

QCD measurements at the LHC

Arthur M. Moraes

Centro Brasileiro de Pesquisas Físicas - CBPF

(on behalf of ATLAS, ALICE, CMS and LHCb)

**XIV International Workshop
on Hadron Physics**

18-23 March 2018
Florianópolis, Santa Catarina, Brazil

Outline:

- ▶ *Introduction: LHC and experiments*
- ▶ *QCD at the LHC*
- ▶ *Soft QCD*
- ▶ *Hard QCD*
- ▶ *Summary*

Please, also check out the talk
“QCD probes at LHC”, by
Gustavo Gil da Silveira
(presented on Monday)

Disclaimer: obviously there are many results we will not be able to show in this talk! This talk is an attempt to present **some** of the “latest” results on QCD measurements at the LHC. For a complete list of results, please check:

<http://aliceinfo.cern.ch/ArtSubmission/publications>



http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_all.html



<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults>



<http://cms-results.web.cern.ch/cms-results/public-results/publications/>



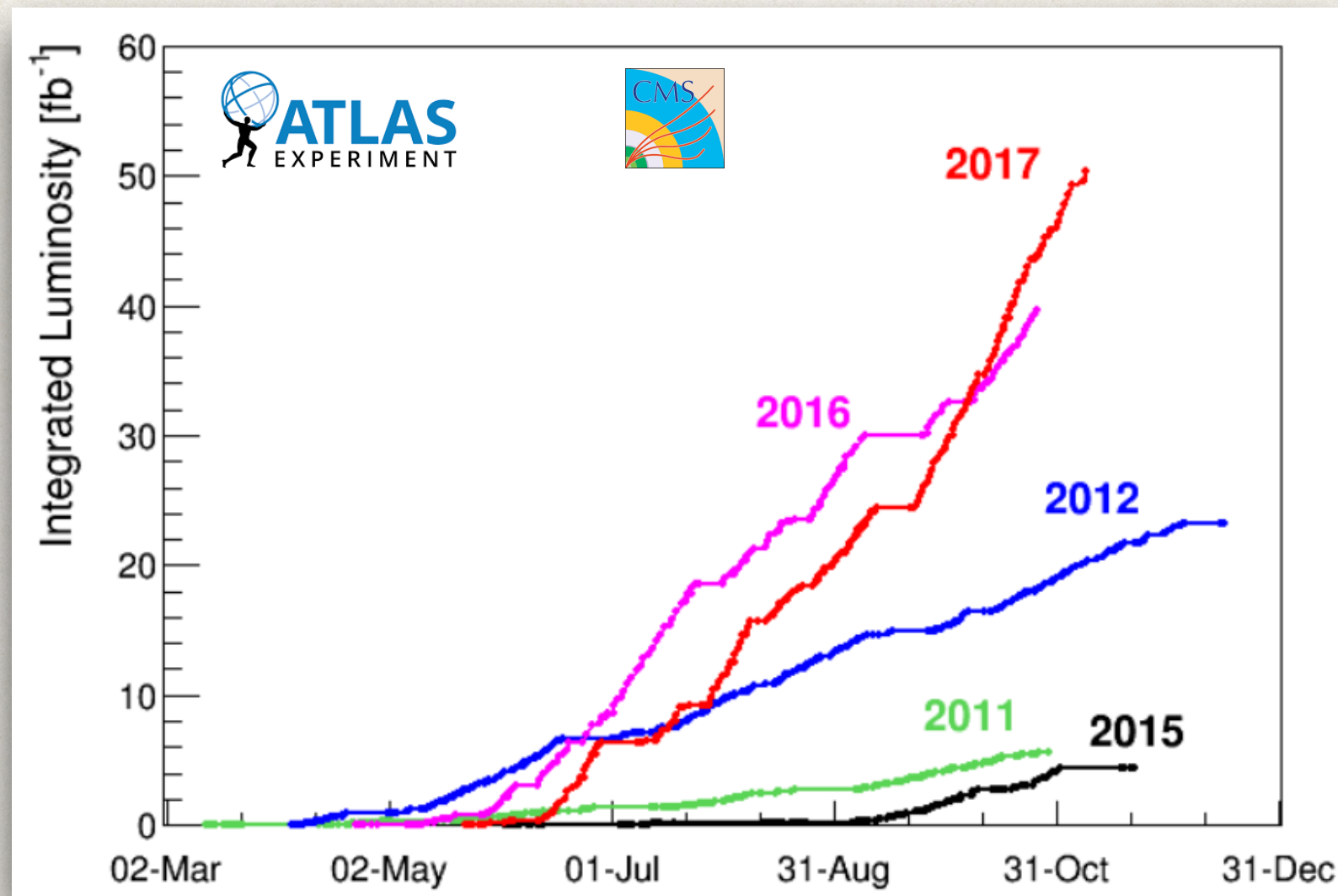
The Large Hadron Collider



QCD measurements at the LHC:

- test predictions of QCD phenomena at **high(est) energies** with **large statistical samples** of rare processes;
- detector allow measurements with unprecedented precision and fiducial coverage (wide x-coverage; unprecedented high- Q^2 interactions)

The Large Hadron Collider: pp collisions



The LHC has also delivered several runs on pA and AA collisions.

<https://lpc.web.cern.ch>

$\sqrt{s}=0.9$ TeV

$\sqrt{s}=7$ TeV
& 8 TeV

“Long
Shutdown 1”

$\sqrt{s}=13$ TeV

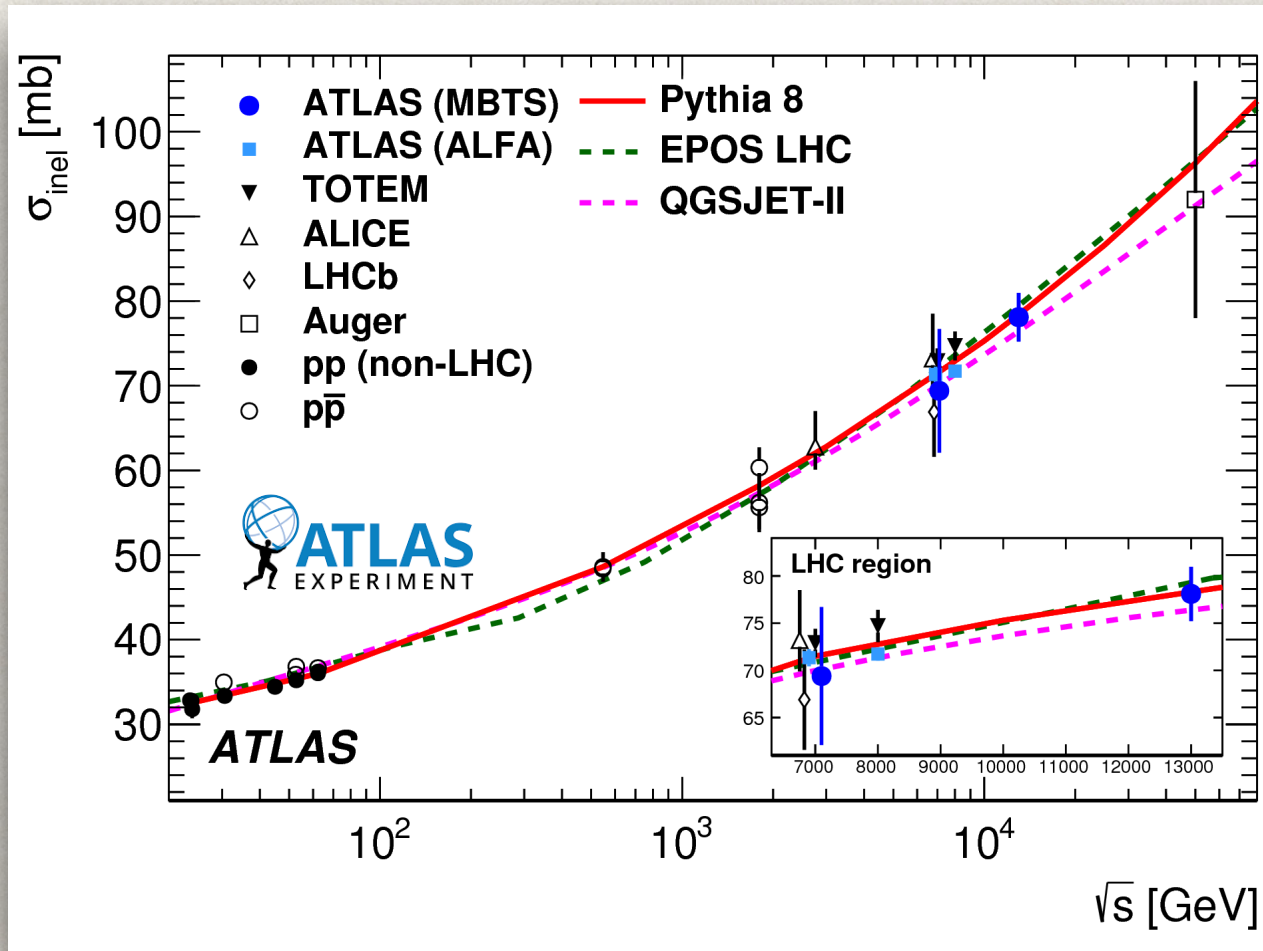
“Long
Shutdown 2”

2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

Run 1

Run 2

Inelastic pp cross-section



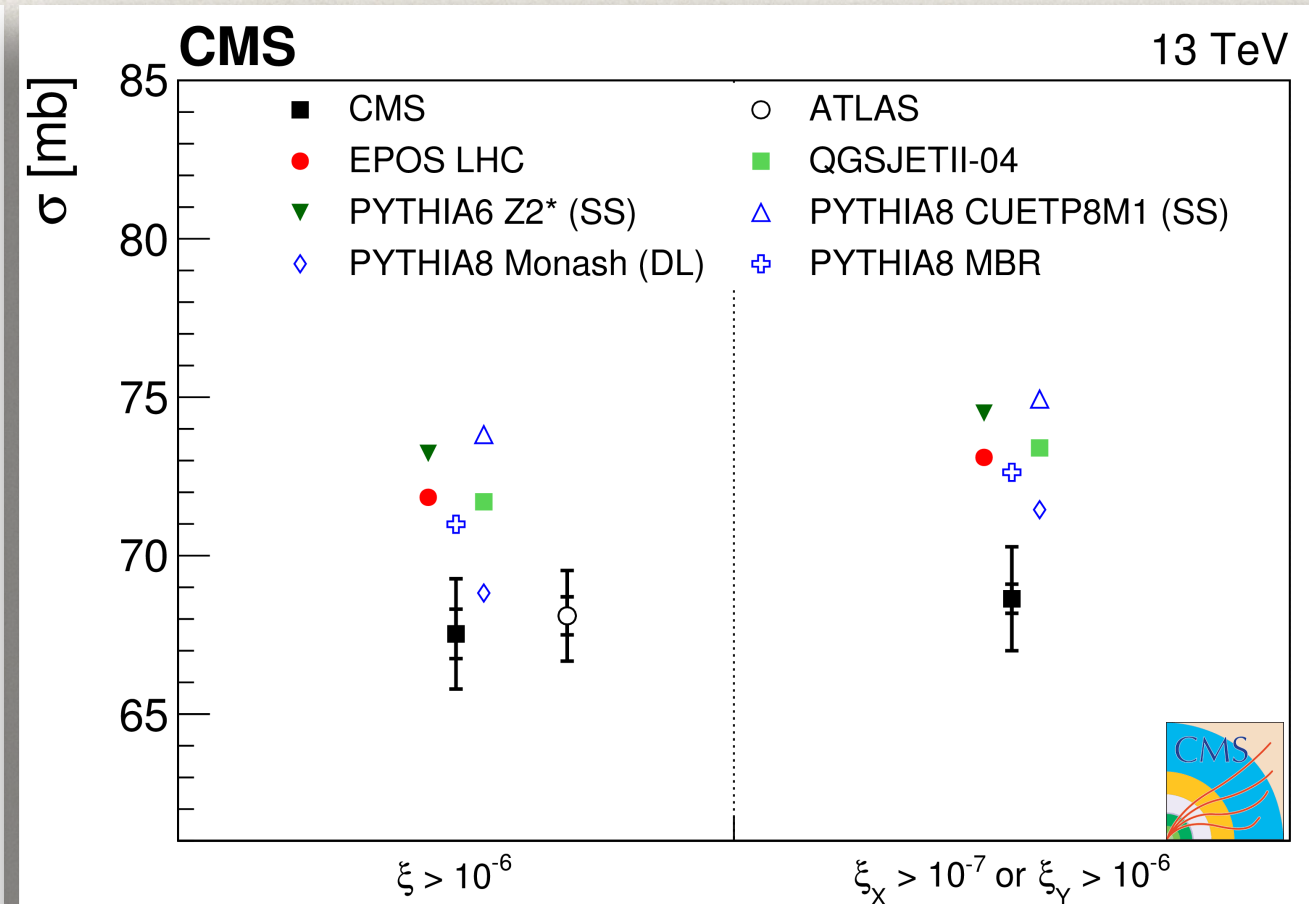
The inelastic proton-proton cross section versus \sqrt{s} .

Inelastic interactions are selected using rings of plastic scintillators (MBTS) in the forward region ($2.07 < |\eta| < 3.86$)

A cross section of 68.1 ± 1.4 mb is measured in the fiducial region $\xi = M^2_X/s > 10^{-6}$

When extrapolated to the full phase space, a cross section of 78.1 ± 2.9 mb is measured.

[Phys. Rev. Lett. 117 \(2016\) 182002](https://arxiv.org/abs/1802.02613v1)



Proton-proton inelastic cross section at $\sqrt{s}=13$ TeV in two phase space regions, where $\xi=M^2/s$, compared to different models and to the ATLAS result.

The analysis is based on events with energy deposits in the forward calorimeters, which cover η of $-6.6 < \eta < -3.0$ and $+3.0 < \eta < +5.2$ (HF and CASTOR).

$$\sigma(\xi > 10^{-6}) = 67.5 \pm 0.8 \text{ (syst)} \pm 1.6 \text{ (lumi)} \text{ mb}$$

$$\sigma(\xi_X > 10^{-7} \text{ or } \xi_Y > 10^{-6}) = 68.6 \pm 0.5 \text{ (syst)} \pm 1.6 \text{ (lumi)} \text{ mb}$$

[arXiv:1802.02613v1](https://arxiv.org/abs/1802.02613v1)

Submitted to J. High Energy Phys. (Feb 2018)

Florianópolis, 21st March 2018

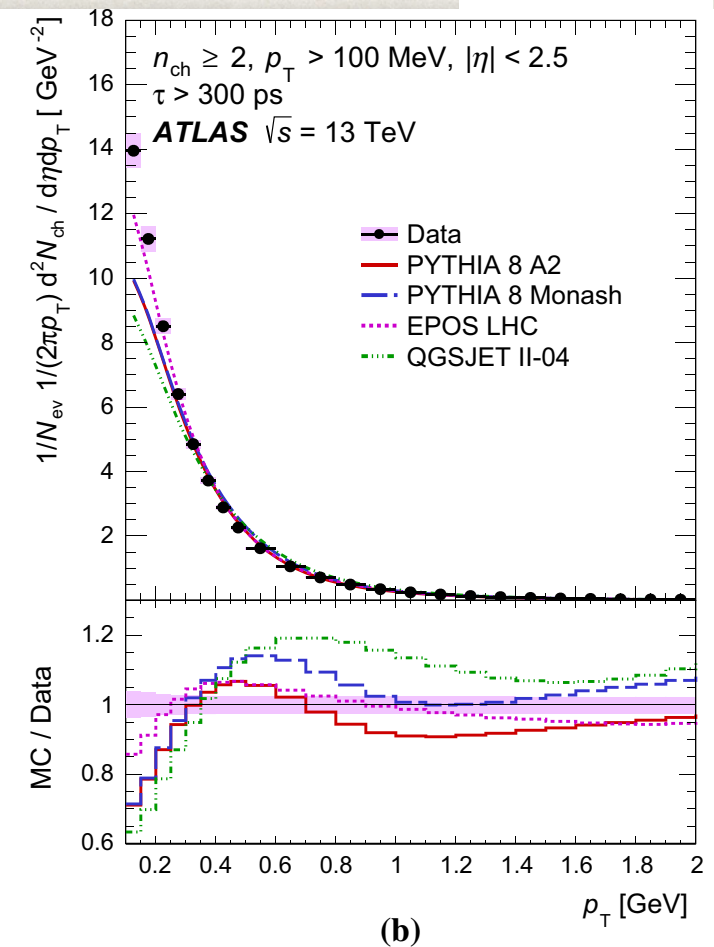
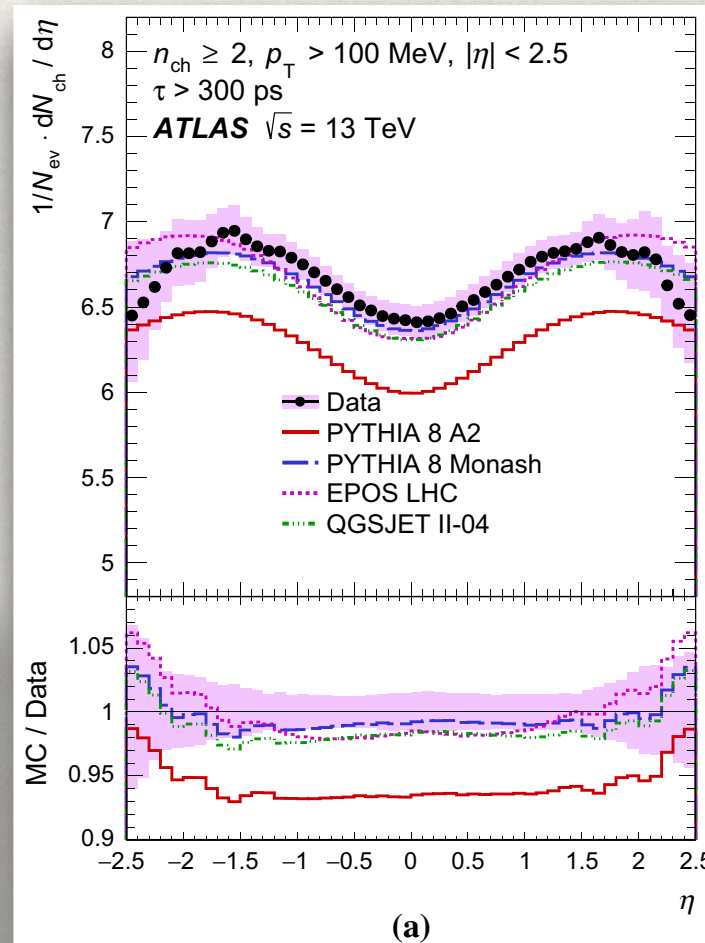
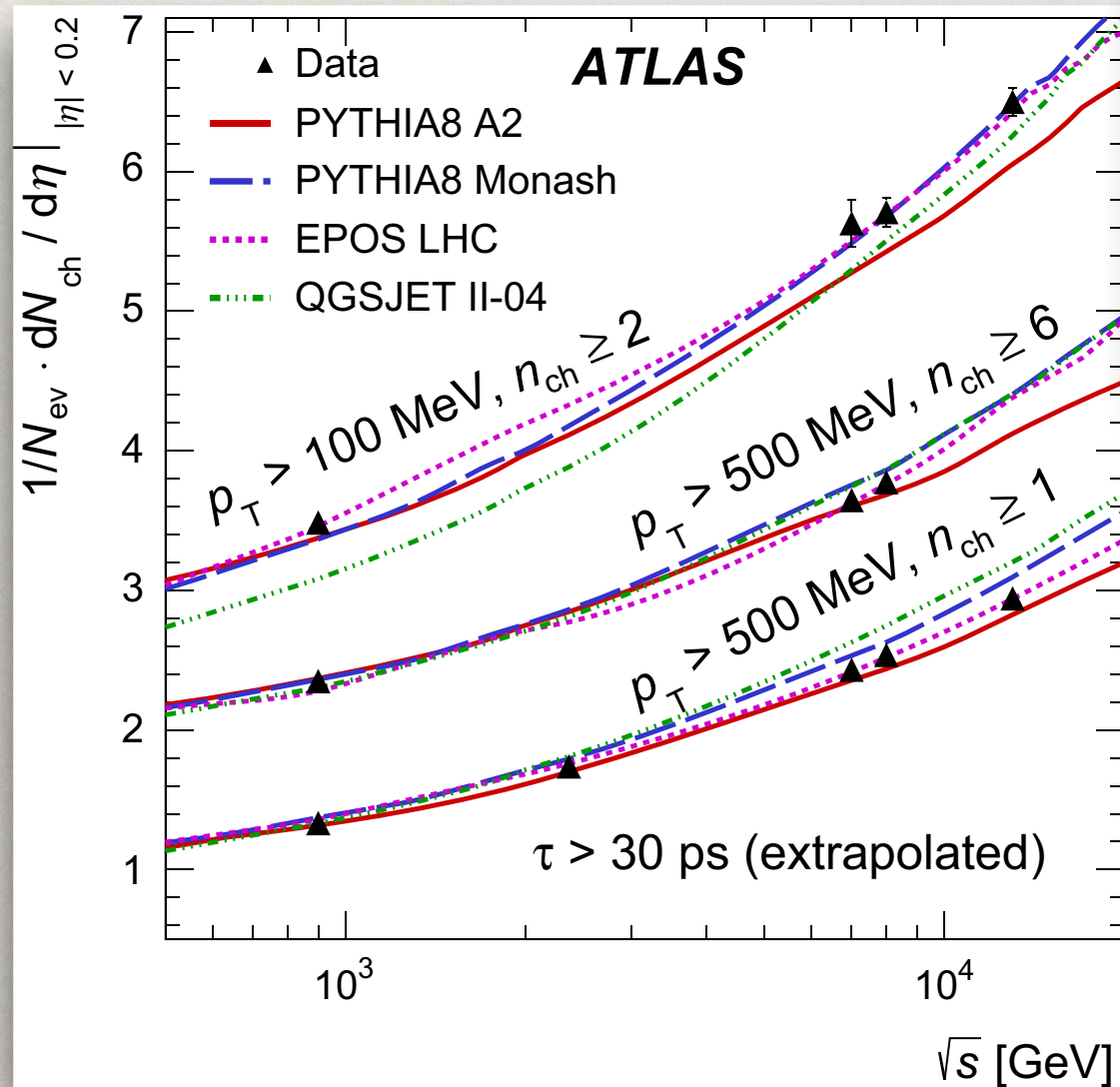
Charged Particle Density



$$n_{\text{ch}} > 2$$

$$|\eta| < 2.5$$

$$p_{\text{T}} > 100 \text{ MeV}$$



Particle multiplicity at different c.m. energies, with different phase space selections: **Important input to generator tuning!**

Amongst the models considered, EPOS has the best overall description of the data using tracks with $p_{\text{T}} > 500 \text{ MeV}$.

PYTHIA 8 A2 and PYTHIA 8 MONASH provide a reasonable overall description.

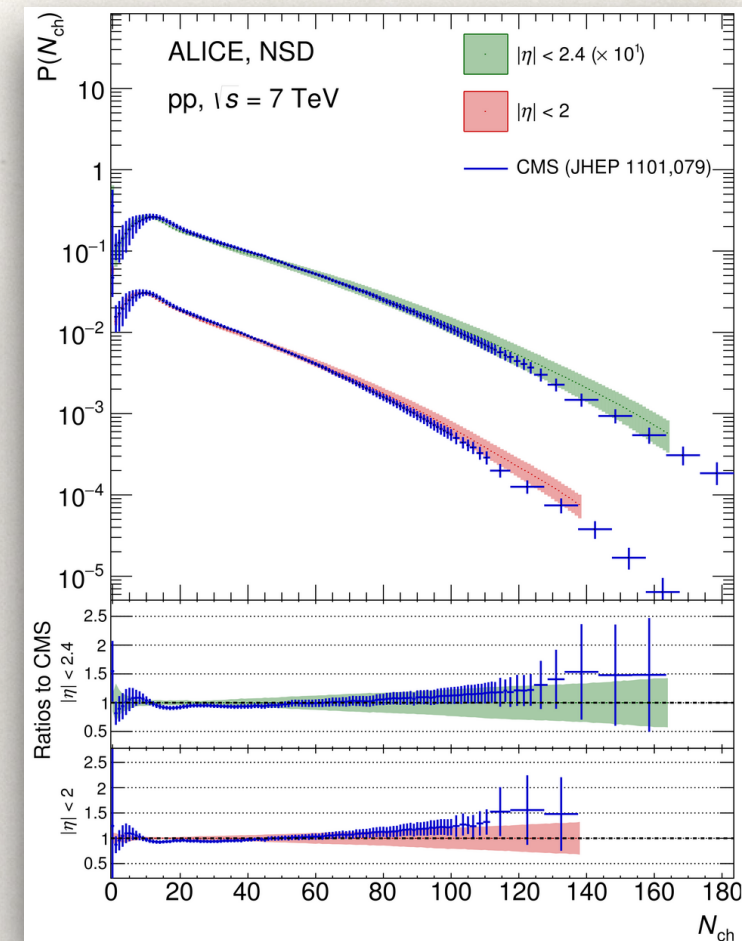
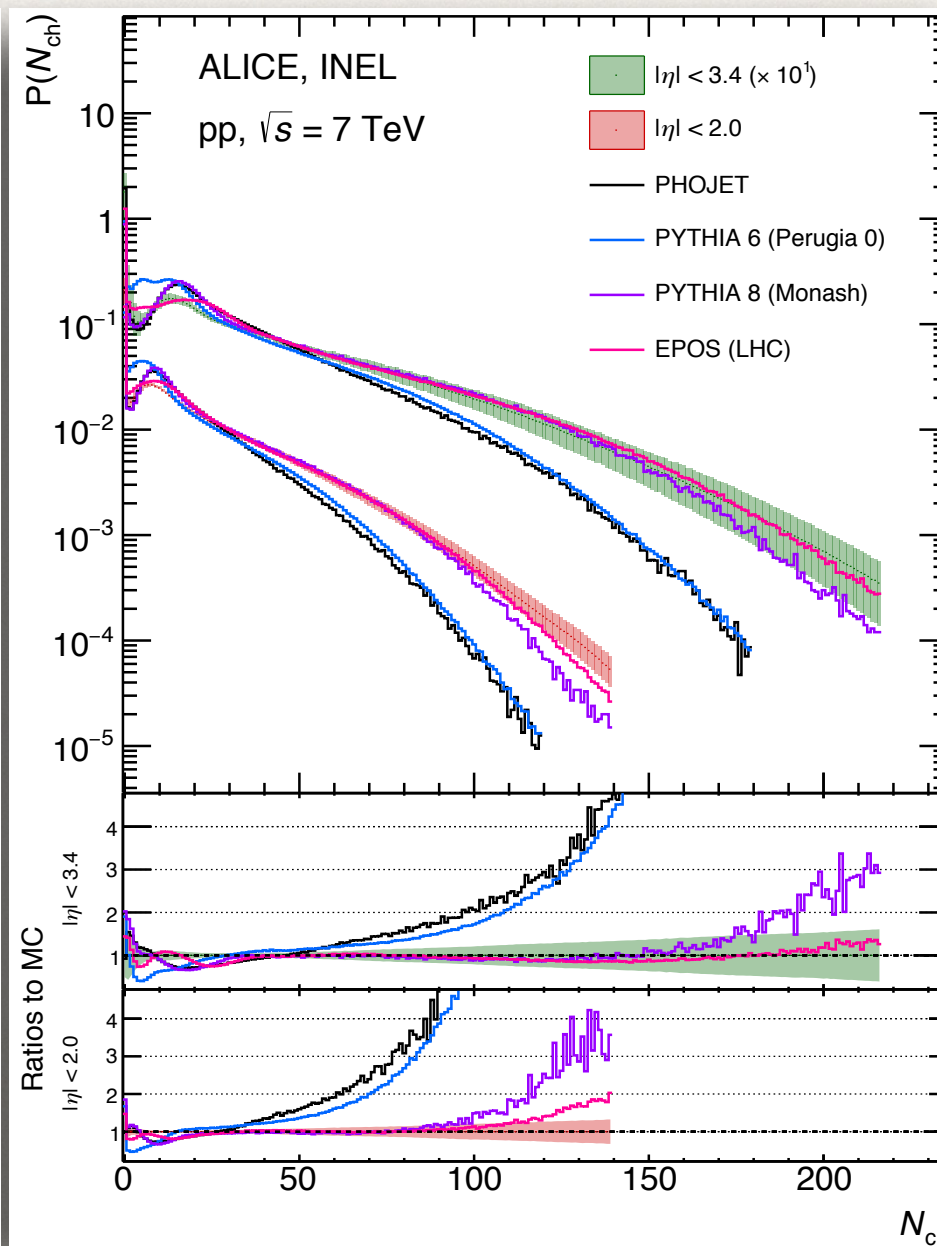
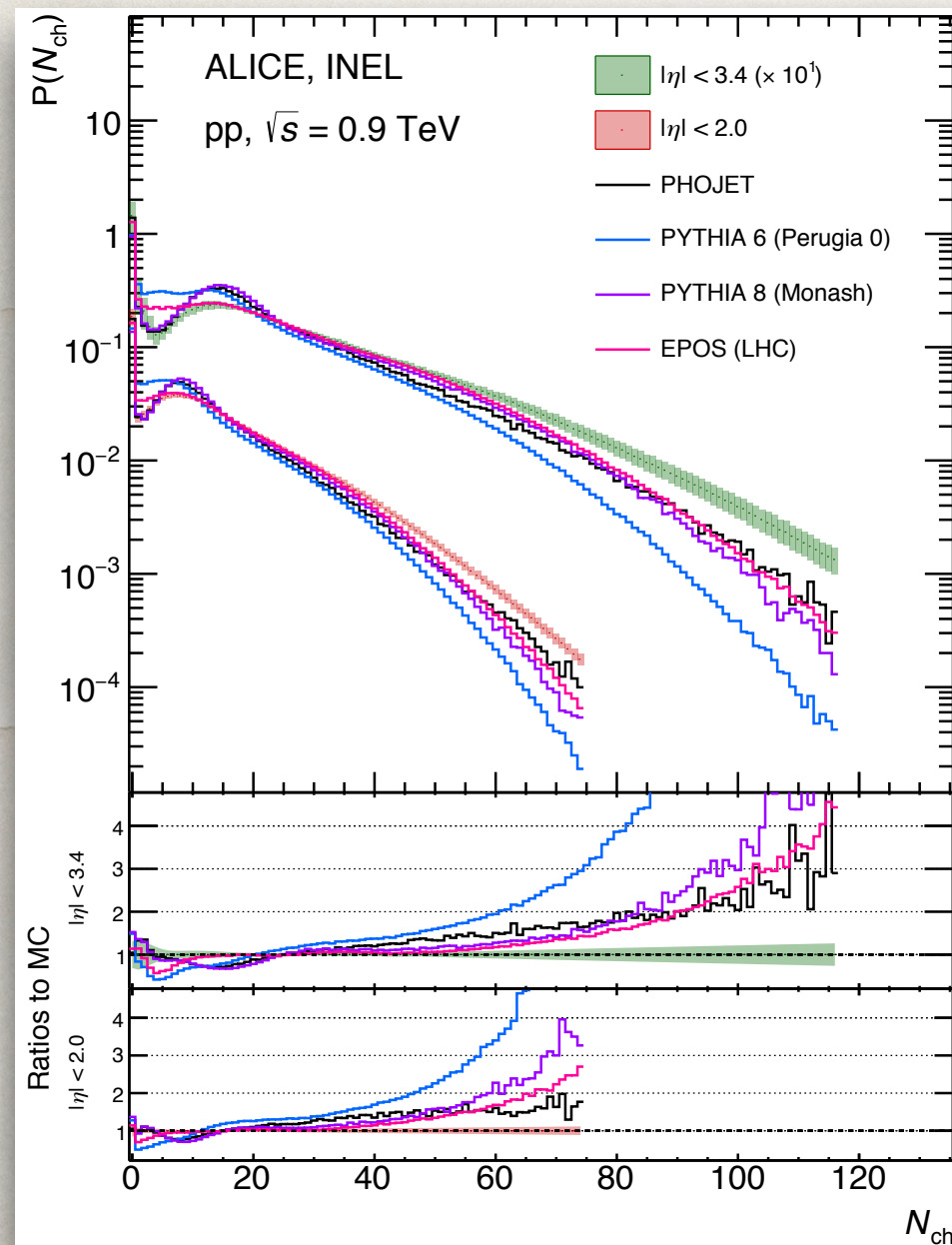
Eur. Phys. J. C (2016) 76:502

Charged Particle Multiplicity

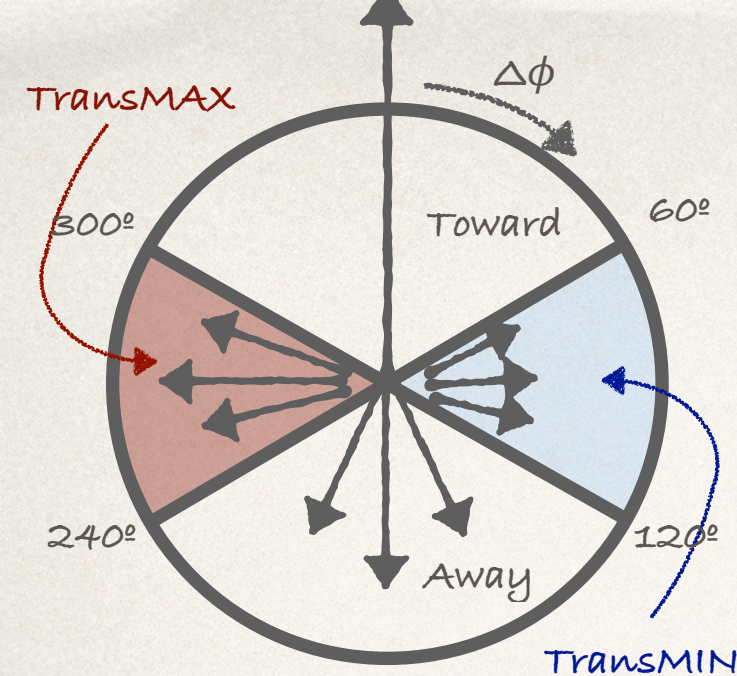


Results are based on information from the Silicon Pixel Detector and the Forward Multiplicity Detector of ALICE, extending the pseudorapidity coverage of the earlier publications and the high-multiplicity reach.

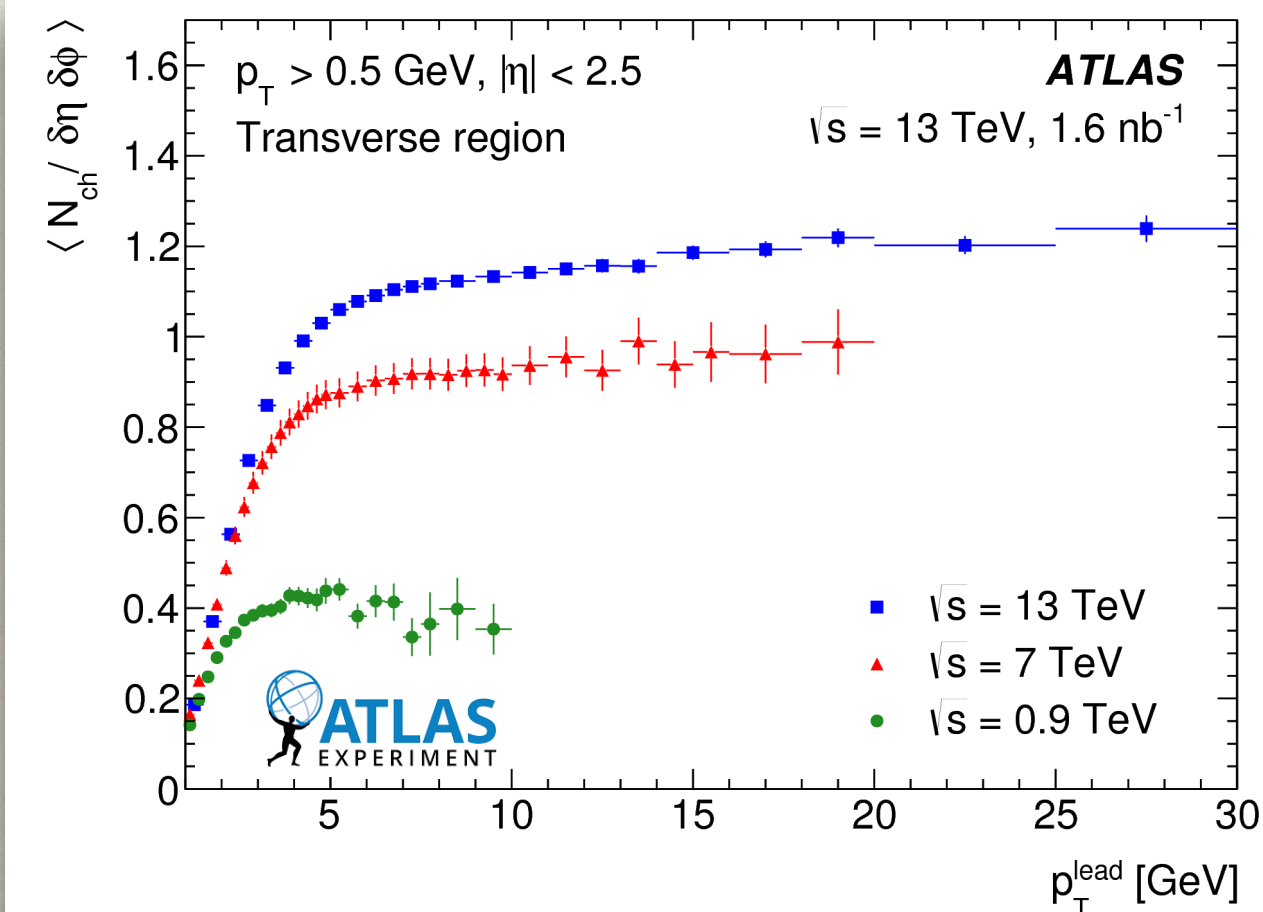
The measurements are compared to results from the CMS experiment and to PYTHIA, PHOJET and EPOS LHC event generators.



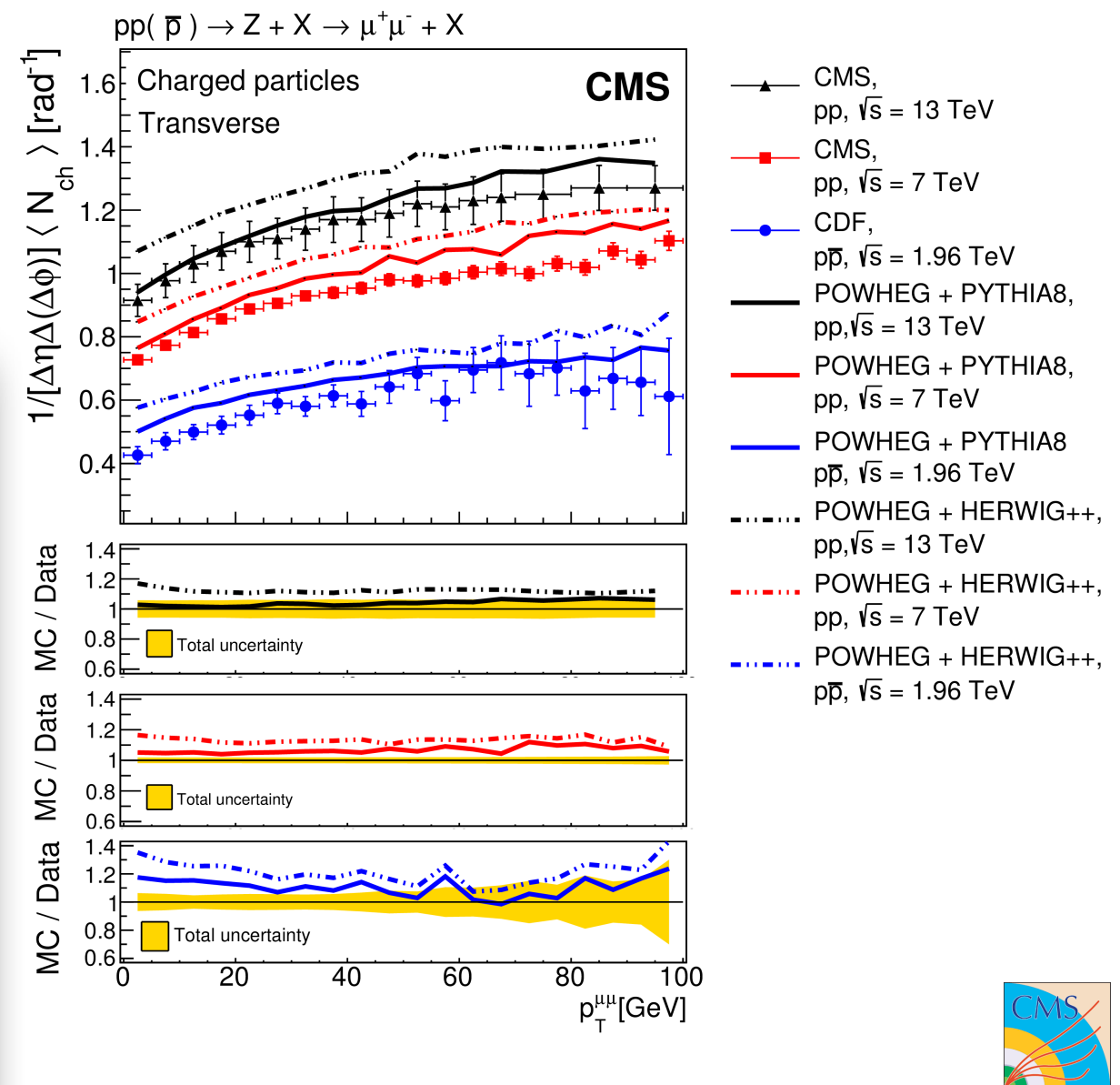
The underlying event



Measurement of the underlying event activity in pp collisions at 13 TeV associated to the leading charged particle (ATLAS).



Measurement of the underlying event activity in pp collisions at 13 TeV, using inclusive Z boson production events (CMS).

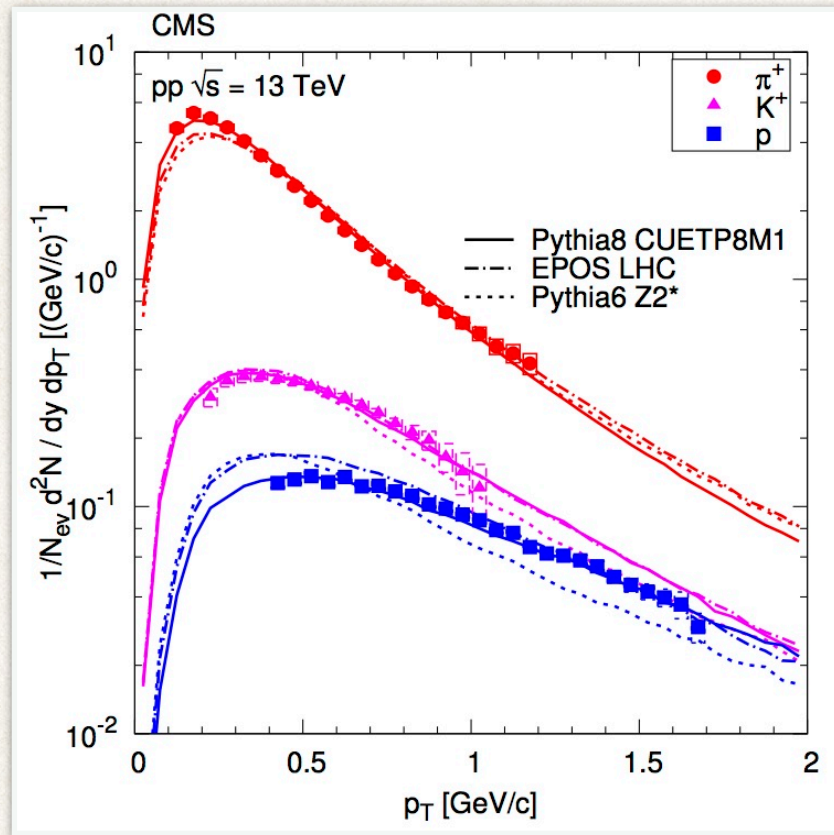


[arXiv:1711.04299](https://arxiv.org/abs/1711.04299)

Submitted to J. High Energy Phys. (Nov 2017)

[JHEP03\(2017\)157](https://arxiv.org/abs/1711.04299)

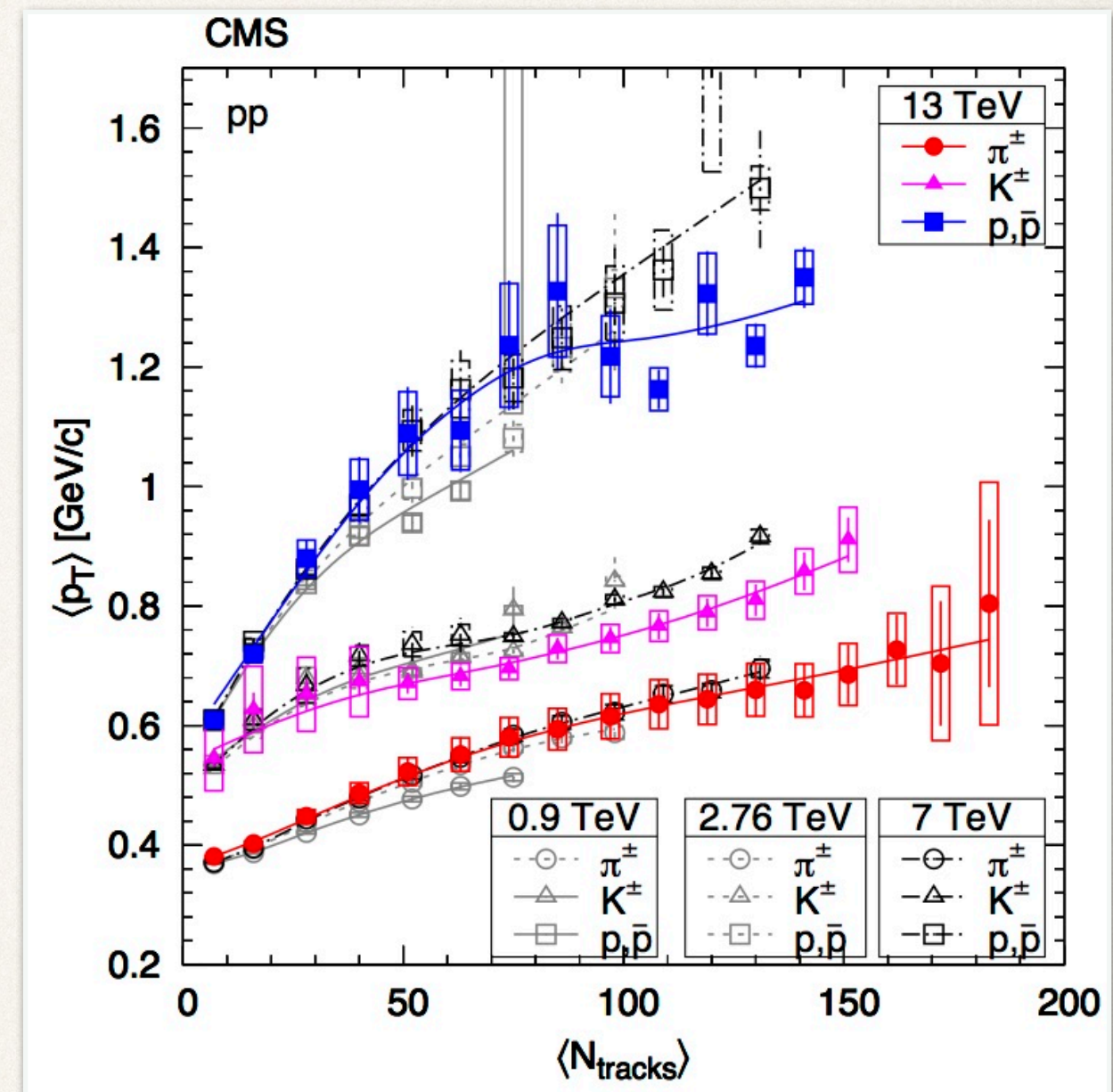
Measurement of charged pion, kaon, and proton production in proton-proton collisions at $\sqrt{s} = 13$ TeV



Transverse momentum spectra have been measured for different charged hadron species produced in inelastic pp collisions at $\sqrt{s} = 13$ TeV.

Charged pions, kaons, and protons are identified from the energy deposited in the silicon tracker and the reconstructed particle trajectory.

The yields of such hadrons at rapidities $|y| < 1$ are studied as a function of the event charged particle multiplicity measured in the pseudorapidity range $|\eta| < 2.4$.

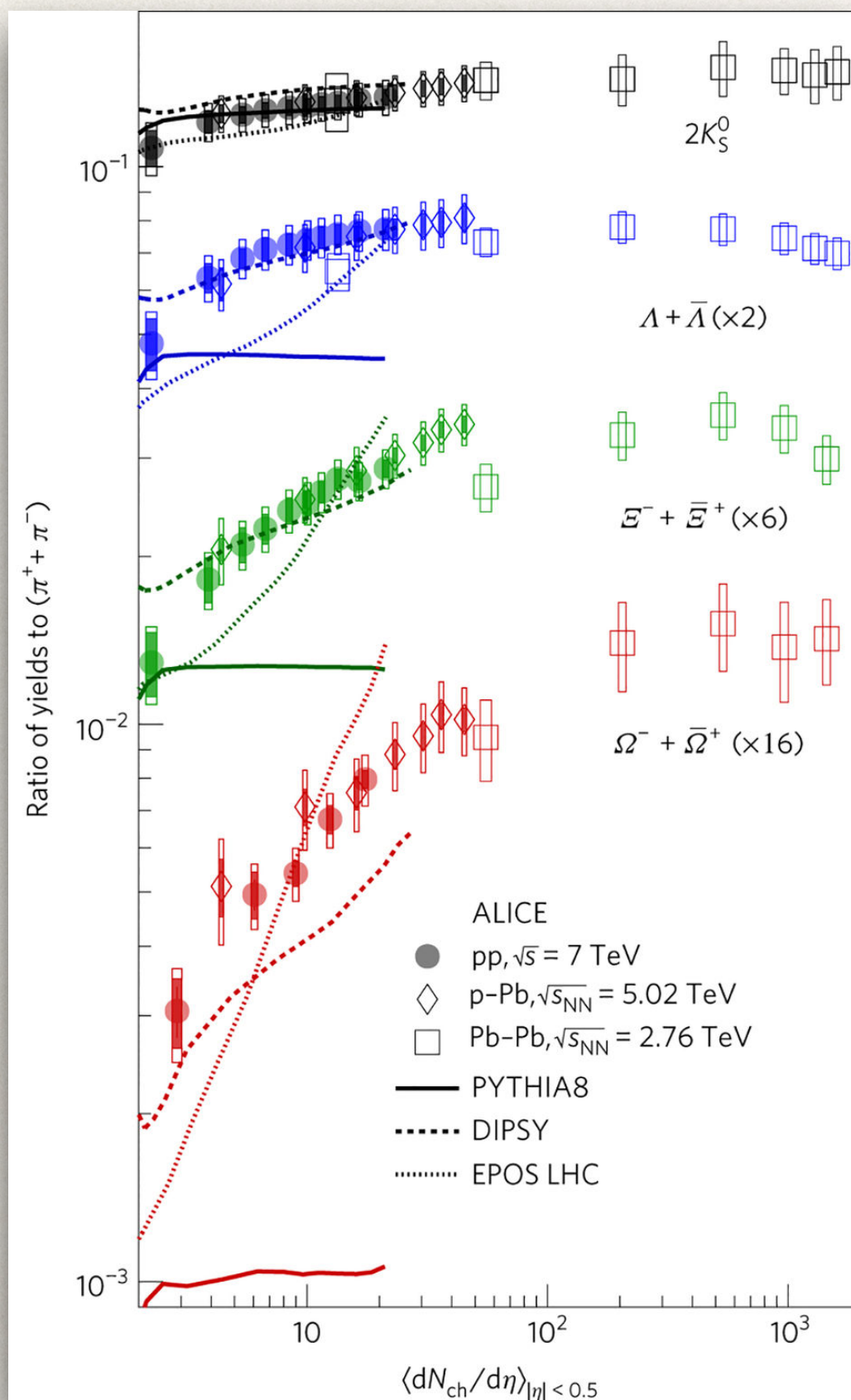


As observed in lower-energy data, the $\langle p_T \rangle$ and the ratios of particle yields are strongly correlated with event particle multiplicity.

No significant dependence with the c.m. energy is observed.

PRD 96 (2017) 112003

Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions



ALICE presented the **first observation of strangeness enhancement** in high-multiplicity proton–proton collisions.

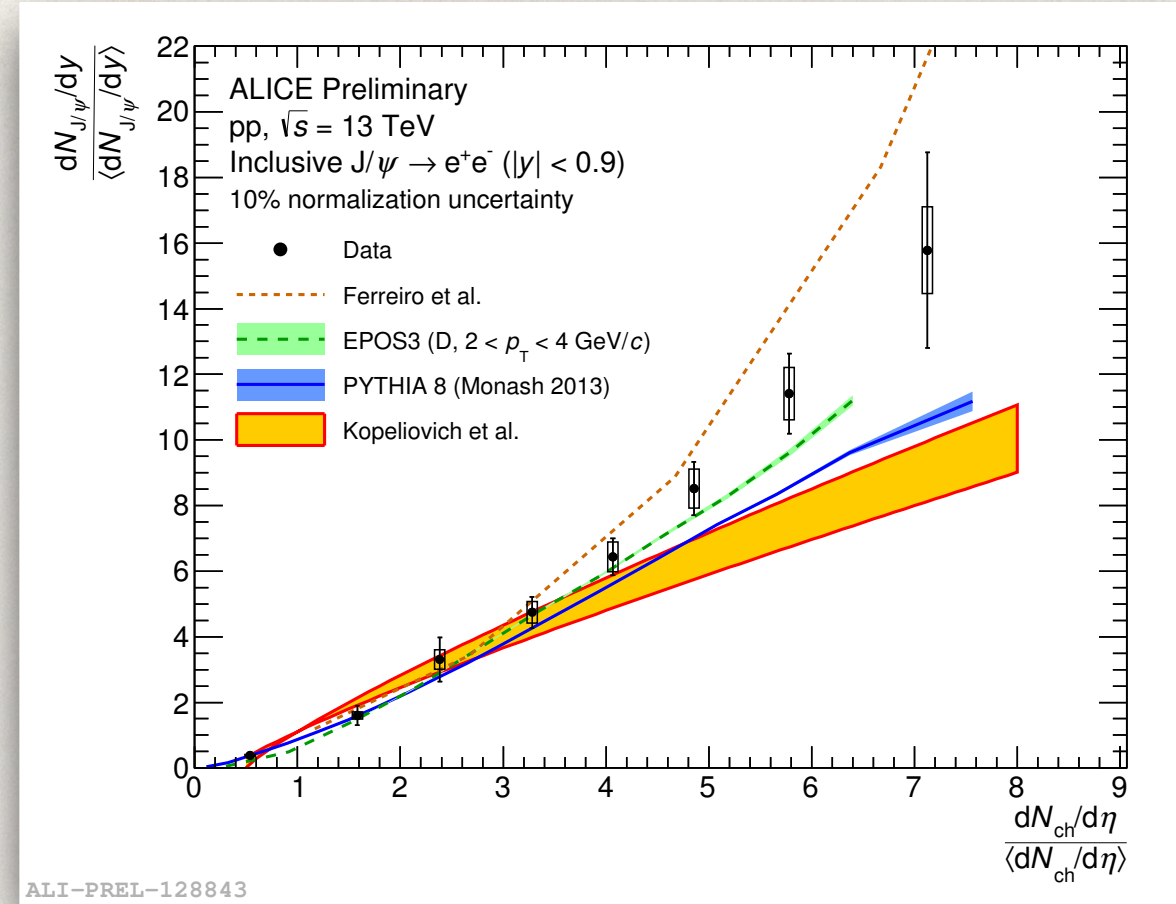
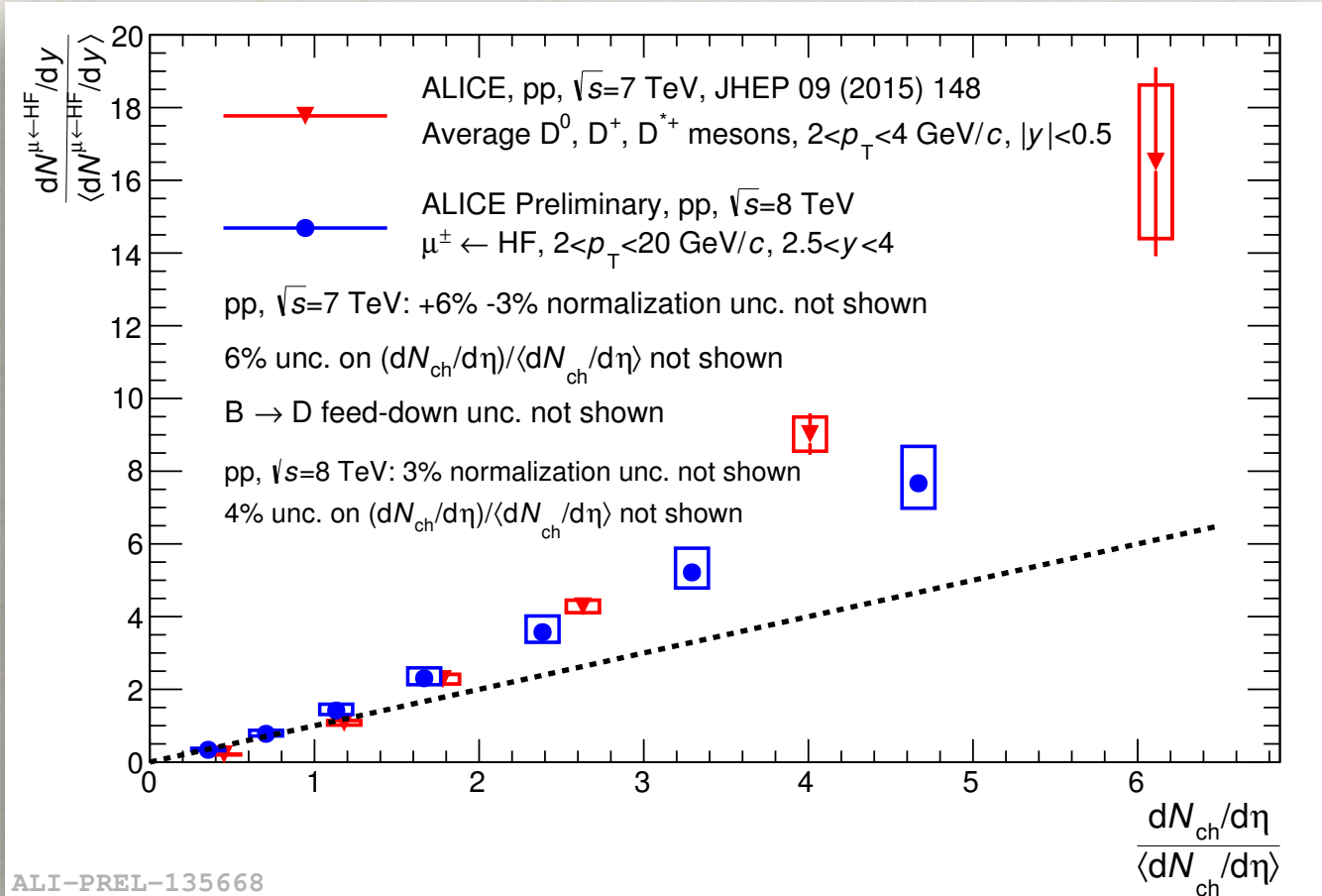
They found that the integrated yields of strange and multi-strange particles, relative to pions, increases significantly with the event charged-particle multiplicity.

The measurements are in remarkable agreement with the p-Pb collision results, indicating that the phenomenon is related to the final system created in the collision.

In high-multiplicity events strangeness production reaches values similar to those observed in Pb–Pb collisions, where a QGP is formed.

Nature Physics **13**, 535–539 (2017)

Heavy Flavor production vs Multiplicity



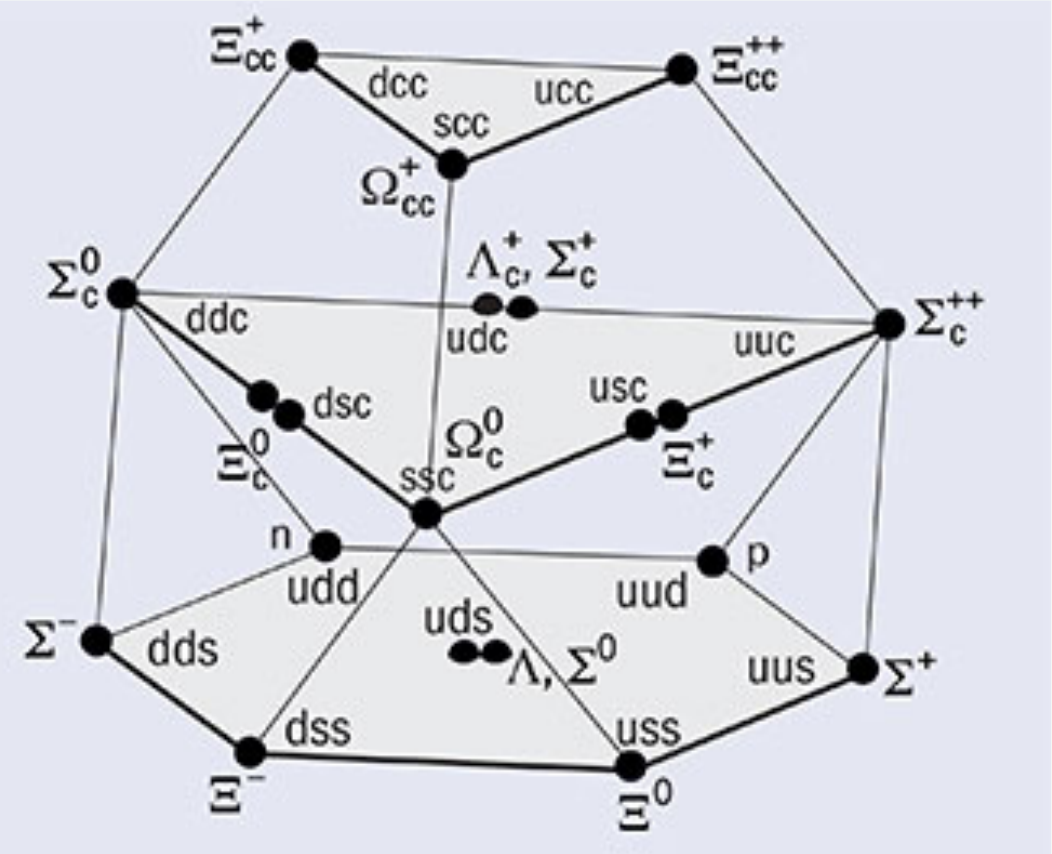
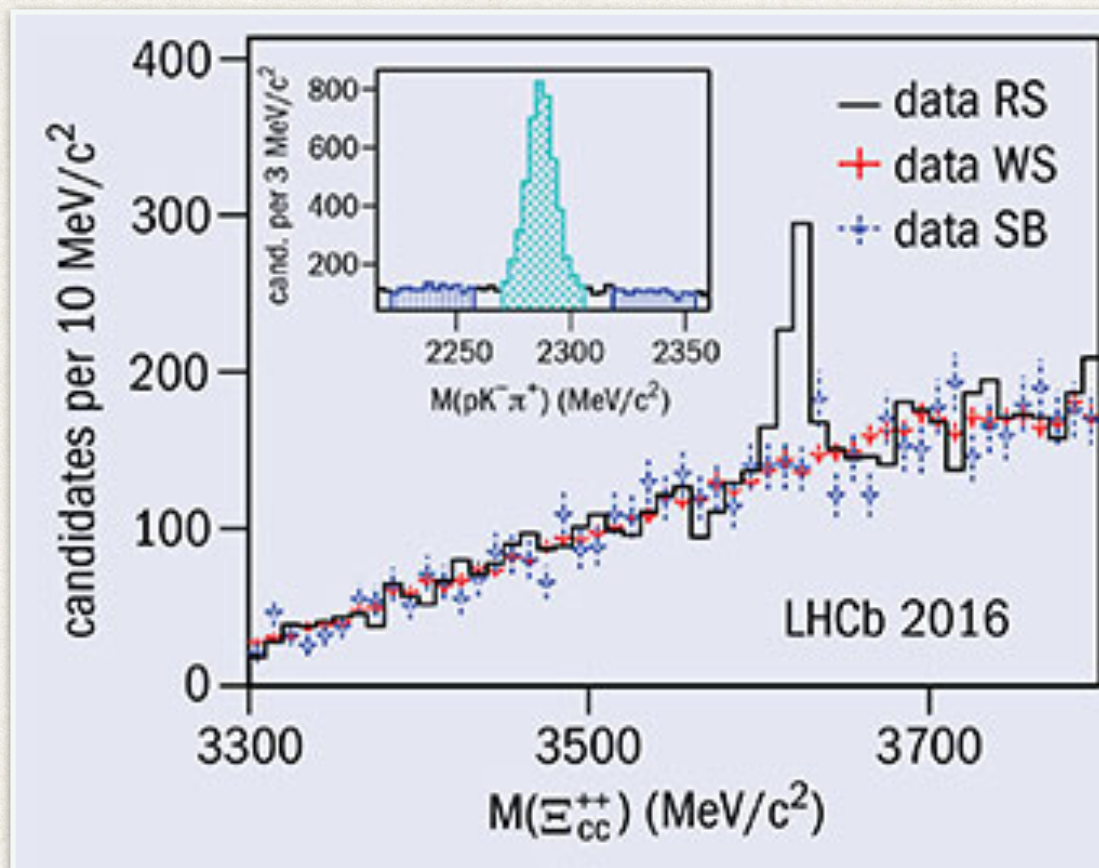
- Yield of D mesons ($|y| < 0.5$), HF-decay muons ($2.5 < y < 4$) and J/Ψ ($|y| < 0.9$) **show faster-than-linear increase with charged-particle multiplicity at central rapidity**

Feature not related to hadronisation, but rather to production process.

- Observed a qualitative agreement with models assuming:
 - Multi-parton interactions influencing HF production (PYTHIA8, EPOS3 w/ hydro)
 - Contributions of higher Fock-states (Kopeliovich et al.)
 - Soft-particle saturation (Ferreiro: percolation, PYTHIA8: color reconnection)

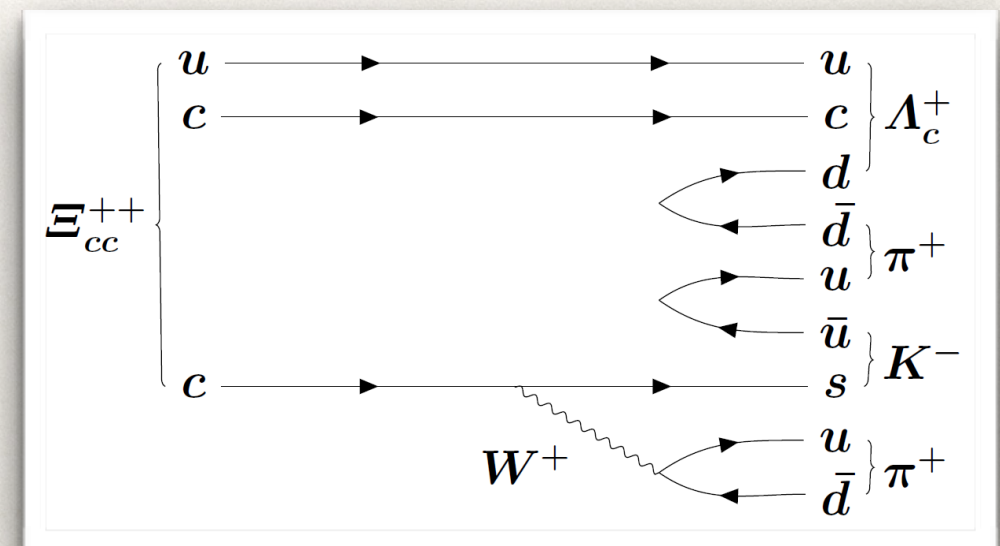


Observation of the doubly charmed baryon: Ξ^{++}_{cc}

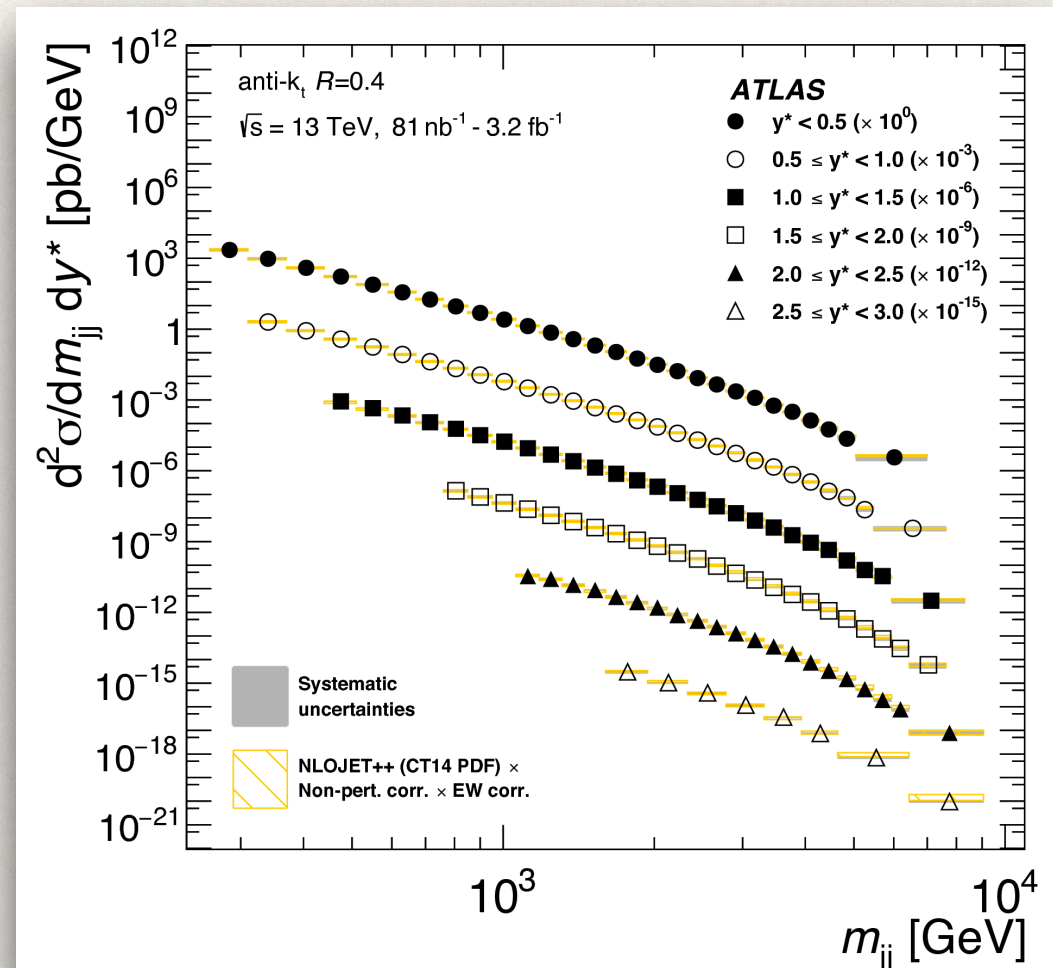
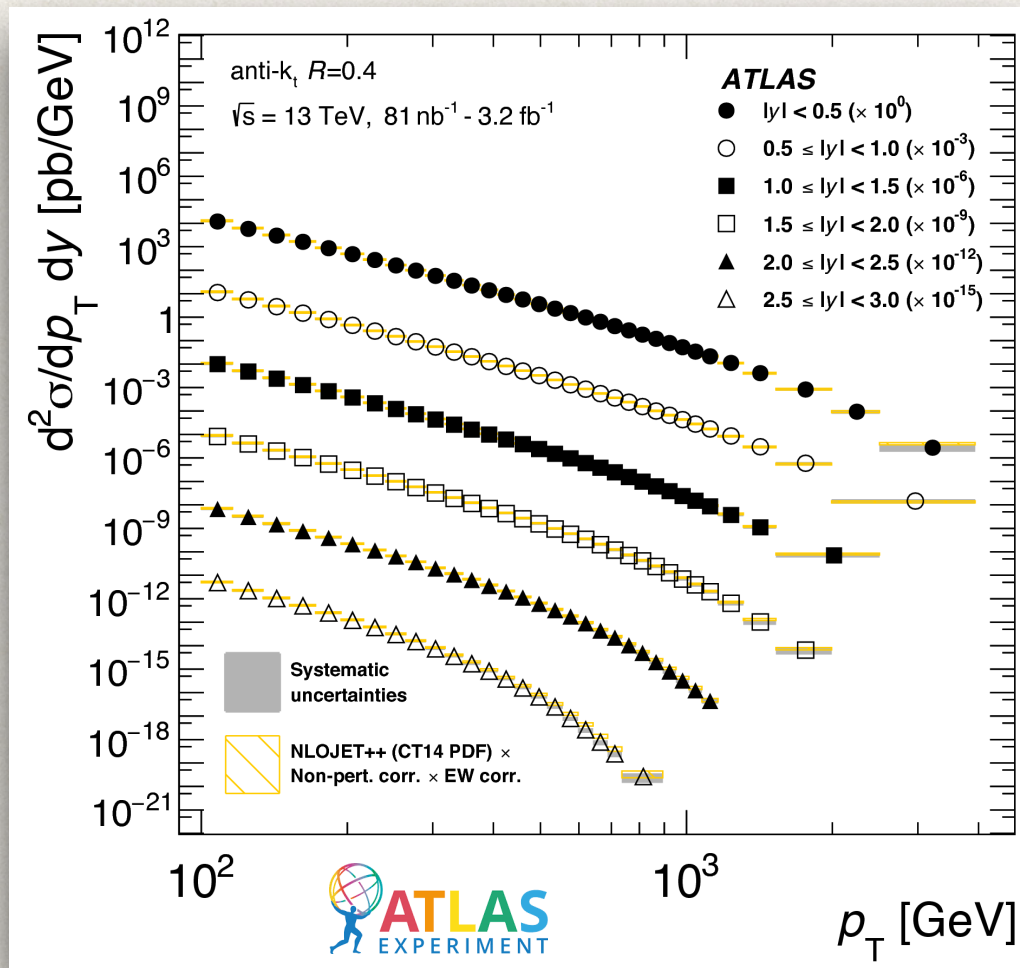


$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14 \text{ MeV}/c^2$$

LHCb: largest recorded c, b -hadron yields – hard quark mass scale as opportunity for QCD studies.



Measurement of inclusive jet and dijet cross-sections in pp collisions at 13 TeV



Inclusive jet and dijet cross-sections are measured in pp collisions at a $\sqrt{s}=13 \text{ TeV}$.

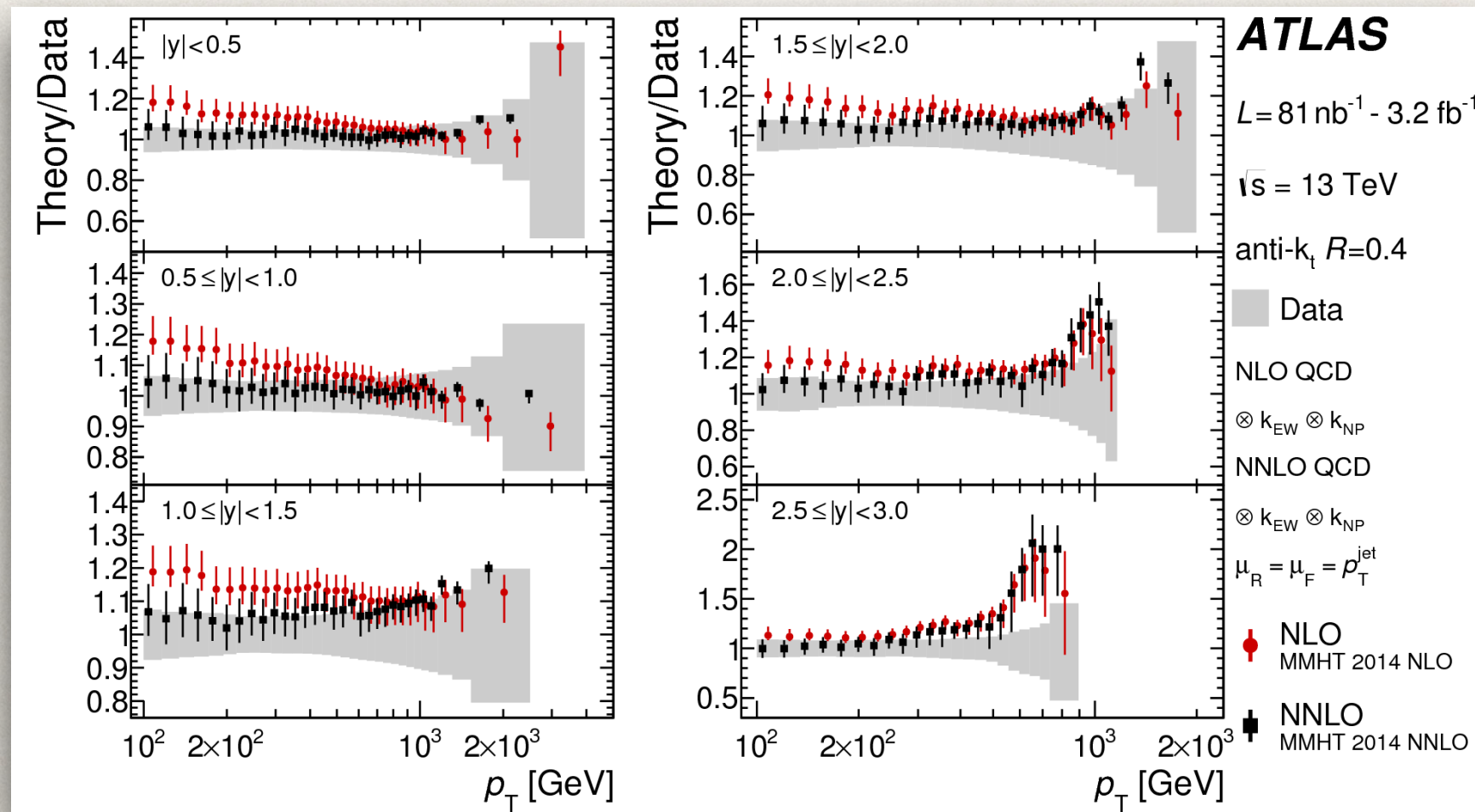
The measurement uses a dataset with an integrated luminosity of 3.2 fb^{-1} recorded in 2015 with the ATLAS detector. Jets are identified using the anti- k_t algorithm with a radius parameter value of $R=0.4$.

The inclusive jet cross-sections are measured as a function of the jet p_T , covering the range from **100 GeV to 3.5 TeV**, and $|y| \leq 3$.

The double-differential dijet production cross-sections are presented as a function of the dijet mass, covering the range from 300 GeV to 9 TeV.

Next-to-leading-order, and next-to-next-to-leading-order for the inclusive jet measurement, perturbative QCD calculations corrected for non-perturbative and electroweak effects are compared to the measured cross-sections.

Measurement of inclusive jet and dijet cross-sections in pp collisions at 13 TeV



Ratios of the NLO and NNLO pQCD predictions to the measured inclusive jet cross-sections, shown as a function of the jet p_T in six $|y|$ bins for anti- k_t jets with $R=0.4$.

The NLO predictions are calculated using NLOJET++ with the MMHT 2014 NLO PDF set.

The NNLO predictions are calculated using NNLOJET with p_T^{jet} as the QCD scale and the MMHT 2014 NNLO PDF set.

The grey bands show the total data uncertainty including both the systematic (JES, JER, unfolding, jet cleaning, luminosity) and statistical uncertainties.

Summary of χ^2/dof values obtained from a global fit using all p_T and rapidity bins, comparing the inclusive jet cross-section and the NLO pQCD prediction corrected for non-perturbative and electroweak effects for several PDF sets and for the two scale choices.

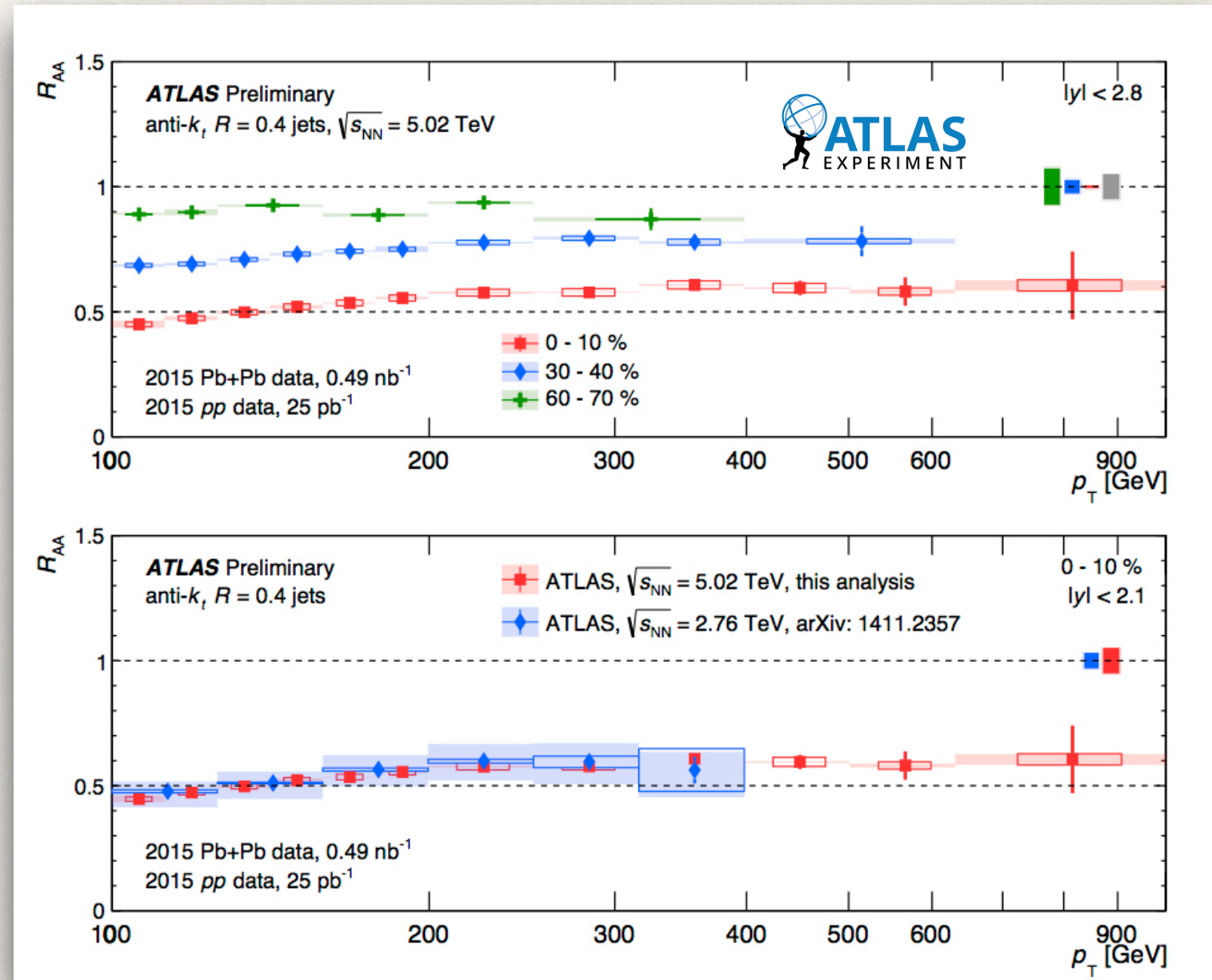
χ^2/dof all $ y $ bins	CT14	MMHT 2014	NNPDF 3.0	HERAPDF 2.0	ABMP16
p_T^{max}	419/177	431/177	404/177	432/177	475/177
p_T^{jet}	399/177	405/177	384/177	428/177	455/177

Study of inclusive jet yields in Pb+Pb collisions at 5.02 TeV

ATLAS-CONF-2017-009

Nuclear modification factor

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}^{\text{tot}}} \frac{d^2 N_{\text{jet}}}{dp_T dy} \Big|_{\text{cent}}}{\langle T_{AA} \rangle \frac{d^2 \sigma_{\text{jet}}}{dp_T dy} \Big|_{pp}}$$

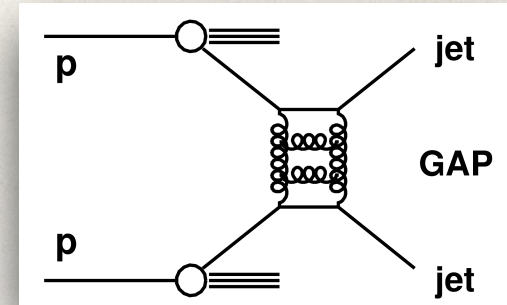
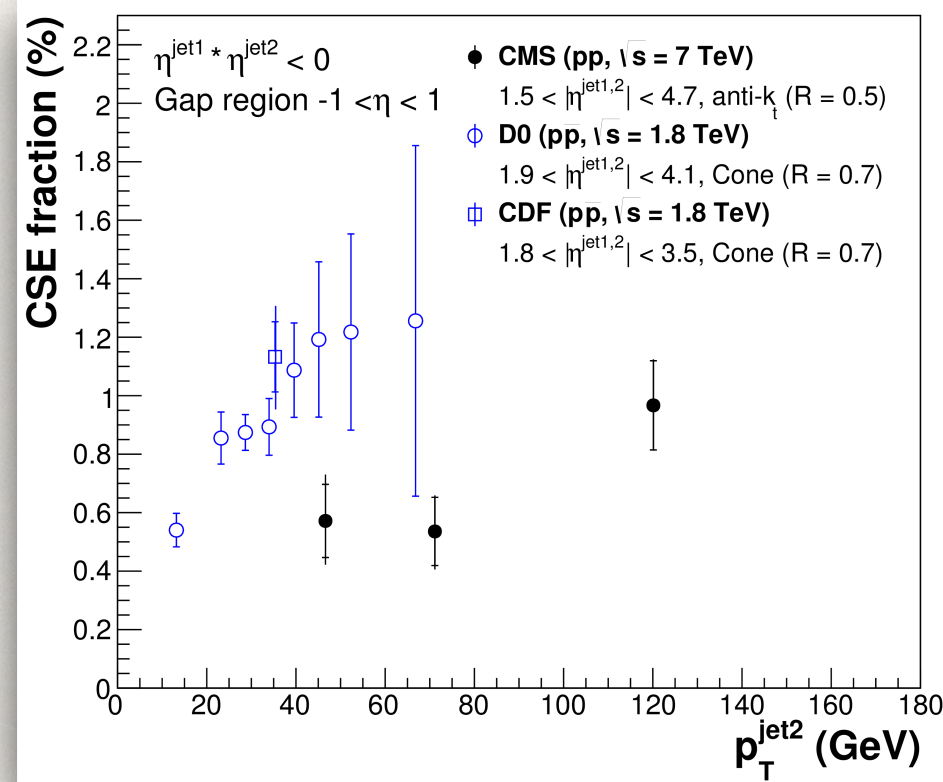
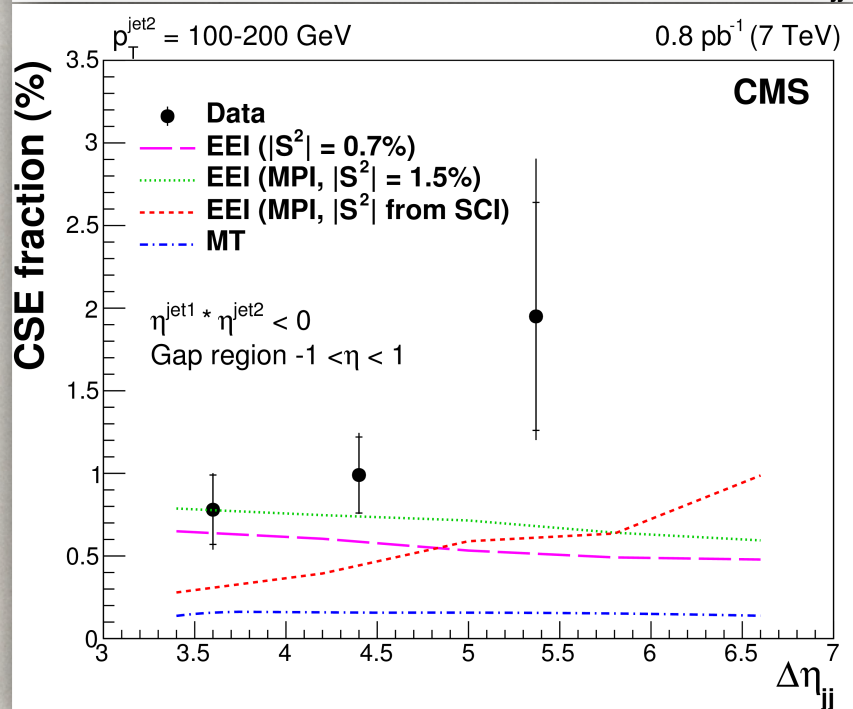
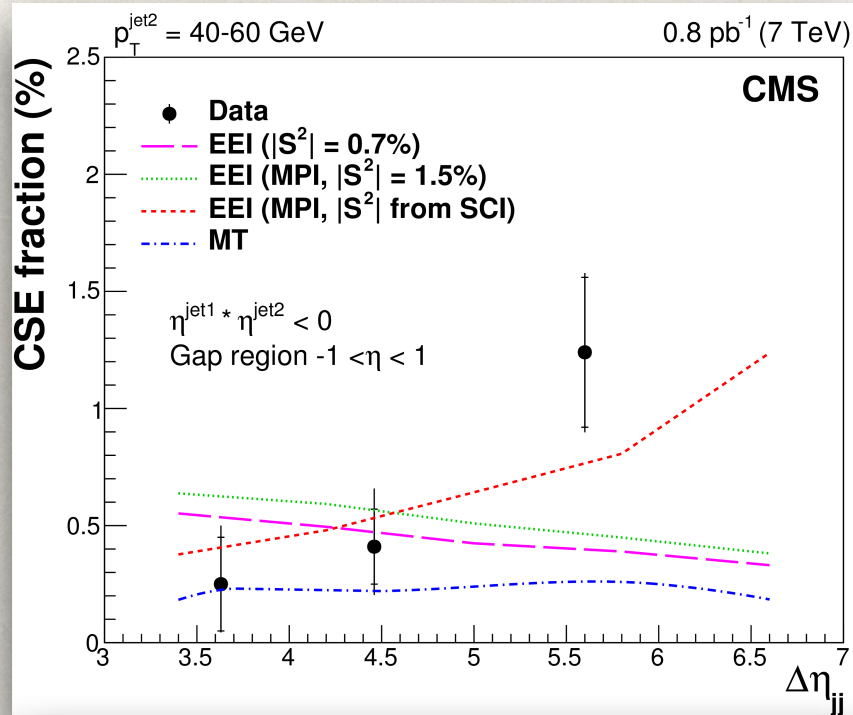


Upper panel: The R_{AA} as a function of jet p_T for jets with $|y| < 2.8$ for three centrality bins.

Bottom panel: The R_{AA} as a function of jet p_T for jets with $|y| < 2.1$ in 0-10% central collisions compared to the same quantity measured in $\sqrt{s_{NN}} = 2.76$ Pb+Pb collisions published.

The magnitude of the R_{AA} monotonically decreases moving from peripheral to central collisions. The R_{AA} is flat with rapidity at low p_T and then decreases with rapidity at high p_T .

Study of dijet events with a large rapidity gap between the two leading jets in pp collisions at $\sqrt{s}=7$ TeV



[arXiv:1710.02586](https://arxiv.org/abs/1710.02586)

Accepted for publication
in *Eur. Phys. J. C*



$p_T^{\text{jet}} > 40 \text{ GeV}$

$1.5 < |\eta^{\text{jet}}| < 4.7$ (jets in opposite hemispheres)

Events with no charged particles with $p_T > 0.2 \text{ GeV}$ in the interval $-1 < \eta < 1$ between the jets are observed in excess of calculations that assume no color-singlet exchange

The measured CSE fractions have been compared to the results of the D0 and CDF experiments at $\sqrt{s}=1.8 \text{ TeV}$.

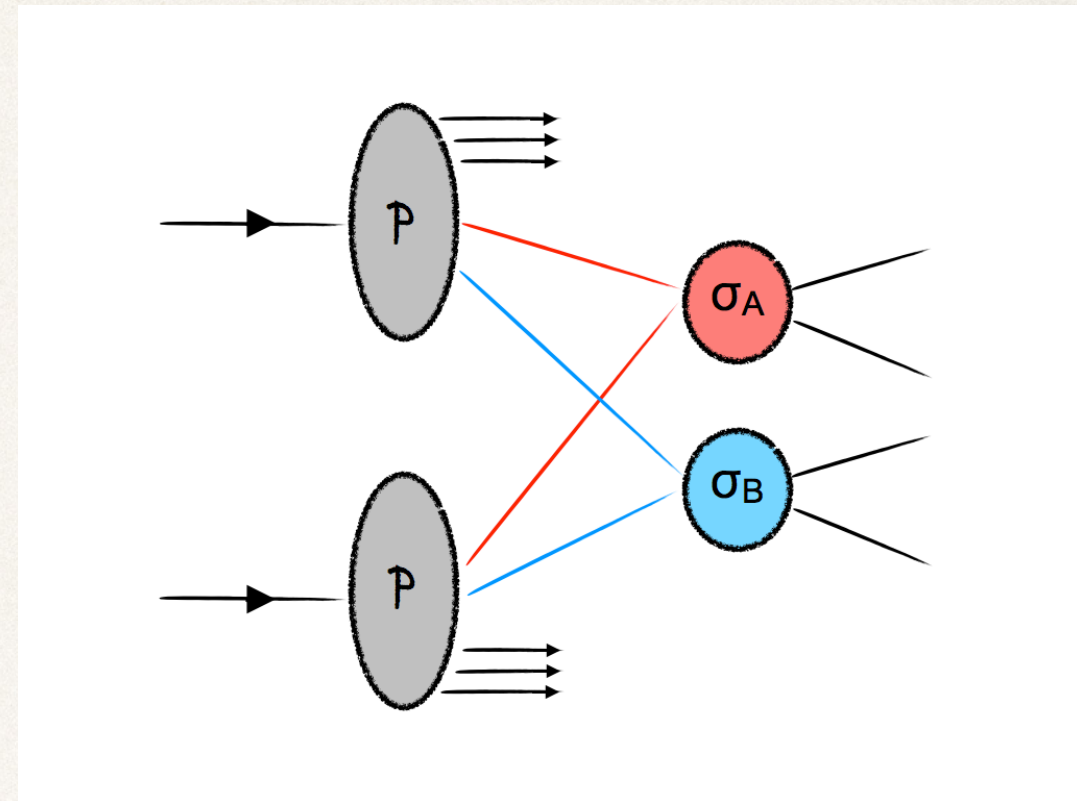
A factor of two decrease of the CSE fraction measured at $\sqrt{s}=7 \text{ TeV}$ with respect to those at lower collision energies is observed.

The next-to-leading-logarithmic BFKL calculations describe many features of the data, but none of the implementations is able to simultaneously describe all the features of the measurement.

Measuring Double Parton Scattering

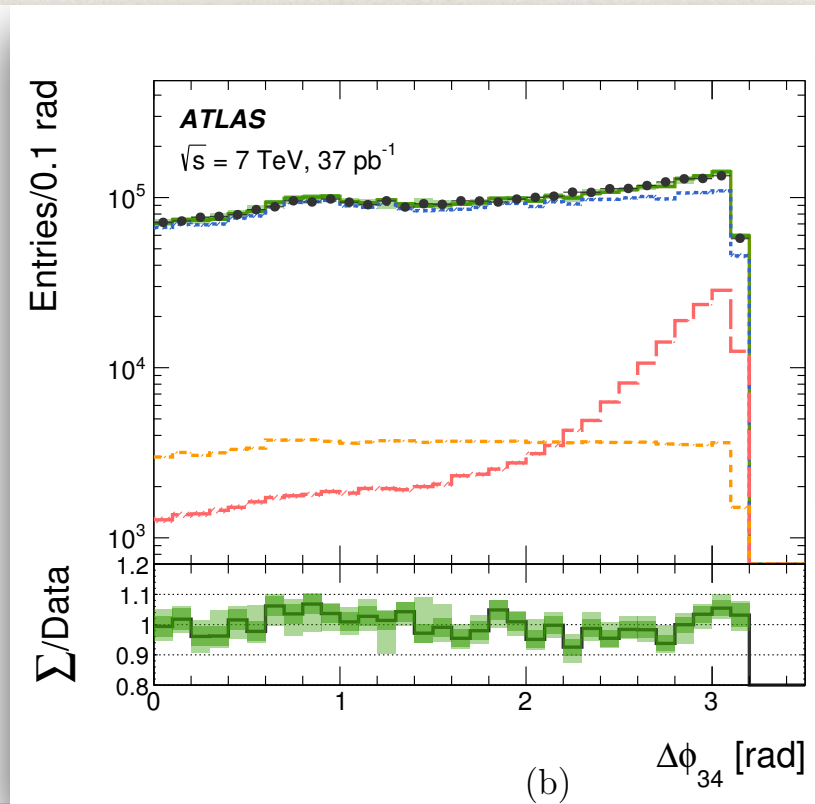
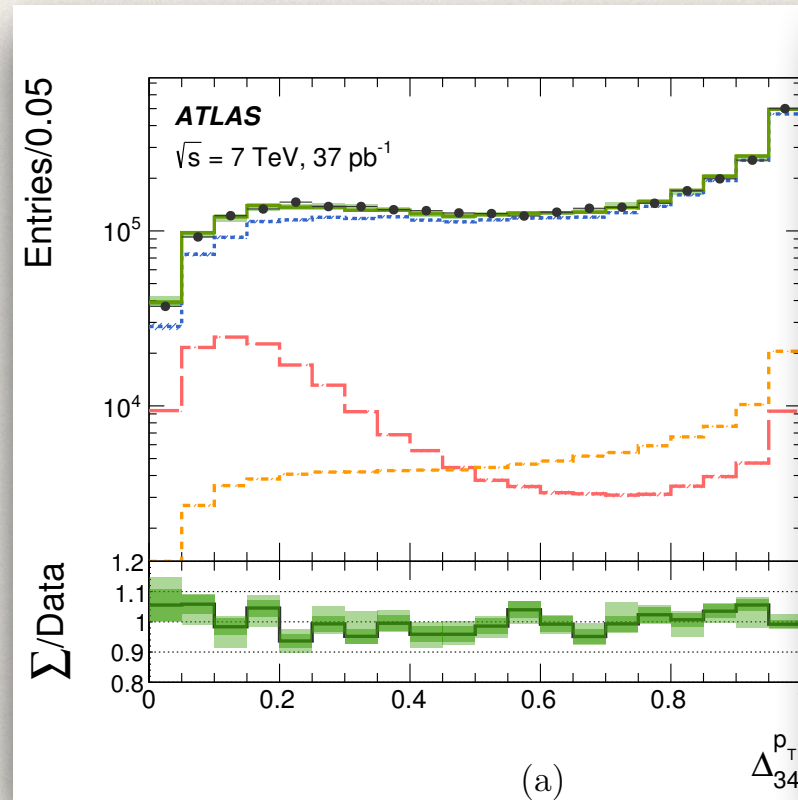
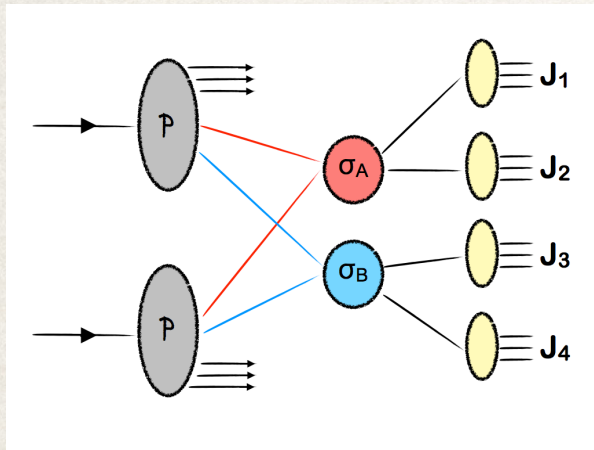
Why measure it?

- insight on parton spatial density:
 - large σ_{eff} : parton uniformly distributed inside the nucleon, σ_{DP} small.
 - small σ_{eff} : highly concentrated parton spatial density, σ_{DP} large.
- better understanding of non-perturbative QCD dynamics
 - is the rate of MPI really independent of the process?
 - correlations?
- accurate estimation of backgrounds for many rare new physics processes as well as for Higgs boson searches.
 - important for the definition of central jet veto cuts.



$$\sigma_{DP} = m \frac{\sigma_A \sigma_B}{2\sigma_{eff}}$$

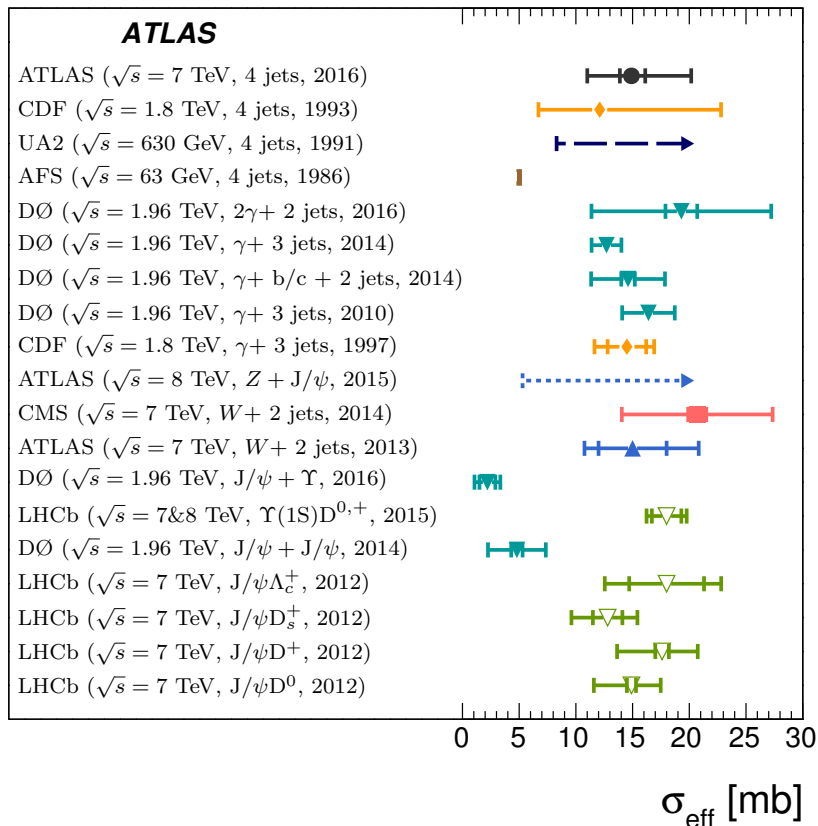
Double parton scattering in **four-jet** events



+ Data 2010
 ... SPS (AHJ)
 - cDPS (data, overlay)
 - sDPS (data, overlay)
 ■ Σ of contributions (stat. uncertainty)
 ■ Σ of contributions (stat. + sys. uncertainty)
 Anti- k_t jets, $R = 0.6$
 $p_T^1 \geq 42.5$ GeV
 $p_T^{2,3,4} \geq 20$ GeV
 $|\eta_{1,2,3,4}| \leq 4.4$



Experiment (energy, final state, year)

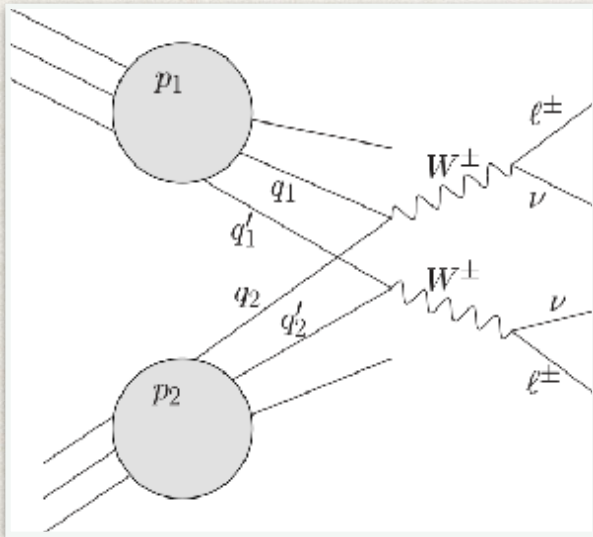


$$f_{\text{DPS}} = 0.092^{+0.005}_{-0.011} \text{ (stat.) }^{+0.033}_{-0.037} \text{ (syst.)}$$

$$\sigma_{\text{eff}} = 14.9^{+1.2}_{-1.0} \text{ (stat.) }^{+5.1}_{-3.8} \text{ (syst.) mb}$$

JHEP11(2016)110

Constraints on the double parton scattering cross section from same-sign W boson pair production



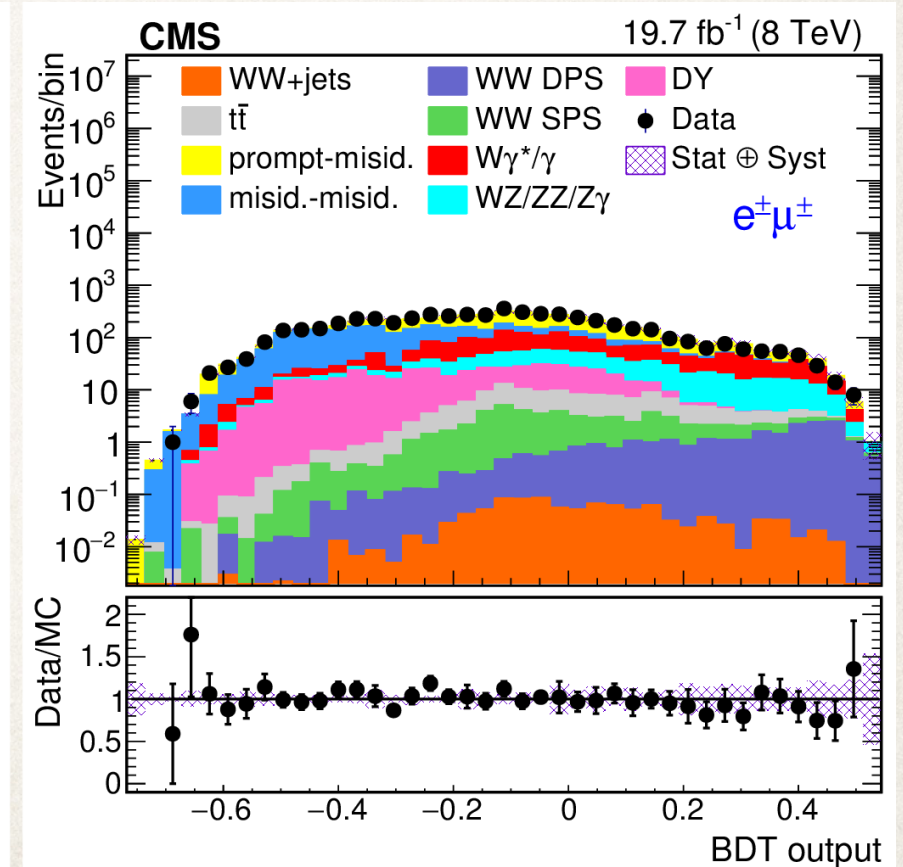
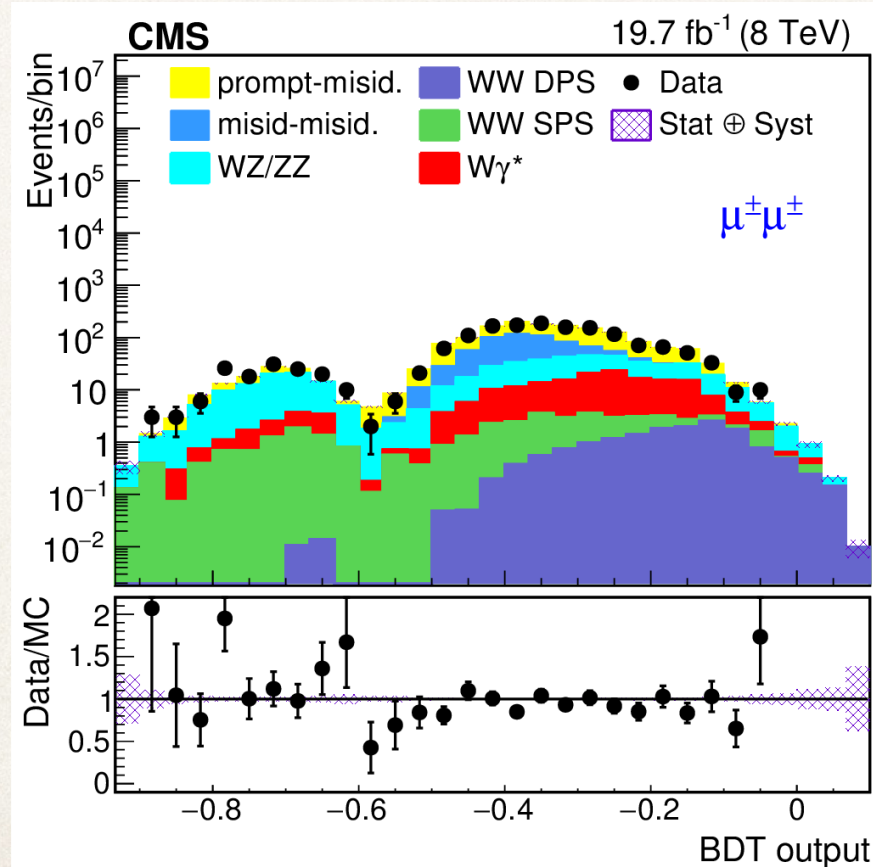
Schematic diagram corresponding to the production of a same-sign W boson pair via the DPS process.

A first search for same-sign W boson pair production via double-parton scattering (DPS) in pp collisions at a center-of-mass energy of 8 TeV has been presented.

The analyzed data were collected by the CMS detector at the LHC during 2012 and correspond to an integrated luminosity of 19.7 fb⁻¹.

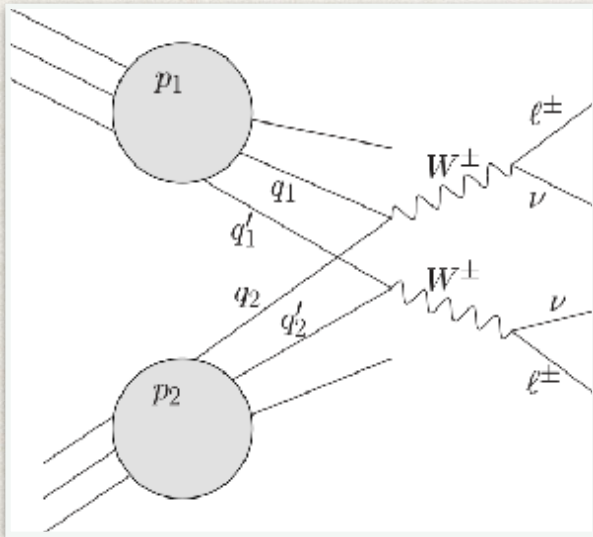
The results presented here are based on the analysis of events containing two same-sign W bosons **decaying into either same-sign muon-muon or electron-muon pairs**.

Several kinematic observables have been studied to identify those that can better discriminate between DPS and the single-parton scattering (SPS) backgrounds.

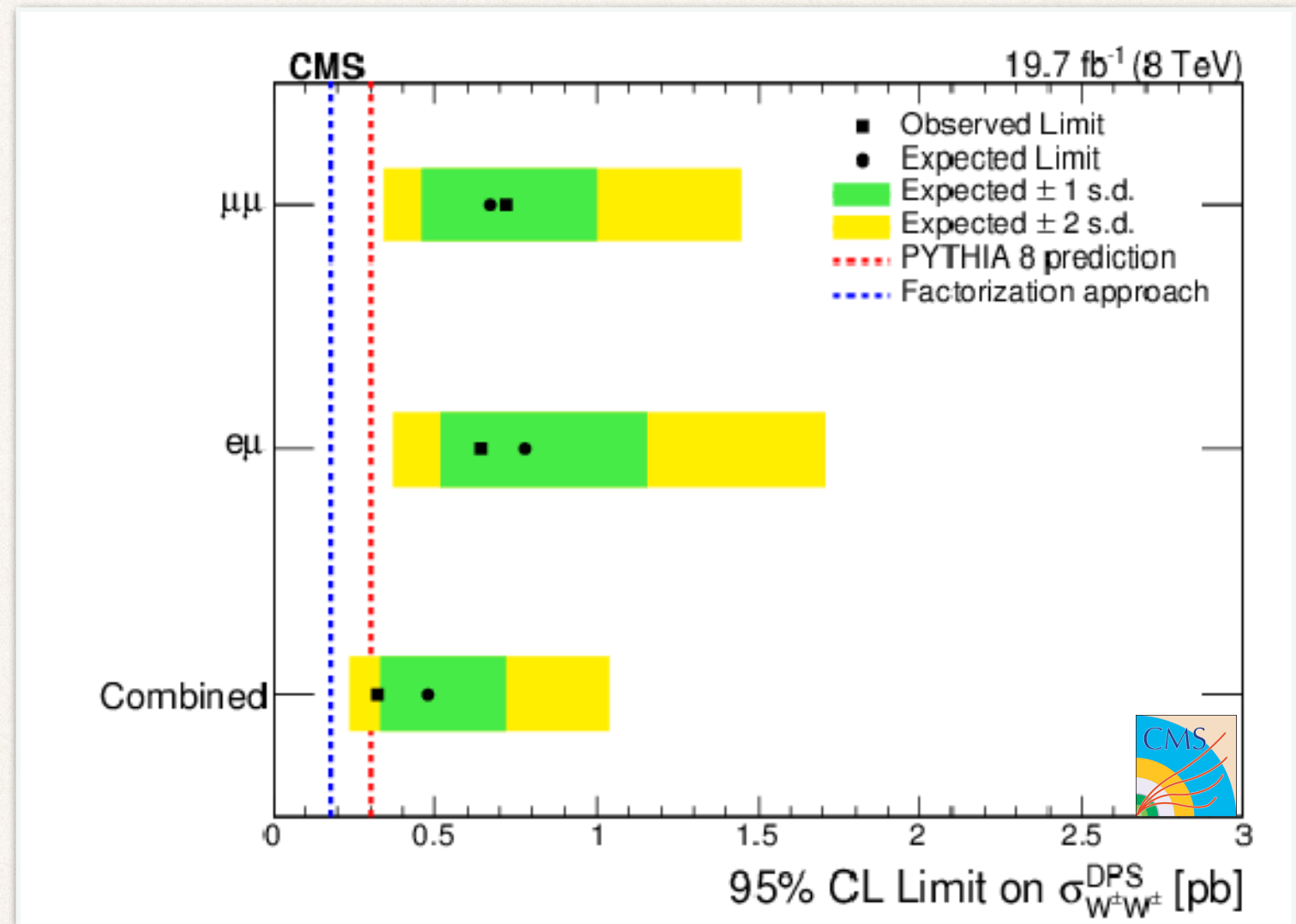


JHEP 02 (2018) 032

Constraints on the double parton scattering cross section from same-sign W boson pair production



Schematic diagram corresponding to the production of a same-sign W boson pair via the DPS process.



No excess over the expected contributions from SPS processes is observed.

A 95% confidence level (CL) upper limit of 0.32 pb is placed on the inclusive cross section for same-sign WW production via DPS.

A corresponding 95% CL lower limit of **12.2 mb on the effective double-parton cross section** is also derived, compatible with previous measurements as well as with Monte Carlo event generator expectations.

Summary

Data from the LHC provides a unique and rich environment to perform QCD studies.

From soft-QCD to very-high p_T jets, LHC detectors are testing QCD as never before!

This talk covered a small sample of results published recently:

Inelastic pp cross-section

Charged Particle Density

Charged Particle Multiplicity

The underlying event

Measurement of charged pion, kaon, and proton production

Production of multi-strange hadrons in high-multiplicity pp collisions

Measurement of inclusive jet and dijet cross-sections

Heavy flavor production

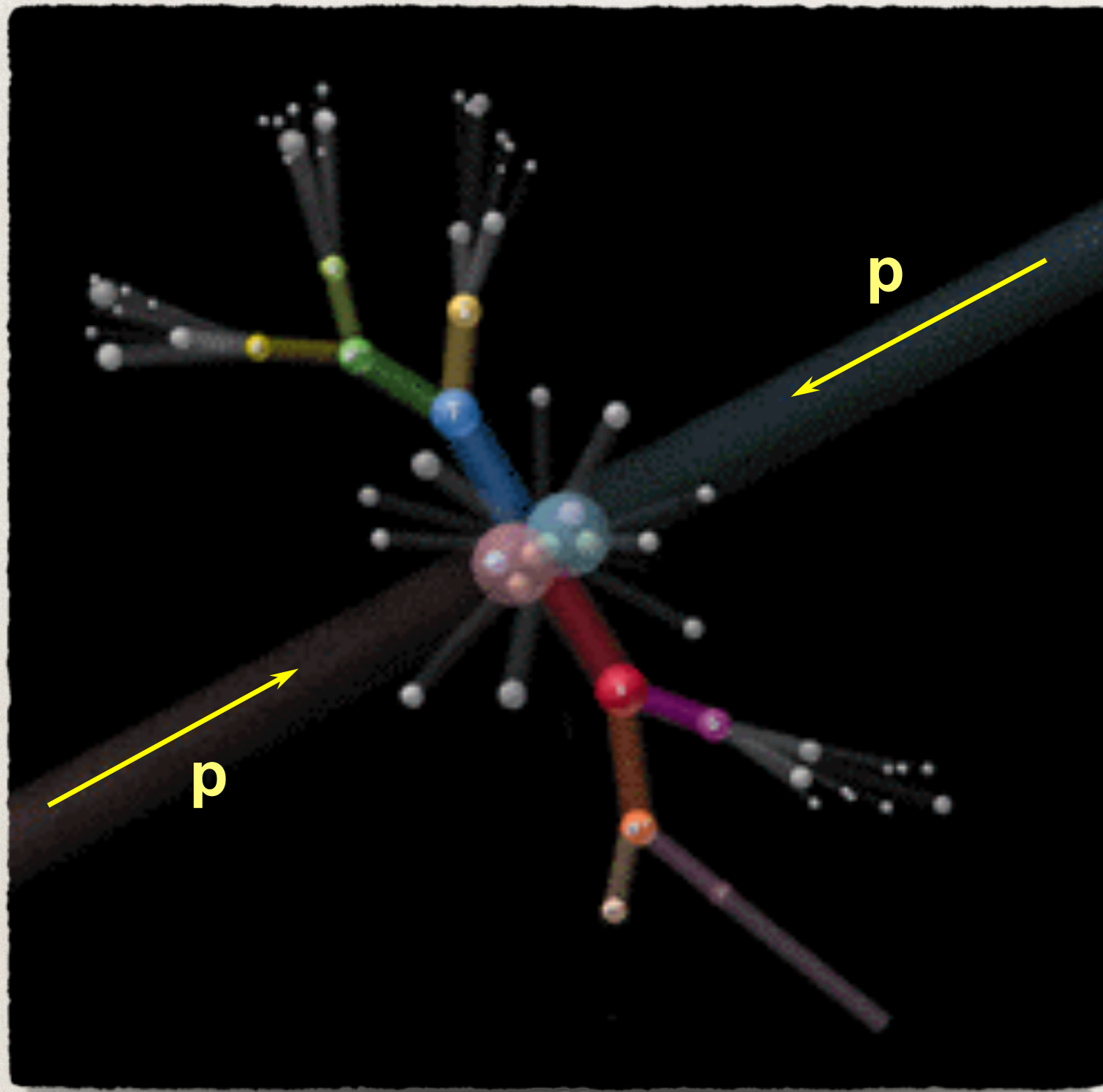
Study of dijet events with a large rapidity gap between the two leading jets

Double Parton Scattering

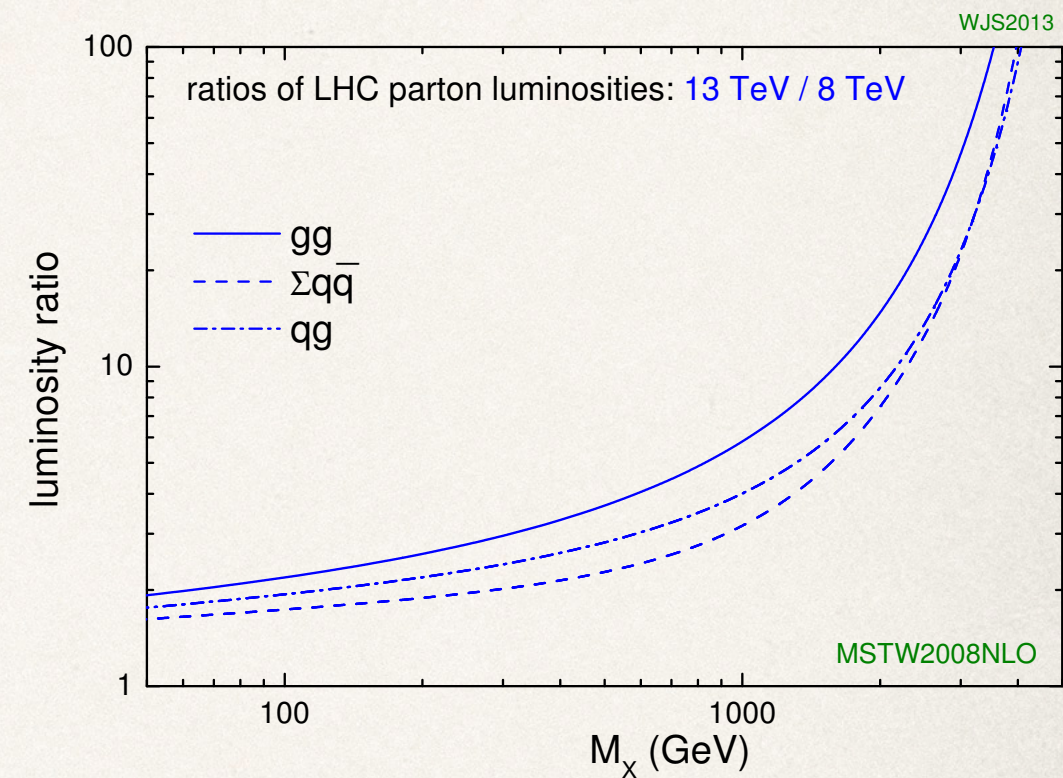
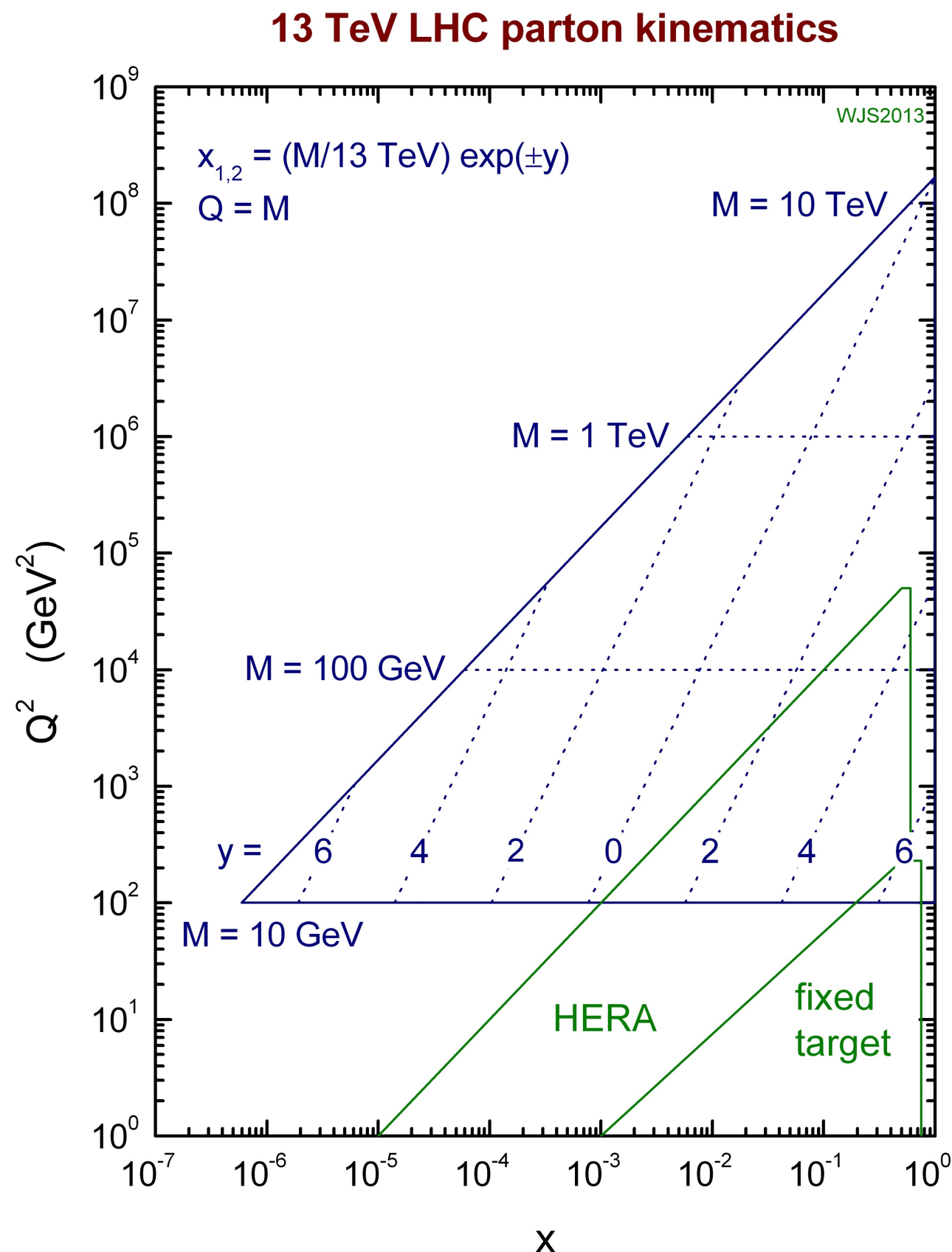
Extras...



QCD at the LHC

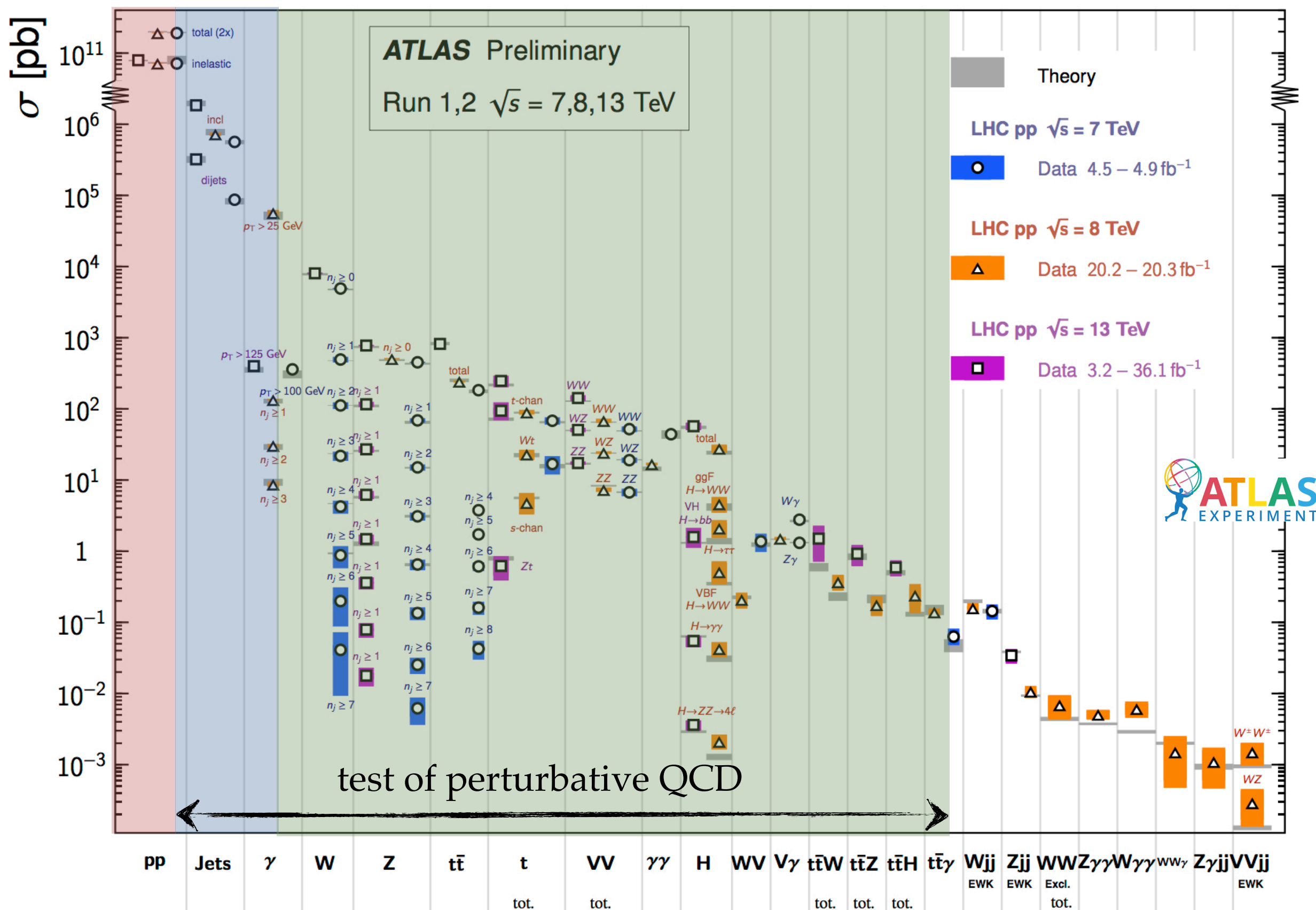


- Essentially all physics at high-energy hadron colliders are connected to the interactions of quarks and gluons (small & large transferred momentum).
 - ▶ **Hard processes (high- p_T):** well described by perturbative QCD
 - ▶ **Soft interactions (low- p_T):** **require non-perturbative phenomenological models**
- Soft Interactions: Problems with strong coupling constant, $\alpha_s(Q^2)$, saturation effects,...
- On average, inelastic hadron-hadron collisions have low transverse energy, low multiplicity.

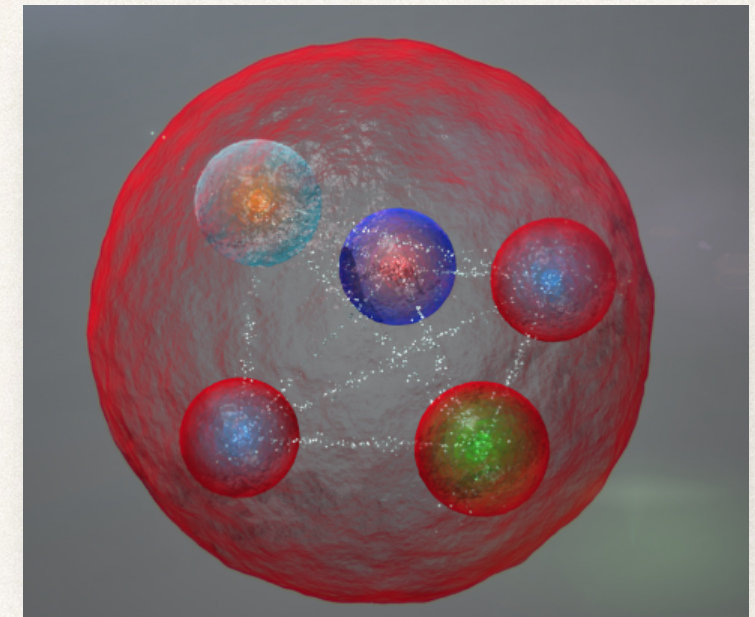
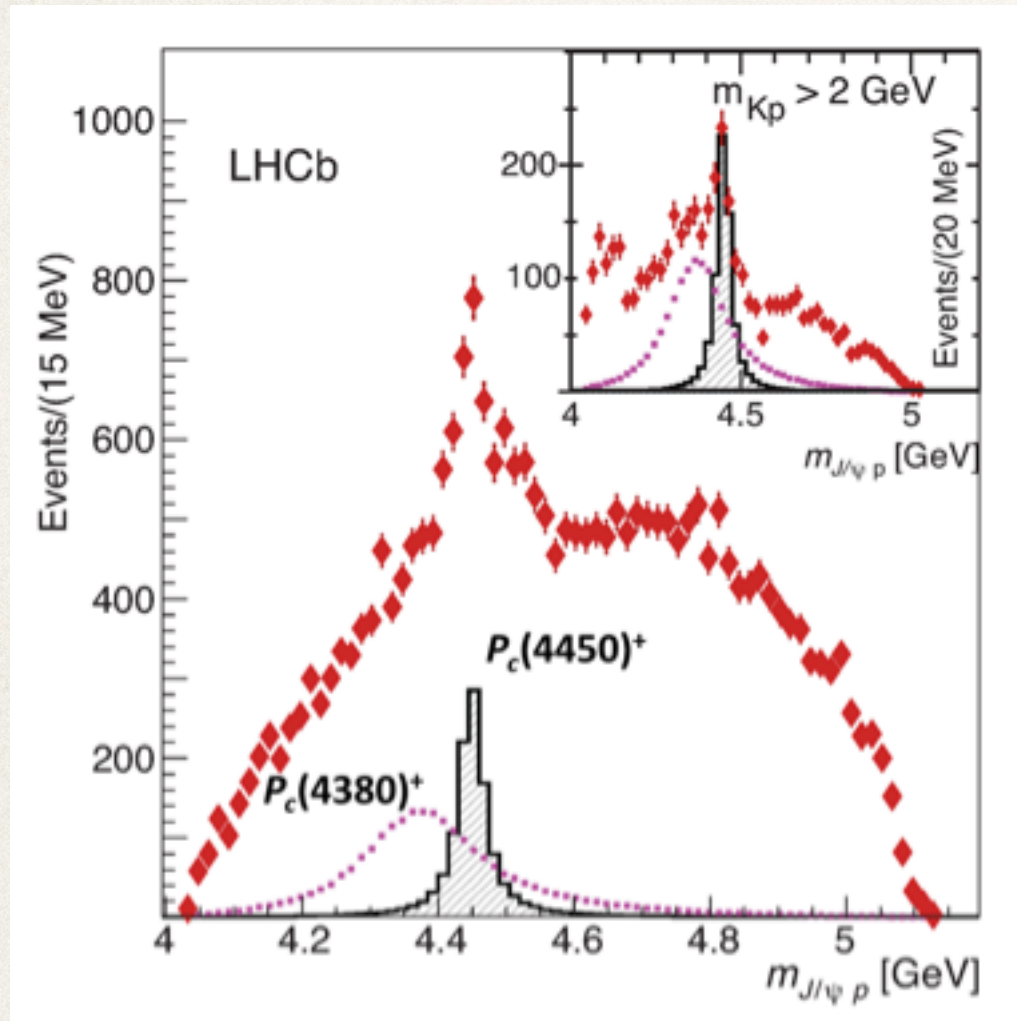


Standard Model Production Cross Section Measurements

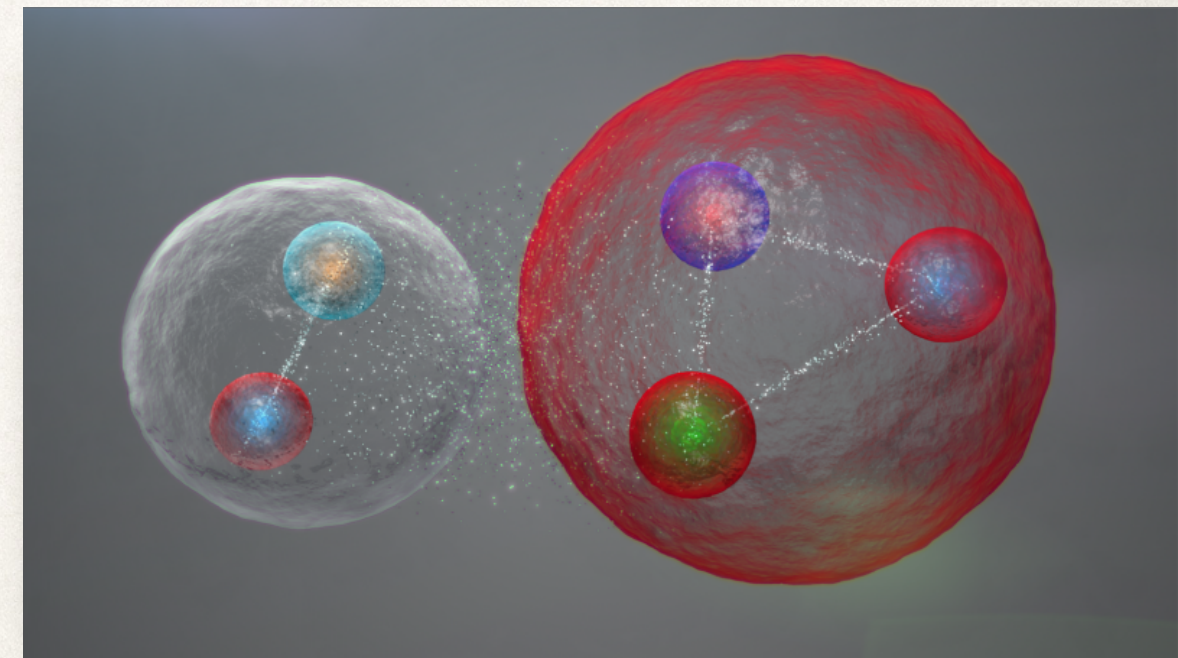
Status: March 2018



July 2015: LHCb announces the observation of exotic Pentaquark particles!



(tightly bound quark states ?)

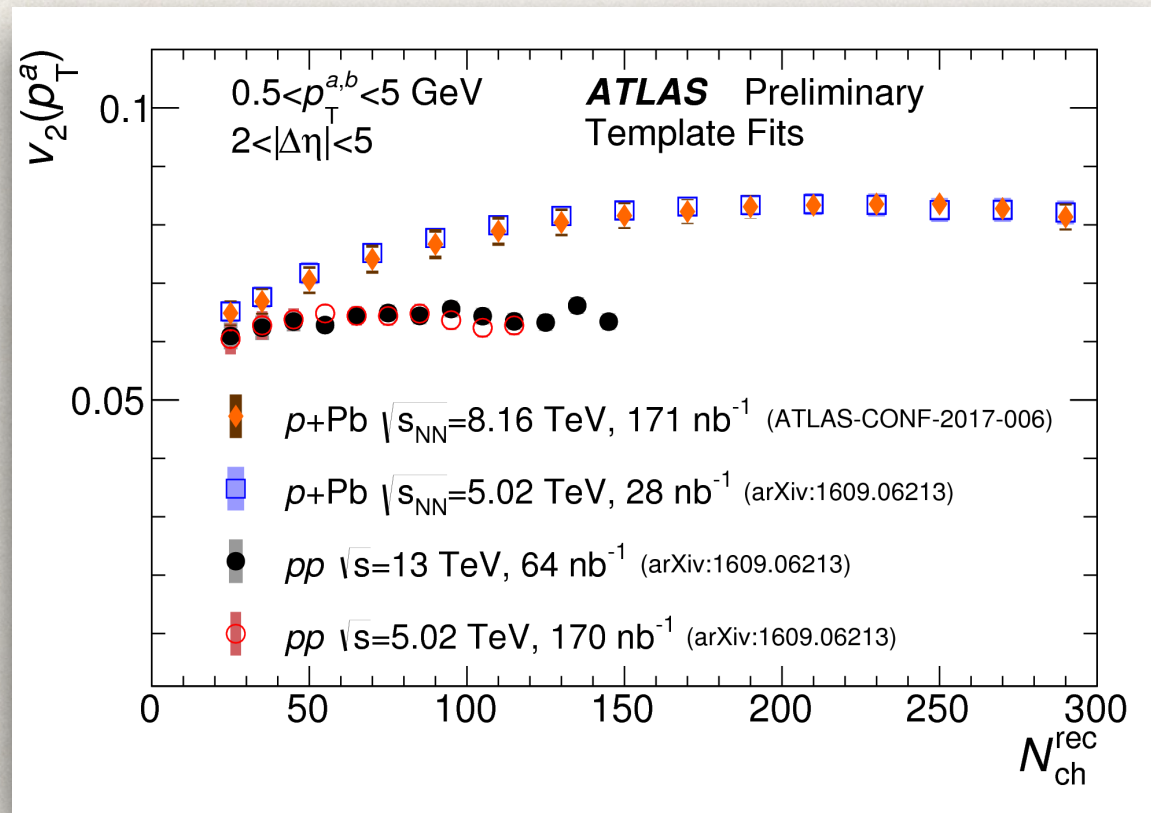


(meson-baryon molecule ?)

$$\Lambda_b \rightarrow J/\psi K^- p$$

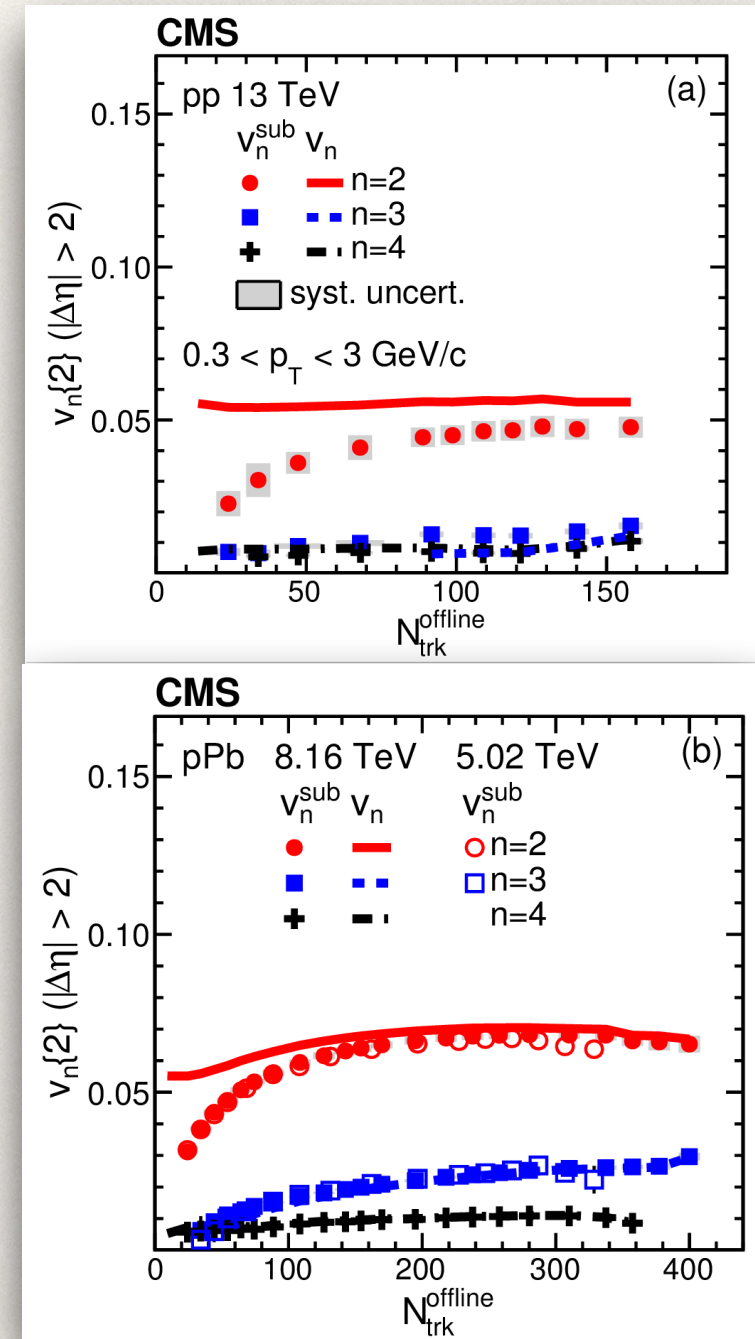
Studied the mass spectrum of $J/\psi p$: can only be explained by pentaquarks!

Measurement of multi-particle azimuthal correlations in pp, p + Pb collisions



Comparison of the second-order azimuthal harmonic v_2 obtained from the template fitting procedure in the 13 TeV pp, 5.02 TeV pp, 5.02 TeV p+Pb and 8.16 TeV p+Pb data, as a function of N_{ch}^{rec} . The results are for $0.5 < p_{T^{a,b}} < 5$ GeV. The error bars and shaded bands indicate statistical and systematic uncertainties, respectively.

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HION/>

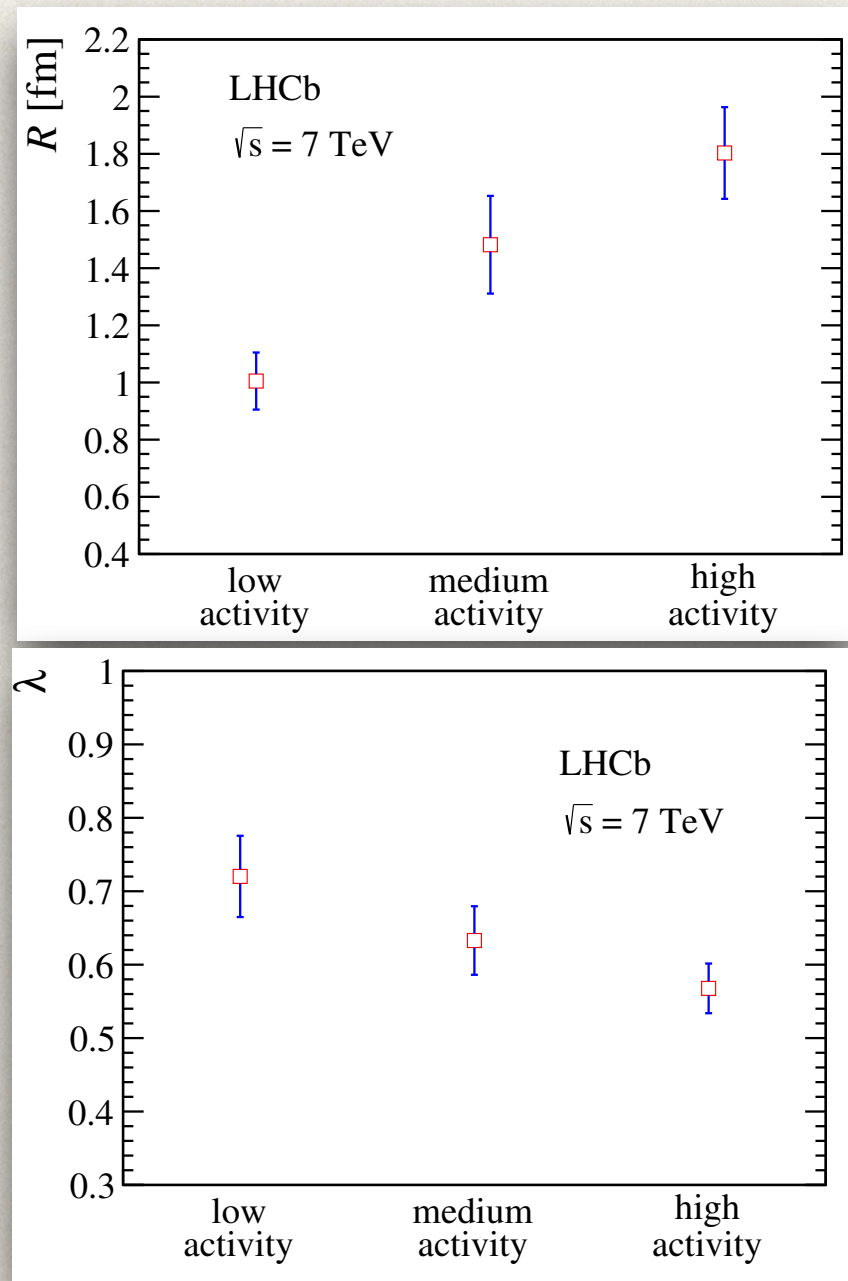


The v_2 , v_3 , and v_4 coefficients from long-range two-particle correlations as a function of $N_{trk}^{offline}$ in 13 TeV pp (a), 5.02 and 8.16 TeV p+Pb (b). The results corrected by low-multiplicity subtraction are denoted as v_n^{sub} . The lines show the v_n results before the subtraction of low-multiplicity correlations.

Phys. Rev. Lett. 120, 092301 (2018)

Florianópolis, 21st March 2018

Bose-Einstein correlations of same-sign charged pions in the forward region in pp collisions at $\sqrt{s} = 7$ TeV



The signature for Bose-Einstein correlations is observed in the form of an enhancement of pairs of like-sign charged pions with small four-momentum difference squared.

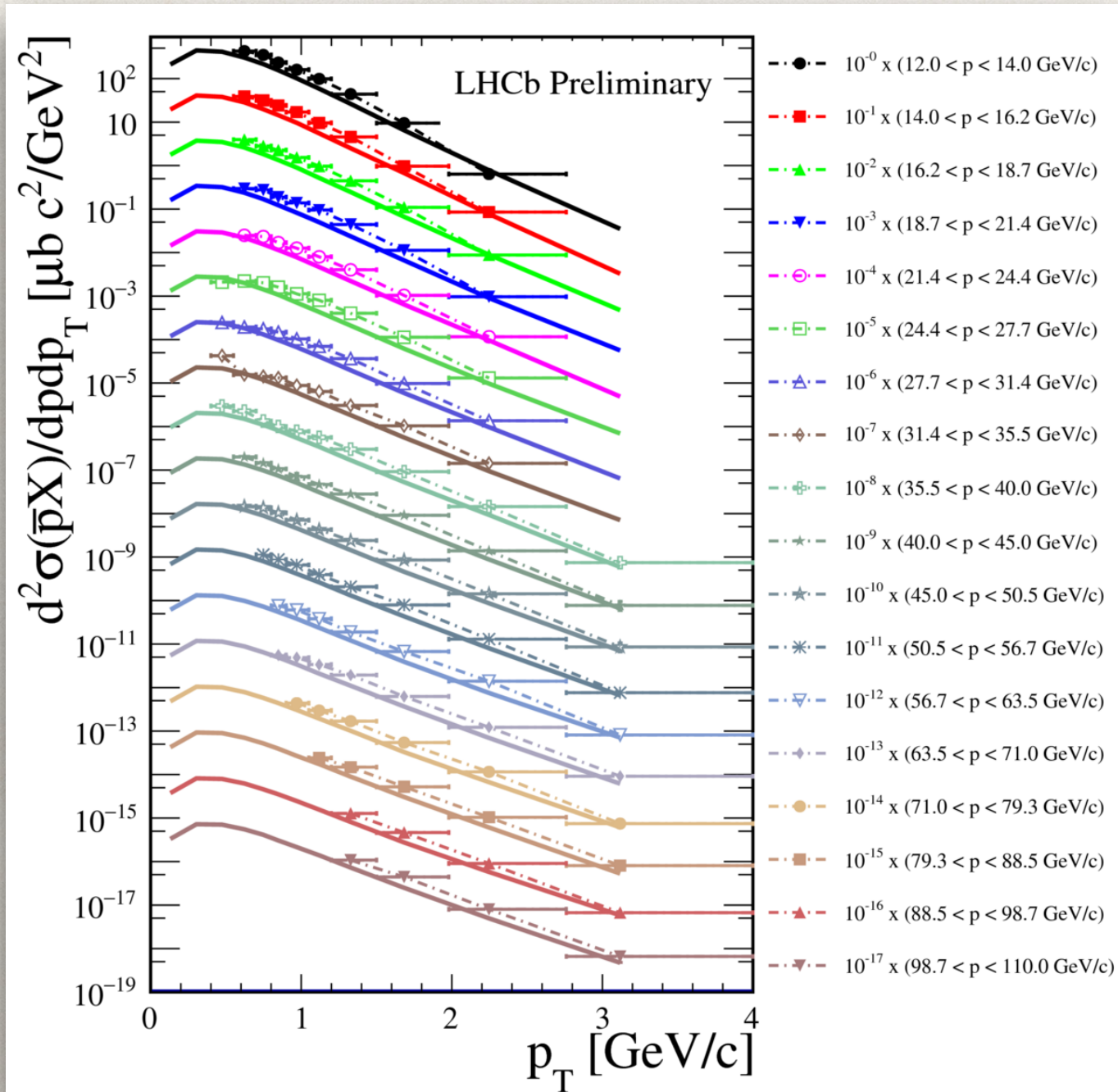
The charged-particle multiplicity dependence of the Bose-Einstein correlation parameters describing the correlation strength and the size of the emitting source is investigated.

The measured correlation radius is found to increase as a function of increasing charged-particle multiplicity, while the chaoticity parameter is seen to decrease.

Activity	N_{ch}	R [fm]	λ	δ [GeV $^{-1}$]
Low	[8,18]	$1.01 \pm 0.01 \pm 0.10$	$0.72 \pm 0.01 \pm 0.05$	$0.089 \pm 0.002 \pm 0.044$
Medium	[19,35]	$1.48 \pm 0.02 \pm 0.17$	$0.63 \pm 0.01 \pm 0.05$	$0.049 \pm 0.001 \pm 0.009$
High	[36,96]	$1.80 \pm 0.03 \pm 0.16$	$0.57 \pm 0.01 \pm 0.03$	$0.026 \pm 0.001 \pm 0.010$

JHEP12(2017)025

Measurement of antiproton production in pHe collisions at $\sqrt{s_{NN}} = 110\text{GeV}$



This result is expected to have a sizeable impact on the accuracy of the prediction for the anti-p/p ratio expected in cosmic rays from spallation of primary protons on the interstellar medium.

Further development of this study in the near future is foreseen, with the inclusion of data collected at $\sqrt{s_{NN}} = 86.6 \text{ GeV}$ during November 2016, and the measurement of the contribution due to hyperon decays.

LHCb-CONF-2017-002

Result for the anti-p cross-section measurement.

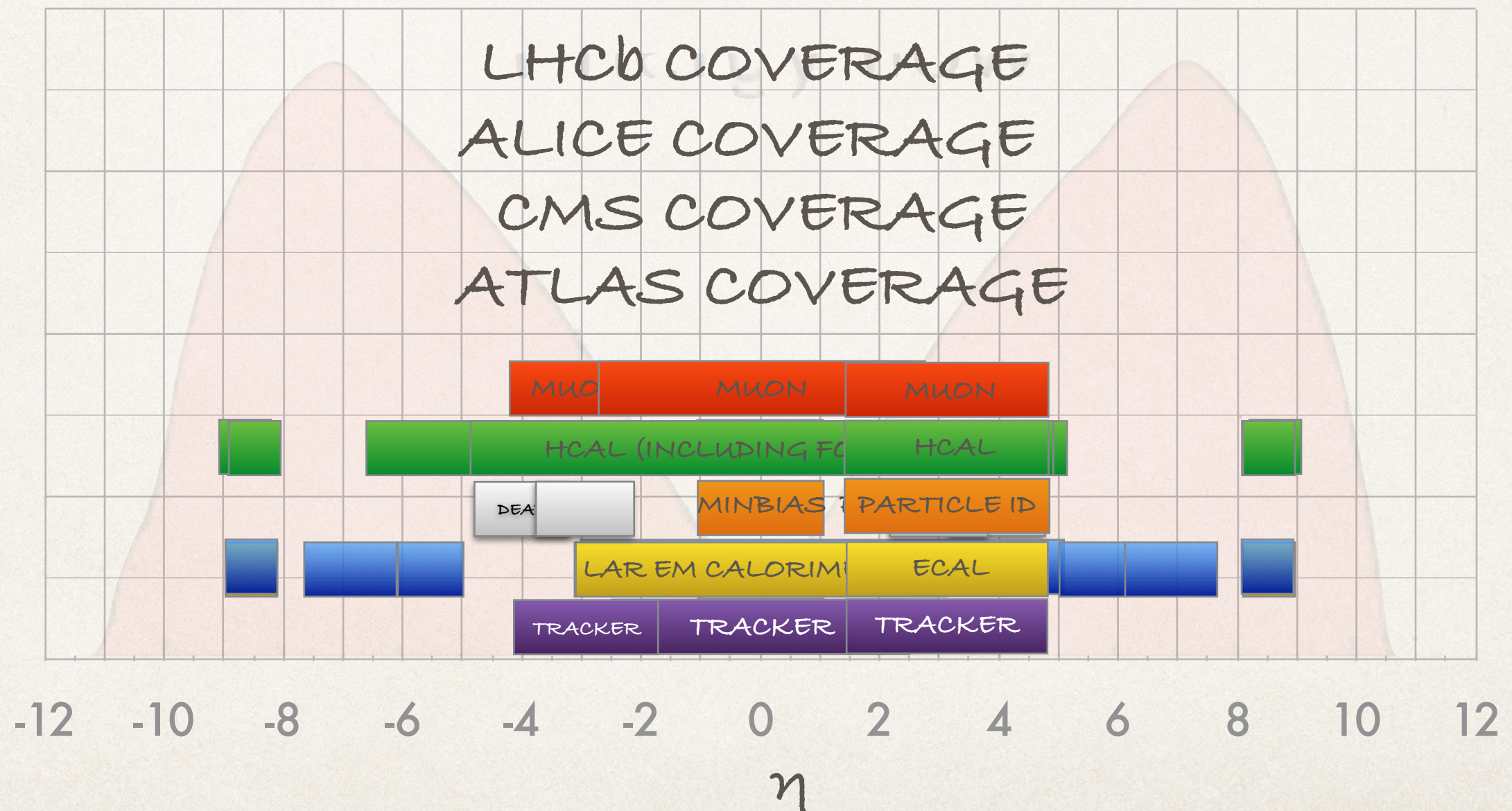
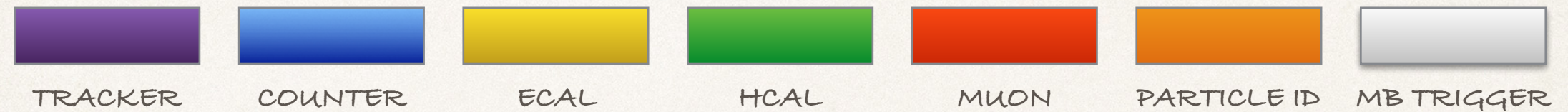
The data points show the double differential cross-section as a function of p_T in the 18 momentum bins, with values successively scaled by a factor 0.1.

The solid curves show the EPOS LHC absolute predictions, scaled with the same factors as the data.

The errors bars, barely visible, show the uncorrelated uncertainty only.

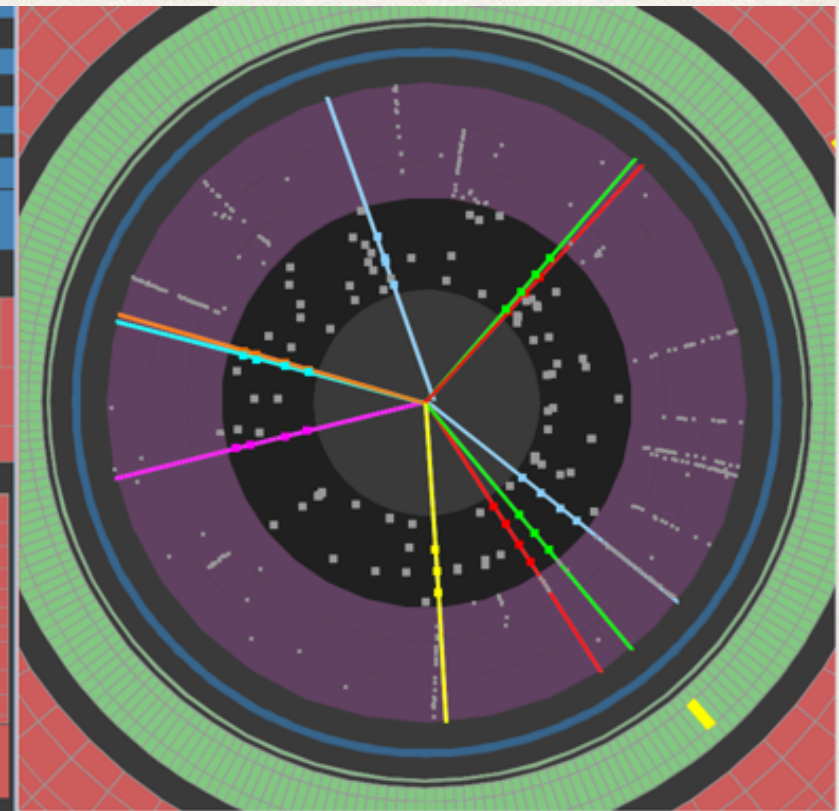
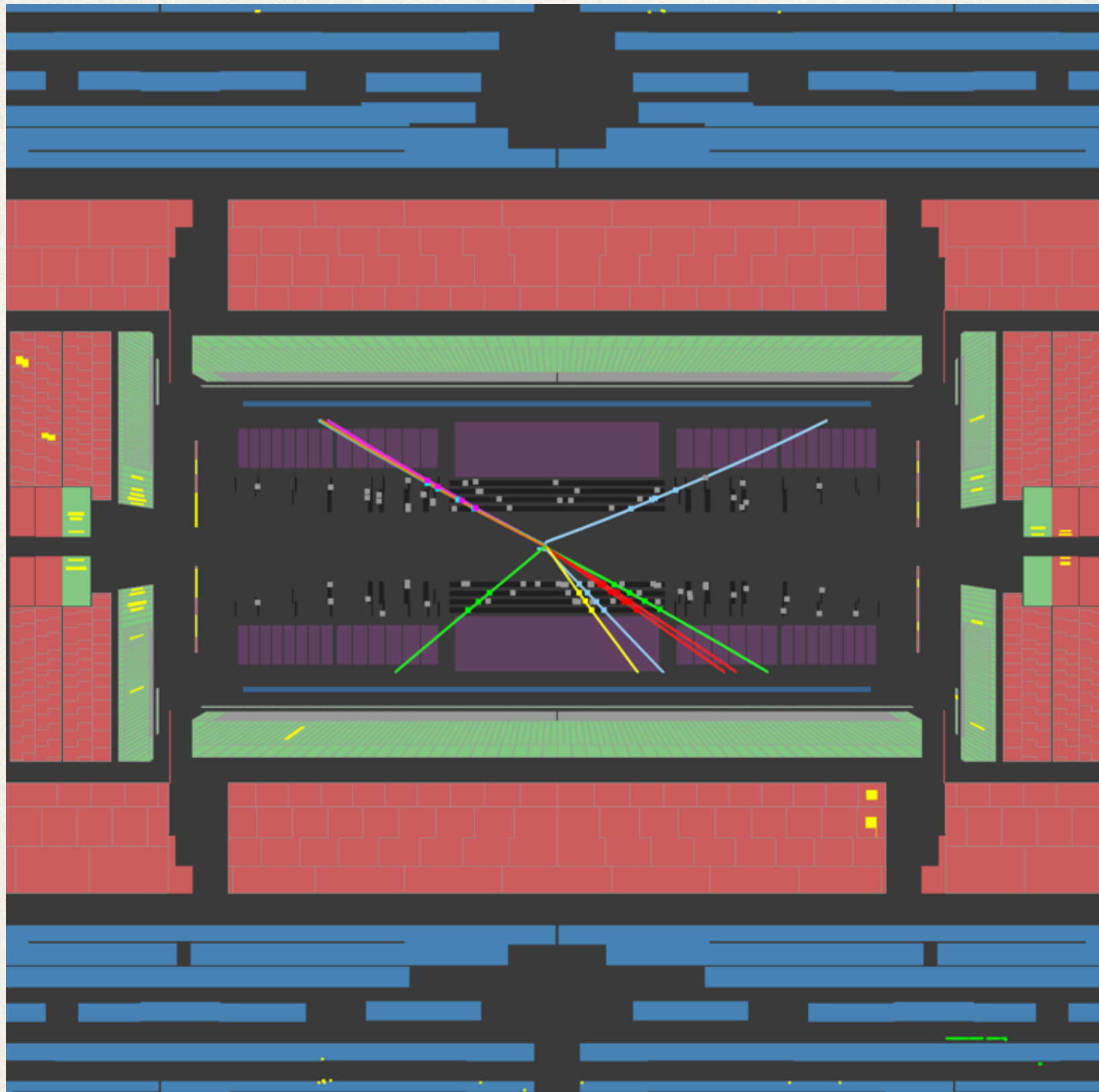


Detector Coverage



2009

single vertex



ATLAS

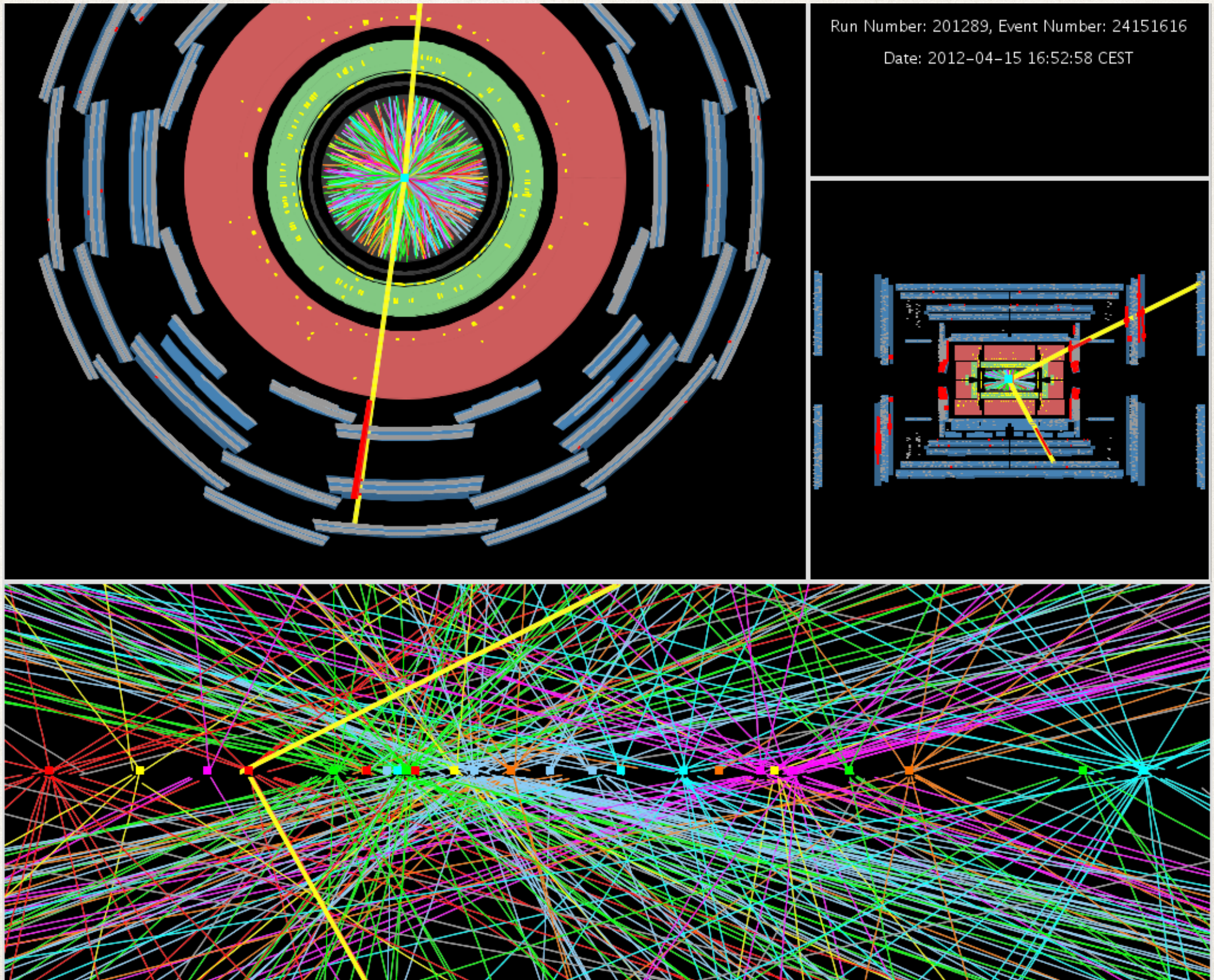
EXPERIMENT

2009-11-23, 14:38 CET
Run 140541, Event 184417

Candidate Collision Event

2012

Pile-up: 25 collisions



Heavy-ion collision

