QCD measurements at the LHC

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PHENOEXP 2018: LHC Physics and beyond

Outline:

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

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)

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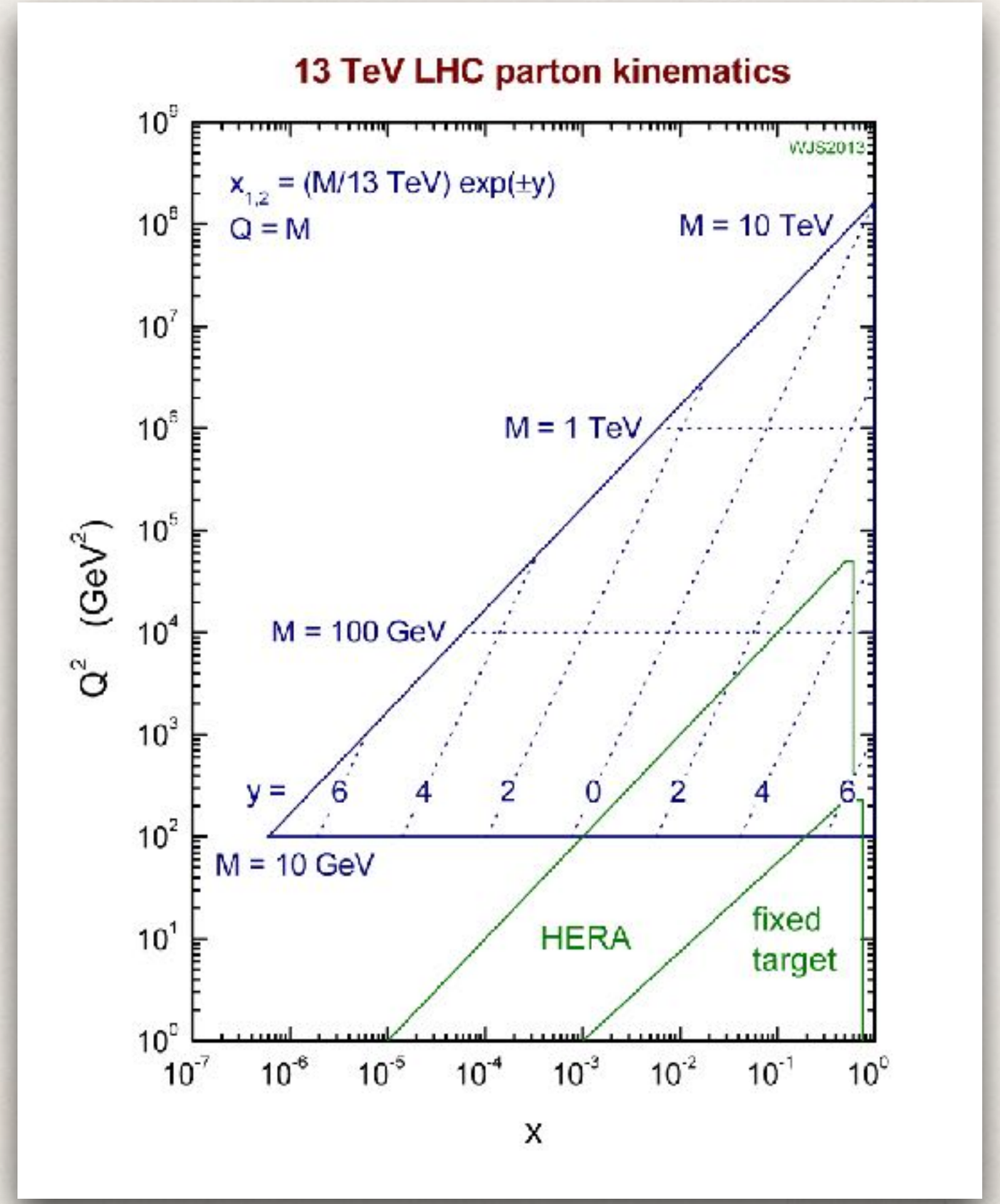
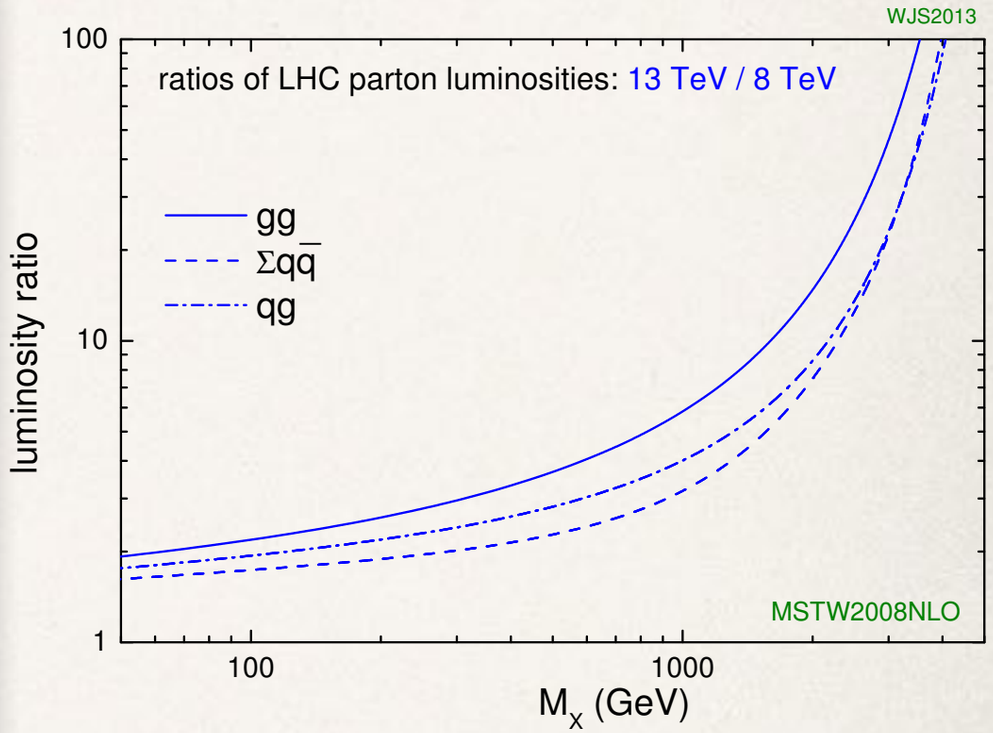
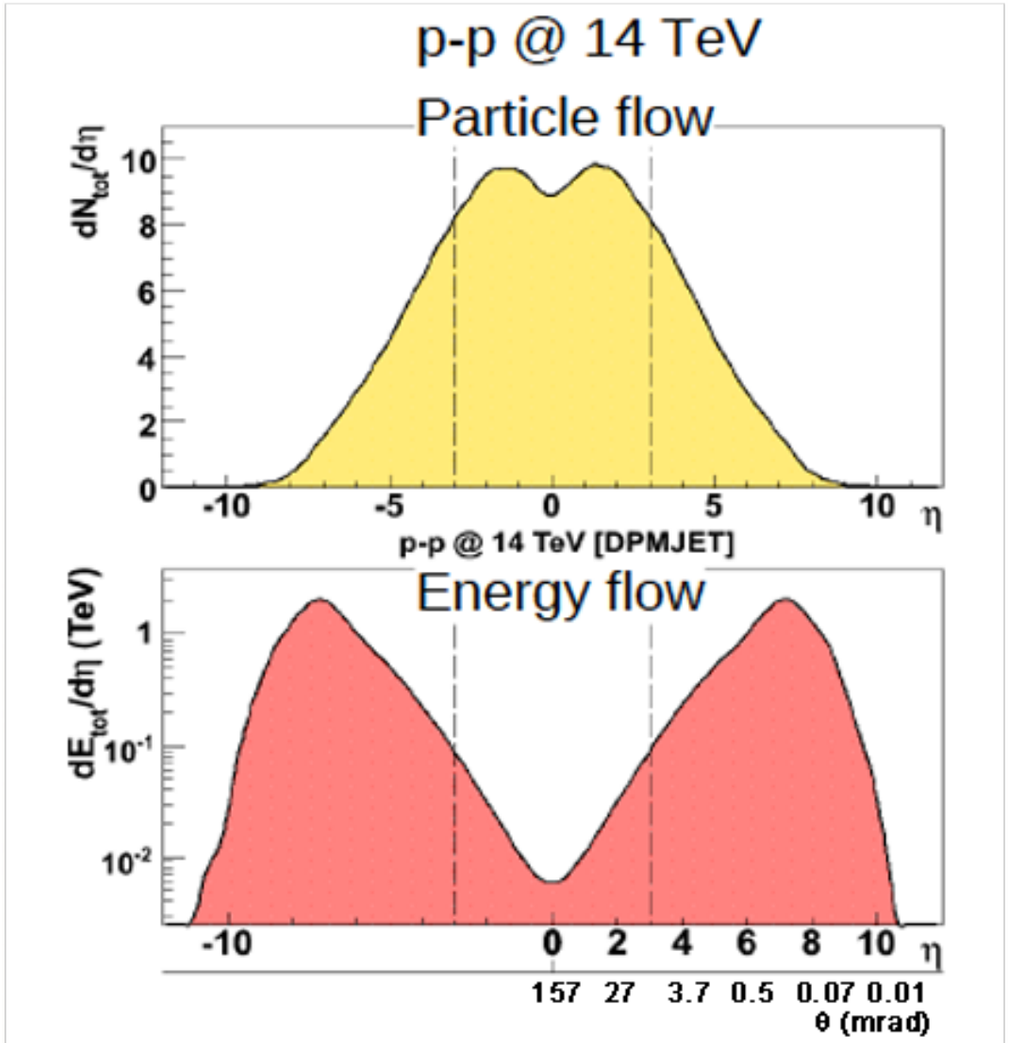
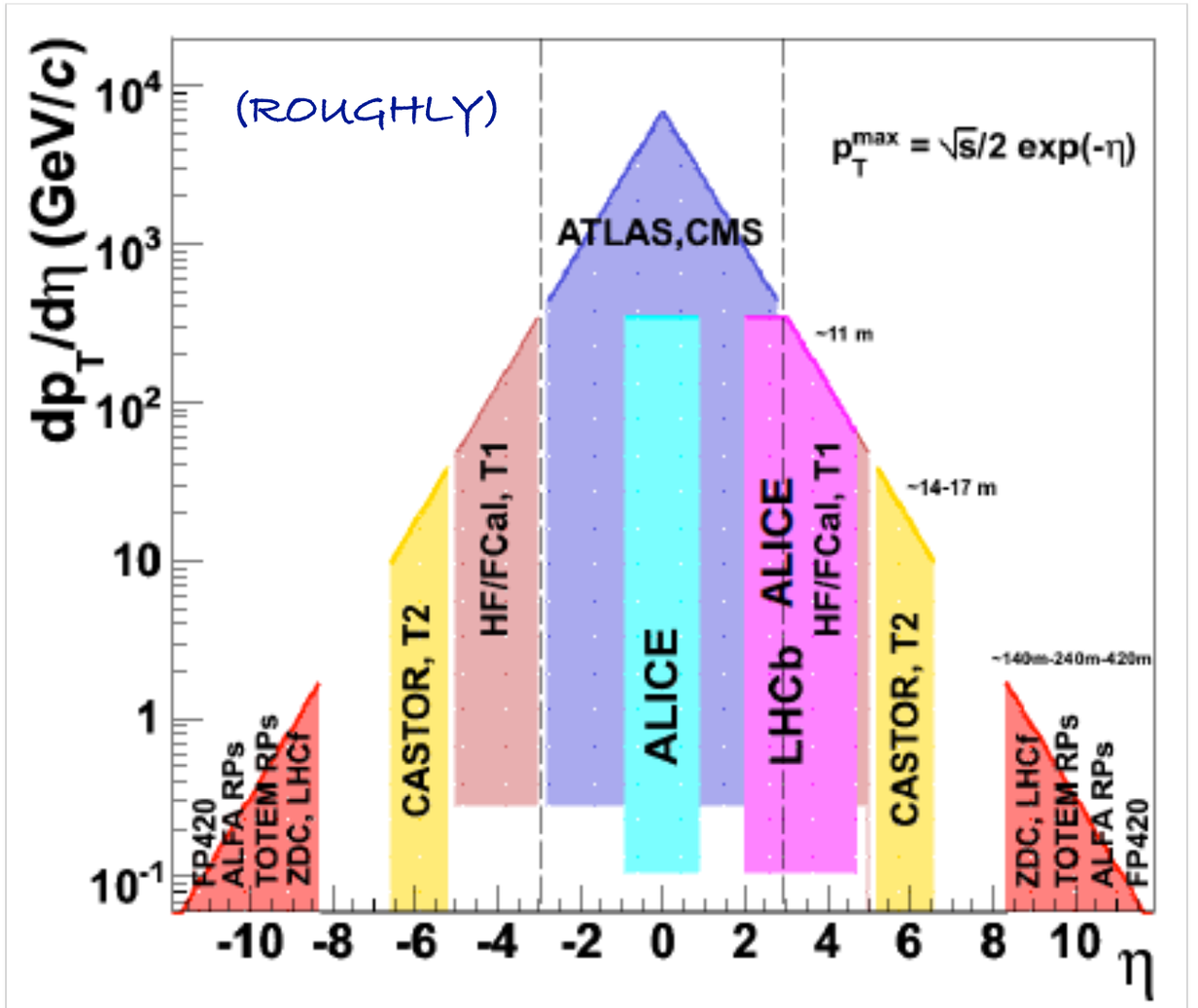
Parton kinematics at the LHC



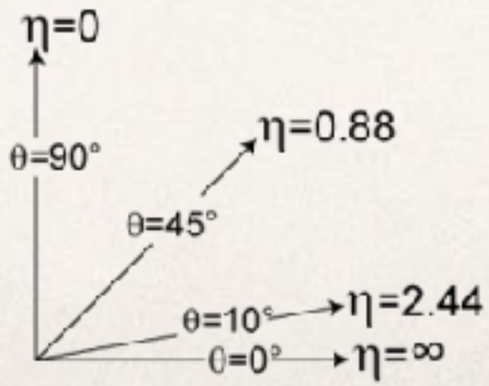


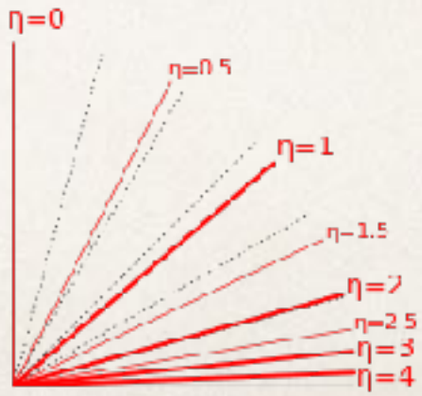
Detector Coverage



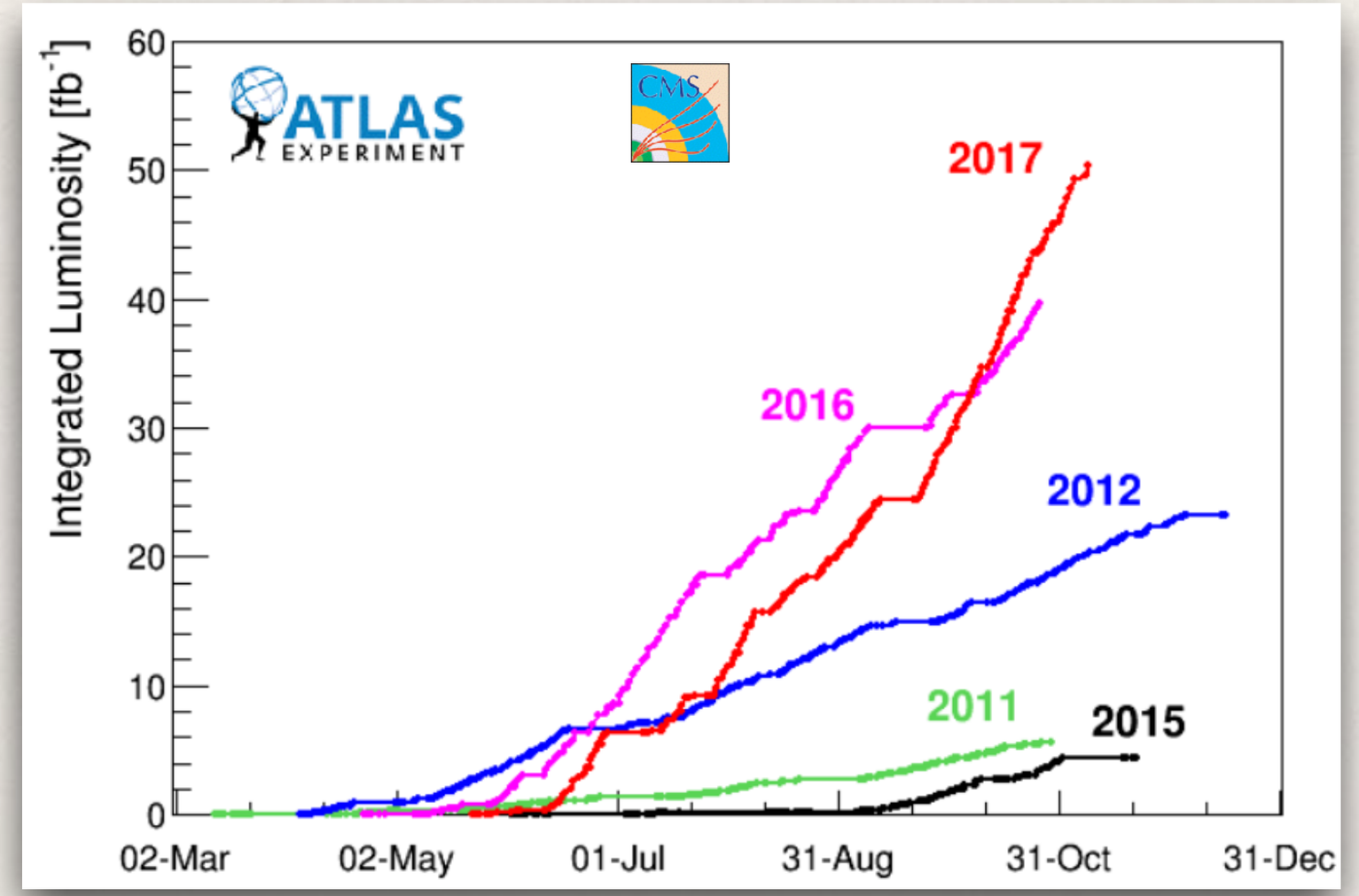


$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$





The Large Hadron Collider: pp collisions



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

https://lpc.web.cern.ch

http://cern.ch/amoraes

$\sqrt{s}$=0.9 TeV

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

"Long Shutdown 1"

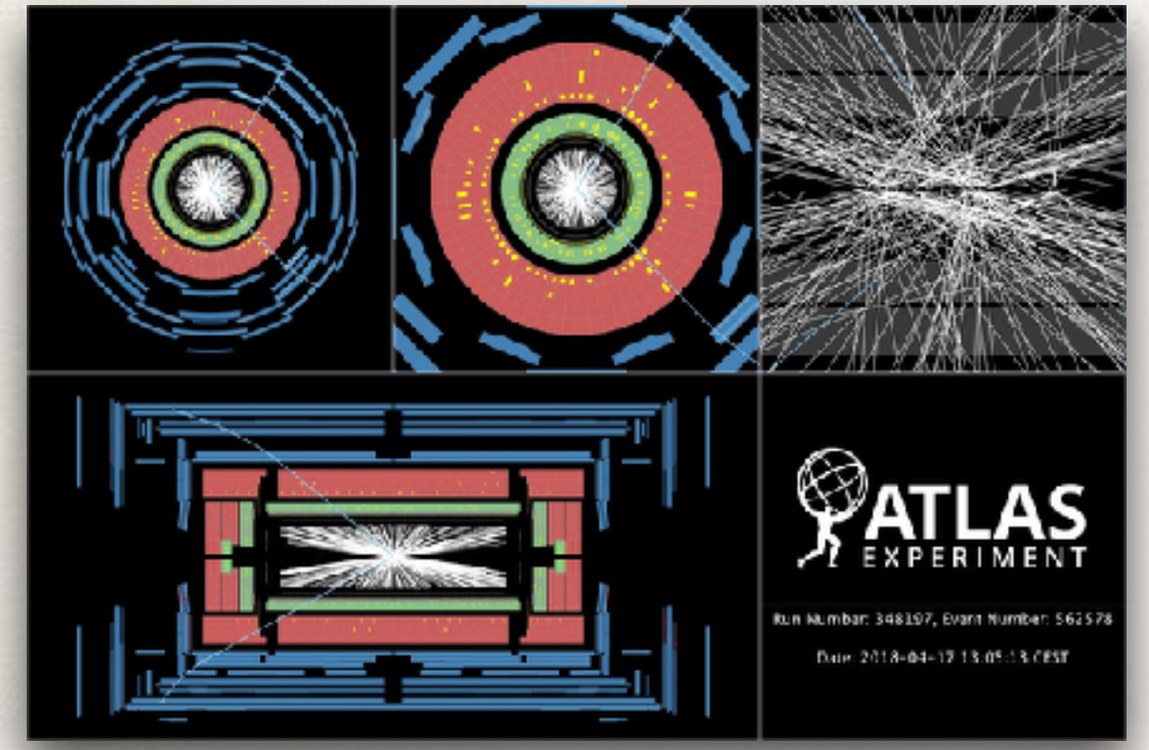
$\sqrt{s}$=13 TeV

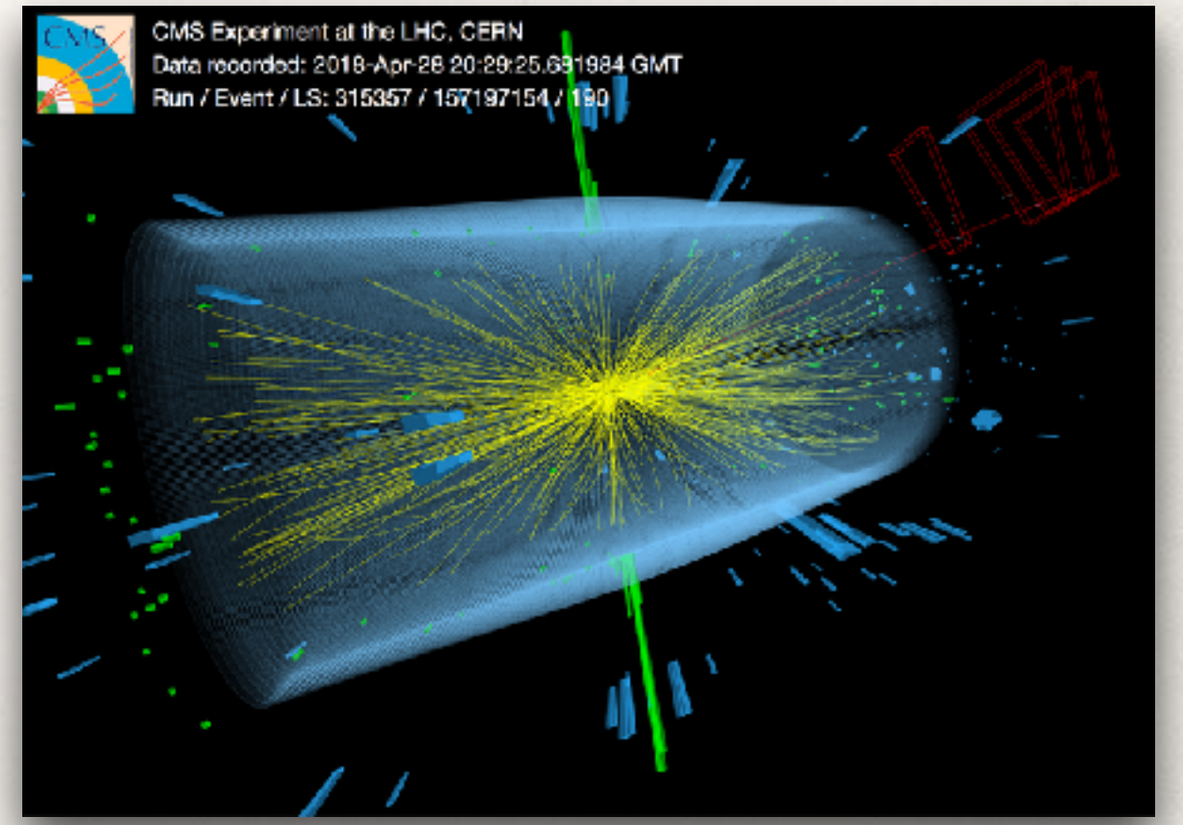
"Long Shutdown 2"

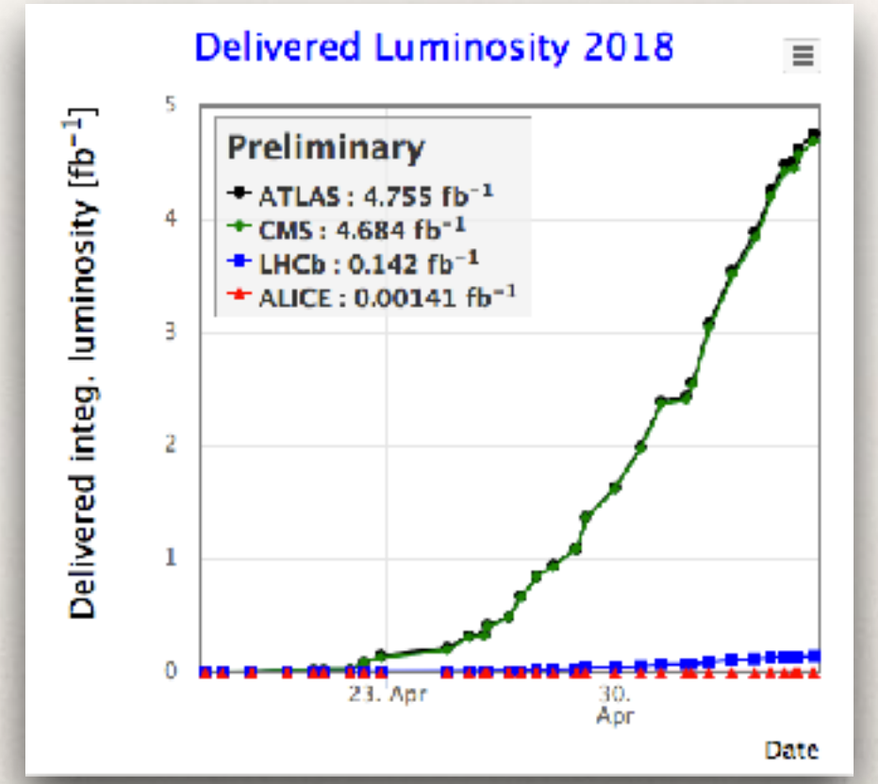
2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

Run 1 Run 2

The 2018 data-taking run at the LHC has begun







On Saturday, 28 April 2018, the LHC successfully injected 1200 bunches of protons into the machine and collided them. This formally marks the beginning of the LHC's 2018 physics season.

The target for LHC this year is to achieve 60 inverse femtobarns (fb^{-1}) of proton-proton collisions delivered to both ATLAS and CMS,

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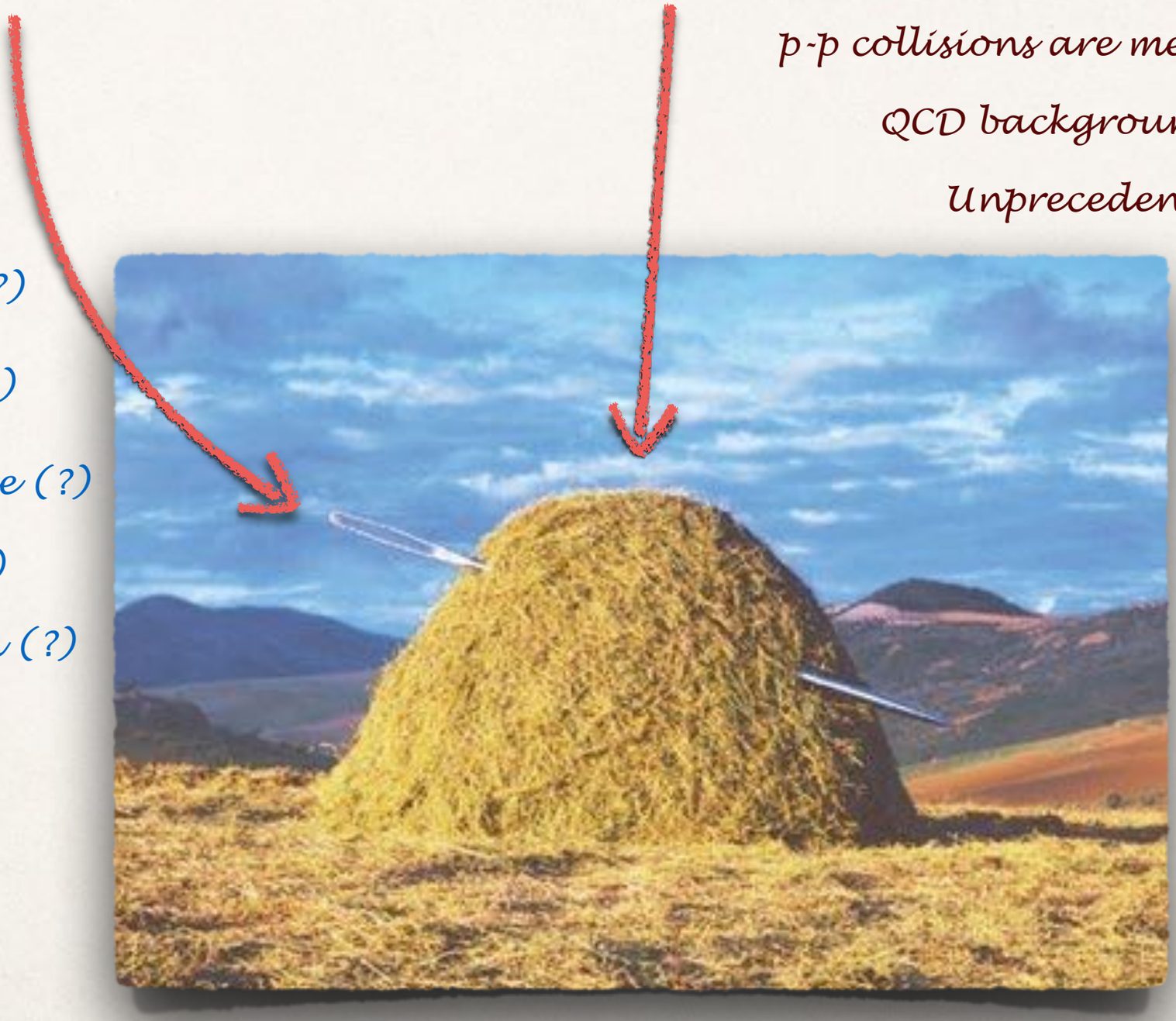
QCD at the LHC: why bother?

"Needle in a haystack" problem!

p-p collisions are messy!

QCD background

Unprecedented pile up



Higgs boson (?)

SUSY decay (?)

heavy resonance (?)

monojet (?)

4th generation (?)

…

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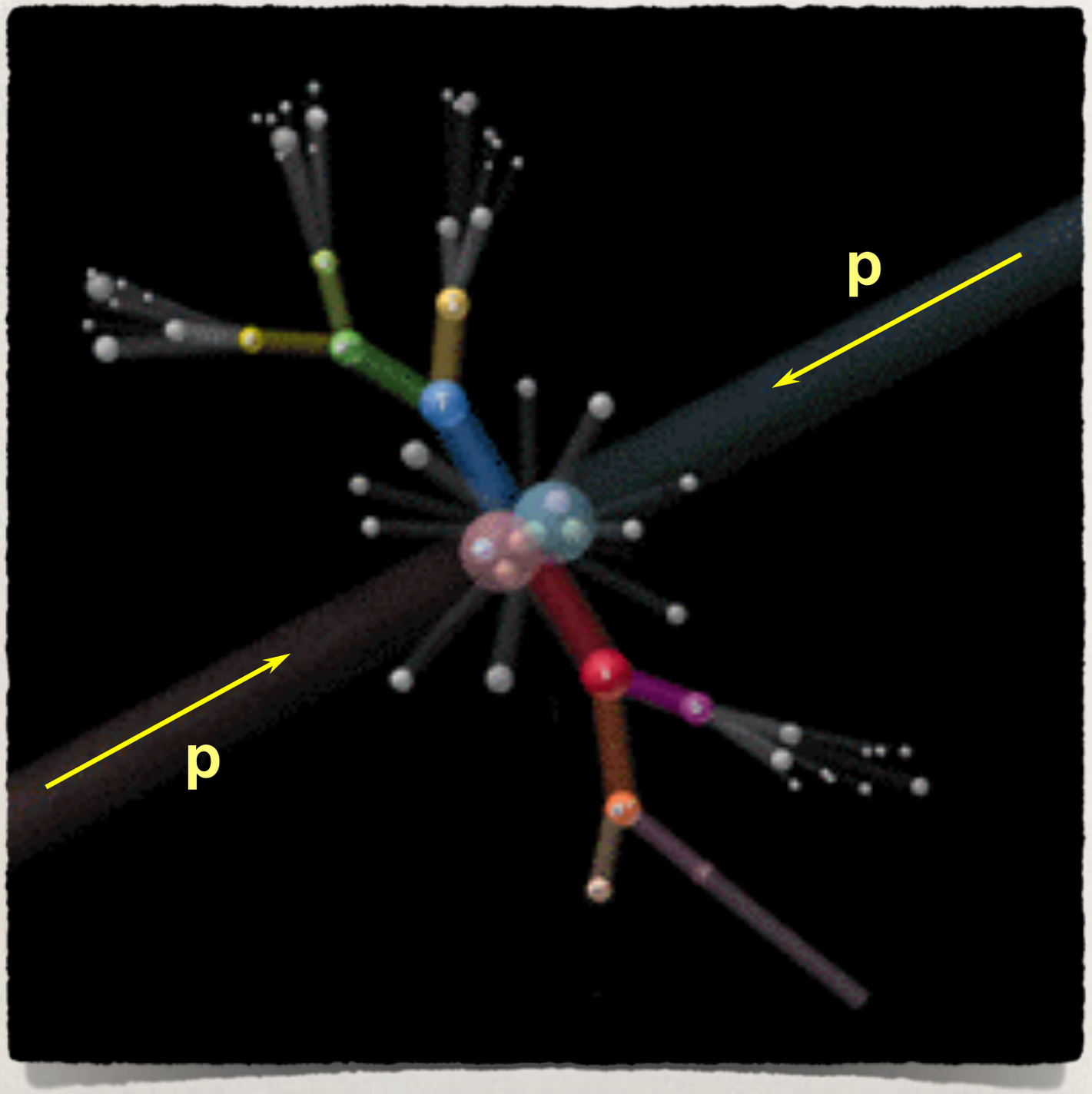
QCD at the LHC



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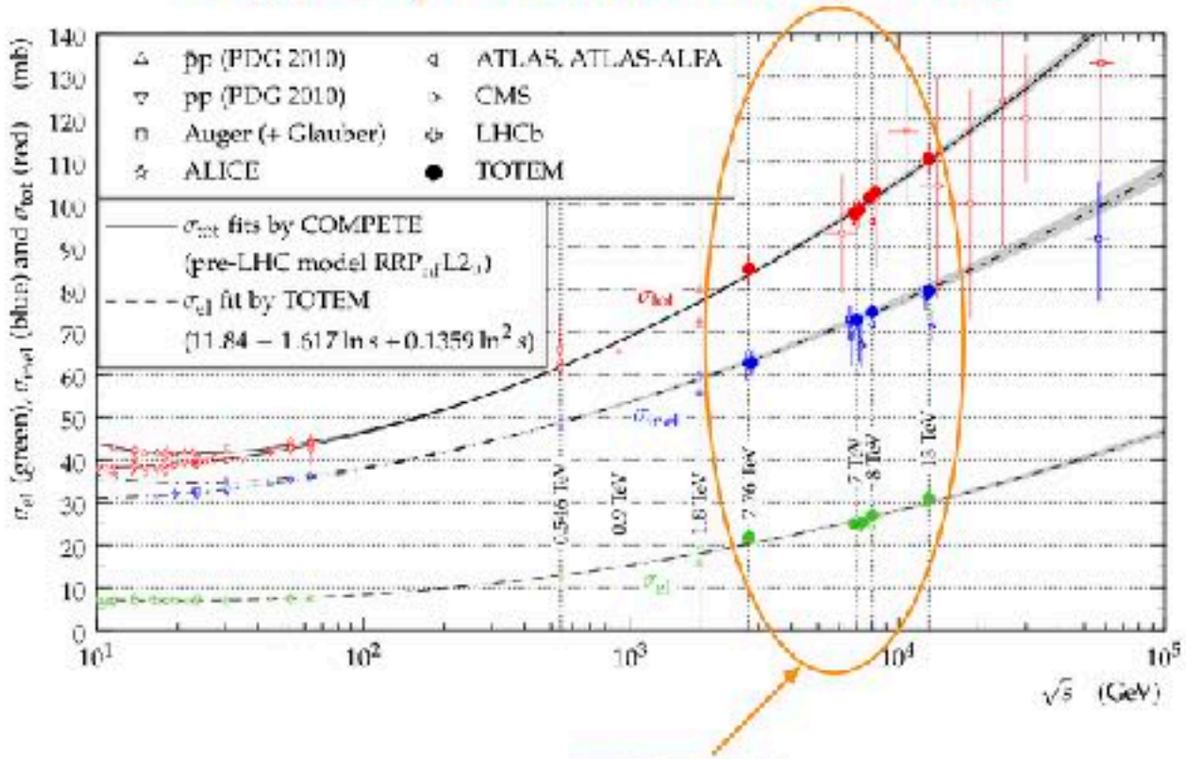
- Essentially all physics at high-energy hadron colliders is connected to the interactions of quarks and gluons (small & large transferred momentum).
  - Hard processes (high-p_T): well described by perturbative QCD
  - Soft interactions (low-p_T): require non-perturbative phenomenological models

- 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.

Total and elastic pp cross-section

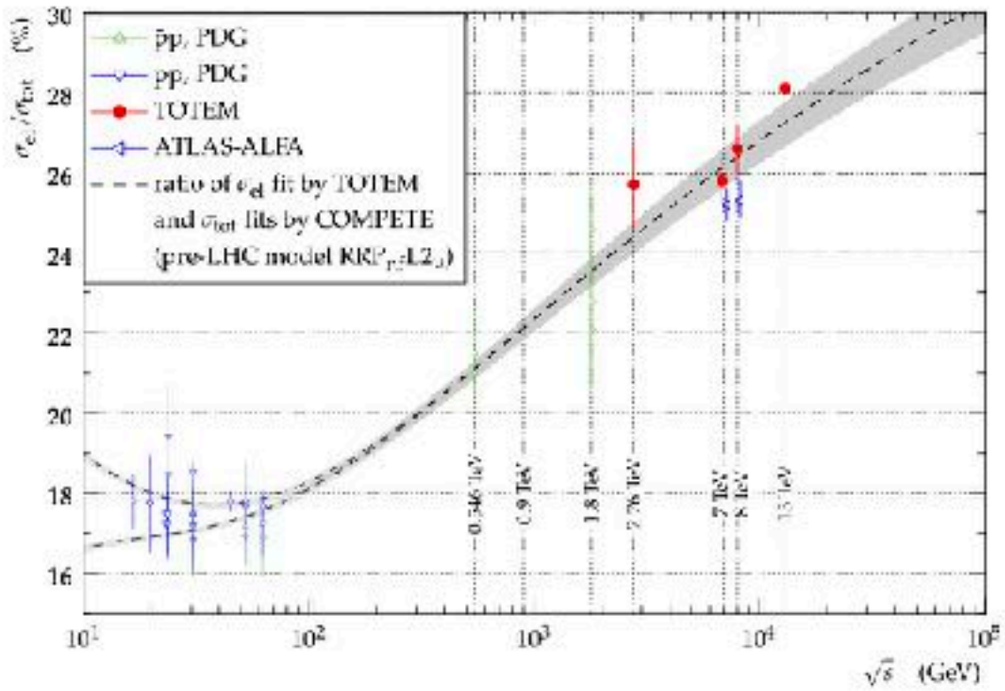
$\sigma_{tot} = (110.6 \pm 3.4)$ mb



TOTEM
published measurements

$\sigma_{el} = (31.0 \pm 1.7)$ mb

$\sigma_{inel} = (79.5 \pm 1.8)$ mb



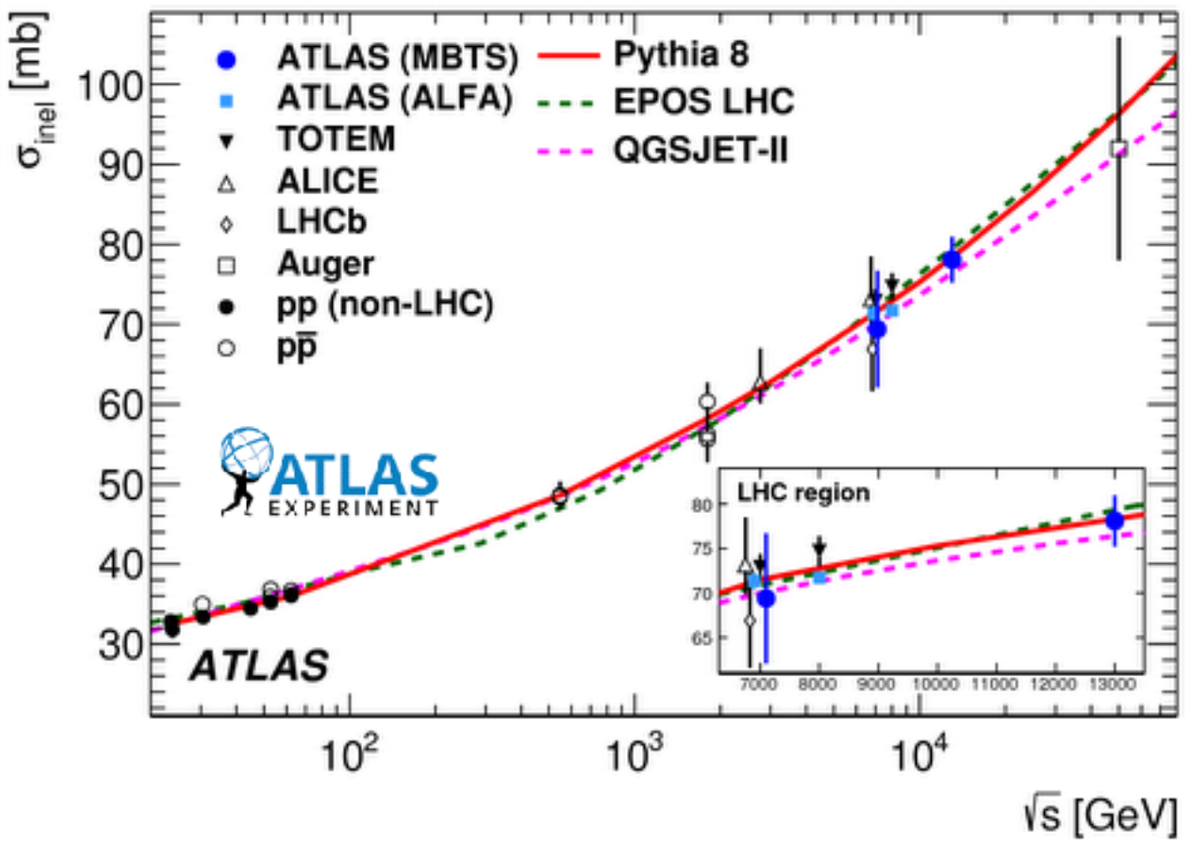
arXiv:1712.06153

The TOTEM collaboration has measured the pp total cross section at √s=13TeV with a luminosity-independent method.

Using dedicated β*=90m beam optics, the Roman Pots were inserted very close to the beam.

The inelastic scattering rate has been measured by the T1 and T2 telescopes during the same LHC fill. After applying the optical theorem the total proton-proton cross section is σtot=(110.6±3.4) mb, well in agreement with the extrapolation from lower energies.

Inelastic pp cross-section



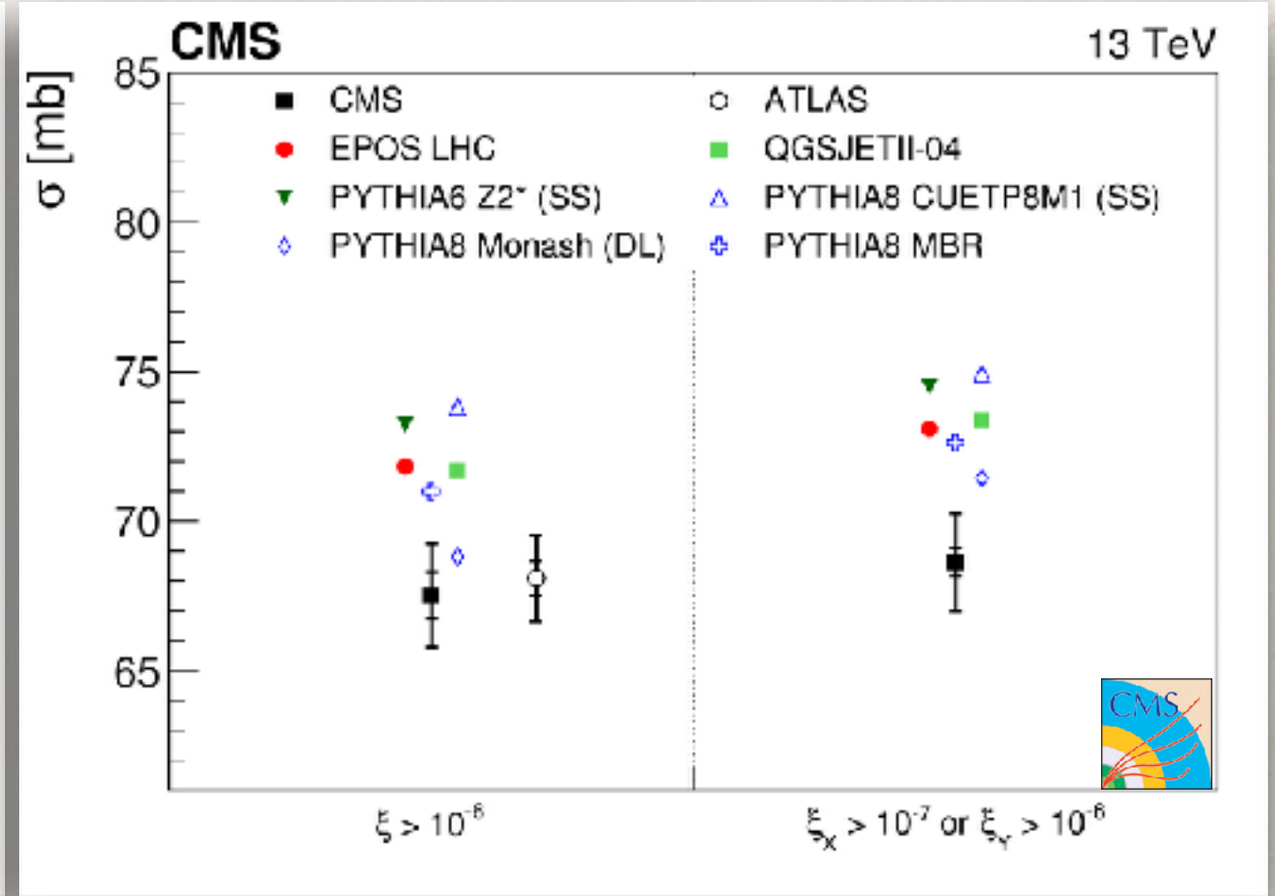
The inelastic proton-proton cross section versus √s.

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



Proton-proton inelastic cross section at √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).

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

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

arXiv:1802.02613v1

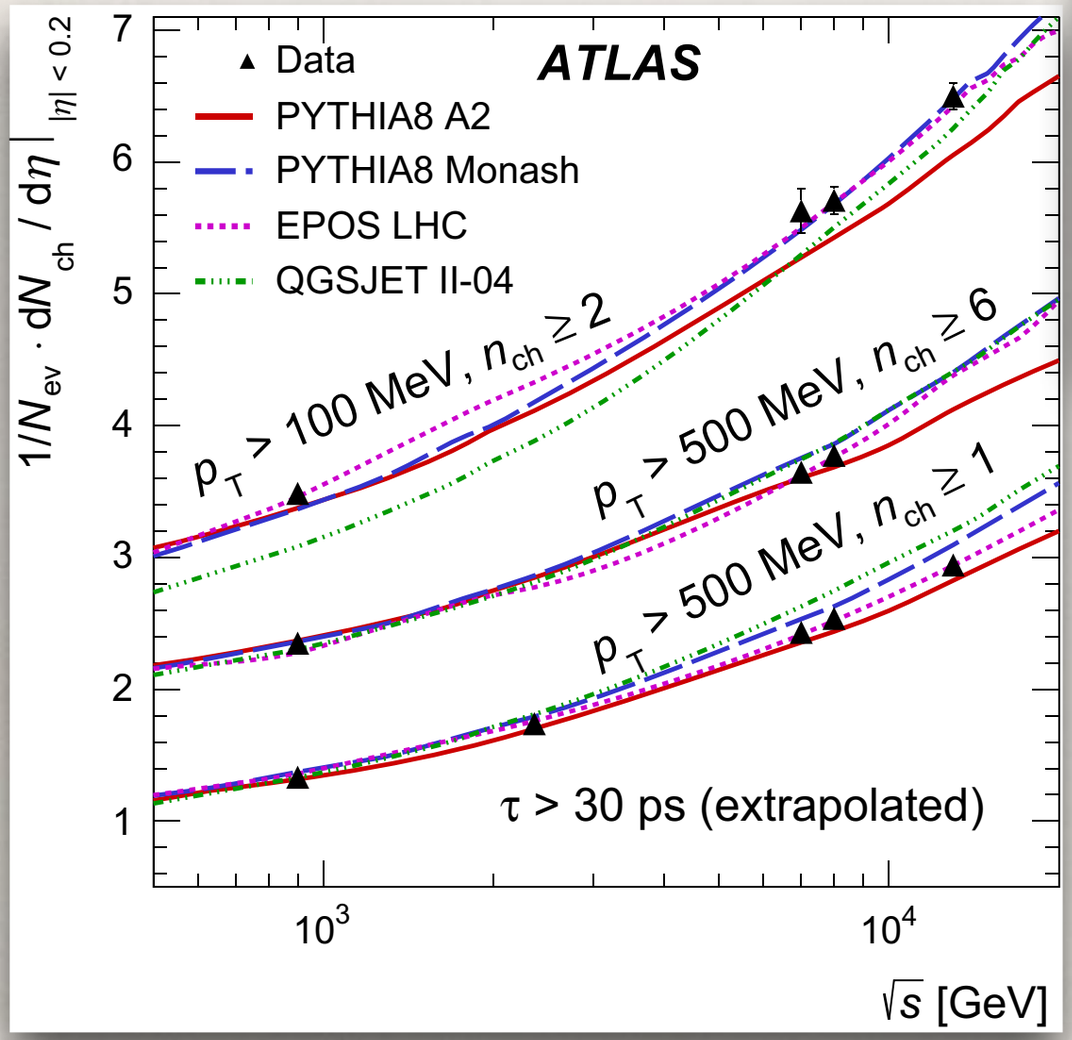
Submitted to J. High Energy Phys. (Feb 2018)

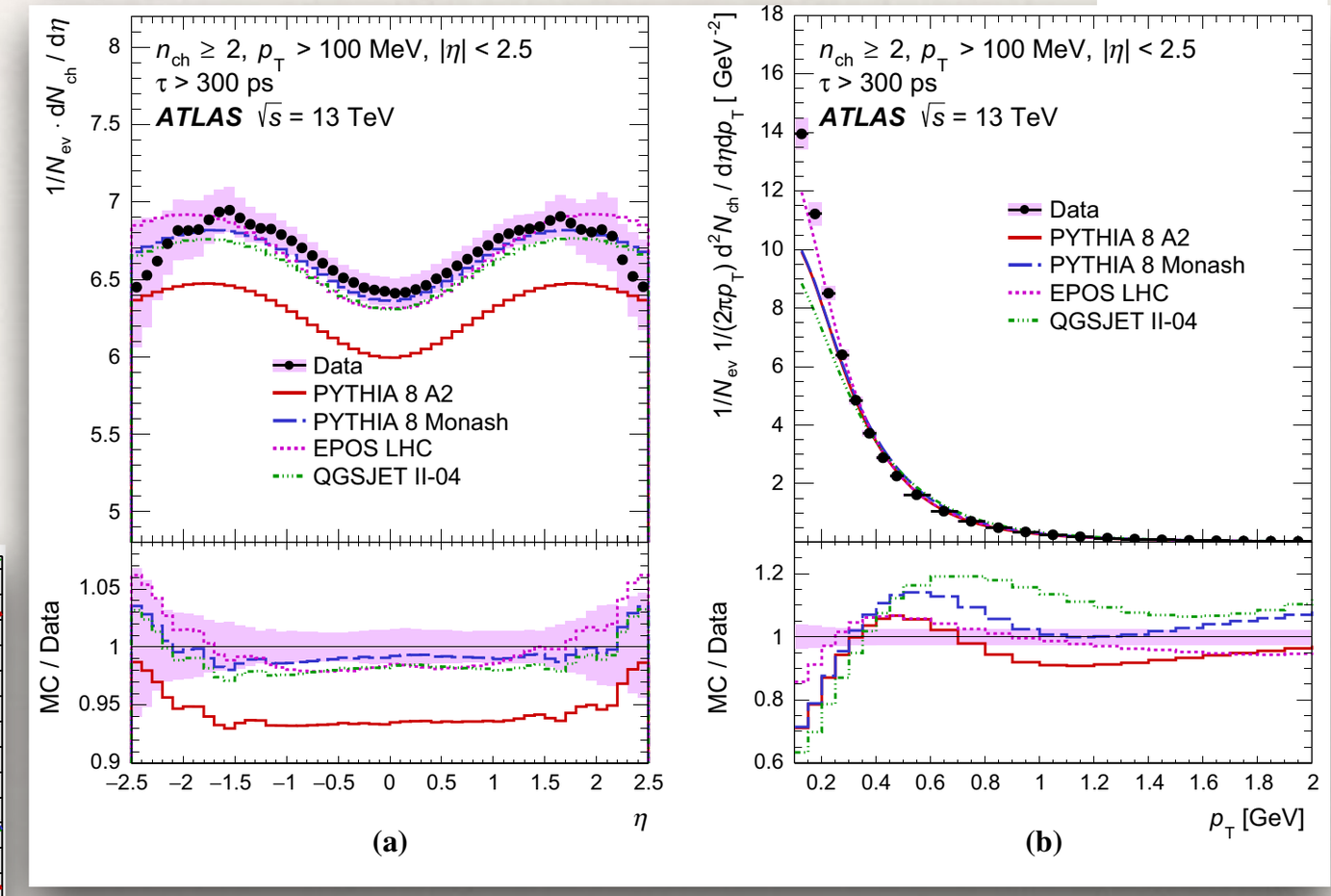
Charged Particle Density

$n_{ch} > 2$

$|\eta| < 2.5$

$p_T > 100$ 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 $p_T > 500$ MeV.

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

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

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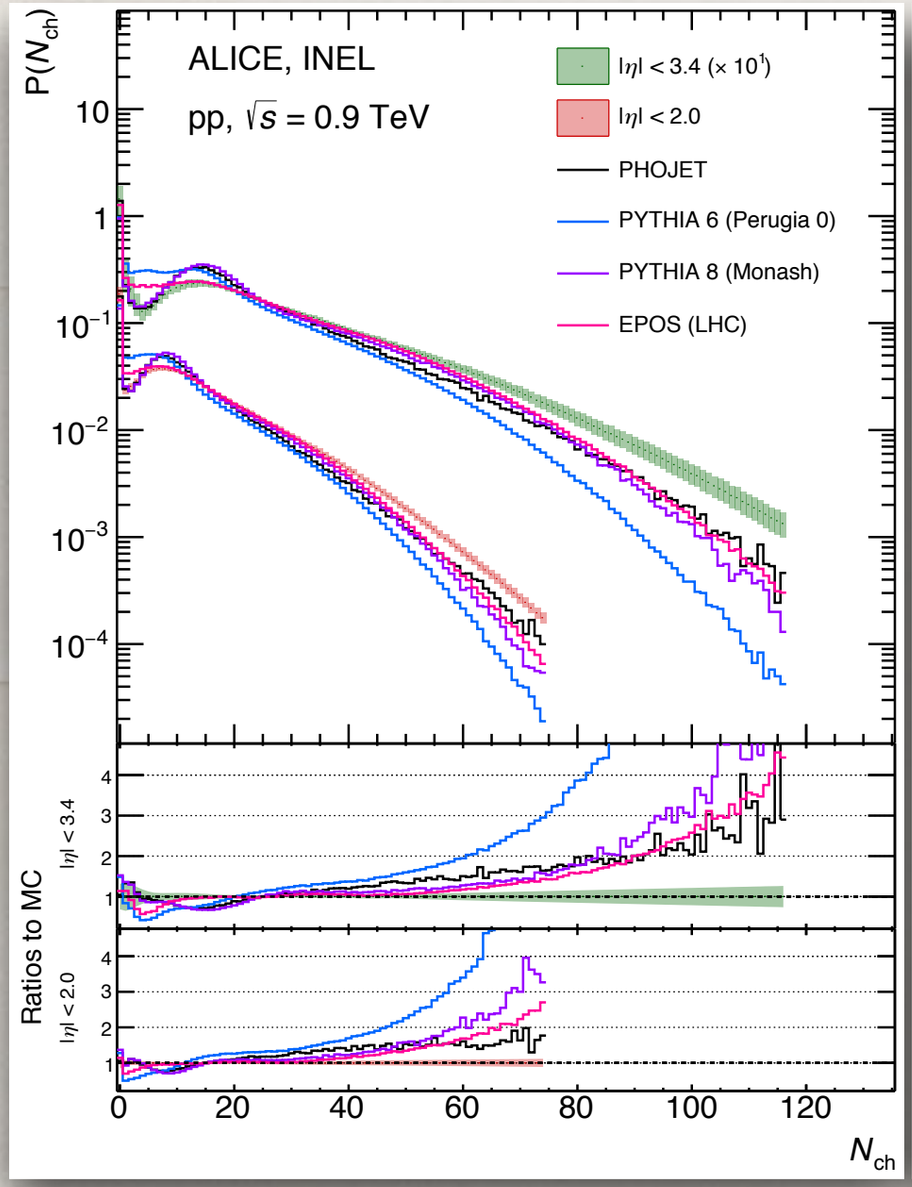
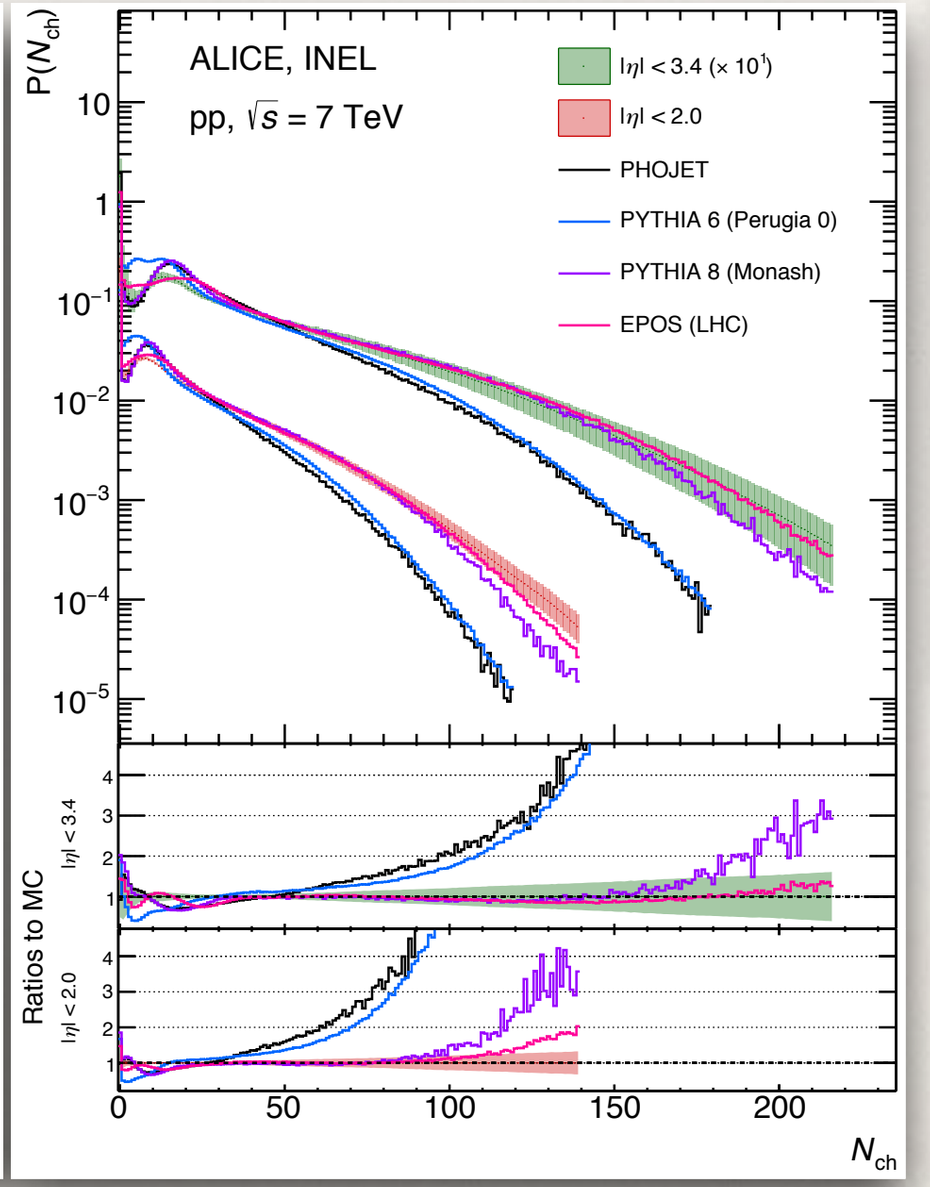
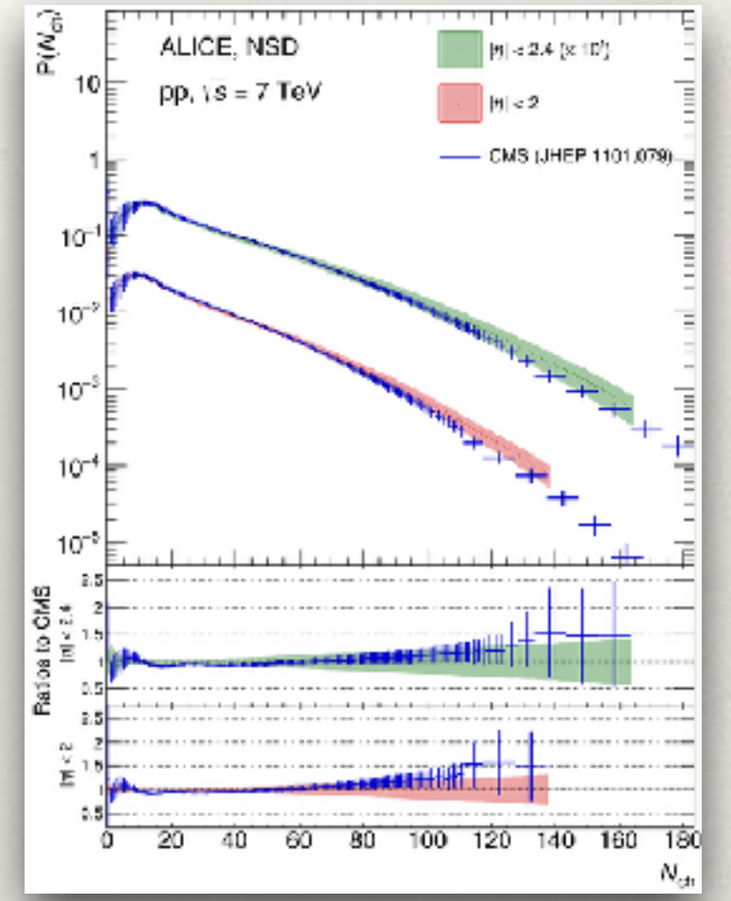
Charged Particle Multiplicity

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.

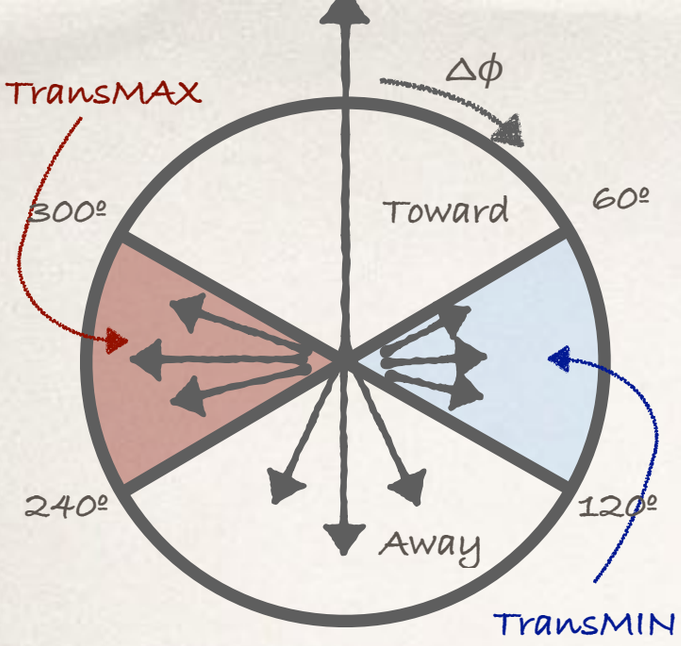




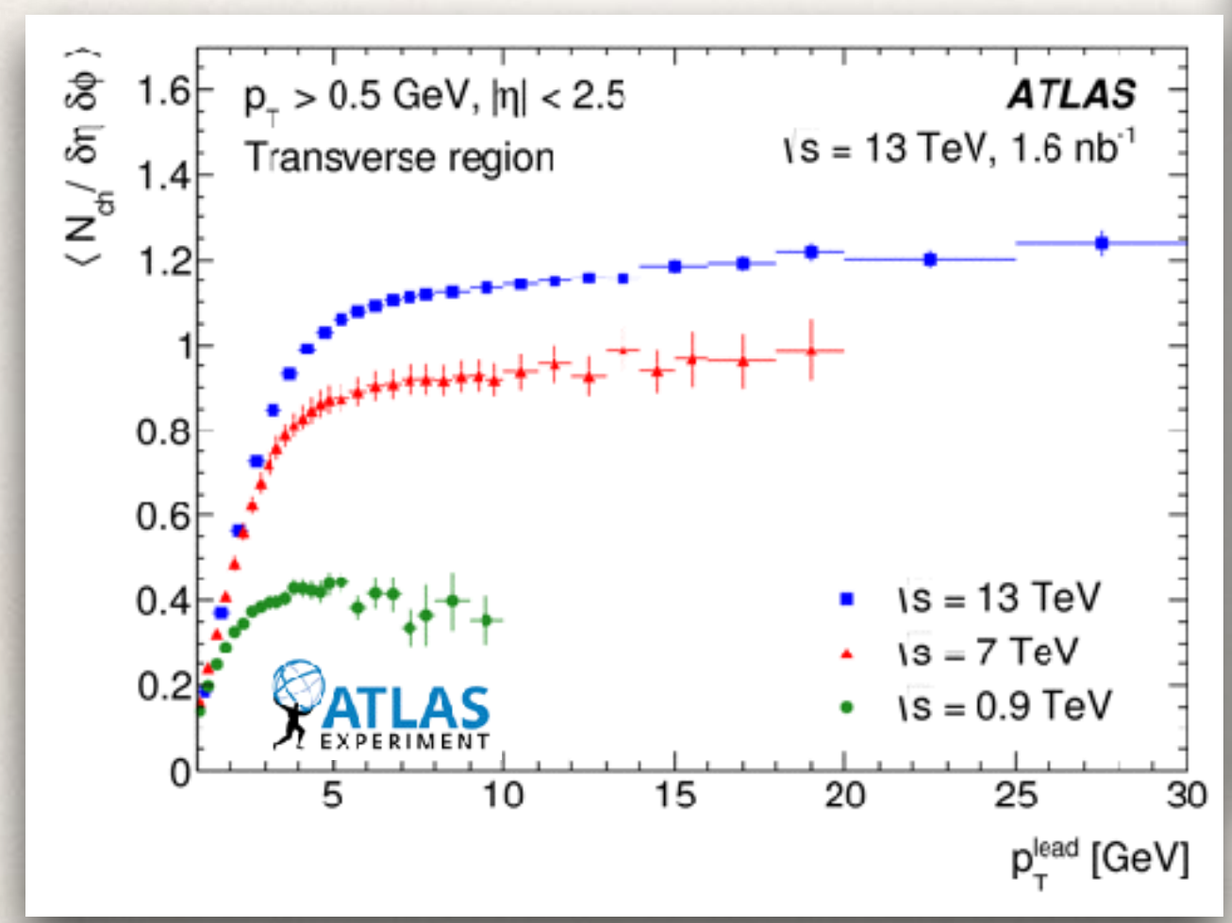


Eur. Phys. J. C 77 (2017) 852

The underlying event

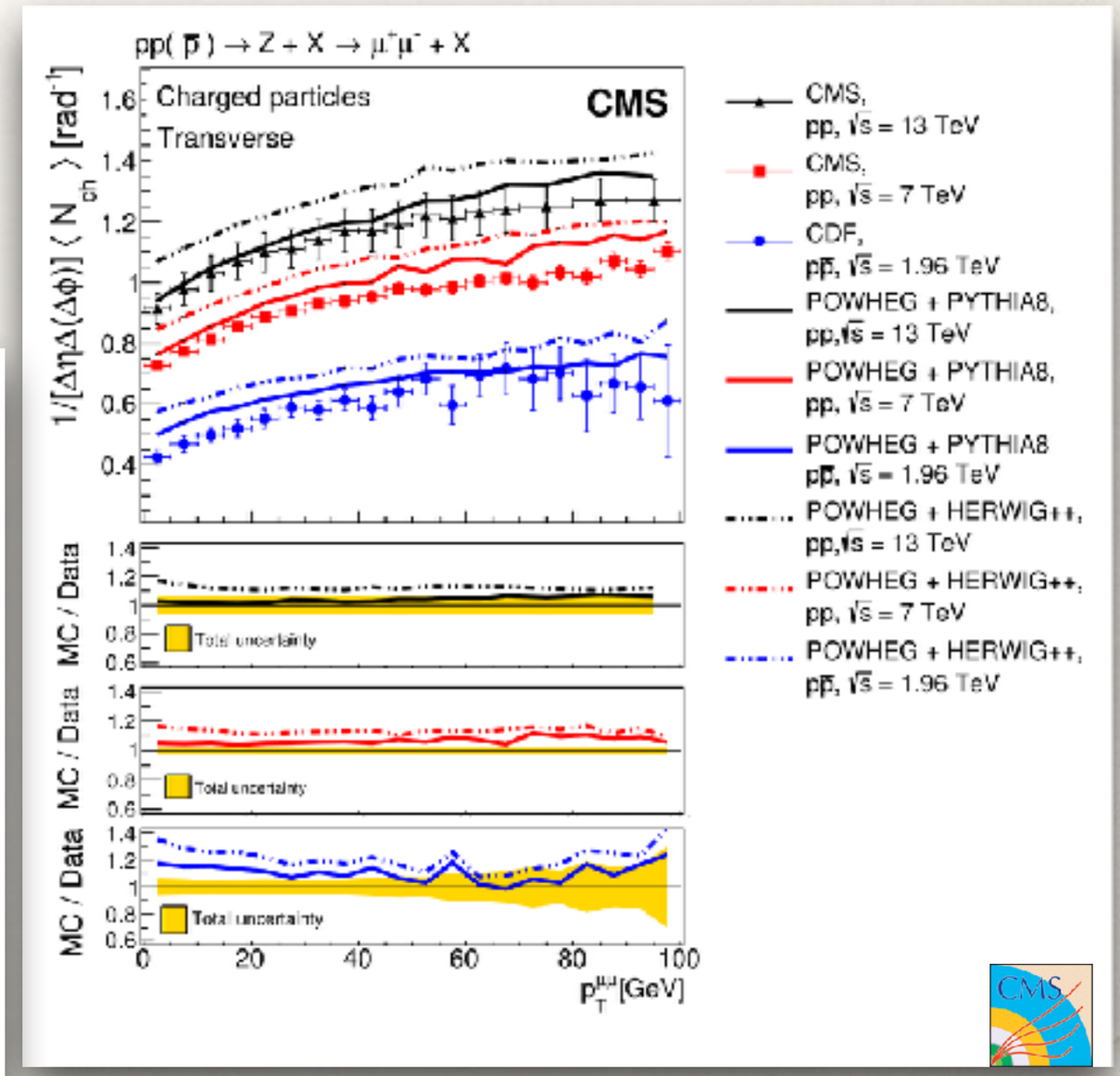


Measurement of the underlying event activity in pp collisions at 13 TeV associated to the leading charged particle (ATLAS).



JHEP03(2017)157

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



arXiv:1711.04299

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

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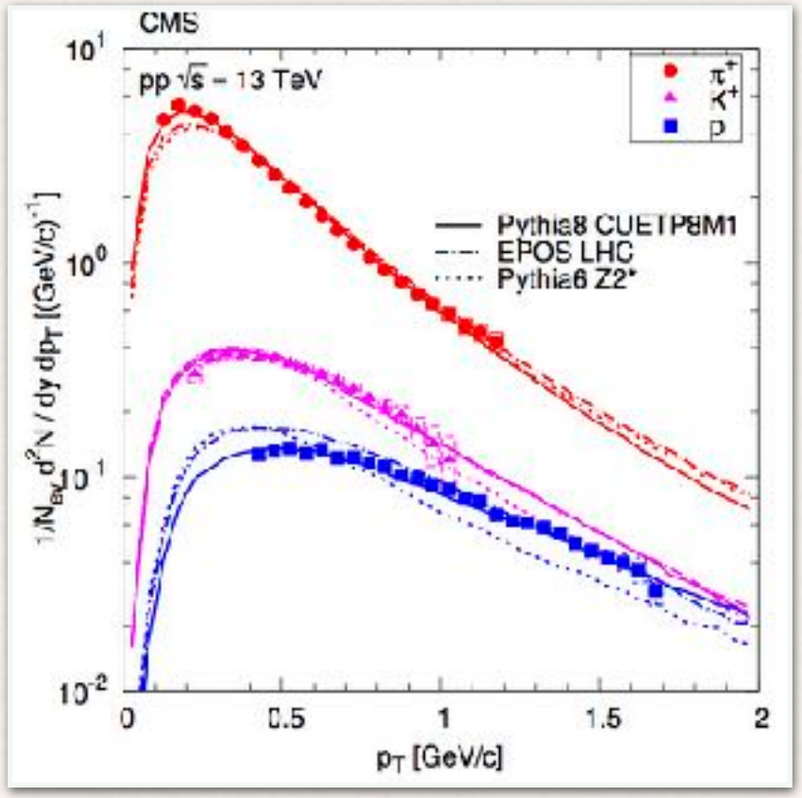
Measurement of charged pion, kaon, and proton production in proton-proton collisions at √s = 13 TeV

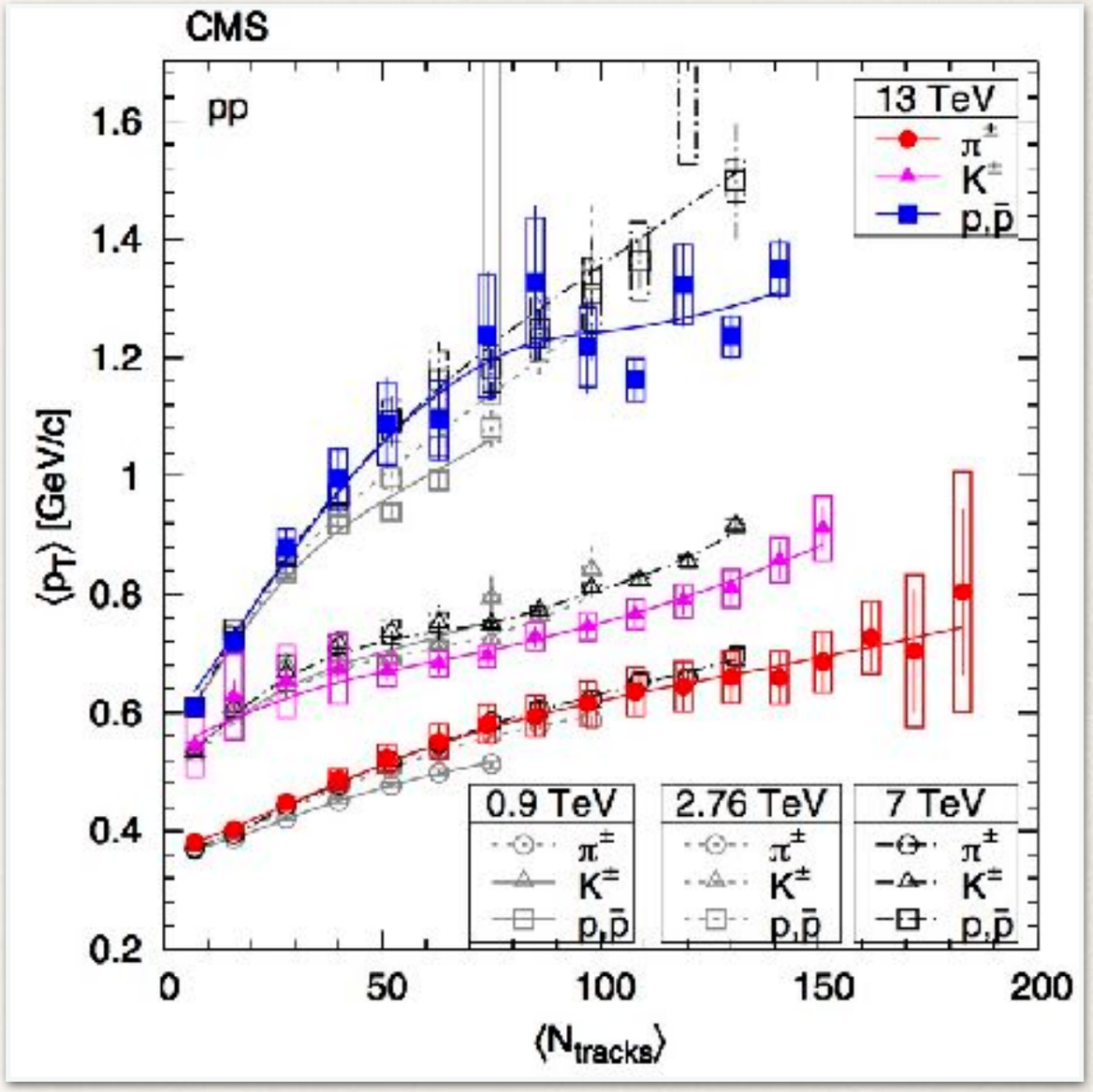


Transverse momentum spectra have been measured for different charged hadron species produced in inelastic pp collisions at
√s=13 TeV.

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 $|\eta|<2.4$.

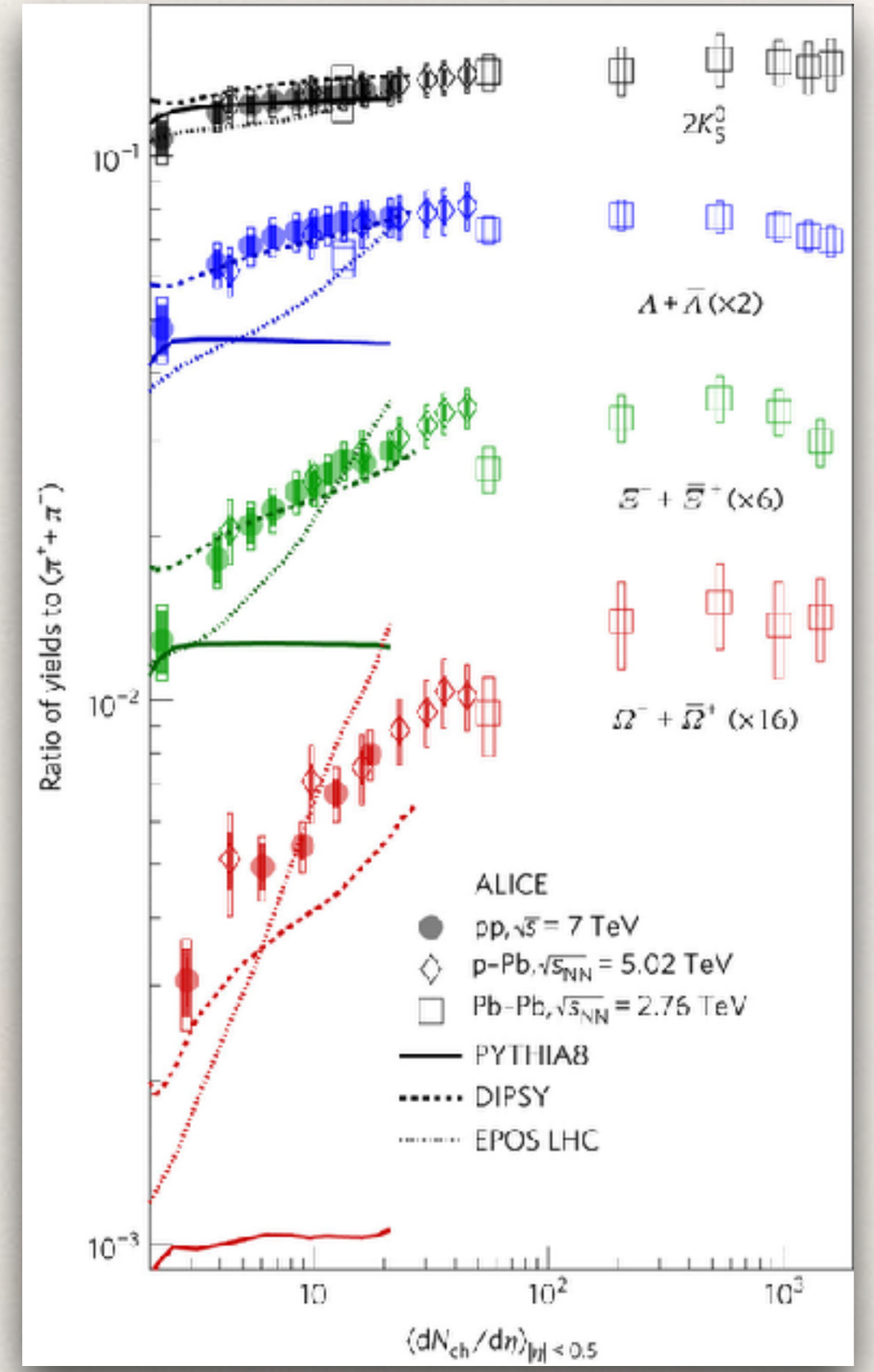
PRD 96 (2017) 112003



As observed in lower-energy data, the <pT> and the ratios of particle yields are strongly correlated with event particle multiplicity.

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

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)

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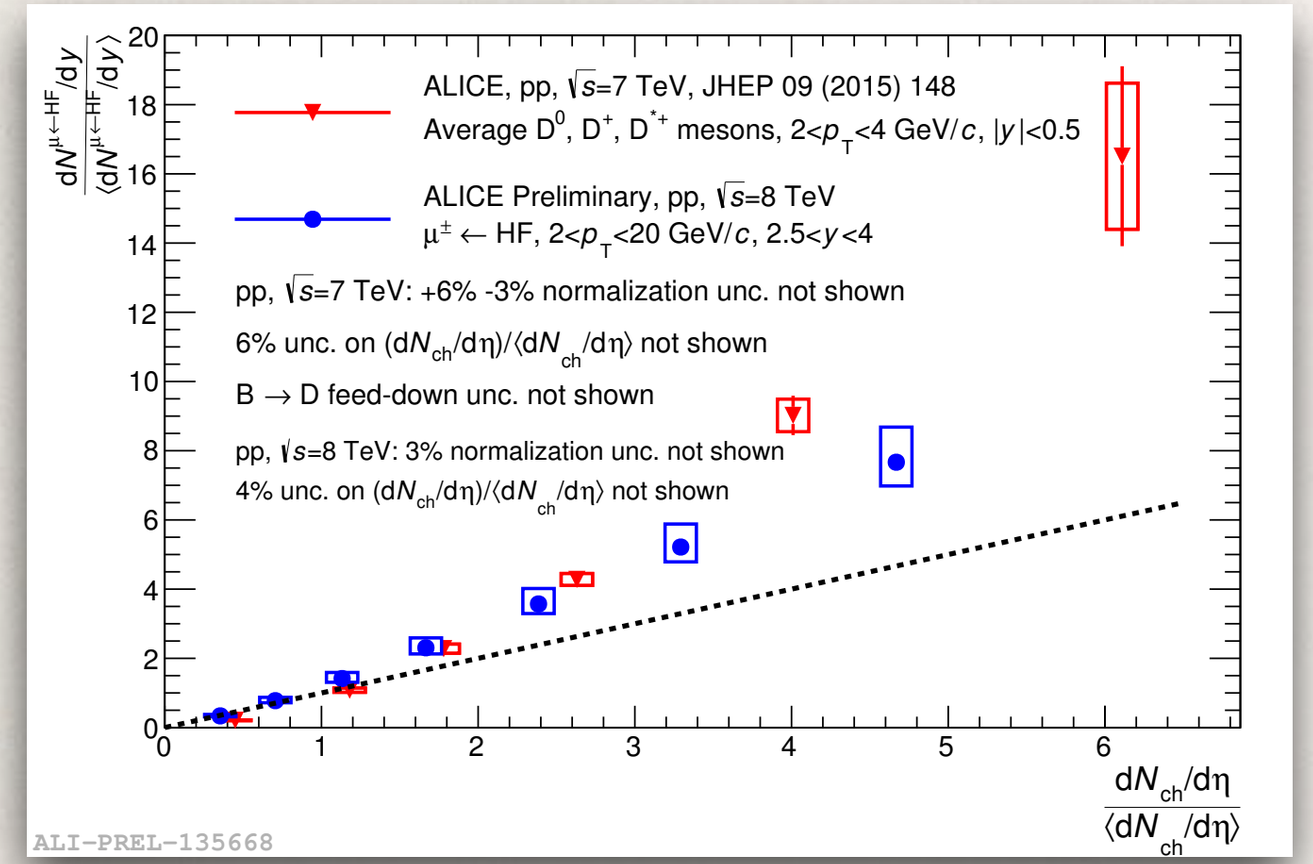
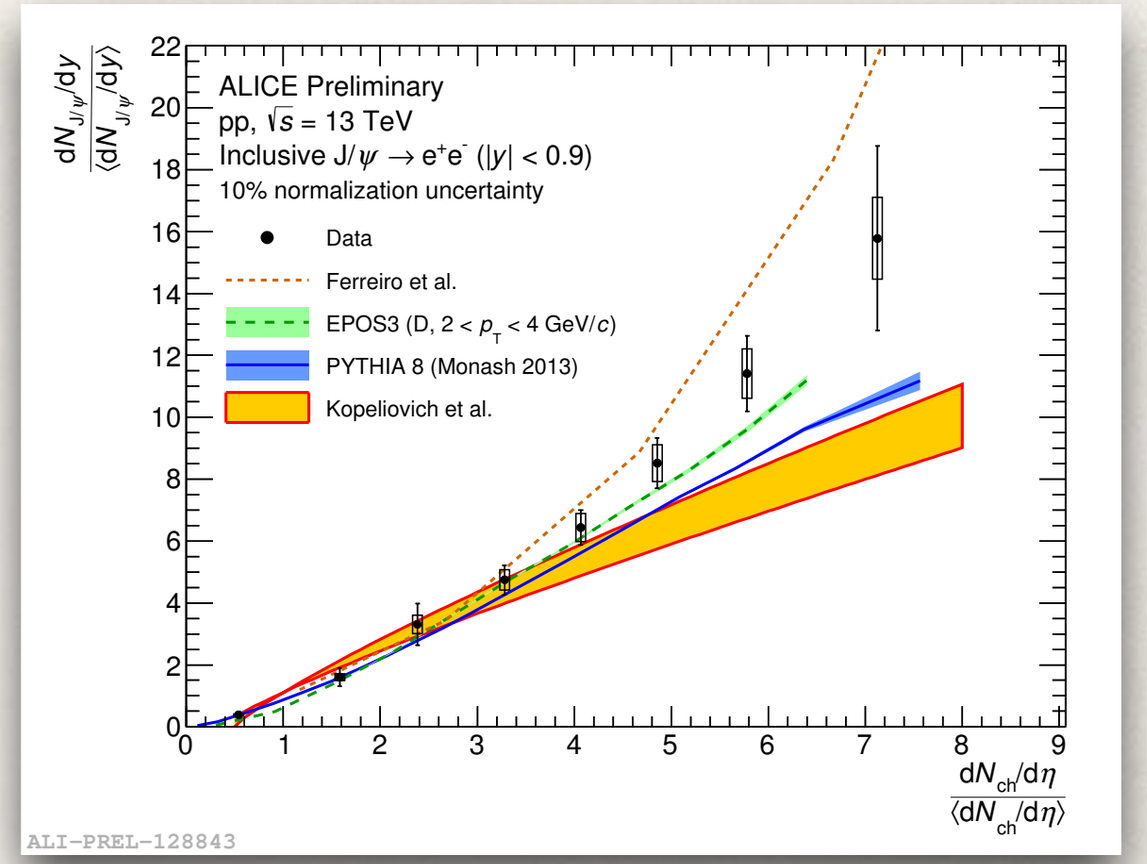
Heavy Flavor production vs Multiplicity





- **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)**

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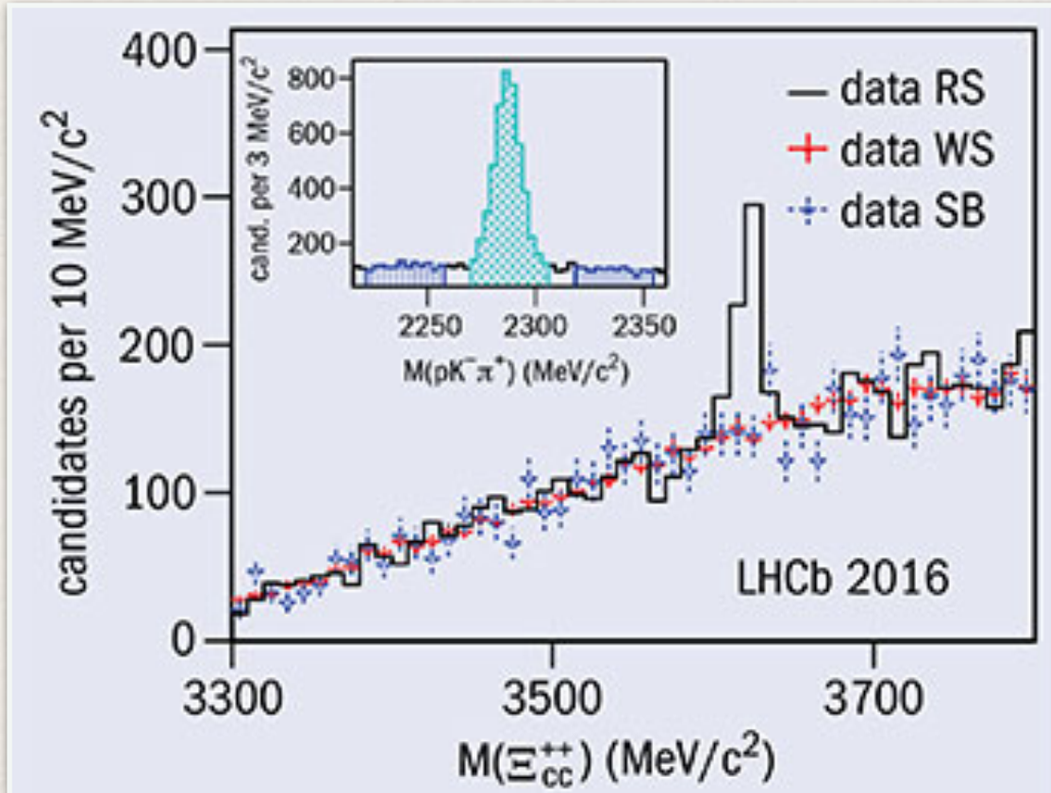
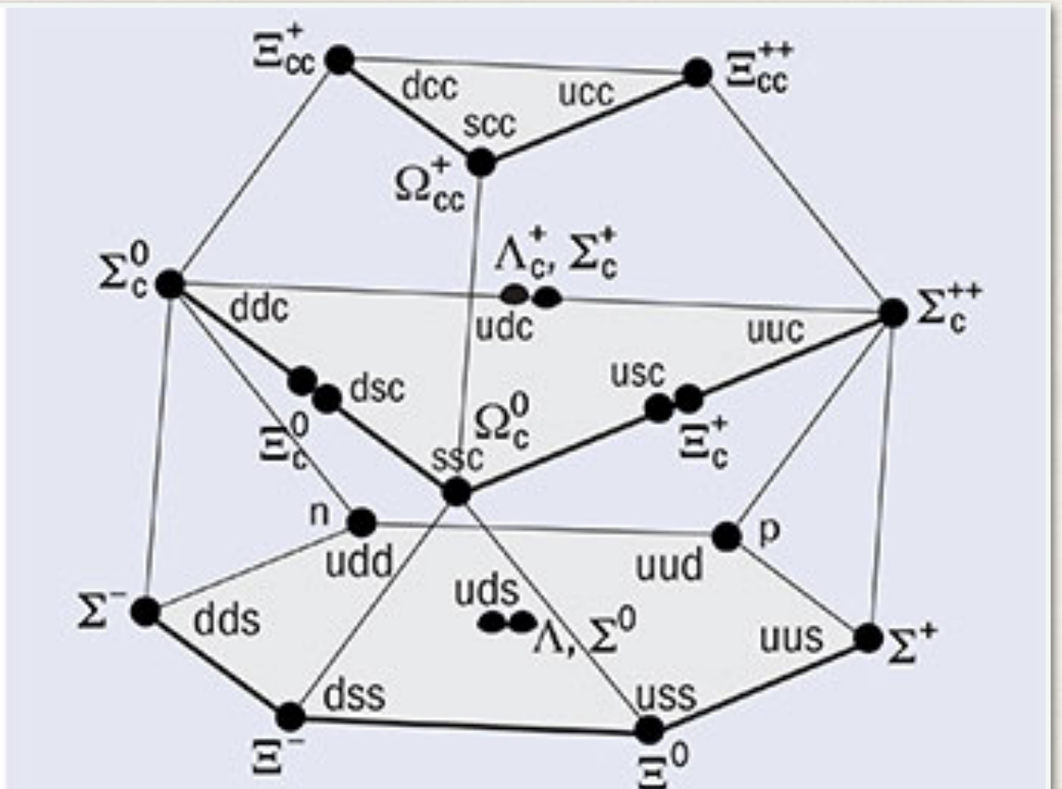
ALICE

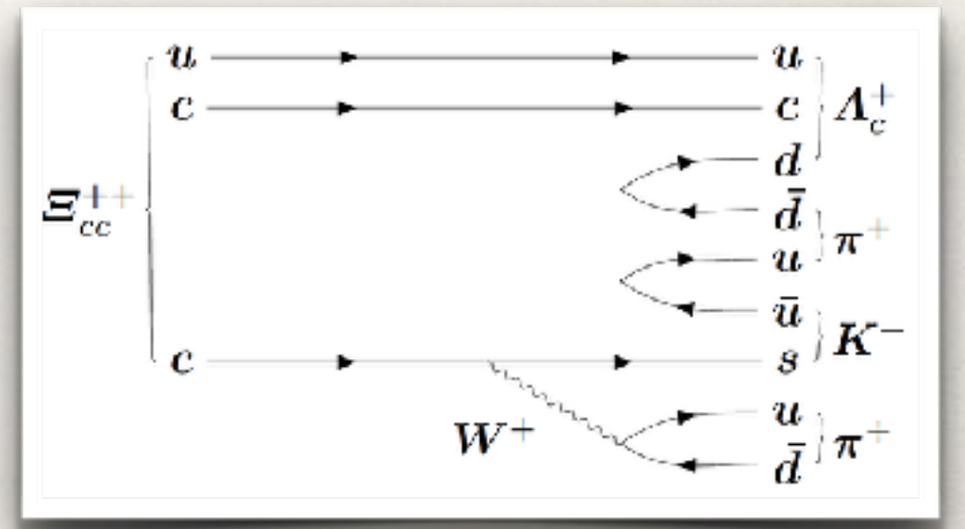
Observation of the doubly charmed baryon: Ξ^{++}_{cc}





$\Xi^{++}_{cc} \rightarrow \Lambda^{+}_{c} K^{-} \pi^{+} \pi^{+}$

$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14$ MeV/c²



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

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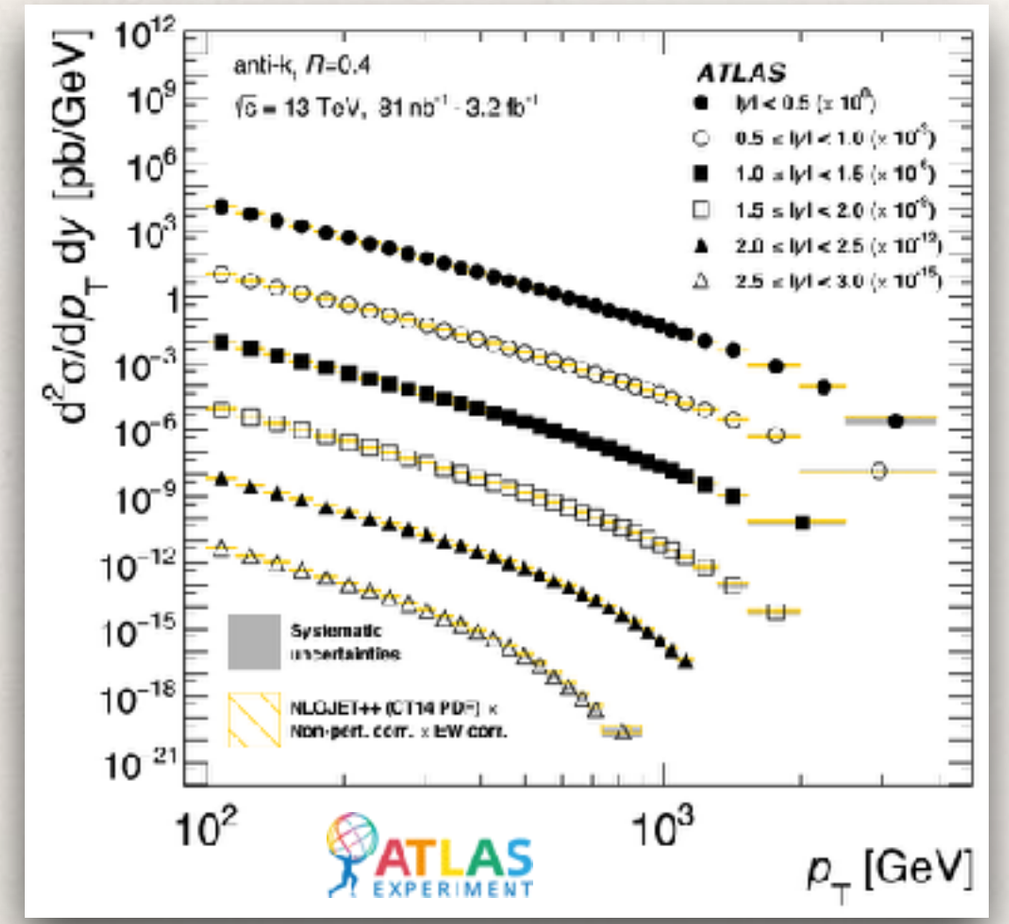
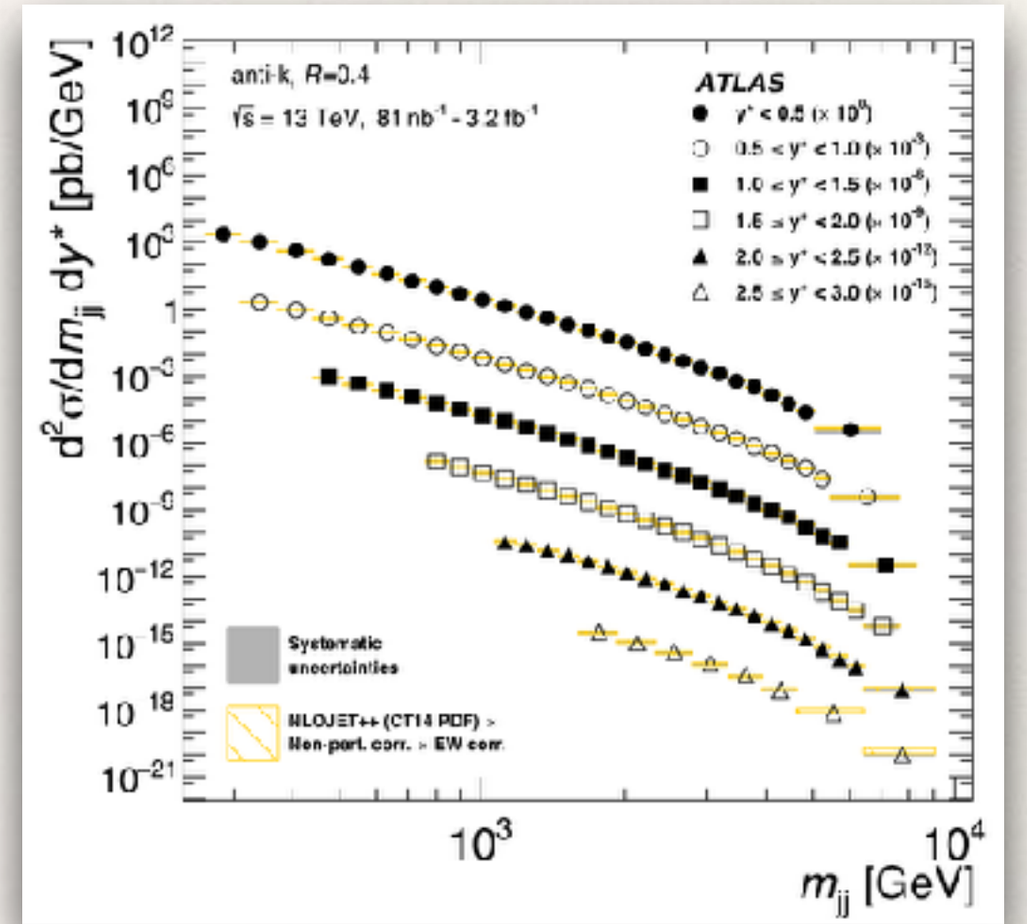
Phys. Rev. Lett. 119, 112001 (2017)

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 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-kt 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.

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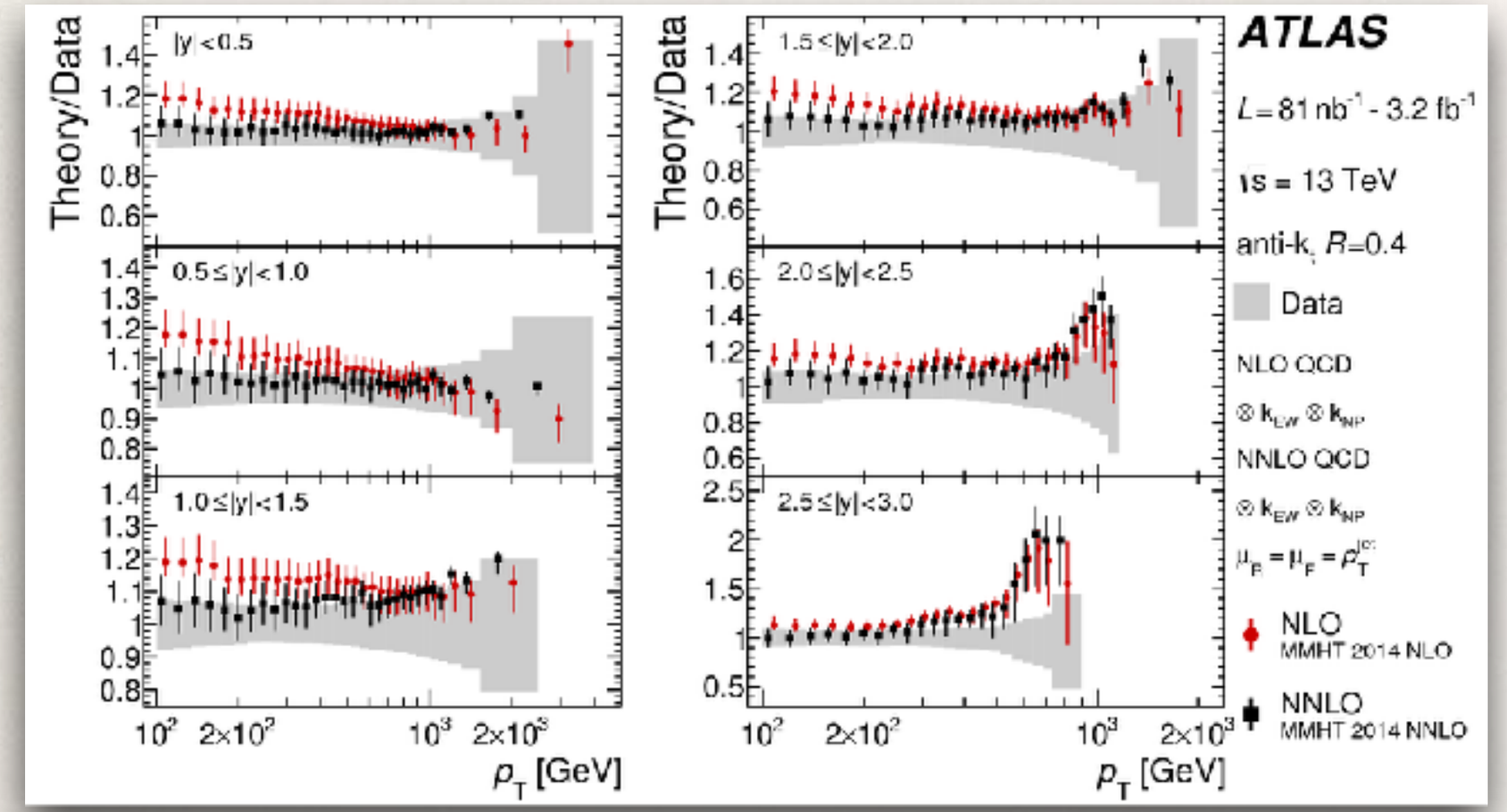
arXiv:1711.02692 submitted to JHEP

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

The strong coupling constant: $\alpha_S(Q)$

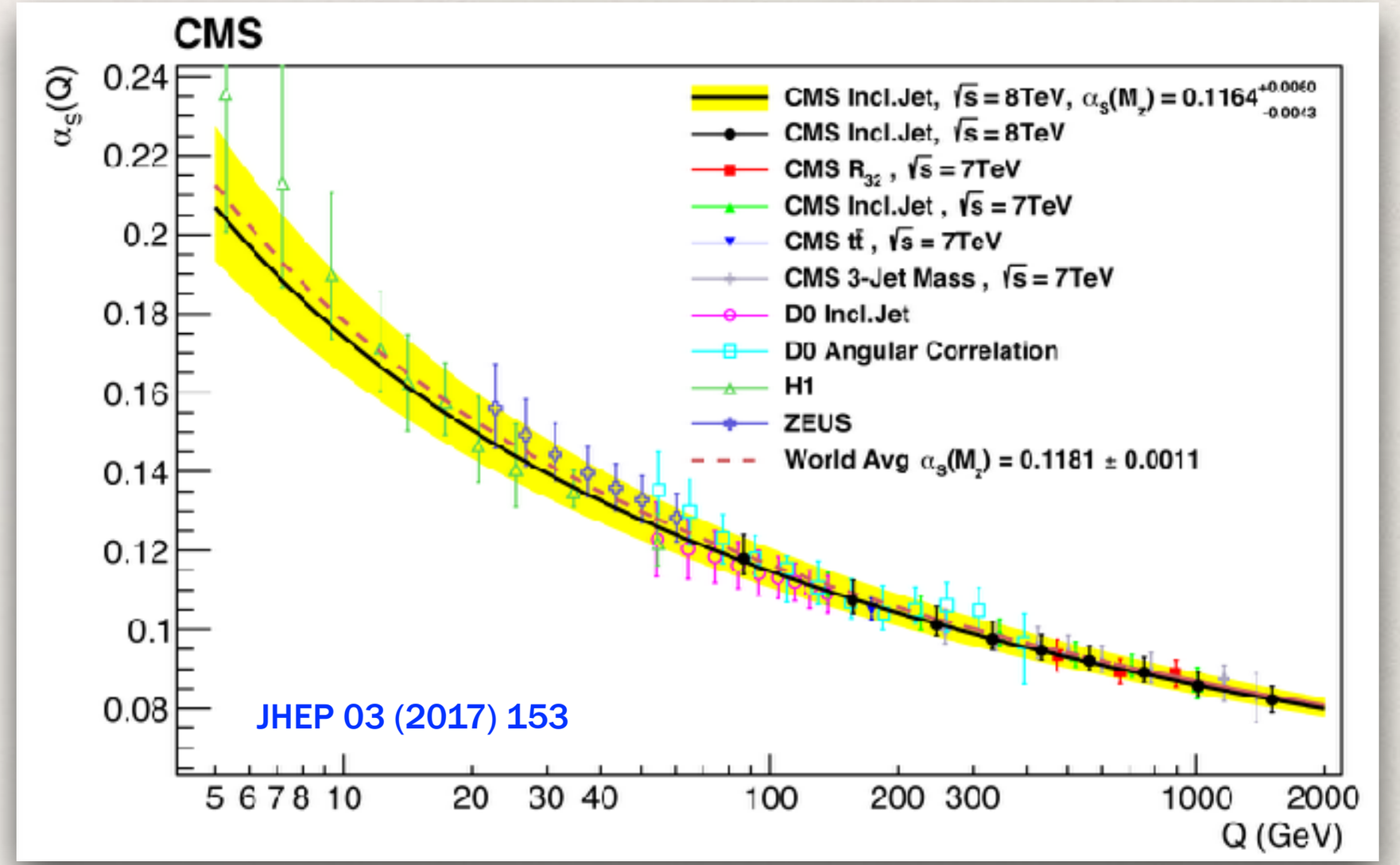
Least precisely known of all couplings

Impacts "all" LHC cross-sections.

Key for precise SM studies.

BSM physics (e.g. new coloured sectors).

Uncertainties: ±4% σ(ggH), ±7% H→cc, ±4% H→gg



	method	$\alpha_s(m_Z)$	scale unc.	exp. unc.	PDF unc.
JHEP 03 (2017) 156	Inclusive jet	0.1164	+0.0053 -0.0028	+0.0015 -0.0016	+0.0025 -0.0029
CMS PAS-SMP-16-008	multijet	0.1150	+0.0050 -0.0000	±0.0025	±0.0013
CMS PAS-SMP-16-011	Triple diff. Xsection	0.1199	+0.0031 -0.0020	+0.0015 -0.0015	+0.0004 -0.0006

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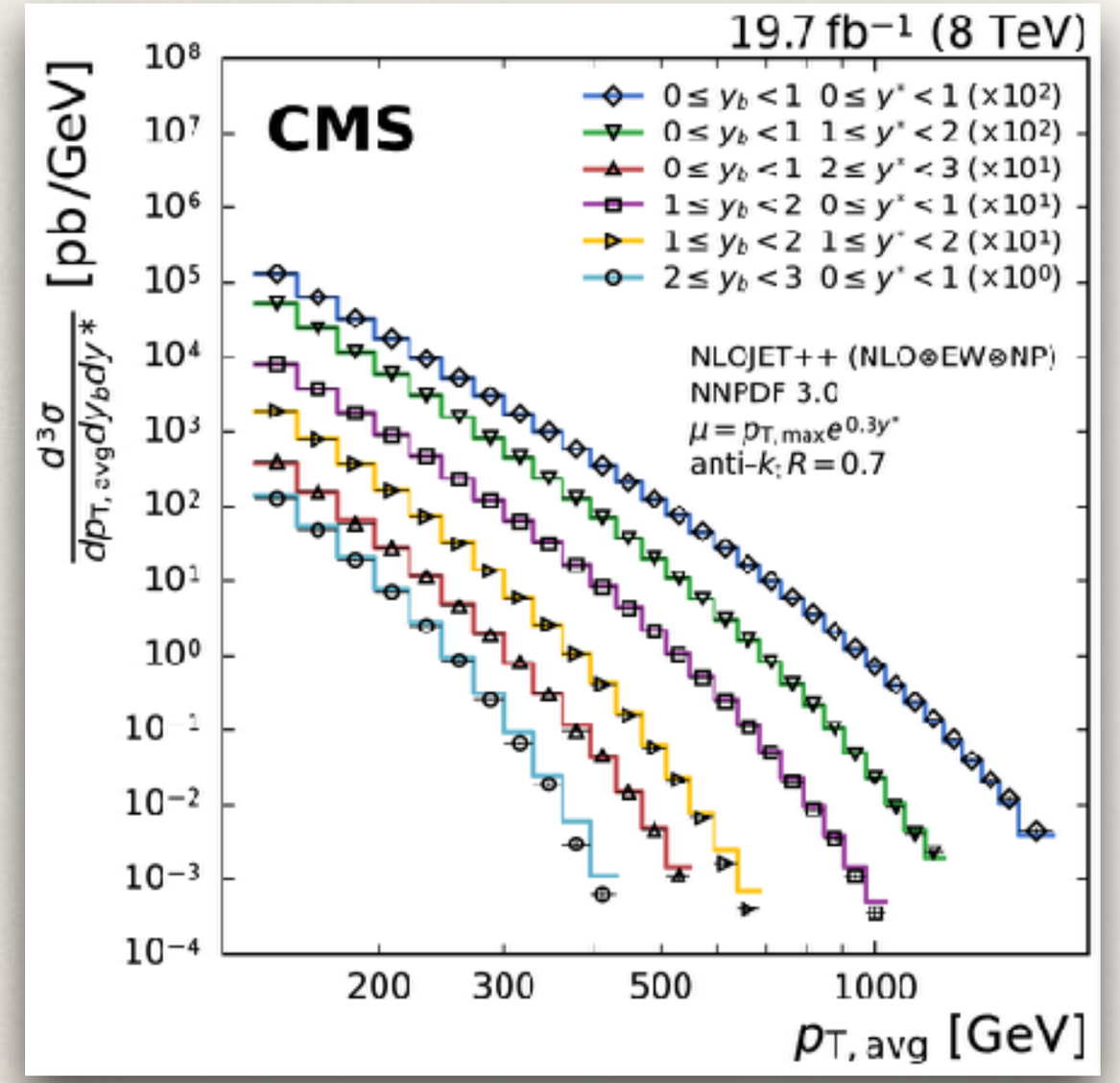
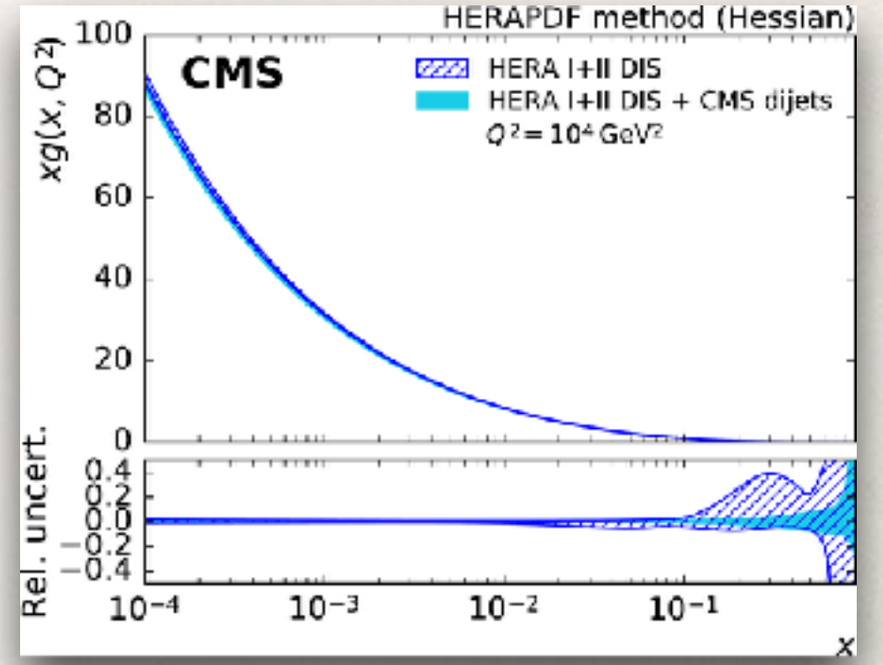
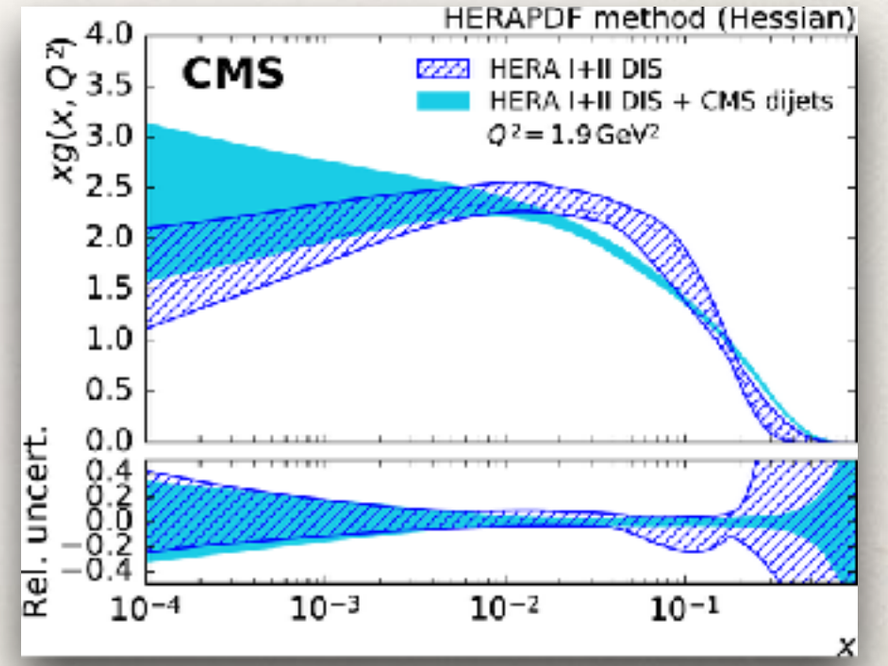
Triple differential dijet cross-section and PDFs





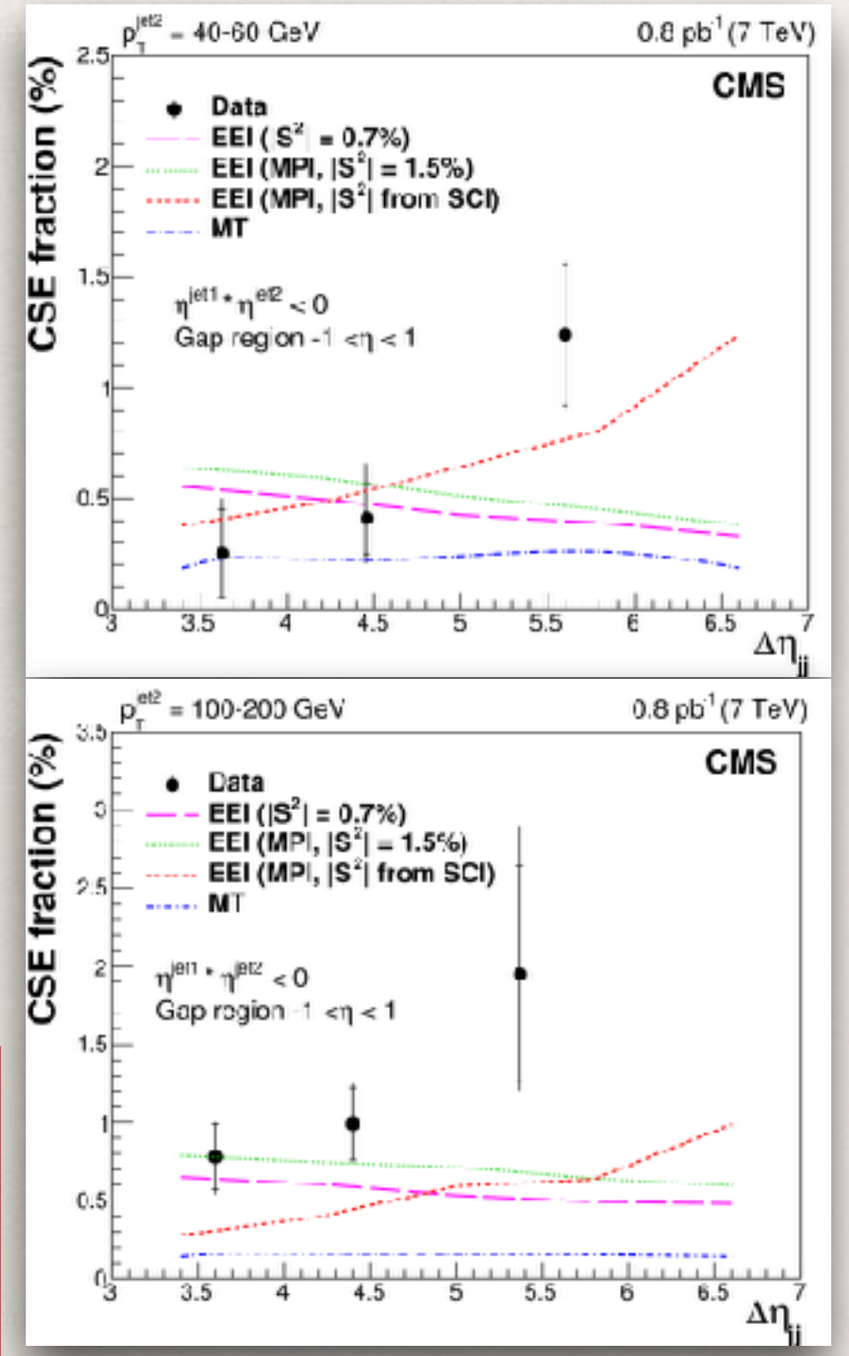


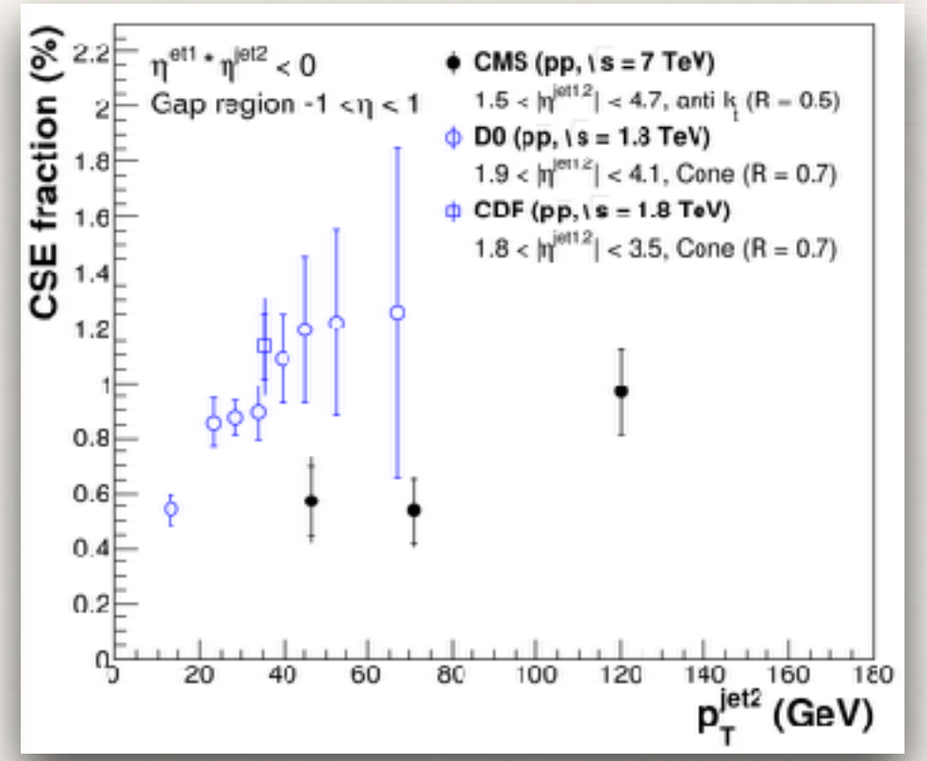
Triple differential dijet cross section

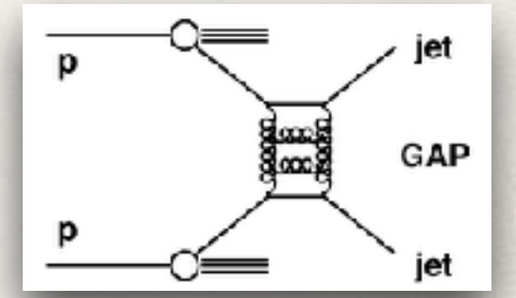
$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_{\mathrm{T,avg}}\mathrm{d}y^*\mathrm{d}y_{\mathrm{b}}} = \frac{1}{\epsilon\mathcal{L}_{\mathrm{int}}^{\mathrm{eff}}}\frac{N}{\Delta p_{\mathrm{T,avg}}\Delta y^*\Delta y_{\mathrm{b}}}$$

EPJC 77 (2017) 746

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

Accepted for publication in Eur. Phys. J. C

$p_T^{jet} > 40$GeV

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

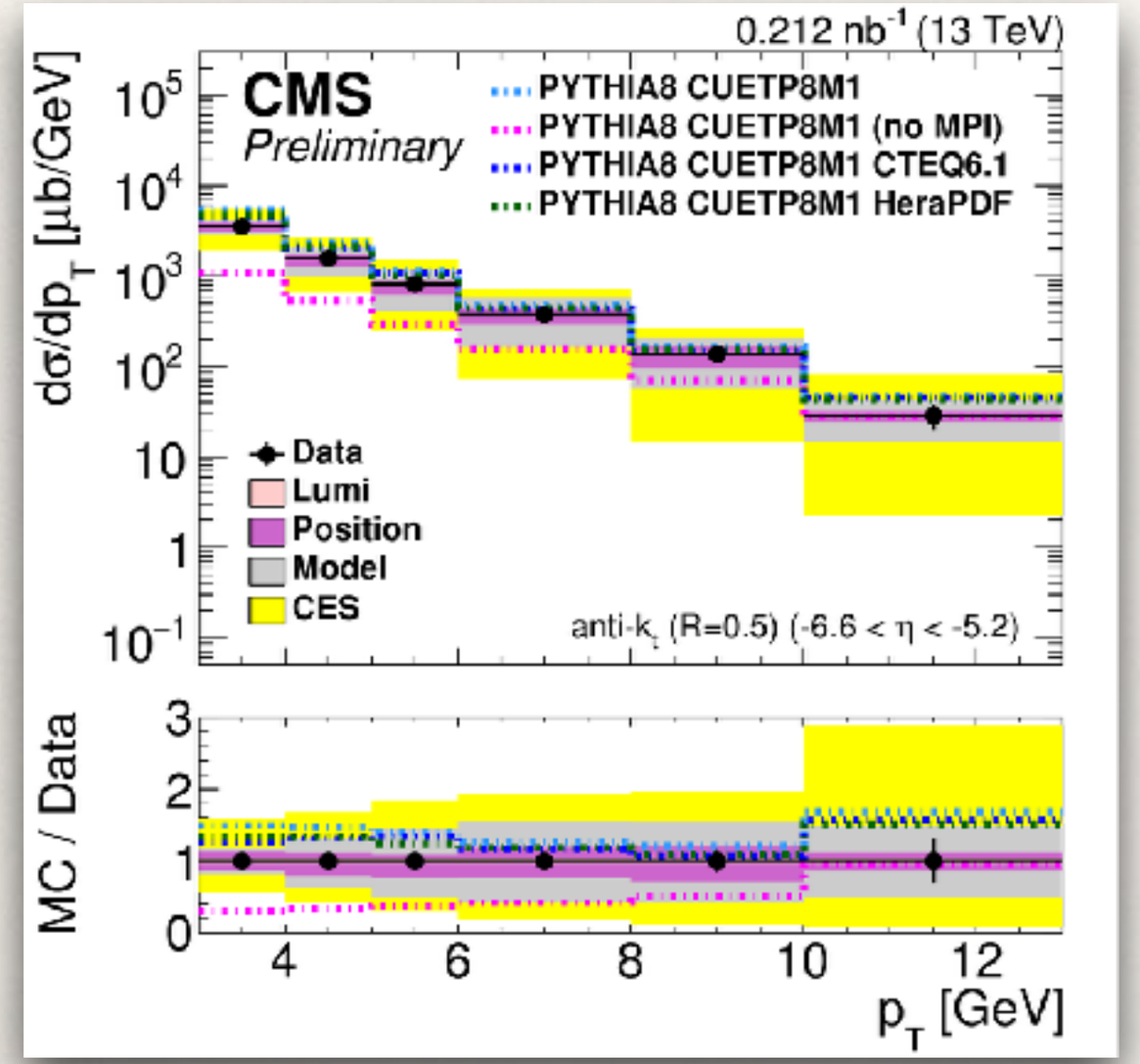
Events with no charged particles with $p_T > 0.2$ GeV in the interval $-1 < \eta < 1$ between the jets are observed in excess of calculations that assume no color-singlet exchange

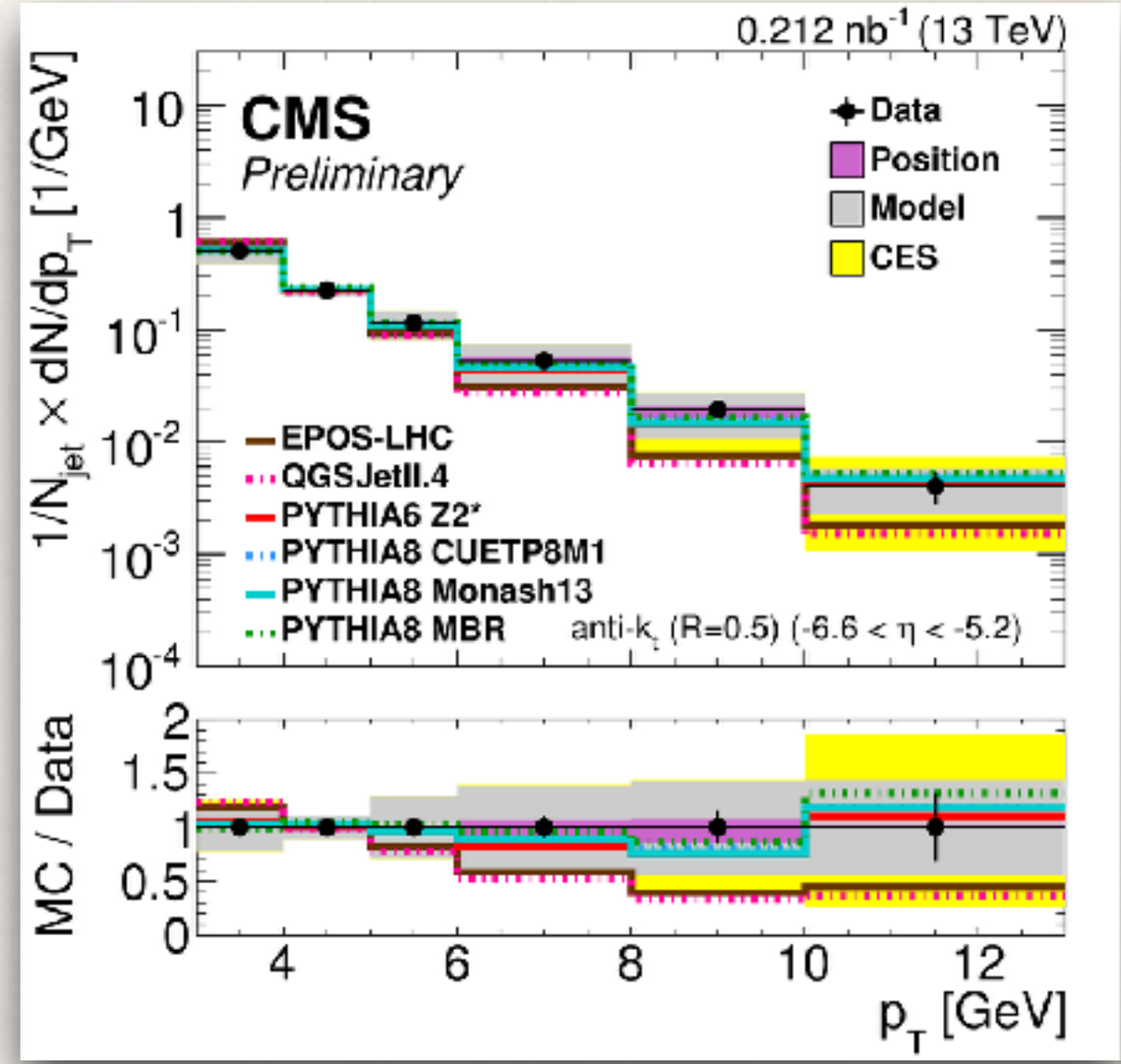
The measured CSE fractions have been compared to the results of the D0 and CDF experiments at $\sqrt{s}$=1.8 TeV.
A factor of two decrease of the CSE fraction measured at $\sqrt{s}$=7 TeV with respect to those at lower collision energies is observed.

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.

Measurements of forward jets

CMS-PAS-FSQ-16-003





The differential jet cross section in the pseudorapidity interval $-6.6<\eta<-5.2$ in proton-proton collisions at 13 TeV fully corrected for all detector effects is shown in the range $3 < p_T < 13$ GeV.

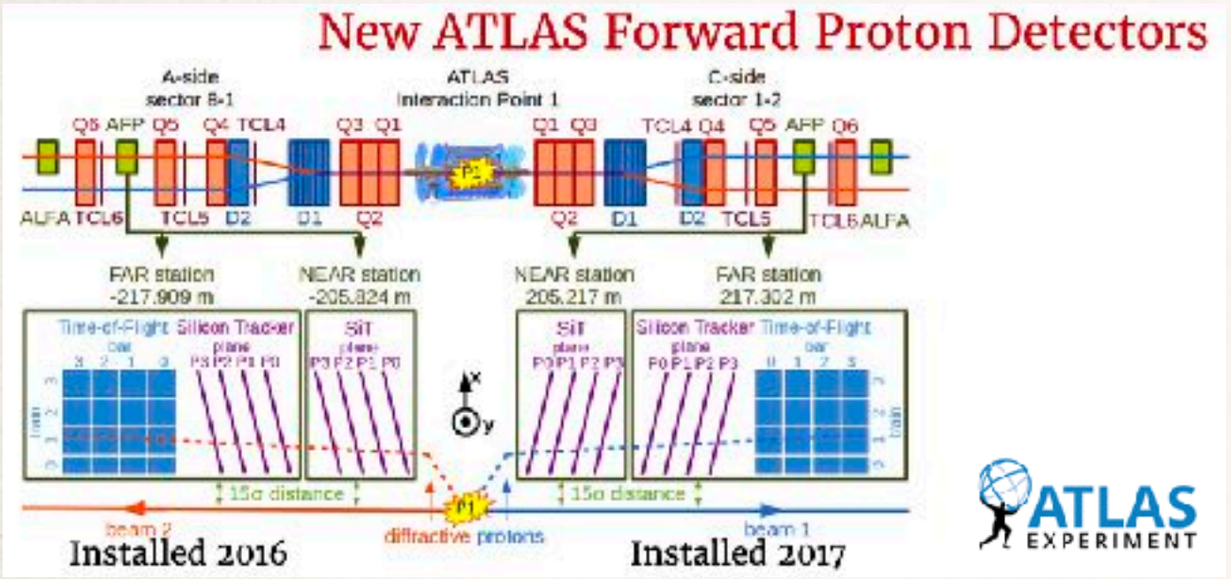
Due to the significant experimental uncertainties all of the models are essentially consistent with the data. However, it is interesting to note that all the PYTHIA tunes tend to slightly overpredict the cross section, while the two Gribov-Regge models EPOS-LHC and QGSJetII.4 tend to underpredict the cross section.

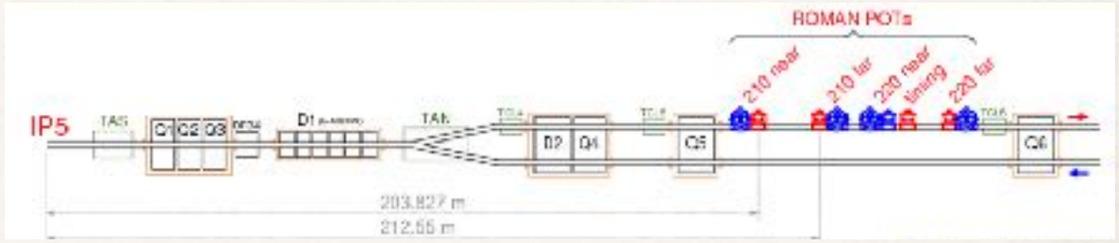
AFP and CT-PPS

arXiv:1803.04496 [hep-ex]

(submitted to JHEP)

ATL-PHYS-PUB-2017-012



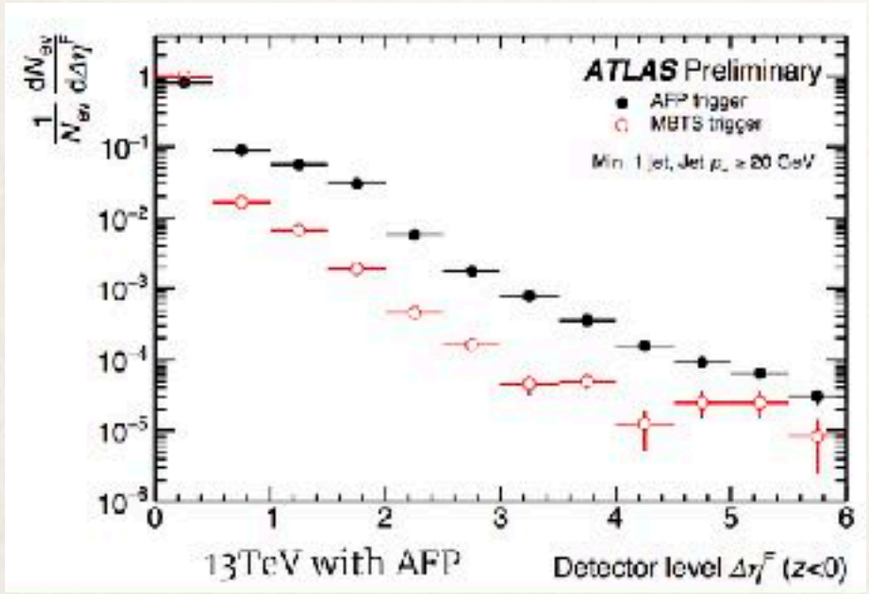


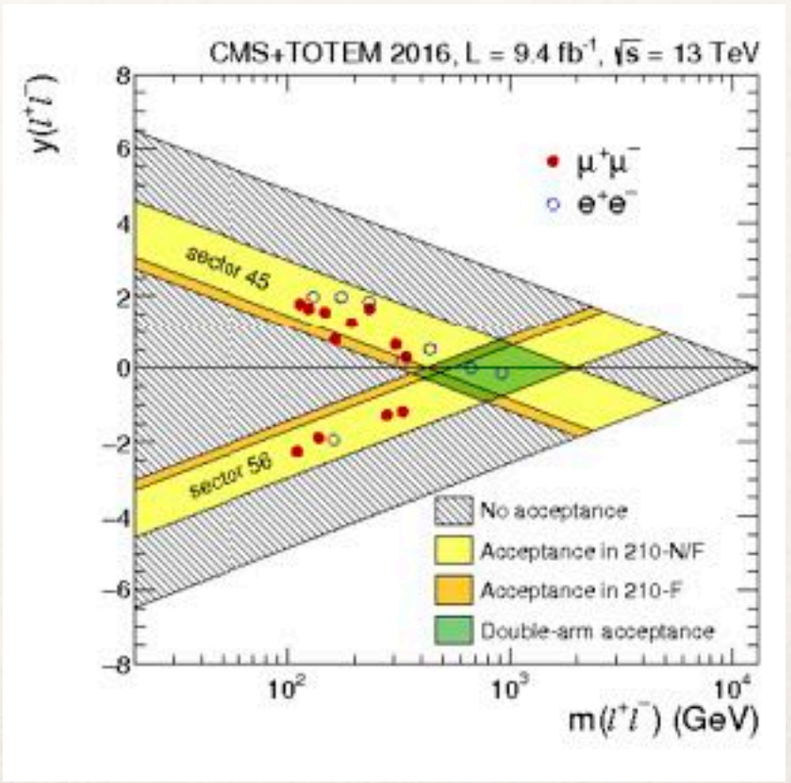
Search for a centrally produced pair of oppositely charged leptons with forward proton tag.

First observation of proton-tagged γγ collisions at the electroweak scale

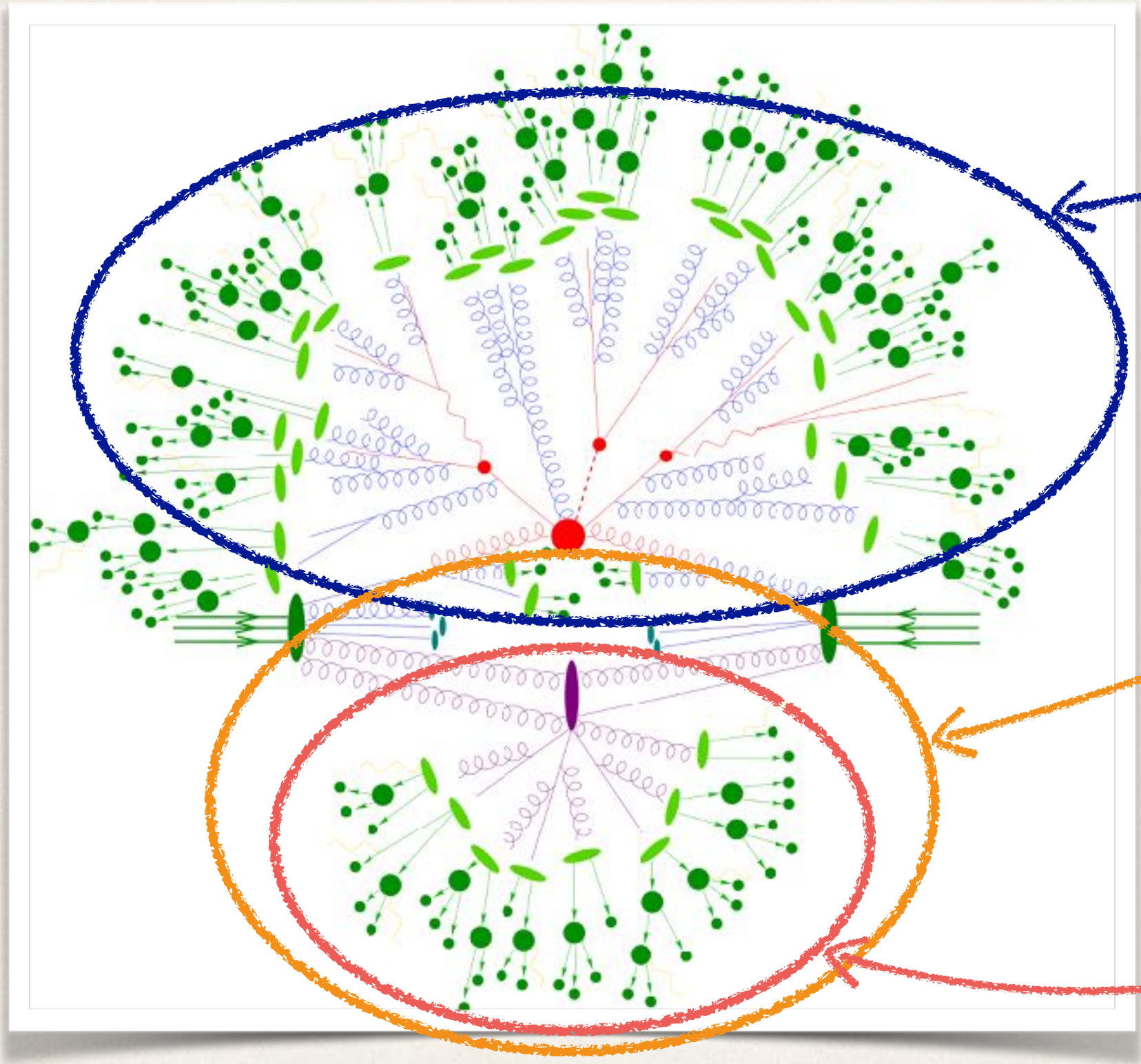
5.1 σ excess over background

Demonstrated that AFP is capable of selecting a highly diffractive-enriched sample





Proton-proton collisions: the event structure



HARD INTERACTION (THE MAIN EVENT)

UNDERLYING EVENT (ISR, FSR, REMNANTS)

MPI, ALMOST INDEPENDENT OF HARD SCATTER GEOMETRY

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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.

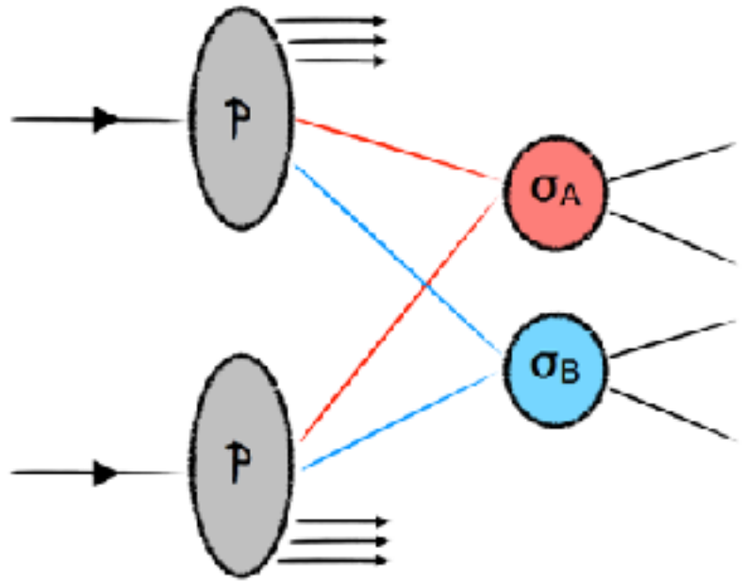
- better understanding of non-perturbative QCD dynamics

  – is the rate of MPI really independent of the process?

  – correlations?

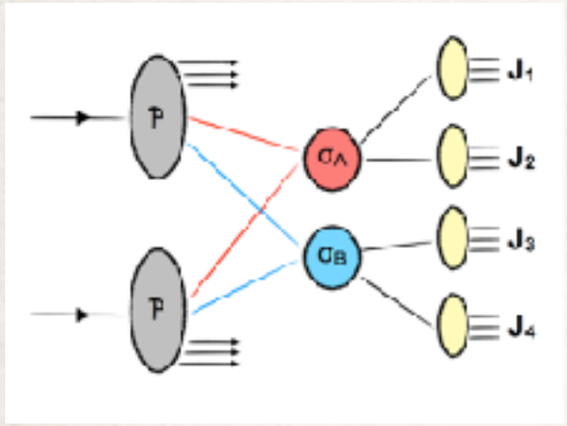
- accurate estimation of backgrounds for many rare new physics processes as well as for Higgs boson searches.

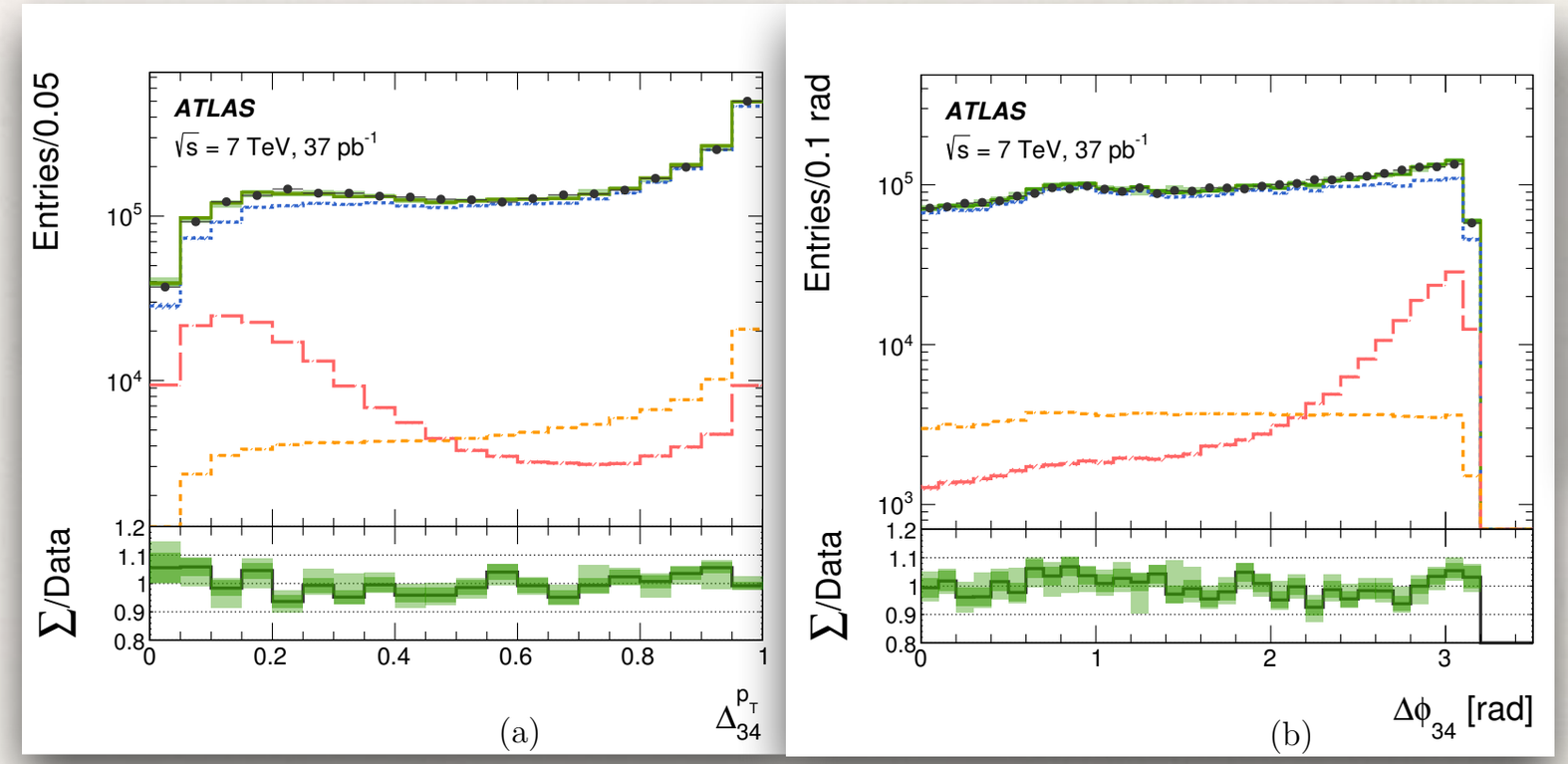
  – important for the definition of central jet veto cuts.

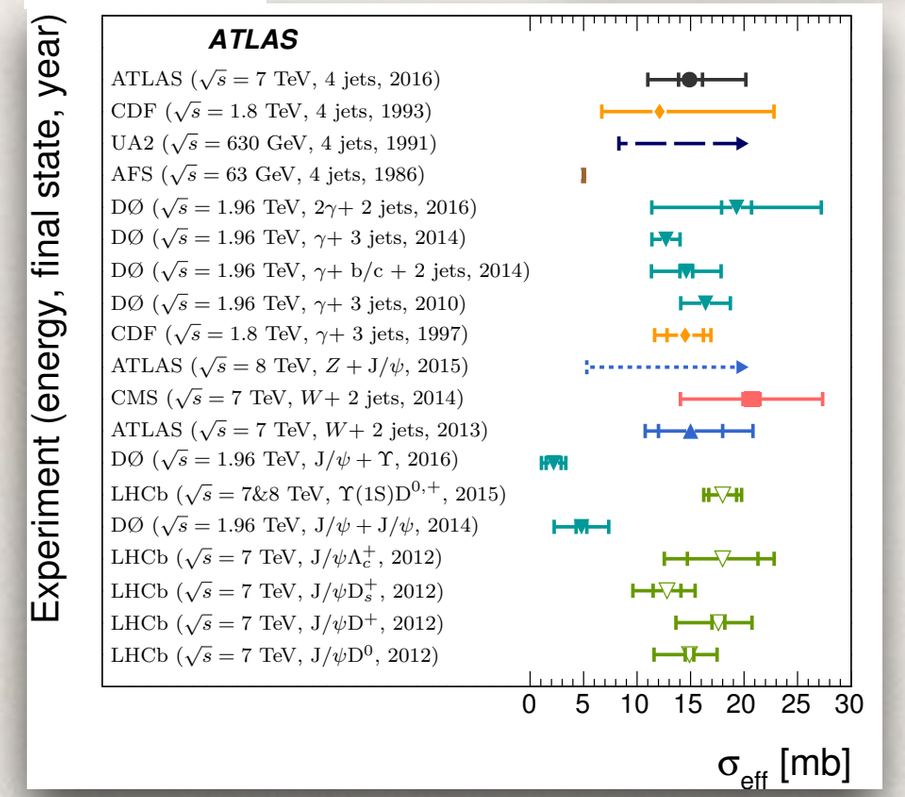


$$\sigma_{DP} = m\frac{\sigma_A \sigma_B}{2\sigma_{eff}}$$

Double parton scattering in four-jet events





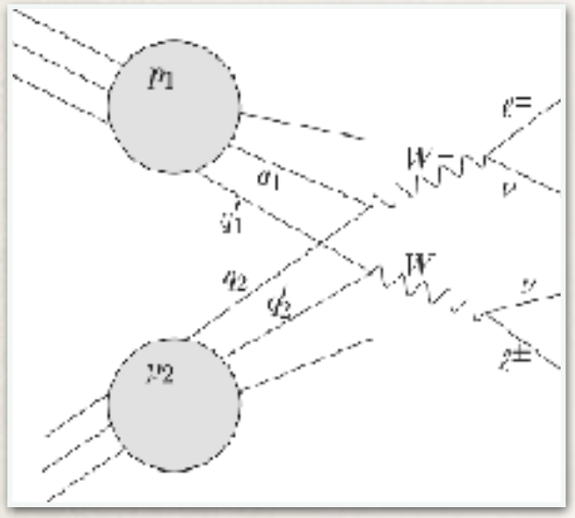


$$f_{\mathrm{DPS}} = 0.092\ ^{+0.005}_{-0.011}\ (\mathrm{stat.})\ ^{+0.033}_{-0.037}\ (\mathrm{syst.})$$

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

JHEP11(2016)110

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



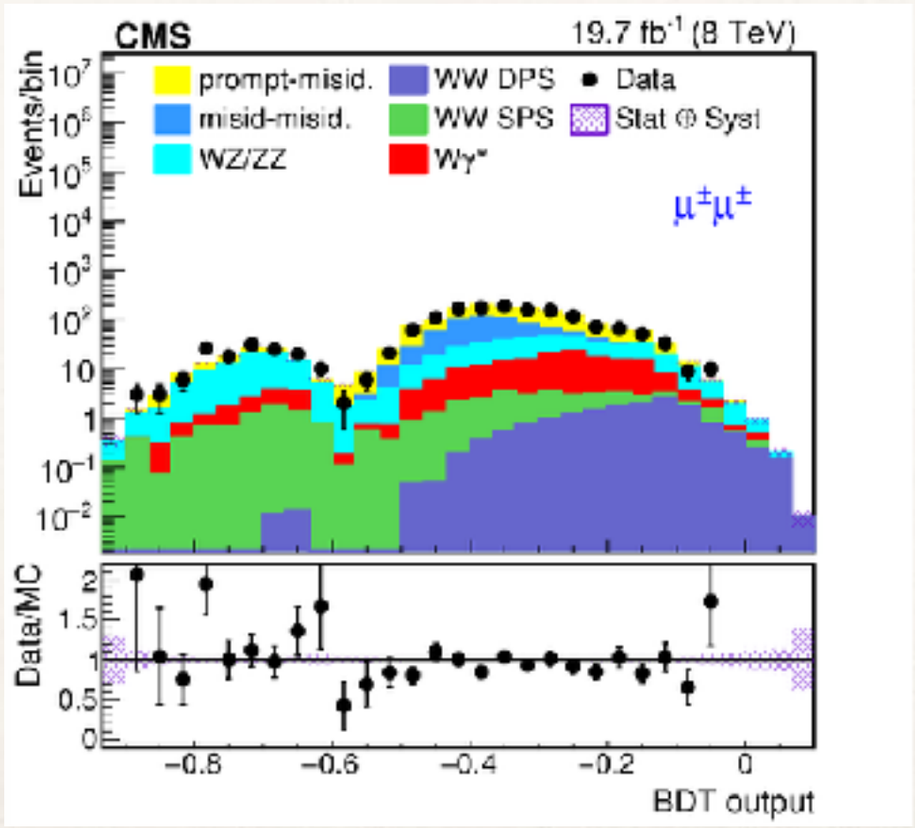
Schematic diagram corresponding to the production of a same-sign W boson pair via the DPS process.

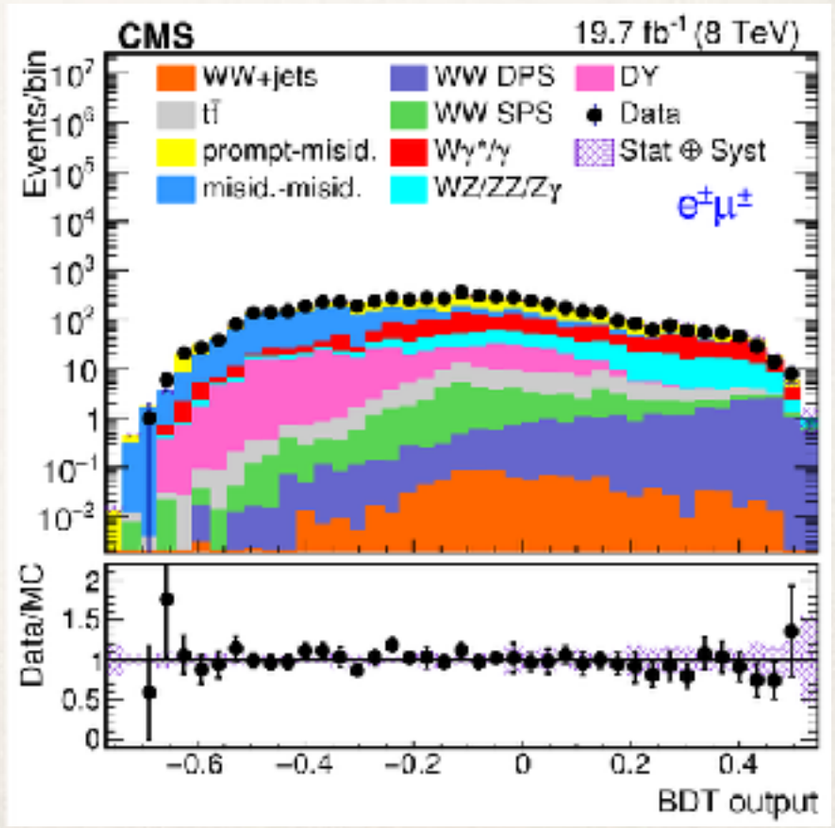
A first search for same-sign W boson pair production via double-parton scattering (DPS) in pp collisions at a center-of-mass energy of 8 TeV has been presented.

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.





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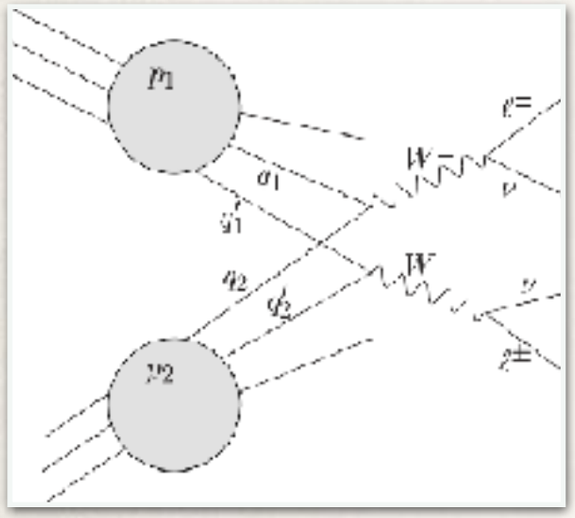
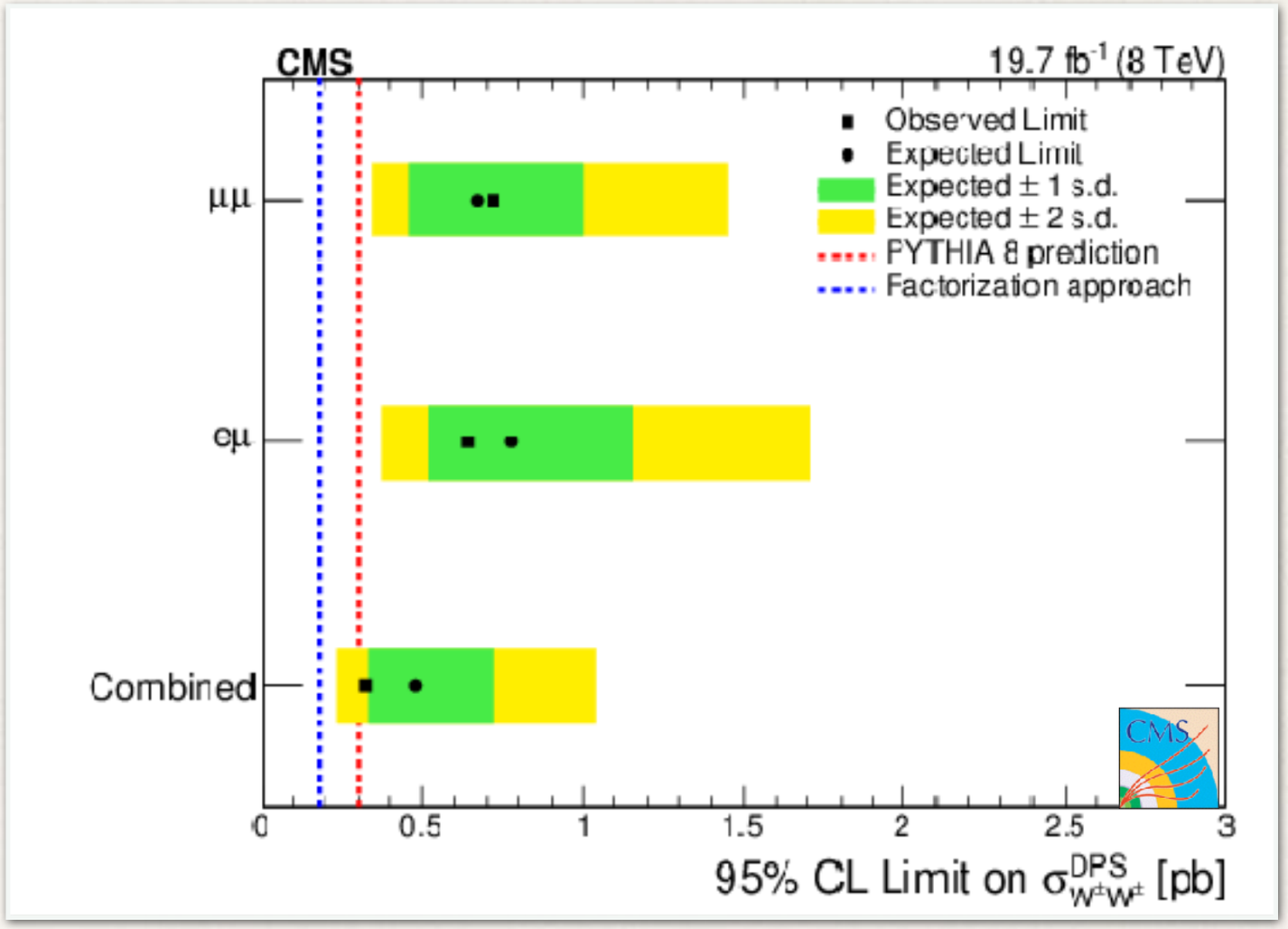
JHEP 02 (2018) 032

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.

JHEP 02 (2018) 032

Summary

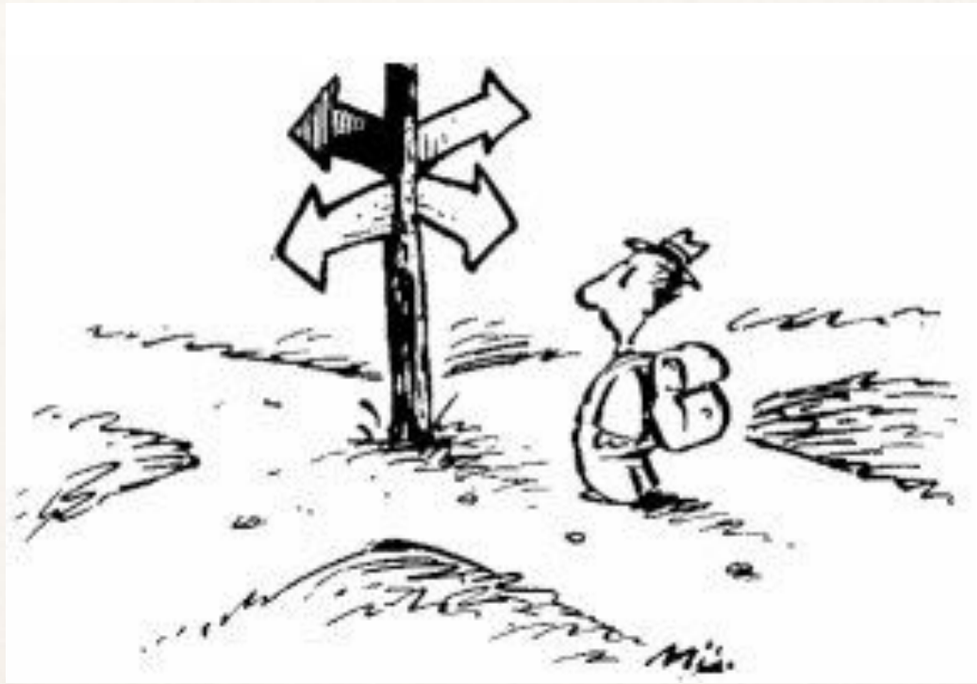
Data from the LHC provides a unique and rich environment to perform QCD studies.

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:

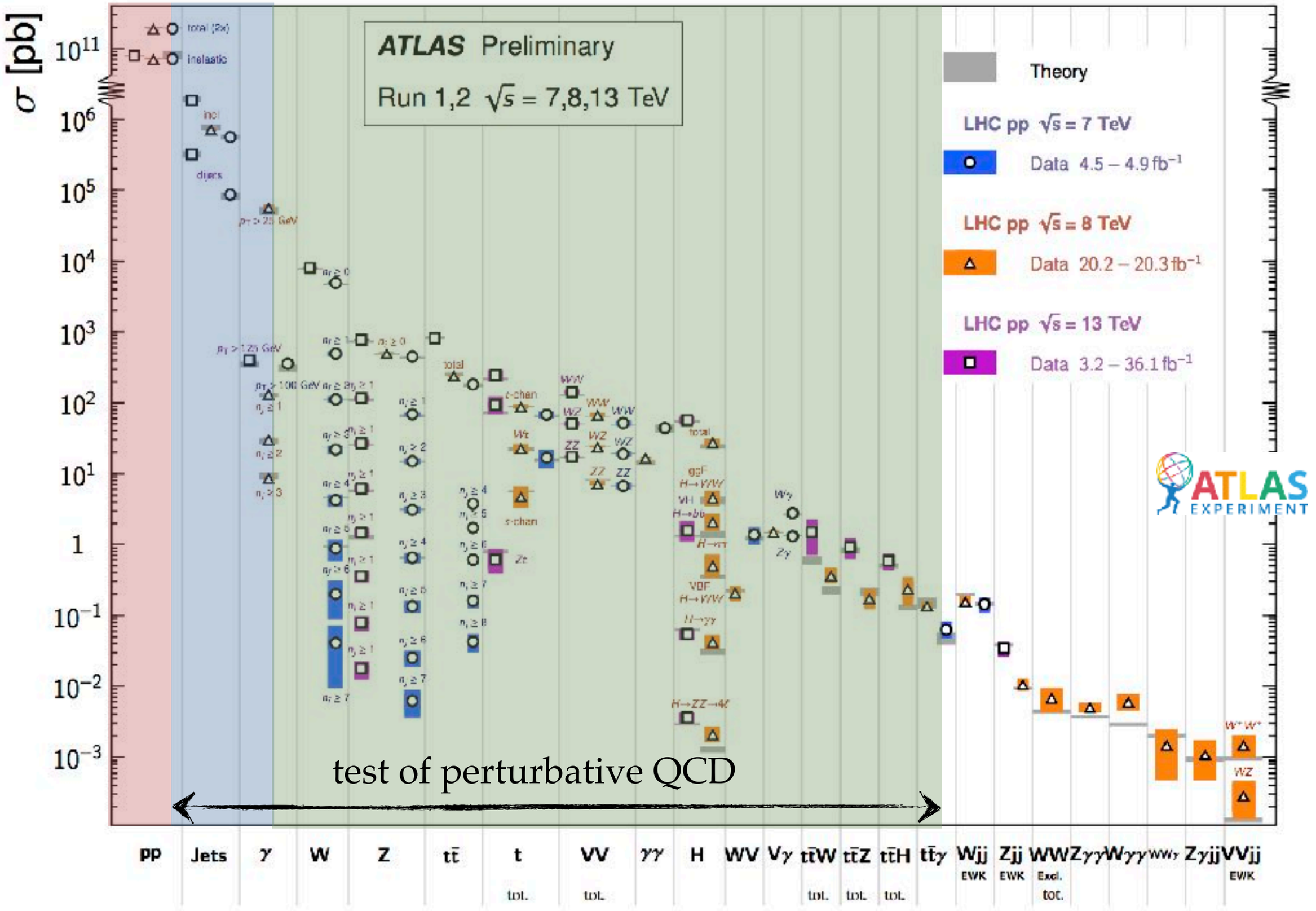
- Inelastic pp cross-section
- Charged Particle Density
- Charged Particle Multiplicity
- The underlying event
- Measurement of charged pion, kaon, and proton production
- Production of multi-strange hadrons in high-multiplicity pp collisions
- Measurement of inclusive jet and dijet cross-sections
- Heavy flavor production
- Study of dijet events with a large rapidity gap between the two leading jets
- Double Parton Scattering

Extras...

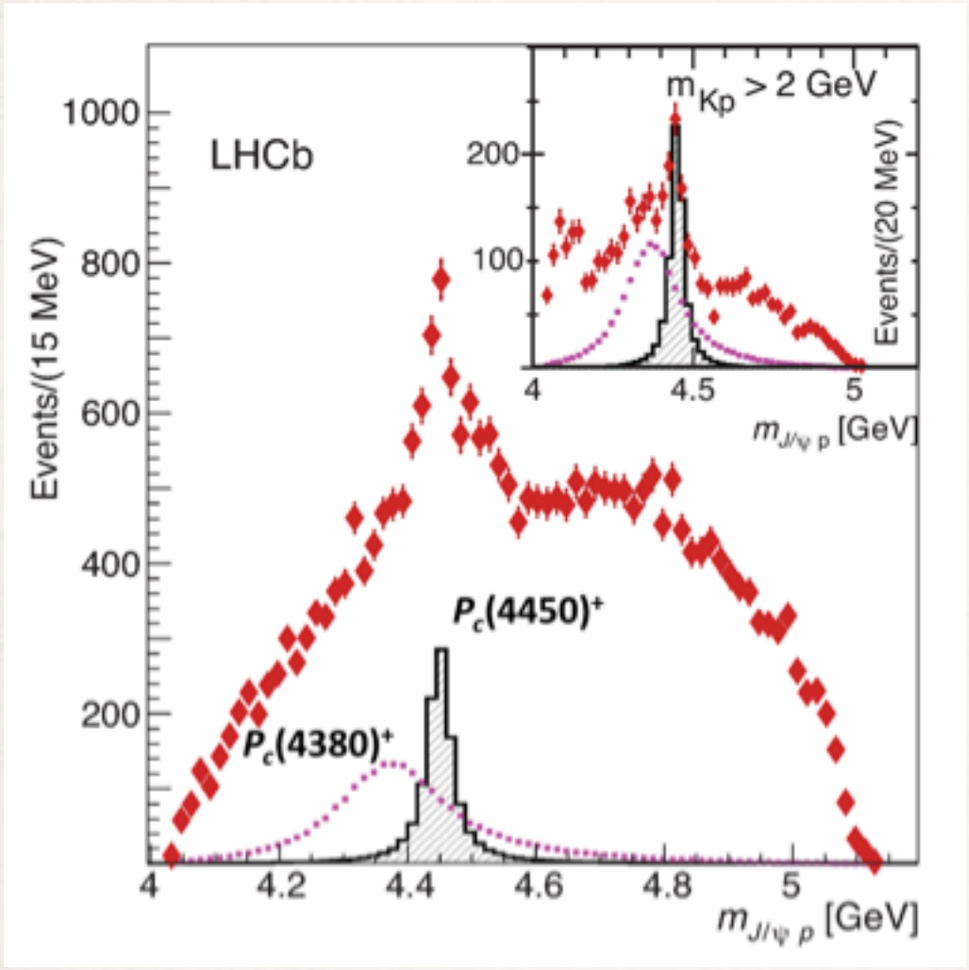


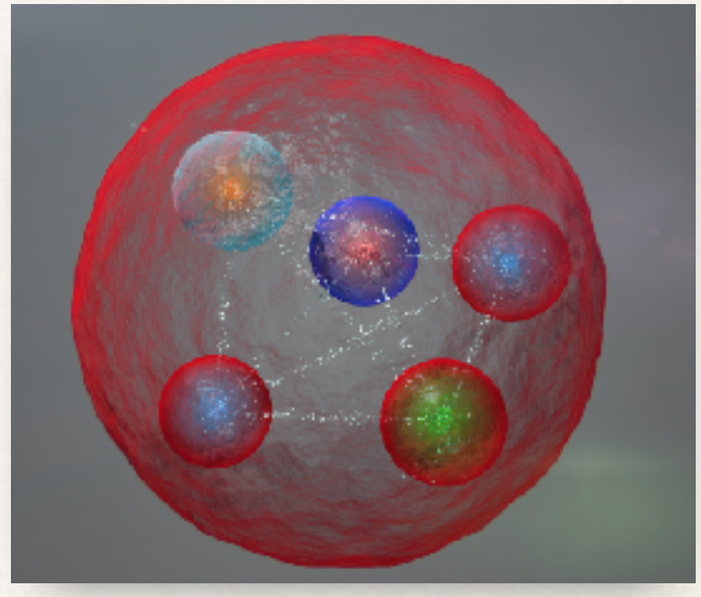
Standard Model Production Cross Section Measurements

Status: March 2018



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

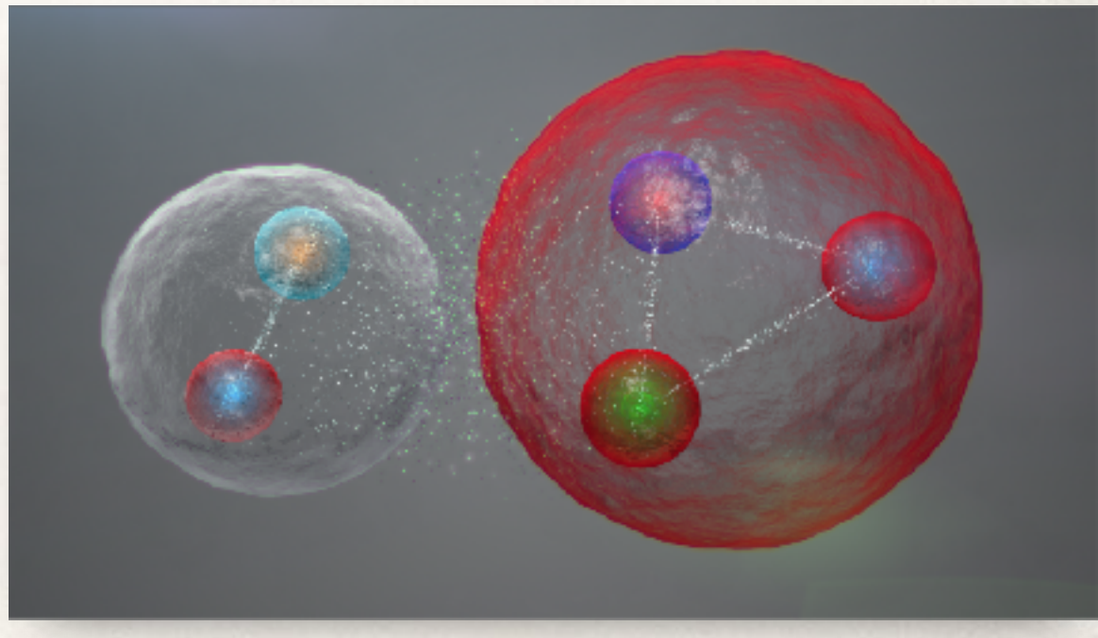




(tightly bound quark states ?)

$\Lambda_b \to J/\Psi\, K^- p$

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



(meson-baryon molecule ?)

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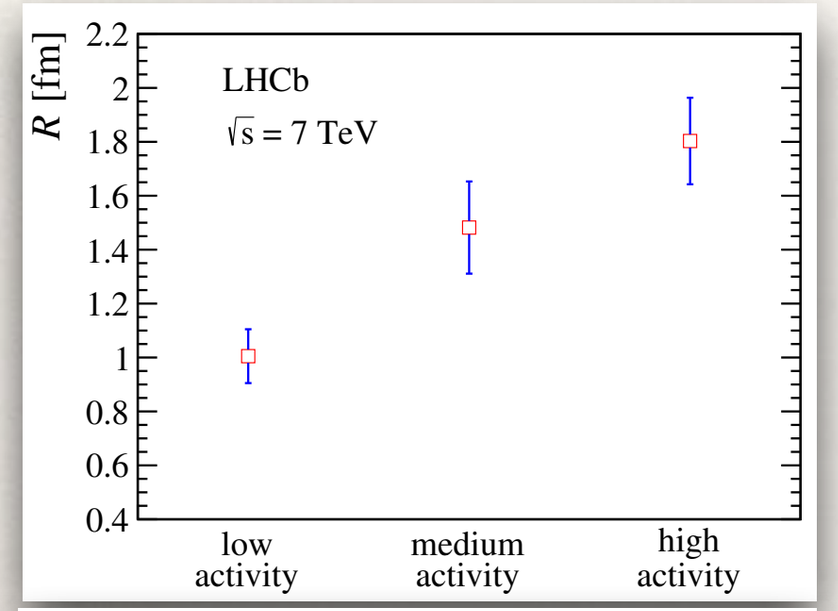
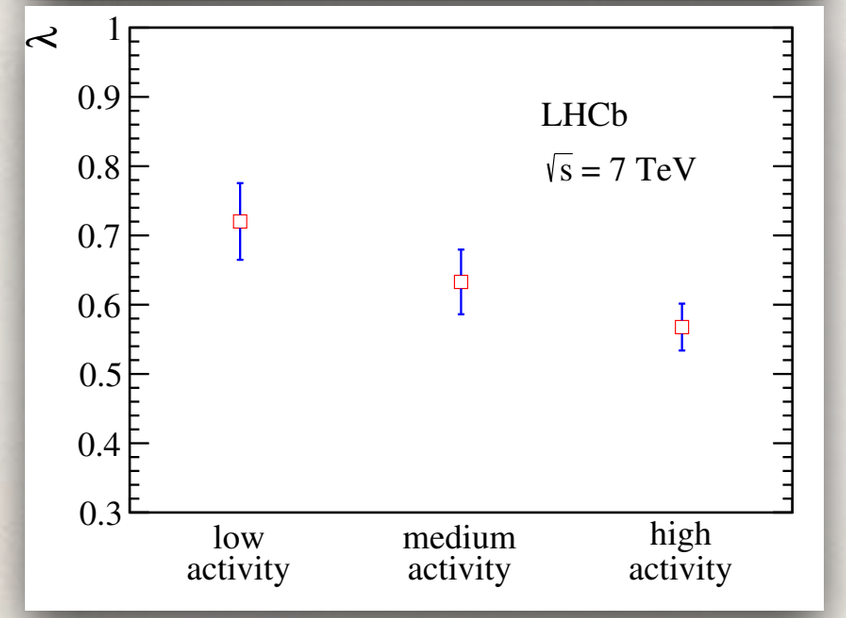
Bose-Einstein correlations of same-sign charged pions in the forward region in pp collisions at $\sqrt{s}$ = 7 TeV





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

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