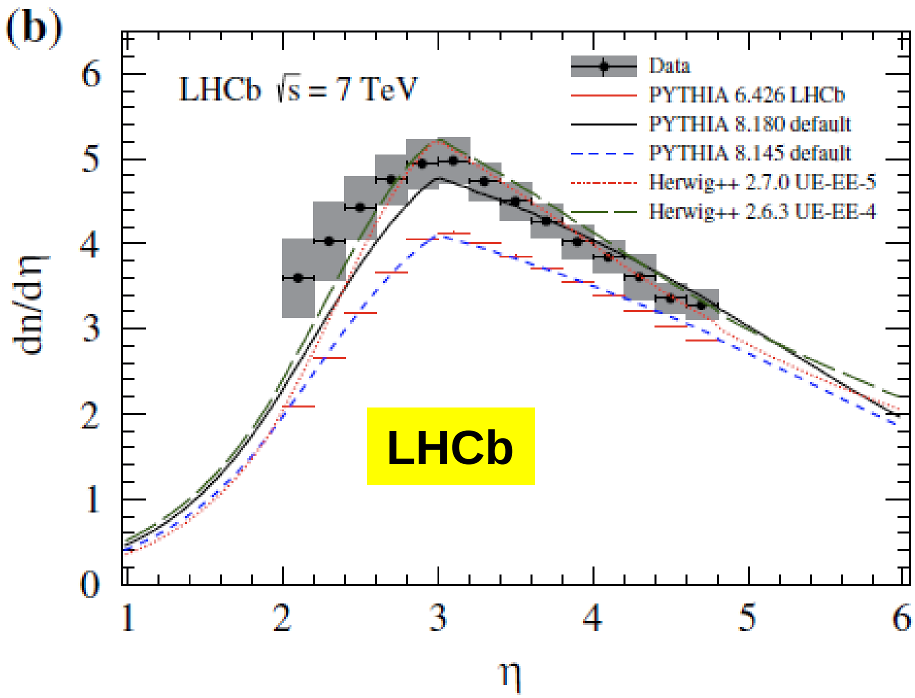
7 TeV predictions (tuned with 2 TeV)



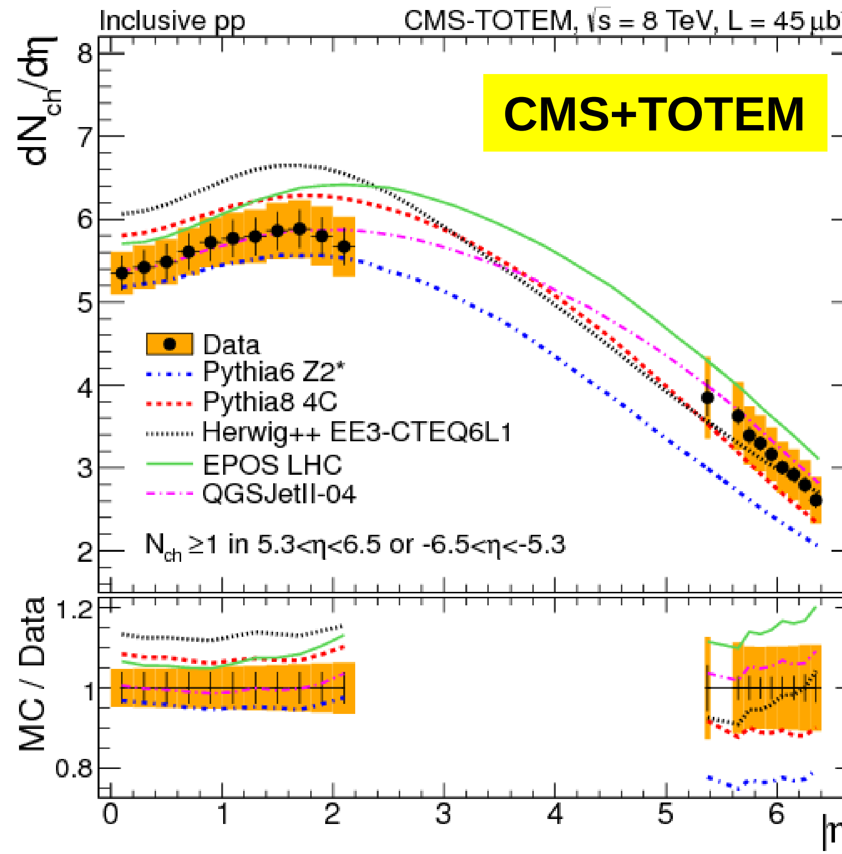


Predictions got much better (√s step also smaller)

Forward Measurements



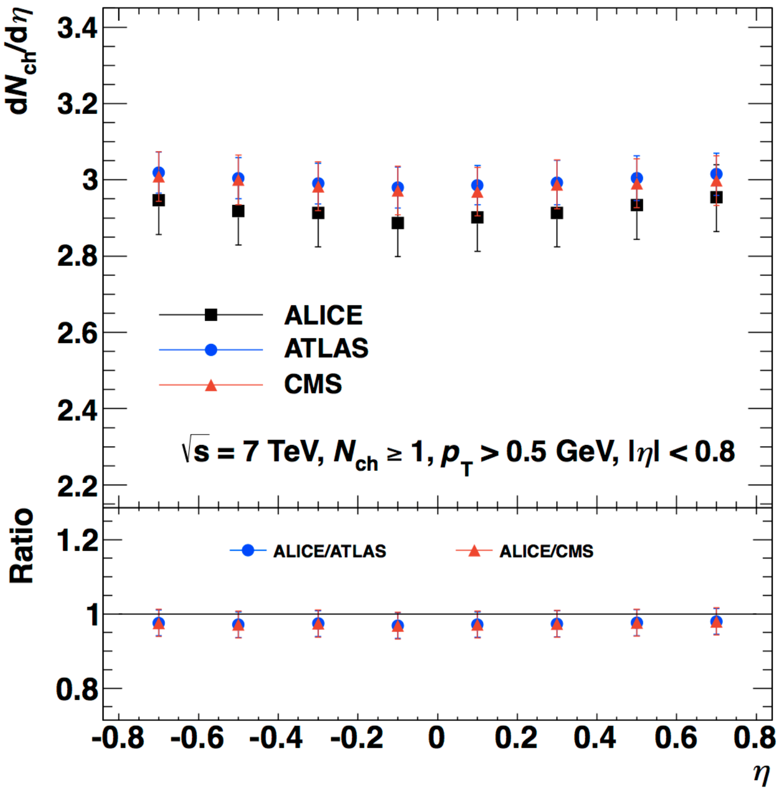
EPJC (2014) 74:2888

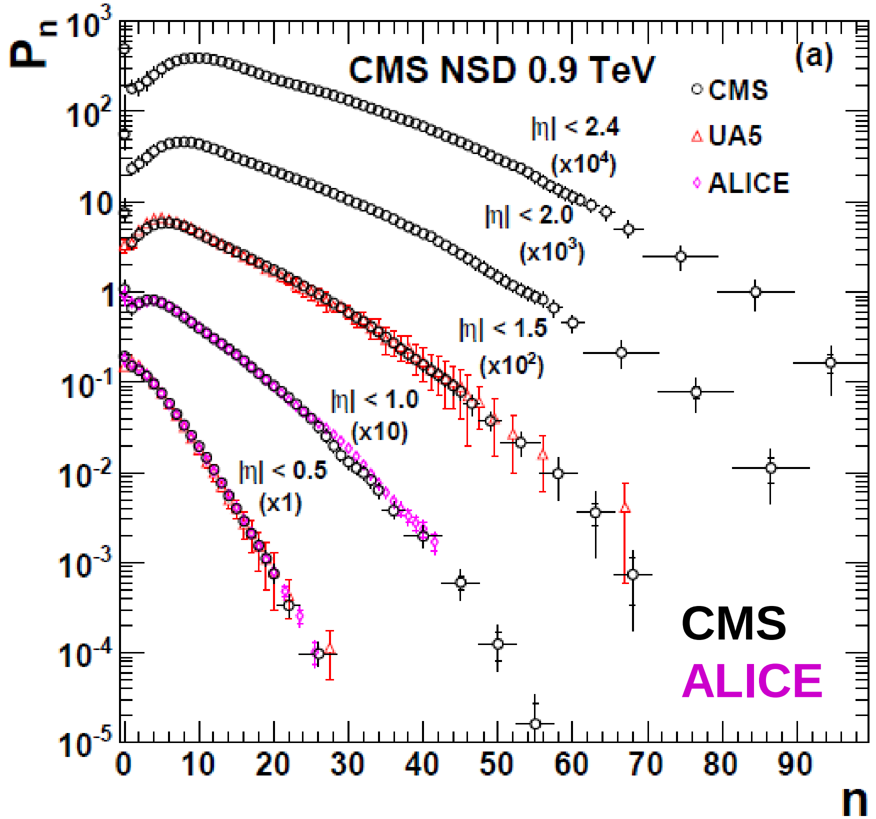


EPJC74 (2014) 10, 3053

Measurements over large fraction of phase space available

LHC Experiments agree !



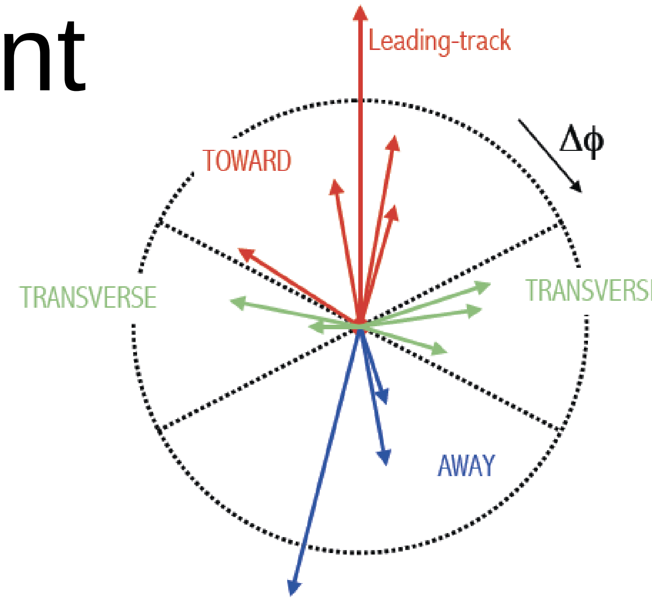


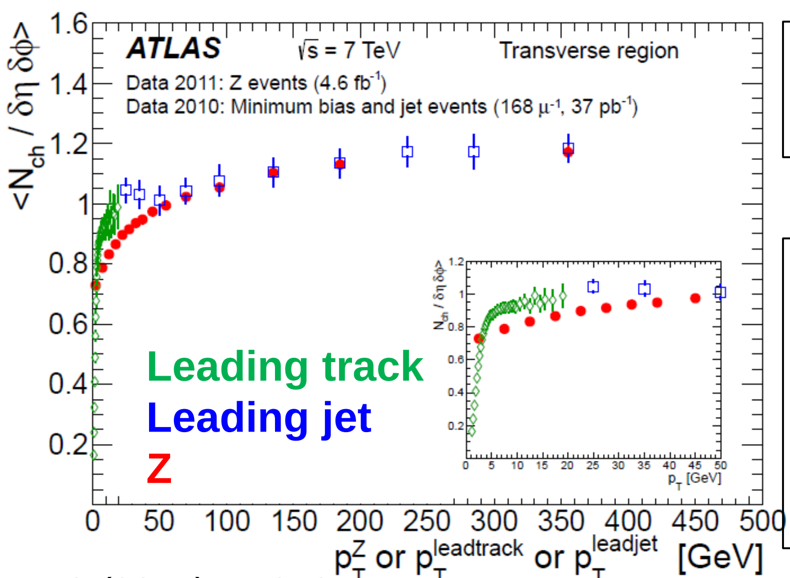
LPCC MB&UE WG

JHEP 1101:079,2011

Underlying Event

- Activity below hardest scattering
  - as a function of hard scale
  - perpendicular to scattering
    “transverse” vs. “towards” / “away”
- Typical observables
  - Number density, Σp_T, σp_T

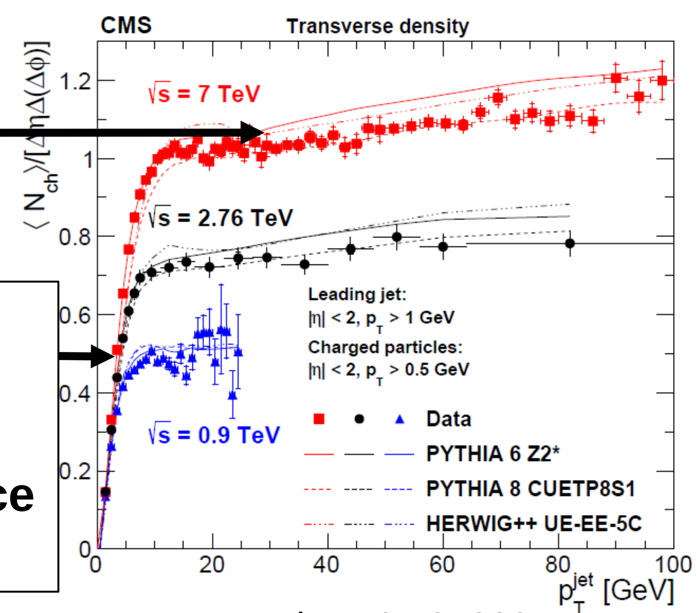




EPJC (2014) 74,3195

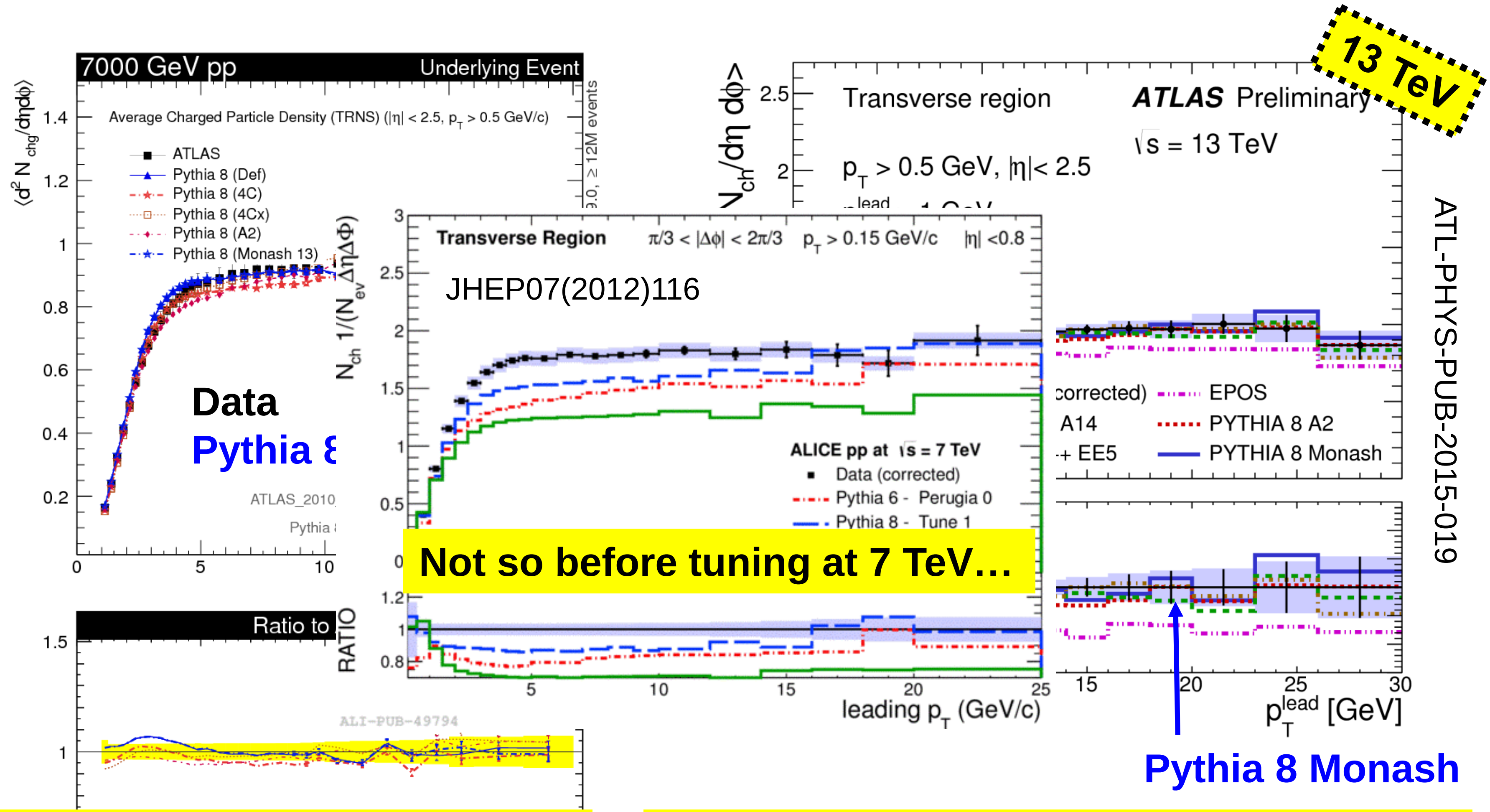
<u>Mild pos. slope:</u>
ISR & FSR

<u>Significant rise:</u>
Impact parameter dependence
→ MPI dependence
(+ selection bias)



arXiv:1507.07229

Underlying Event vs. MC



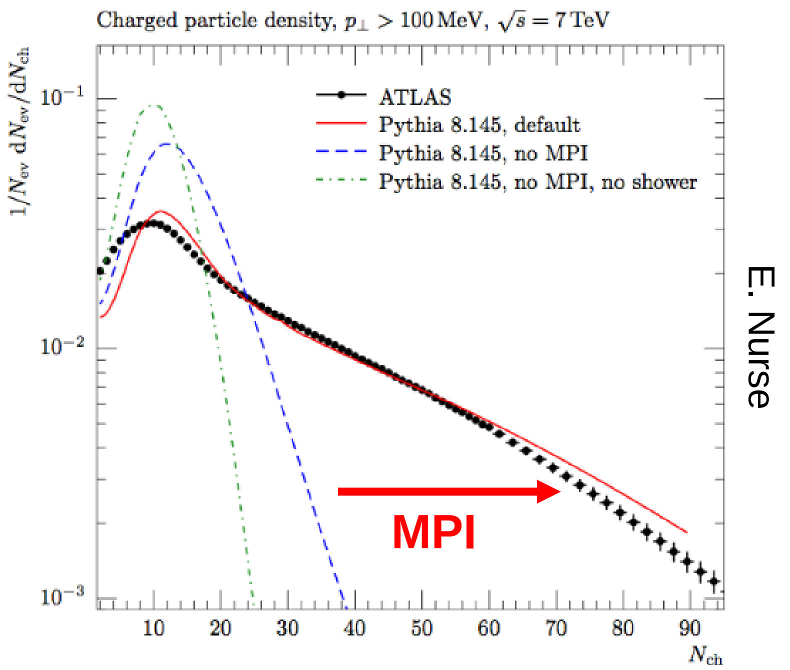
Not so before tuning at 7 TeV…

Very well described at 7 TeV
… after tuning

Good description (by Pythia8 Monash) at 13 TeV
… before tuning

Multiple Parton Interactions

- Minimum-bias and underlying event distribution sensitive to MPI contribution



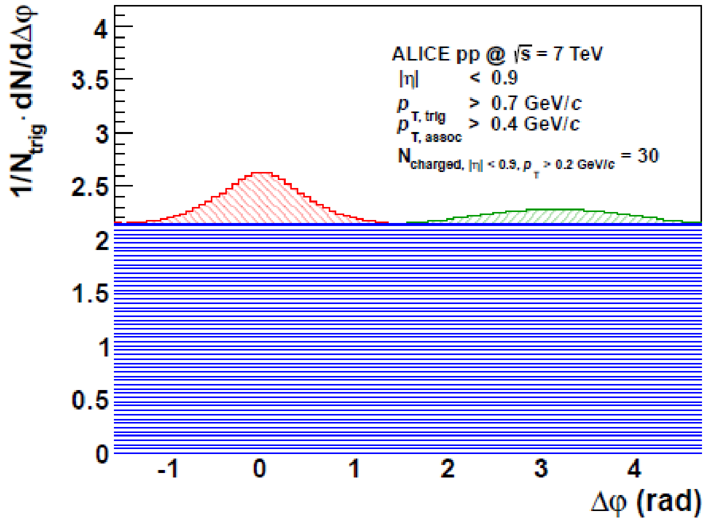
- Is there a more direct way to access MPI?

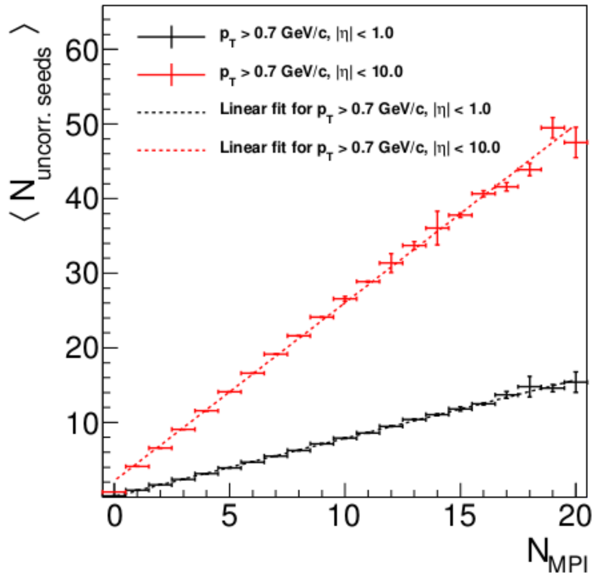
Minijets

- Study MPI by minijets (jets at low p_T)
  - Statistically by two-particle correlations
- Measure near-side and away-side yields above flat baseline
- Calculate uncorrelated seeds

$$\langle N_{uncorrelated\,seeds} \rangle = \frac{\langle N_{trig} \rangle}{\langle 1 + N_{assoc,NS} + N_{assoc,AS} \rangle}$$

- In MCs, proportional to number of MPIs → proxy for number of MPIs

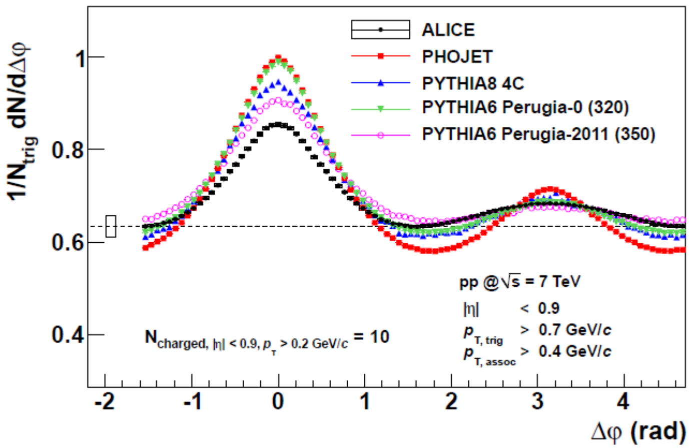




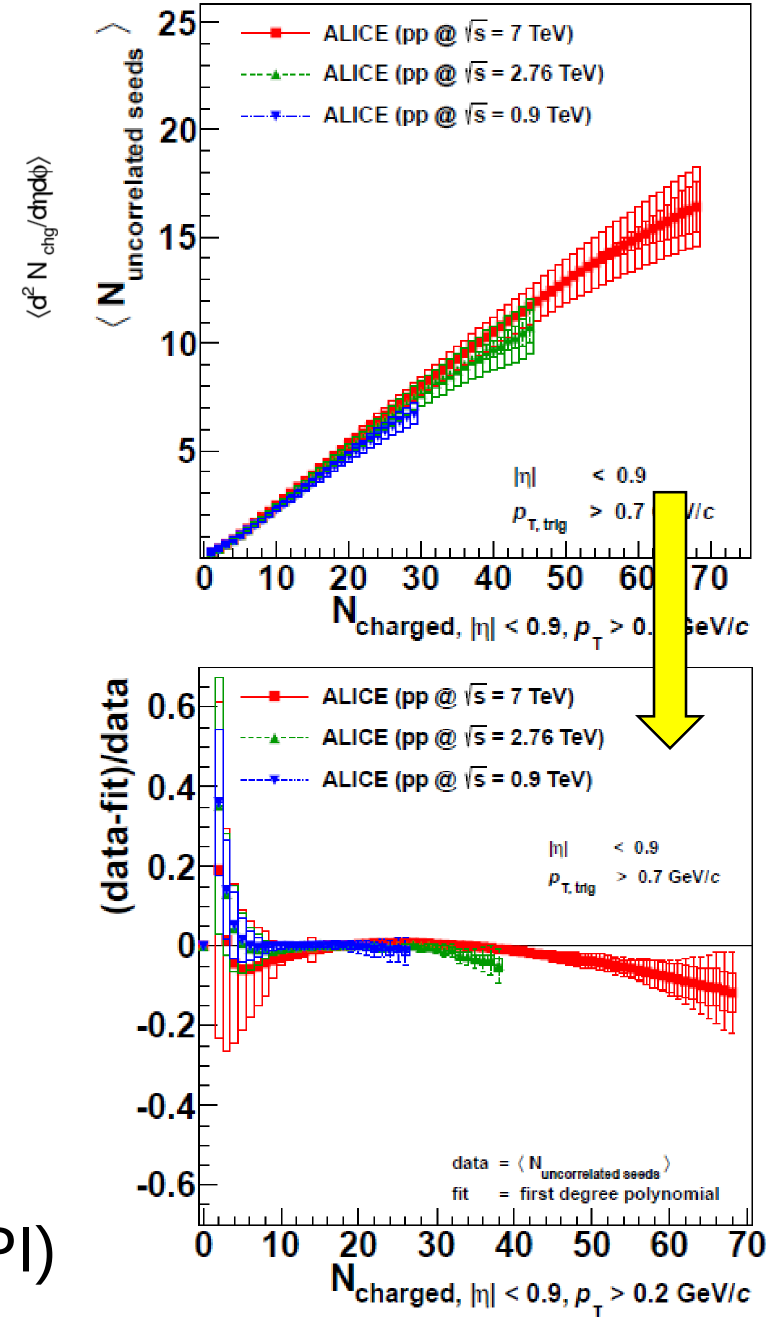
JHEP 09 (2013) 049

Minijets (2)

- Azimuthal distributions provide significant model constraints



- Uncorrelated seeds (~ MPI) increase linearly with N_{ch}
- At large N_{ch}, limit of MPI? (i.e., larger multiplicity by fluctuation, not by additional MPI)

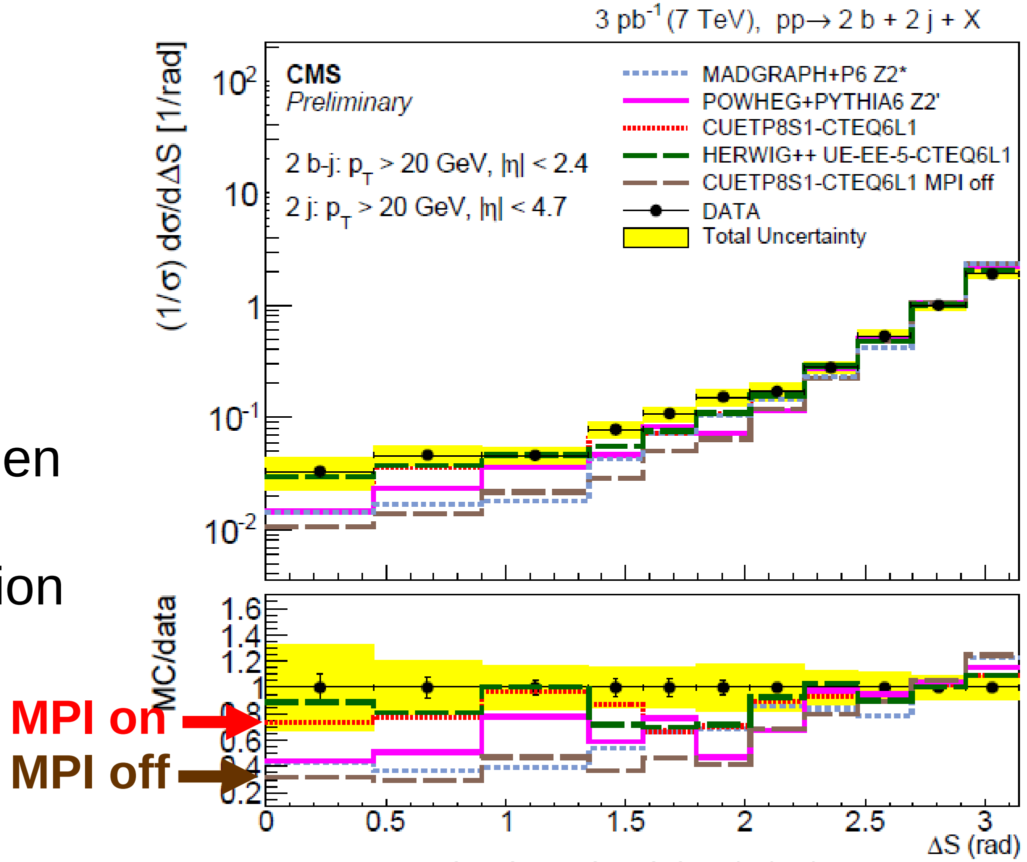


www.mcplots.ch

JHEP 09 (2013) 049

MPI by Double Parton Scattering

- Different way to address MPI is by (harder) observables addressing double parton scattering
- 2 b jets + 2 jets
  - Azimuthal angle ΔS between b dijet and other dijet sensitive to DPS contribution
- Exclusive signals
  - Double charm production
    (JHEP 06 (2012) 141)
  - Pair J/ψ production
    (PLB 707 (2012), 52)

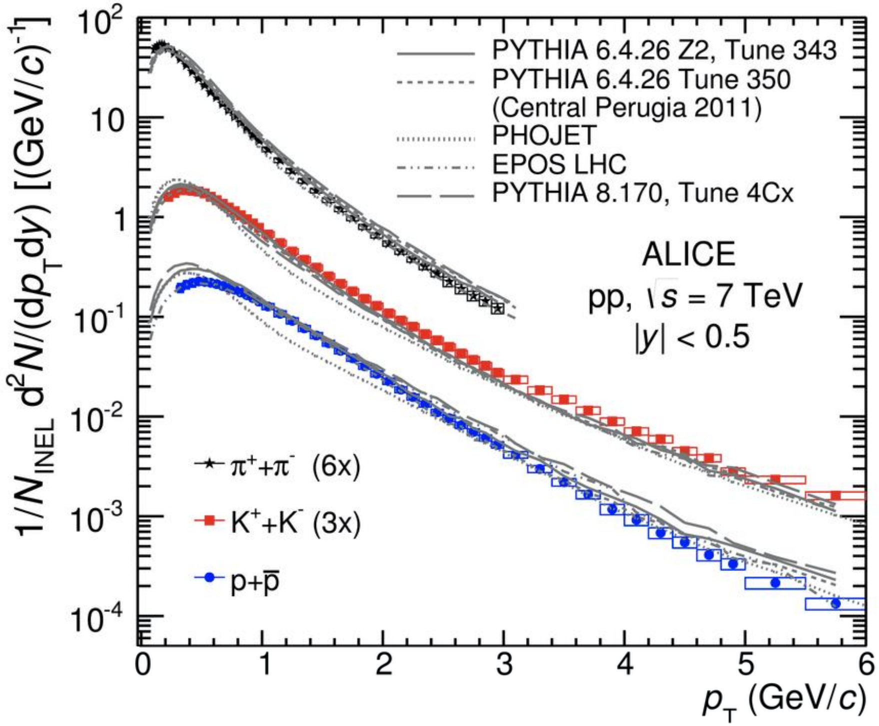


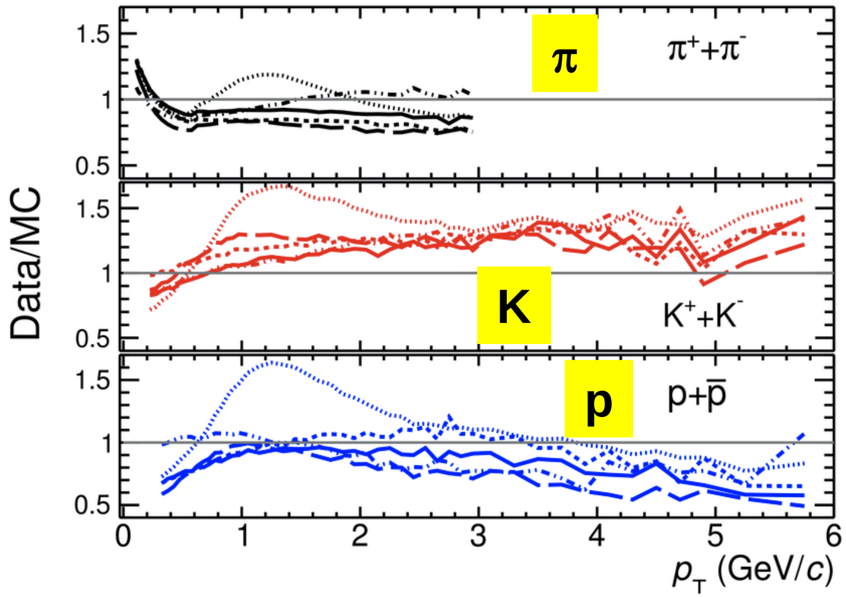
CMS PAS FSQ-13-010

Soft and hard observables to be considered for MPI modeling and tuning

Particle Abundances

- Spectra of π,K,K*,p,ϕ,Λ,Λ^*,Λ_b,Ξ,Σ,Ω,B measured at LHC
- Sensitive to fragmentation, strangeness, baryon number
  - Difficult to tune
  - At present no model which describes all species

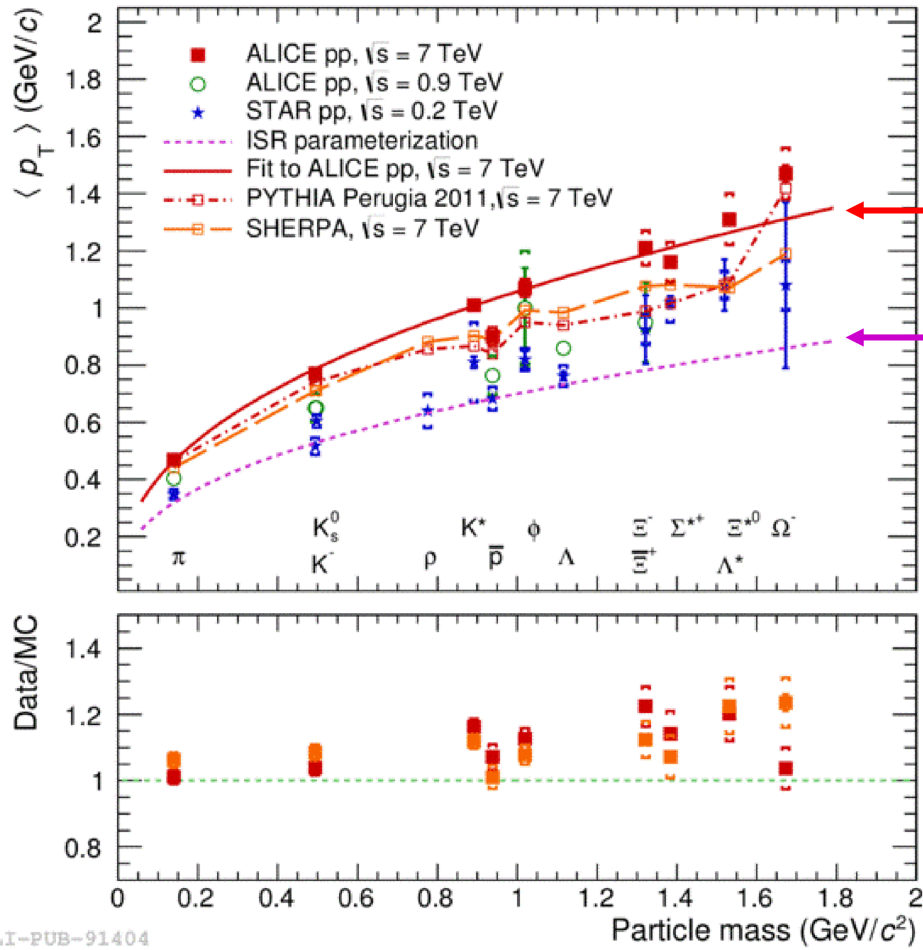




NB. Monash not better…

EPJC75 (2015) 5, 226

Identified $\langle p_T \rangle$

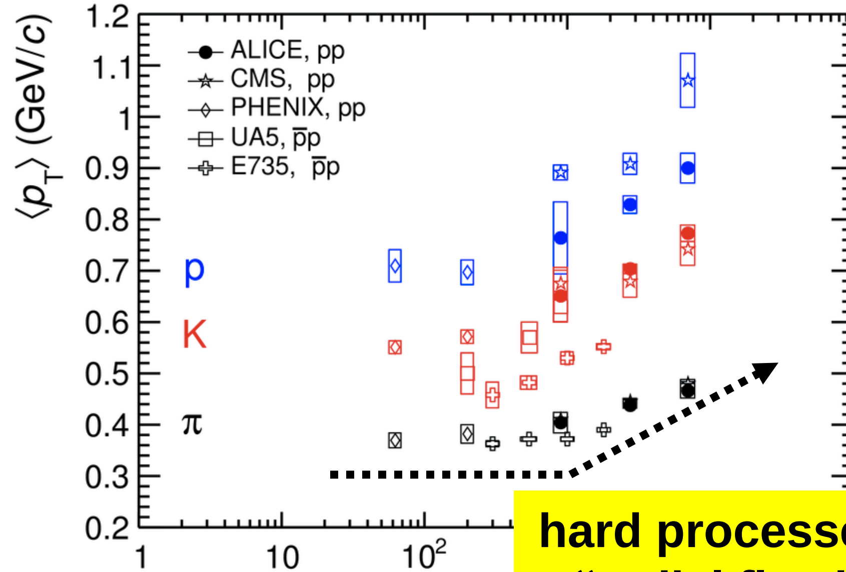


EPJC75 (2015) 1, 1

Similar fit at LHC

$$\langle p_{\mathrm{T}} \rangle = \alpha \left(\frac{M}{1\ \mathrm{GeV}/c^2} \right)^{\beta}$$

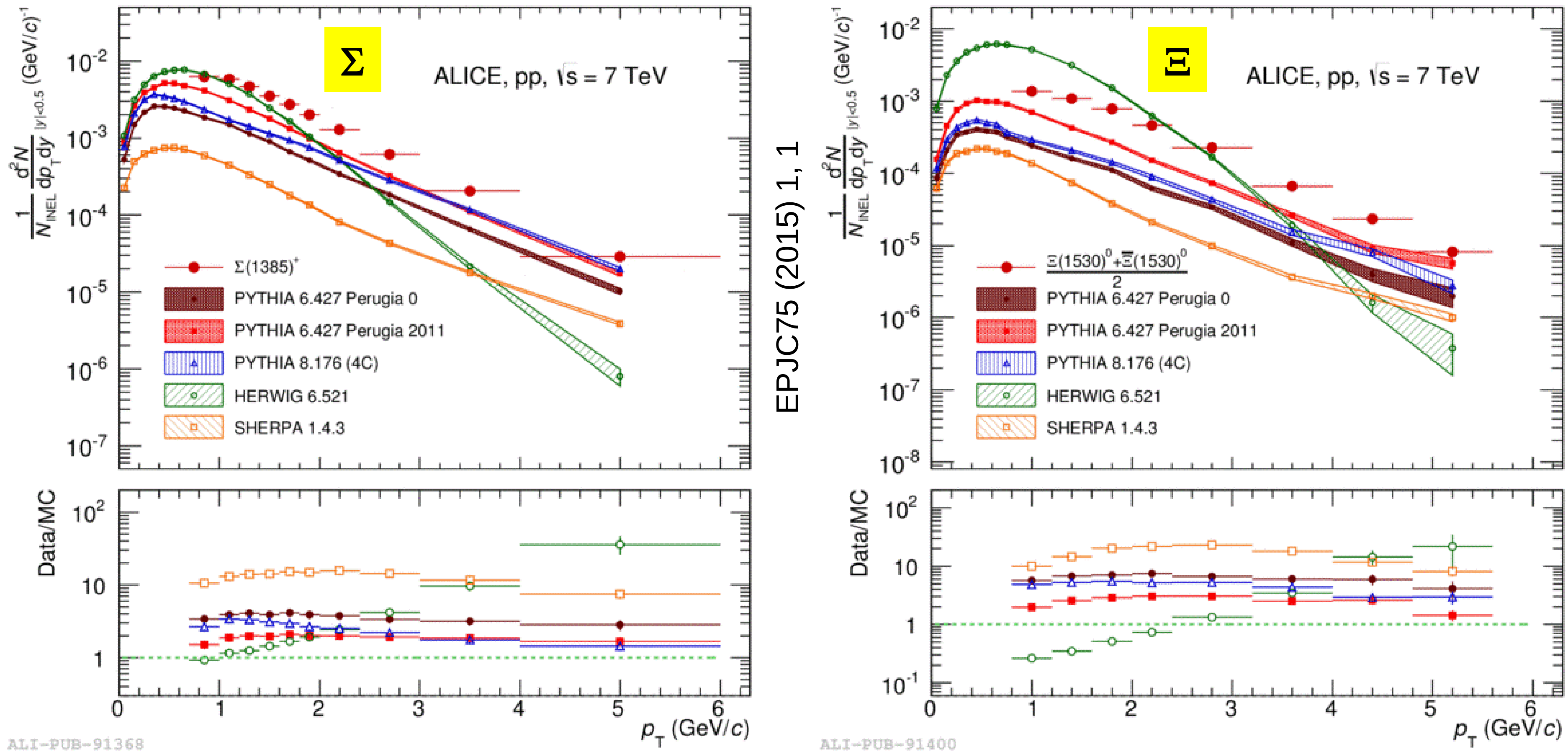
"ISR parameterization"
(fit at 25 GeV, still valid at 200 GeV)



EPJC75 (2015) 5, 226

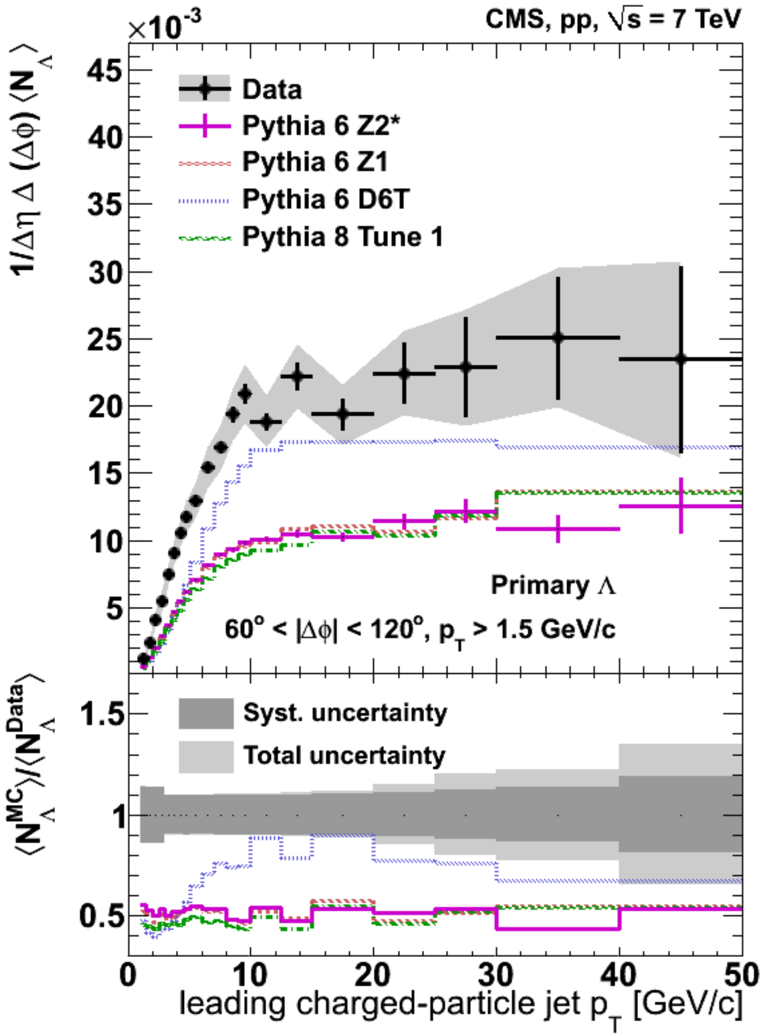
hard processes?
"radial flow"?

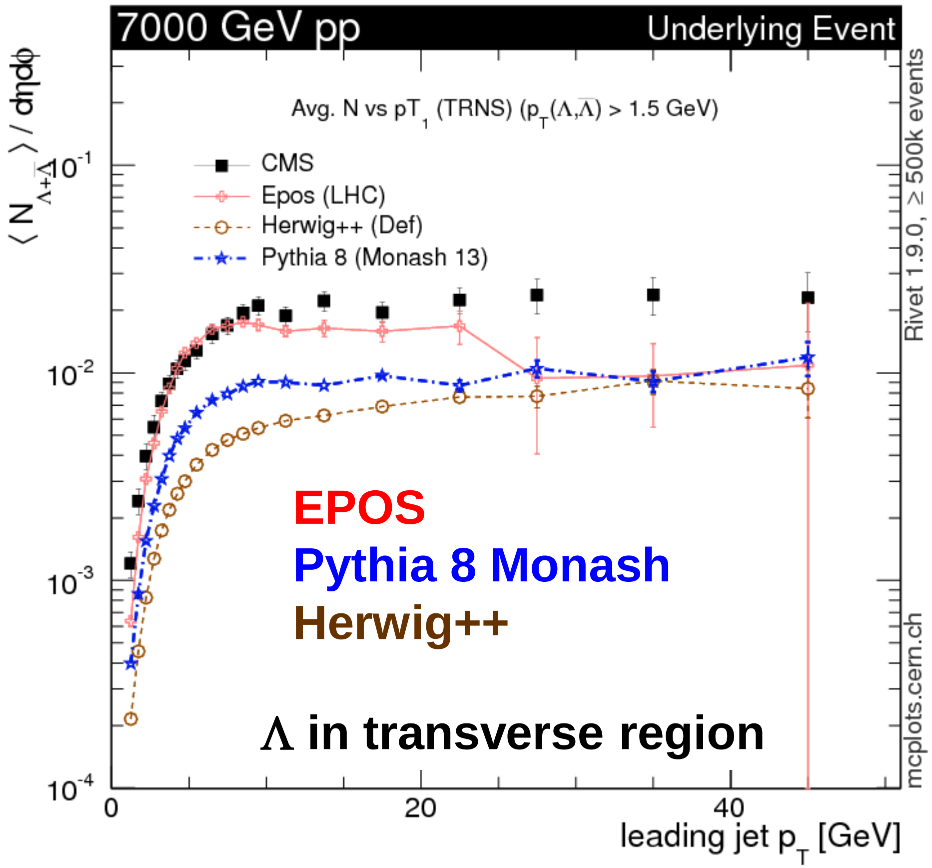
Strangeness



Significantly more strangeness in data than in MCs
→ triggered reworking the color reconnection mechanism in Pythia

Underlying Event with PID





Λ production significantly underestimated … but EPOS again best

PRD88 (2013) 052001

Color Reconnection (CR)

- Pythia process changing color configuration before hadronisation
  - Reconfiguration based on $\lambda = \ln(s/m^2_0)$ measure
  - Minimize total string length
- Enables description of rise of $<p_T>$ with N_{ch}
- Recently improved CR model* (Pythia8)
  - Creates junctions (baryons)

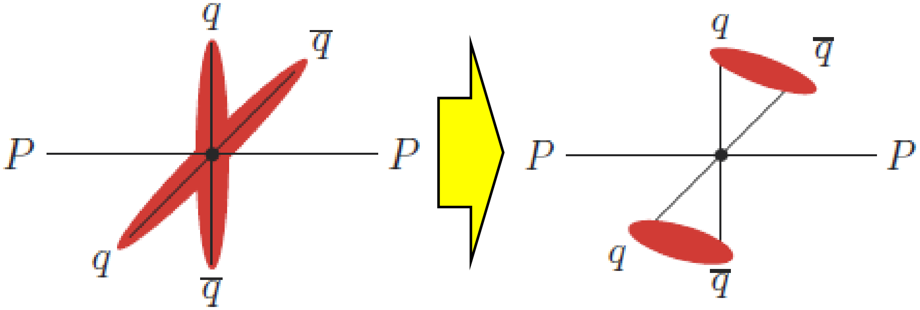
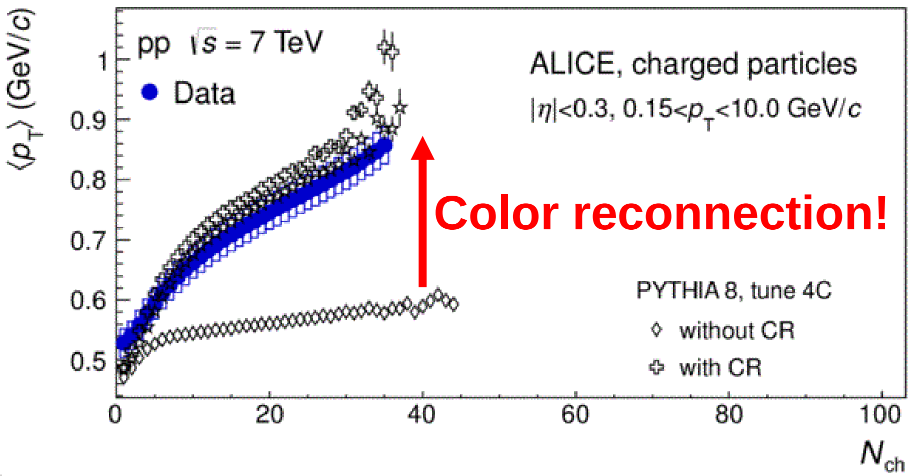


Illustration: J.R.Christiansen



PLB 727 (2013) 371

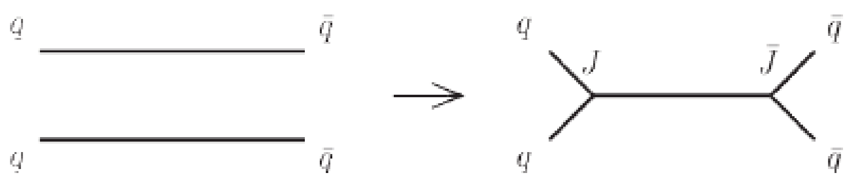
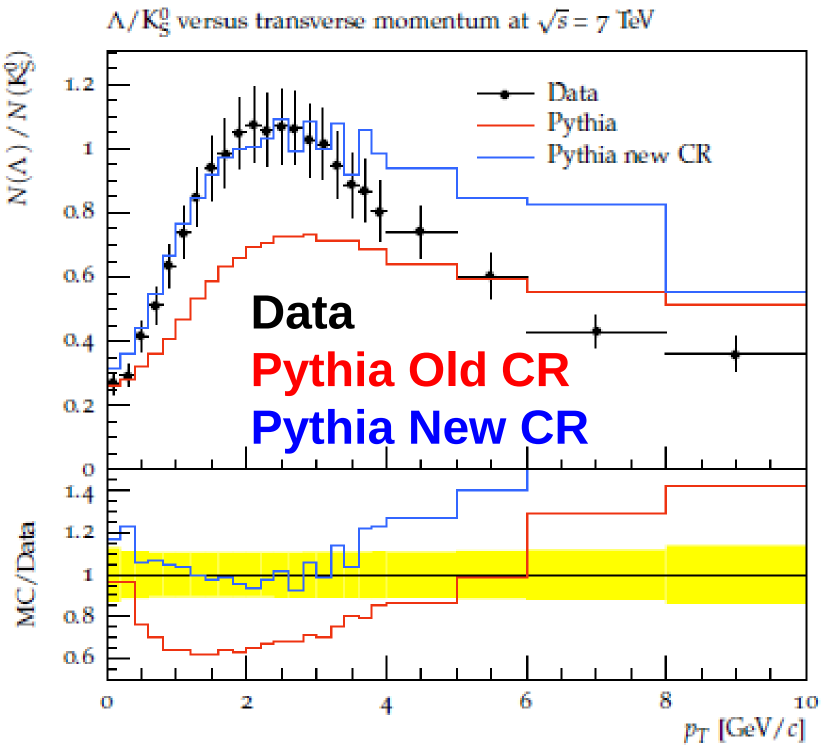


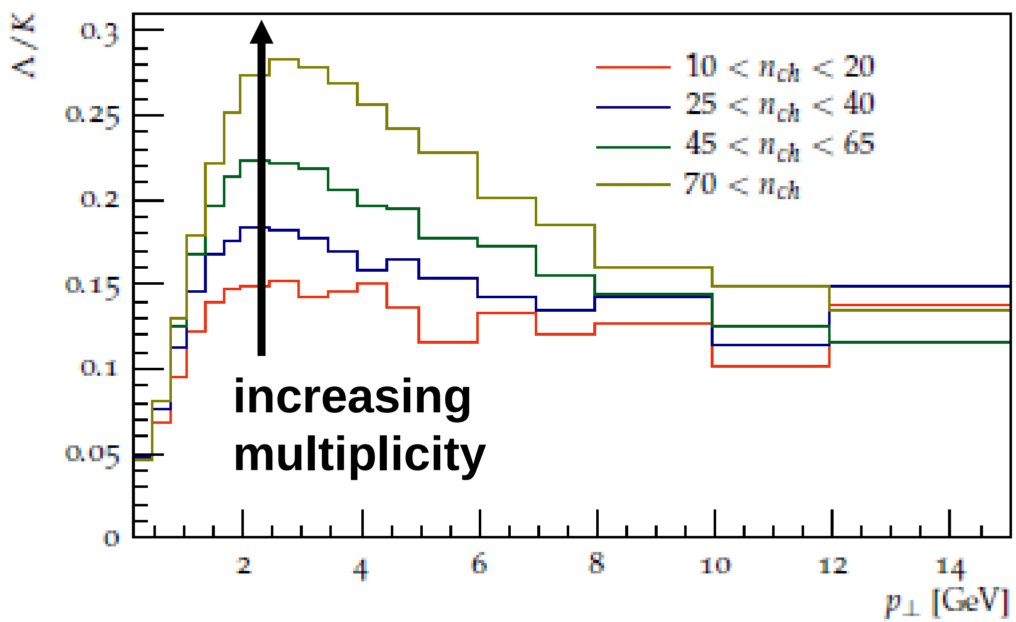
Illustration: J.R.Christiansen

* details in EPS-HEP 2015 talk by J.R.Christiansen (→ LINK)

CR and Strangeness

- Junctions can create baryons, including strange baryons
  - Ratio of Λ over K much better described (Ξ/Λ still too low)
  - Multiplicity-dependent effects observed (as in data, attributed to collective effects in heavy-ion system)





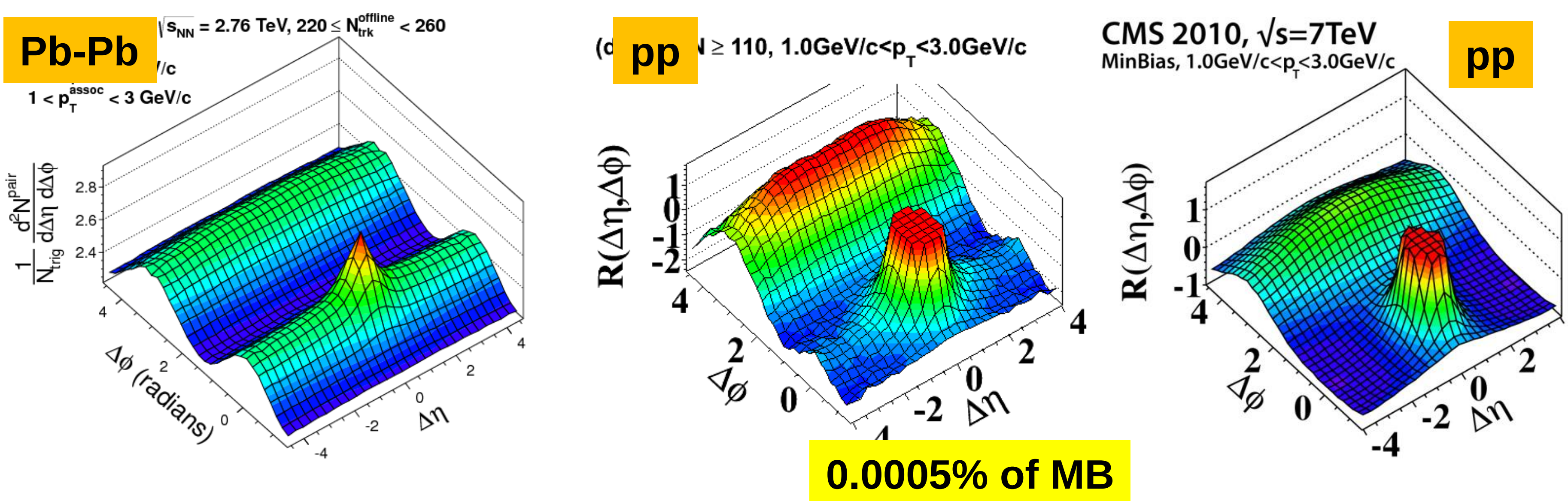
J.R.Christiansen, EPS-HEP 2015

The Ridge

- Tantalizing discovery of ridge structures in pp and p-Pb
  - Provoked lively discussion on collectivity in small systems

What is a ridge?

- An η-elongated structure in two-particle correlations

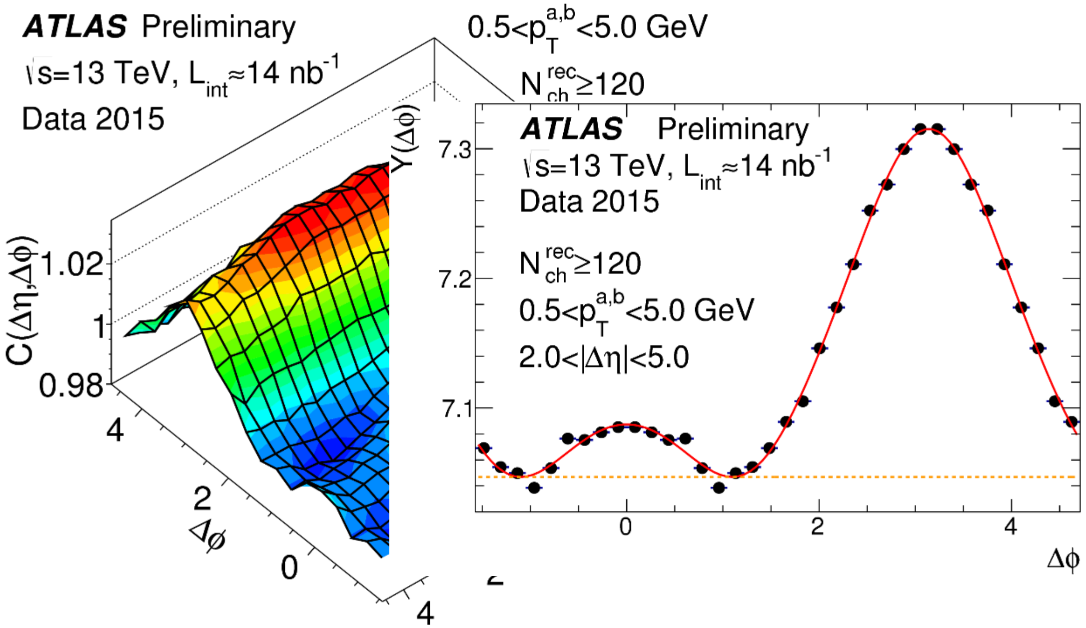


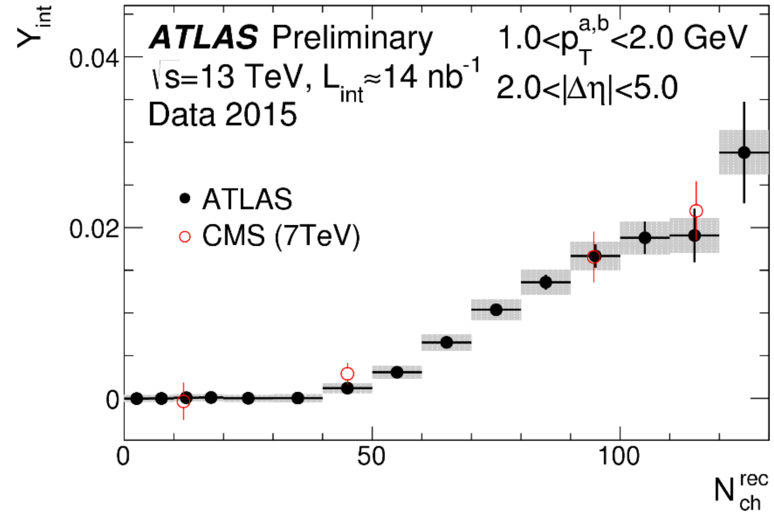
CMS, JHEP09(2010)091

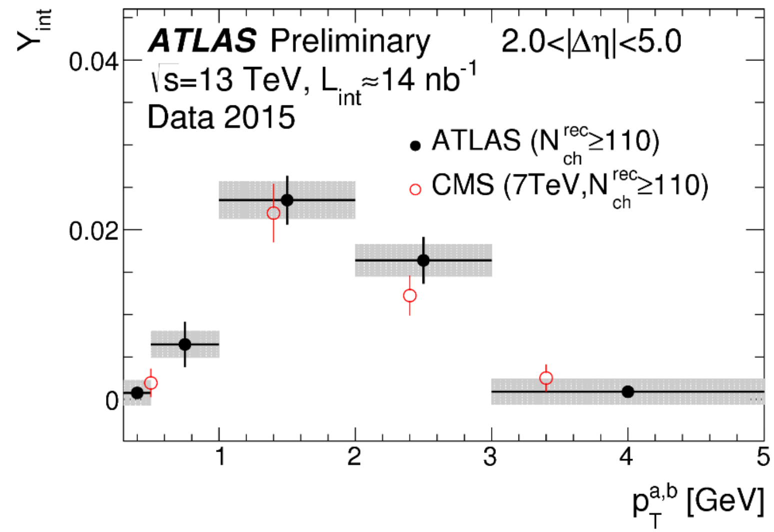
The Ridge in pp

13 TeV

- Near-side ridge discovered in high-multiplicity pp 7 TeV
- At 13 TeV even more abundant
  - due to increase of $\langle N_{ch} \rangle$, $\langle p_T \rangle$, no cms evolution as a function of N_{ch},



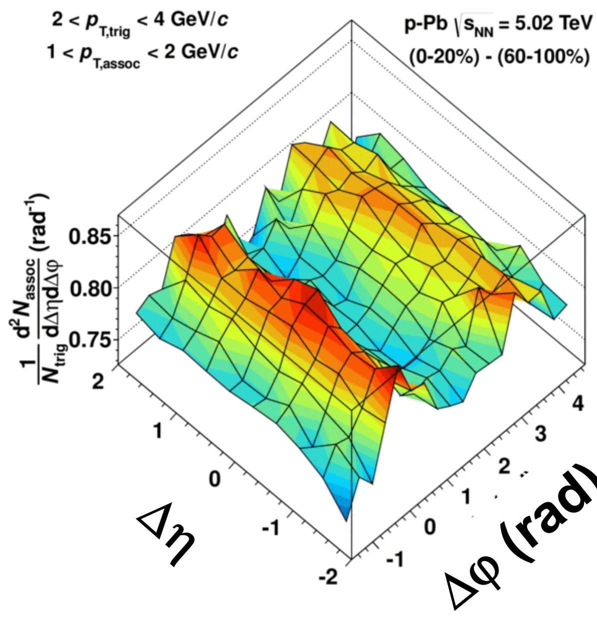




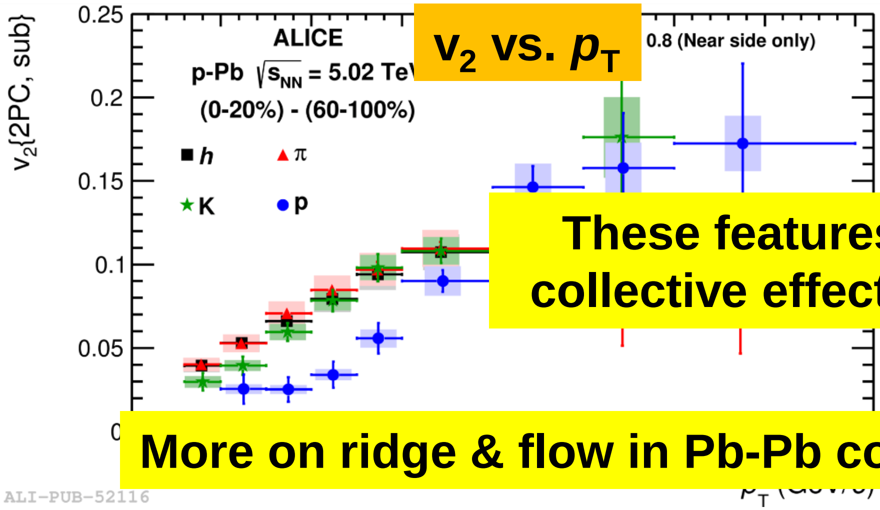
ATLAS-CONF-2015-027

The Ridge in p-Pb

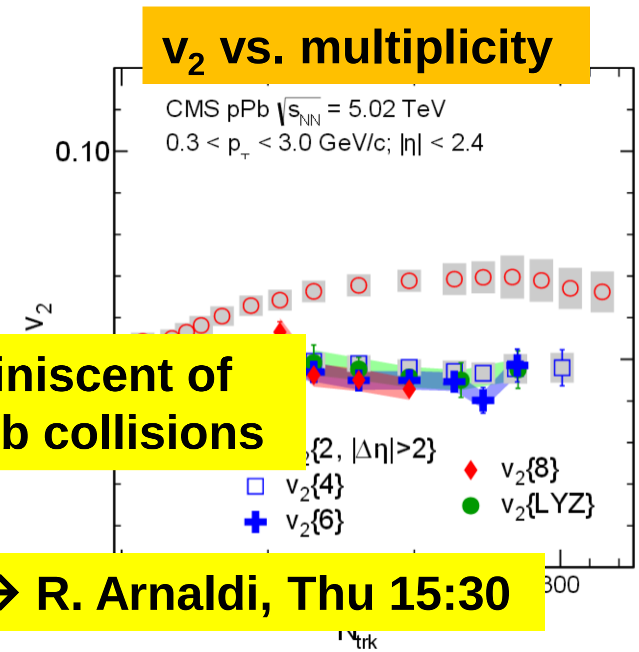
- Near-side and away-side ridge (with low multiplicity subtraction)
  - Characterize as Fourier coefficients v_n
- Higher-order correlation effect
  - $v_2\{4\} = v_2\{6\} = v_2\{8\}$
- Particle-species dependence
  - Mass ordering of $v_2\{p\}$ and $v_2\{\pi\}$



PLB719 (2013) 29



PLB726 (2013) 164



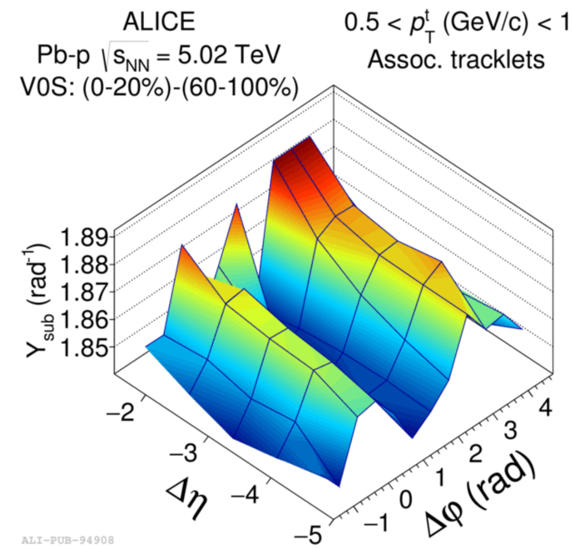
PRL115, 012301 (2015)

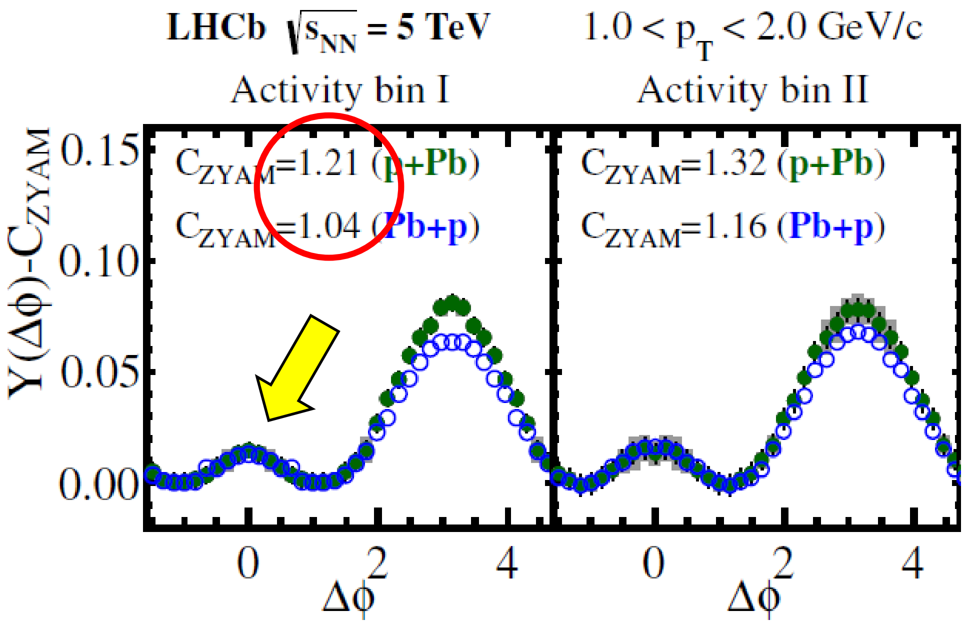
These features are reminiscent of collective effects in Pb-Pb collisions

More on ridge & flow in Pb-Pb collisions → R. Arnaldi, Thu 15:30

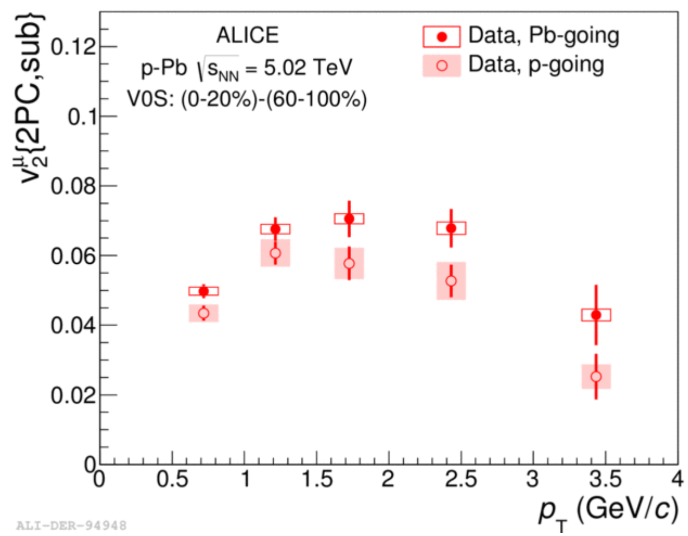
Ridge at Forward Rapidities

- Ridges have been confirmed at forward rapidities (up to $\eta \sim \pm 4$) and up to ten units of $\Delta\eta$
- p-going < Pb-going (10-16% difference)





LHCB-CONF-2015-004

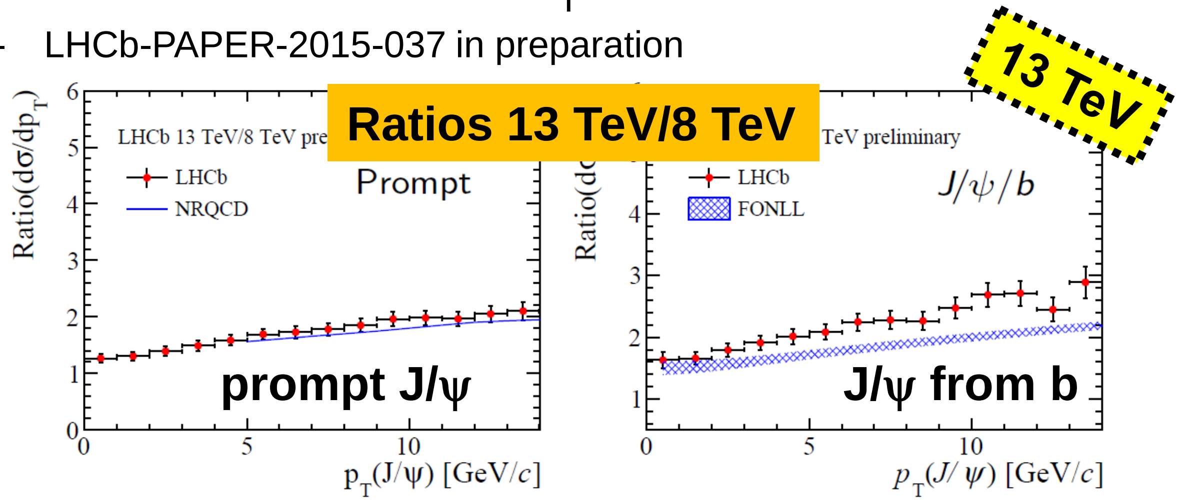


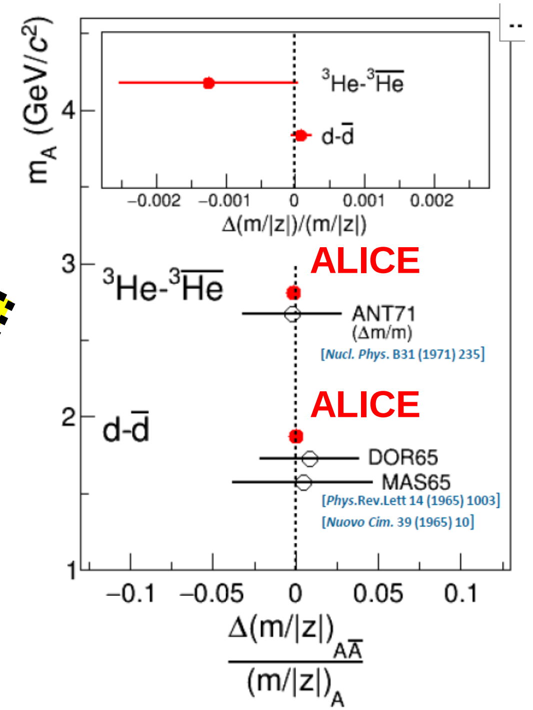
arXiv:1506.08032

Various other topics…

… I had to skip

- Bose-Einstein correlations / femtoscopy
  ALICE: PLB739 (2014) 139 (pp, p-Pb, Pb-Pb), arXiv:1506.07884 (Pb-Pb), ATLAS: arXiv:1502.07947 (pp), CMS: PAS FSQ-13-002 (pp), PAS HIN-14-013 (pp, p-Pb, Pb-Pb)
- Mass difference between light nuclei and anti-nuclei
  - Improves by factor 2 constraints on CPT invariance (ALICE-PUBLIC-2015-002)
- Non-prompt J/ψ fraction at 13 TeV
  - ATLAS-CONF-2015-030
- Double-differential J/ψ cross-section
  - LHCb-PAPER-2015-037 in preparation





Summary

- Run I @ LHC: tremendous legacy of soft QCD results

Charged-particle distributions, underlying event, … well described by now
Identified particles, in particular strangeness … challenge models
Multiple-parton interactions and color reconnection … important processes

- First results from run II available
  - MC tunes well prepared, EPOS LHC impressively good
- Collective-like effects observed in high-multiplicity pp and p-Pb, reminiscent of soft heavy-ion physics
  - Plus success of EPOS LHC which includes hydrodynamic phase

Can we proof the similarity of soft physics in pp, p-Pb, Pb-Pb?
Can we find a uniform description of soft part of pp, p-Pb and Pb-Pb collisions?
Role of color reconnection / escaping / other processes “creating” collectivity?

There are very interesting times ahead for us with Run II

Backup

EPOS3

- Gribov-Regge multiple scattering
  - Pomeron = parton ladder
  - Saturation scale (a la CGC, $Q_s \sim N_{part}\, s^{\lambda}$)
- Core-corona separation
  - (High p_T) Strings in corona escape
  - Remainder forms core → initial conditions for…
- …viscous hydrodynamic expansion ($\eta/s = 0.08$)
- Statistical hadronization
- UrQMD hadronic cascade

Identical treatment for pp, pA, AA !

Hydrodynamic expansion in all systems !

arXiv:1312.1233