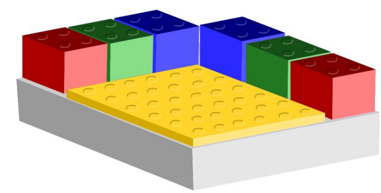
QCD & Jets

at ATLAS, CMS, and LHCb



Lucio Anderlini [1], *Matteo Bauce* [2], *Diego Ciangottini* [3]

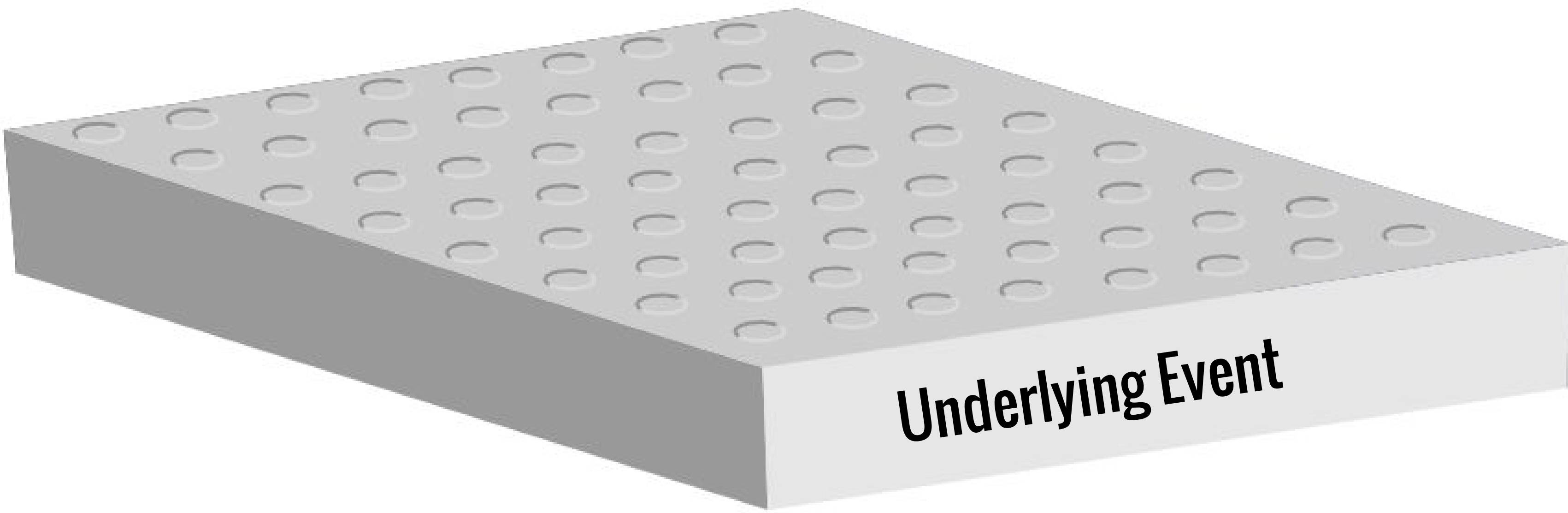
Istituto Nazionale di Fisica Nucleare

[1] Sezione di Firenze - *Gruppo LHCb*
[2] Sezione di Roma 1 - *Gruppo ATLAS*
[3] Sezione di Perugia - *Gruppo CMS*

Istituto Nazionale di Fisica Nucleare

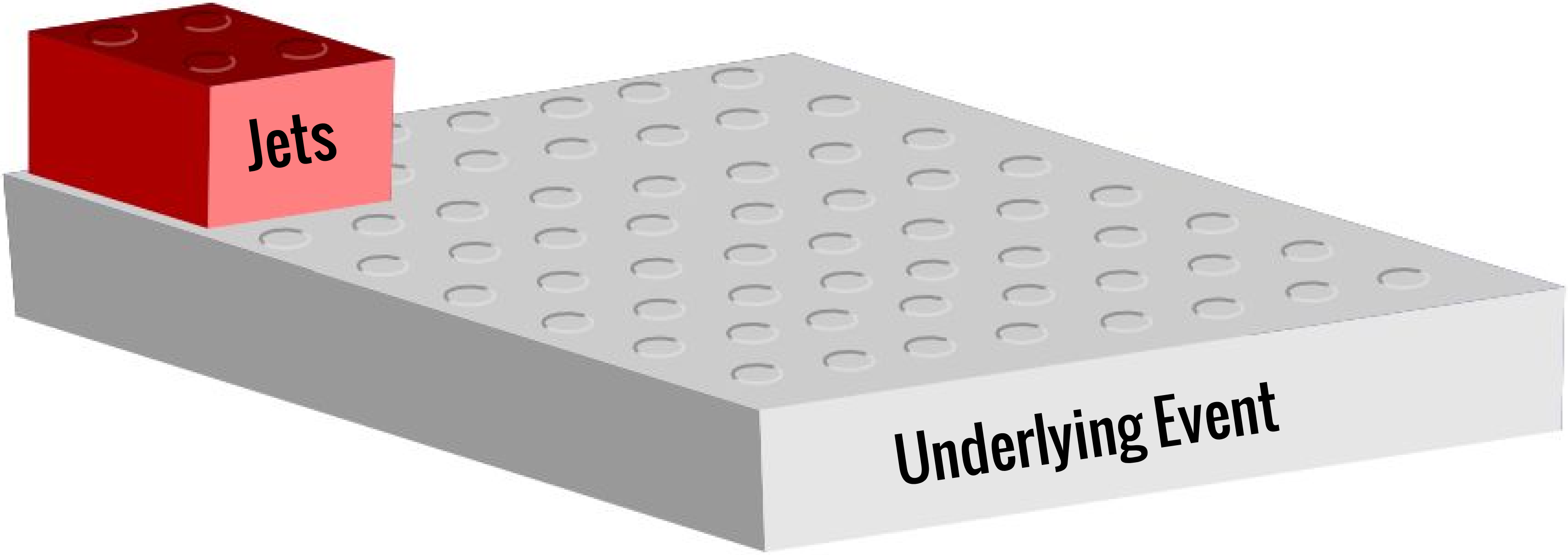
Outline - *Underlying Event*

- Minimum bias
  - Track-based studies
  - Pseudo-rapidity distribution
  - Energy distribution
- Long-range near-side particle correlation
- Inelastic pp cross-section



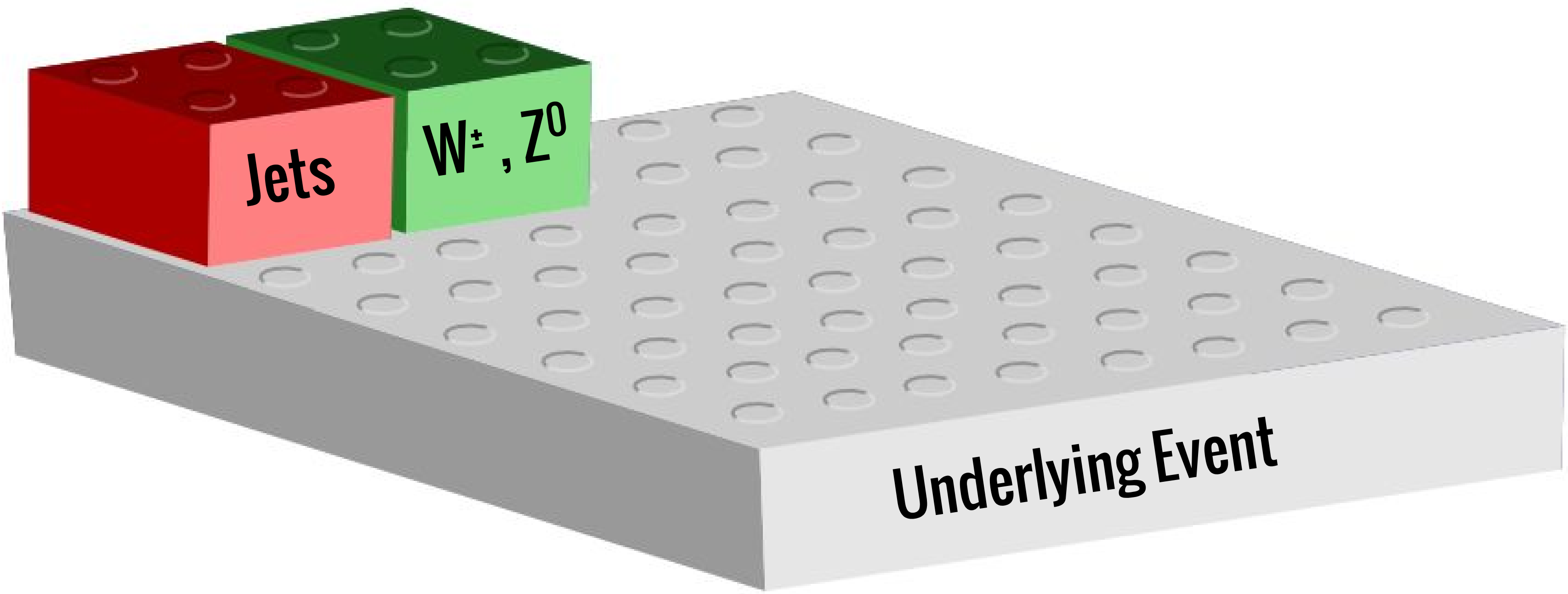
Outline - *Jets*

- Double-differential inclusive jet cross section
- Charged particle multiplicity inside jets
- Jet production cross section in the very forward region
- First measurements with jets from *LHCb*



Outline - *Electroweak bosons*

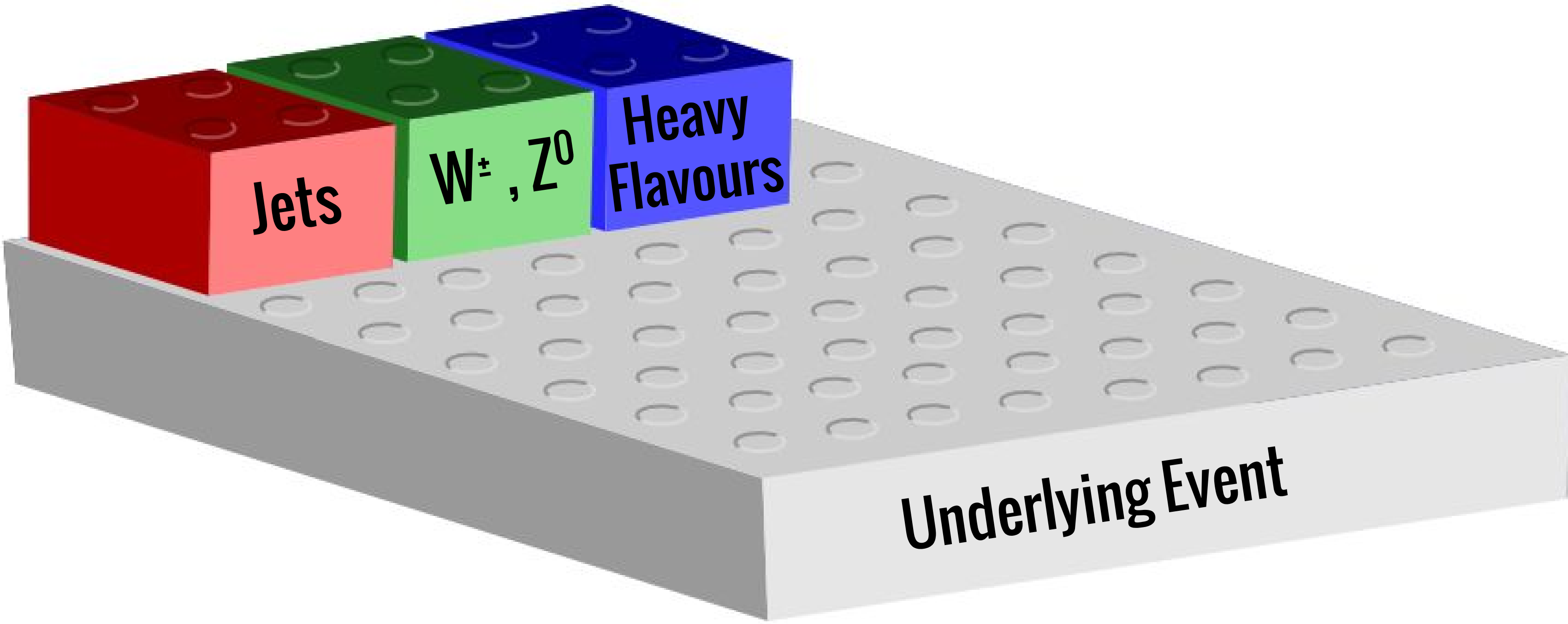
Production of single electroweak bosons covered in the EW talk



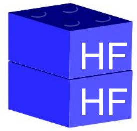
Outline - *Heavy Flavours*

- Production cross-section of *b*-mesons and *c*-mesons
- Production cross-section of quarkonium states
- Central Exclusive Production (*diffractive physics*)

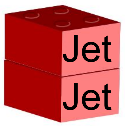
top-quark production covered in the dedicated talk



Outline - *Associative production*

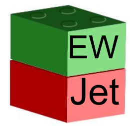


Pairs of charmonia in CEP

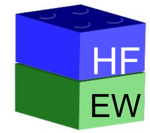


Dijets

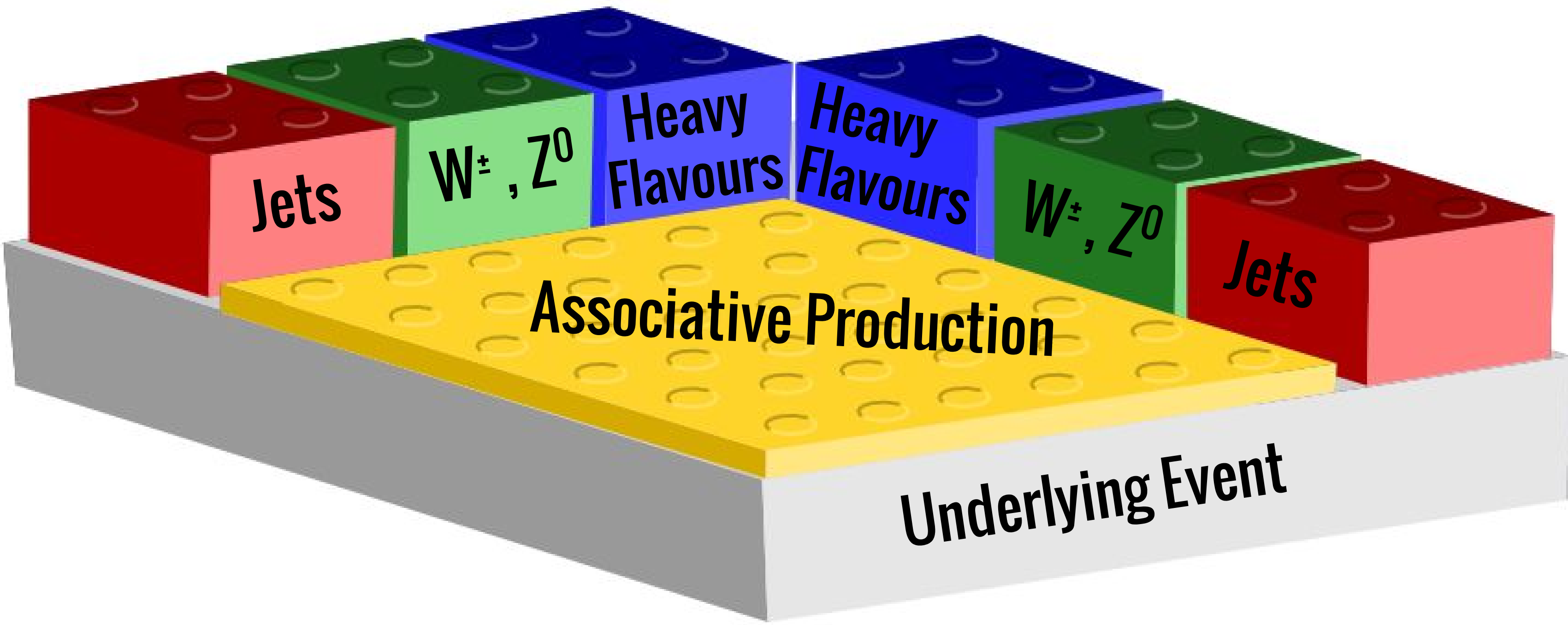
4-jet cross-section



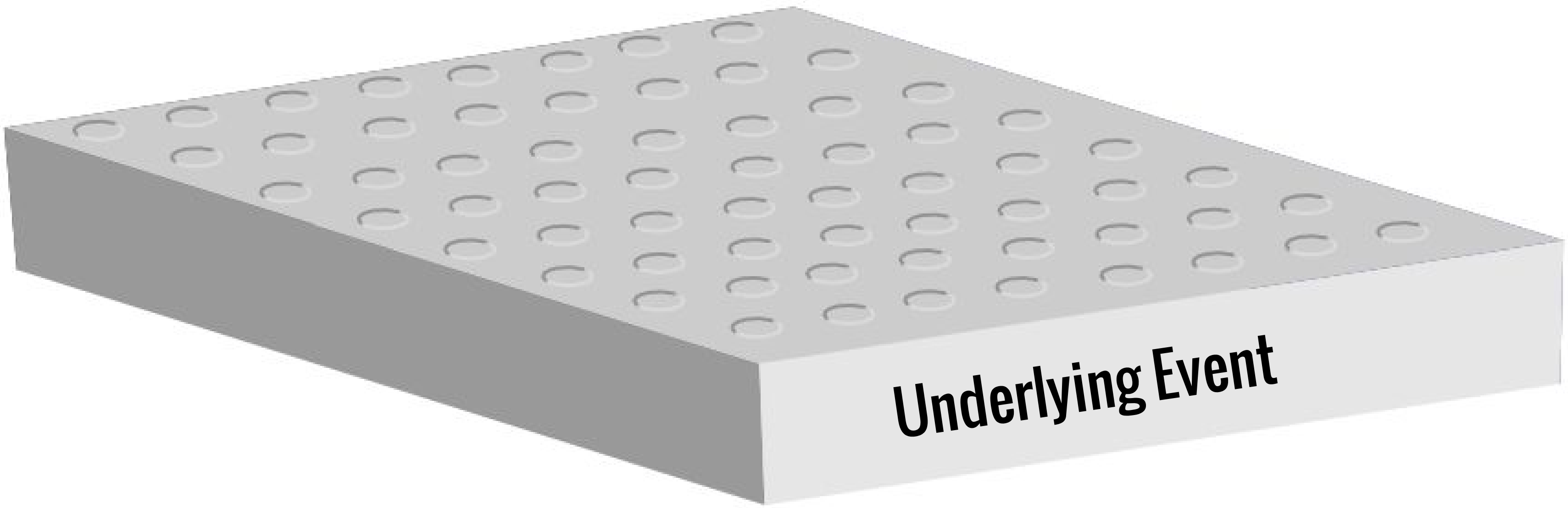
Z + jet



Z + *b*-jet



The Underlying Event



Studying the underlying event

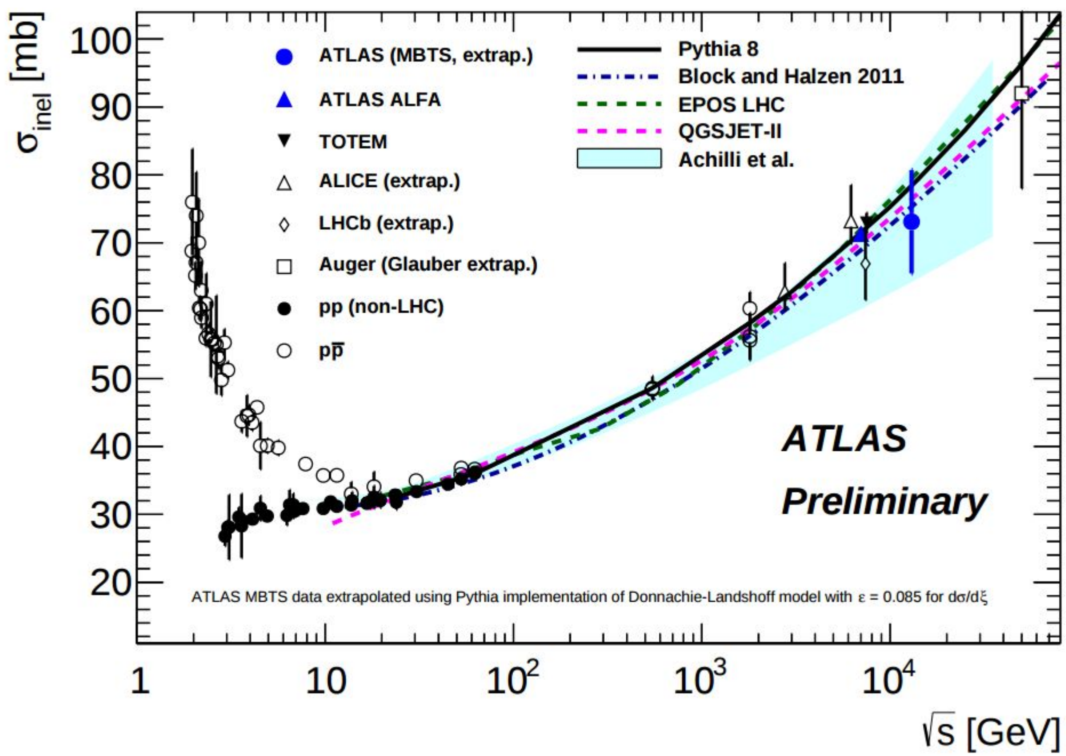
Interesting Hadron Physics

- Behaviour of QCD at low-*x*
- Saturation of the parton distribution functions at low-*x*
- Multiple parton interaction
- Soft diffractive components

Important to tune the simulation (background for EW and new physics)

- Large theoretical uncertainties from allowed parameter space
- Difficult to model dependence on center-of-mass energy
- Integrate previous measurements at 0.9 and 1.96 TeV (CDF) and 7 TeV (CMS)

Proton inelastic cross-section measurement (13 TeV)



Definition of the fiducial region based on the *mass of the dissociation systems.*

Extrapolation is based on Simulation.

CMS combines 3.8 T and 0 T data samples.

The statistical uncertainty is negligible.

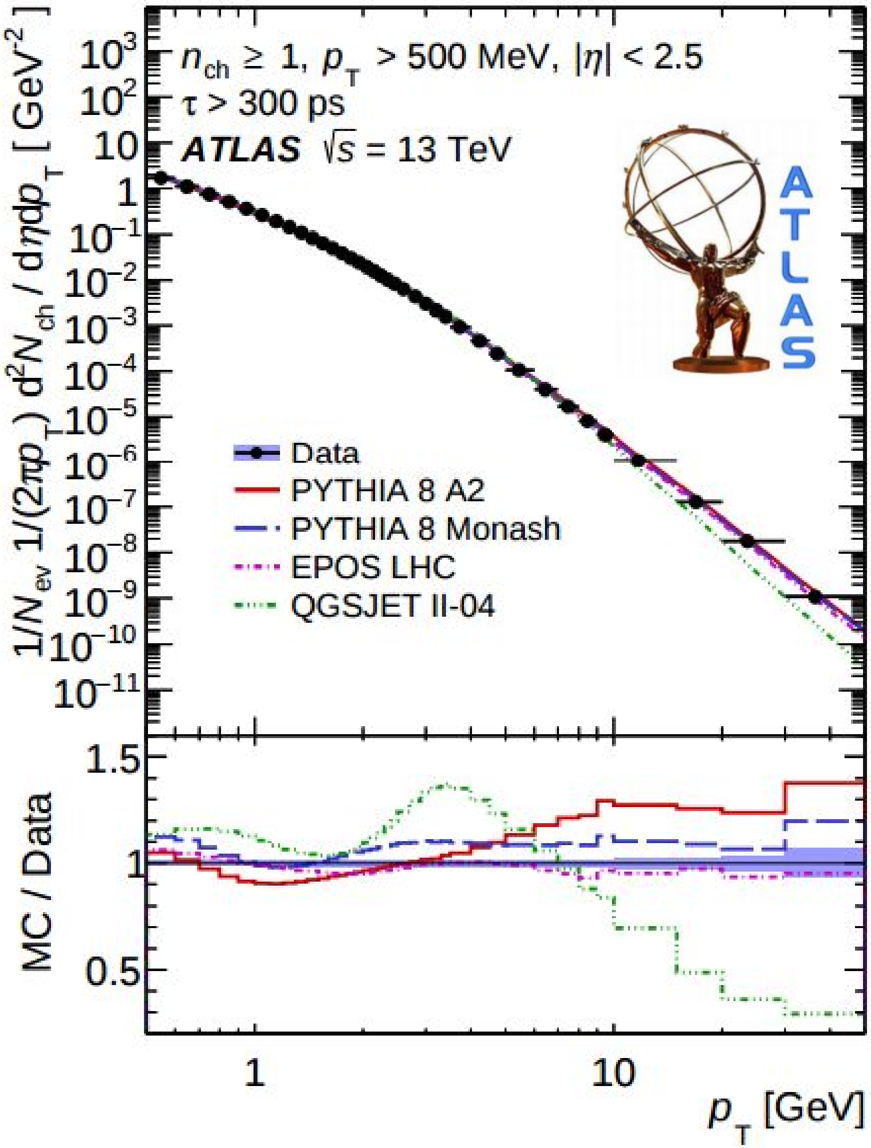
$$73.1 \pm 0.9\,(\text{exp.}) \;\pm 6.6\,(\text{lum.}) \;\pm 3.8\,(\text{extr.})\text{ mb}$$

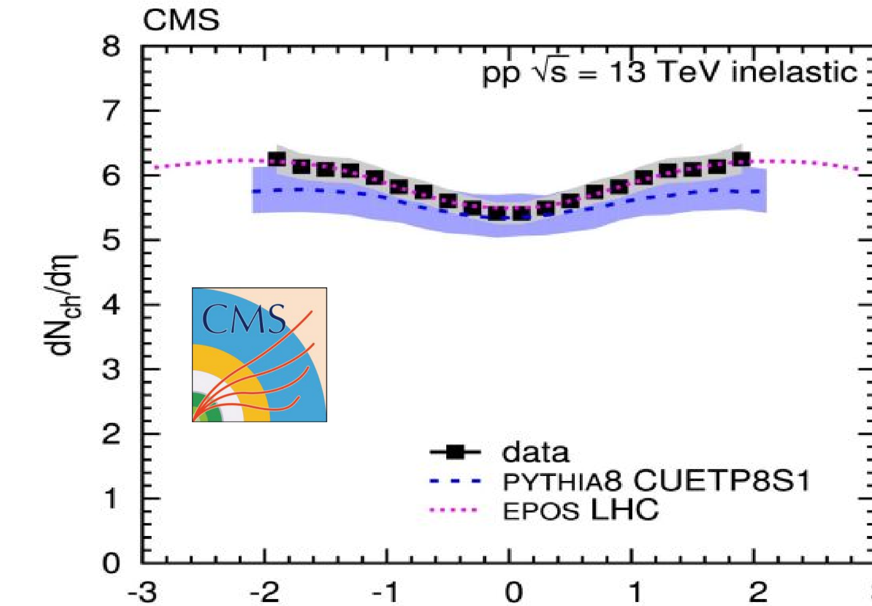
[ATLAS-CONF-2015-038]

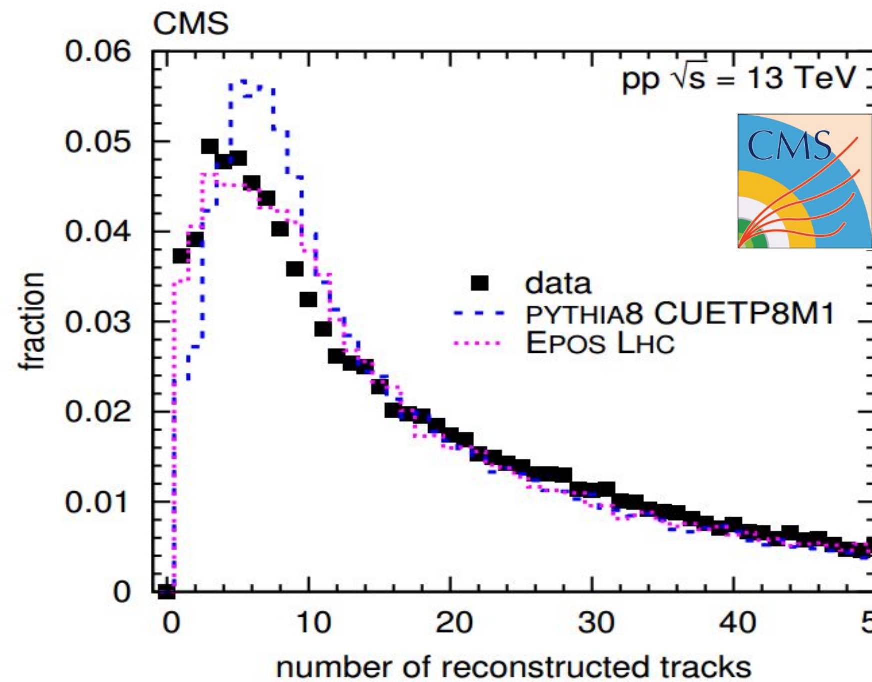
$$71.3 \pm 0.5\,(\text{exp.}) \pm 2.1\,(\text{lum.}) \pm 2.7\,(\text{ext.})\text{ mb.}$$

[CMS-PAS-FSQ-15-005]

Track distributions at 13 TeV







2015 Early Measurements: *Leading Particle*

Leading track: track with the highest p_T

The leading track (or the leading jet) represents the direction of the hard scatter.

Azimuthal angle wrt. the leading track defines «*regions*» of the underlying event.

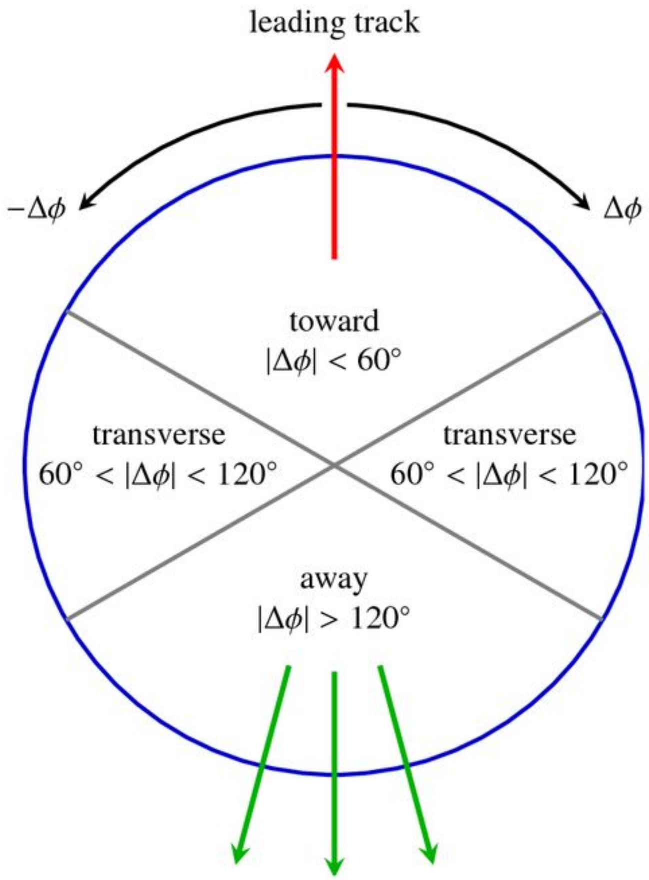
Observables.

- $$\frac{\langle N_{ch} \rangle}{\Delta\eta\Delta(\Delta\phi)} \quad ; \quad \frac{\langle \sum p_T \rangle}{\Delta\eta\Delta(\Delta\phi)}$$

TransMIN (TransMAX) *- Each observable is computed on the "side" where it is smaller (larger).*

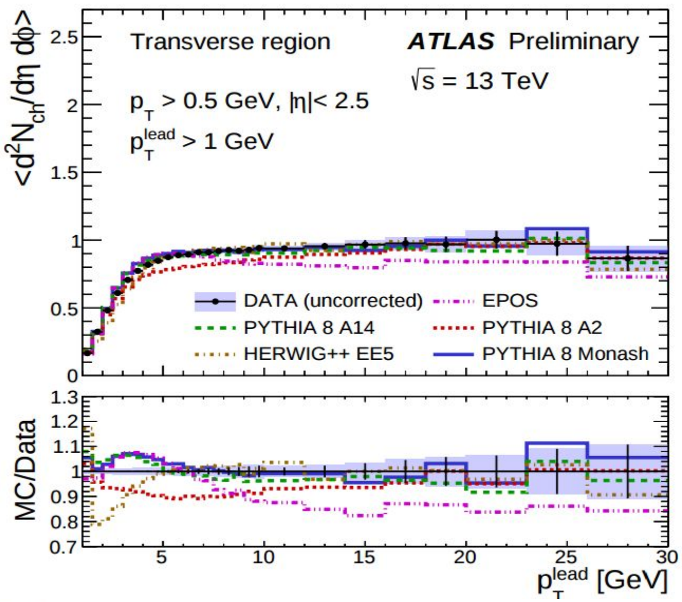
$$\text{TransAVE} = \frac{\text{TransMIN} + \text{TransMAX}}{2}$$

$$\text{TransDIFF} = \text{TransMIN} - \text{TransMAX}$$

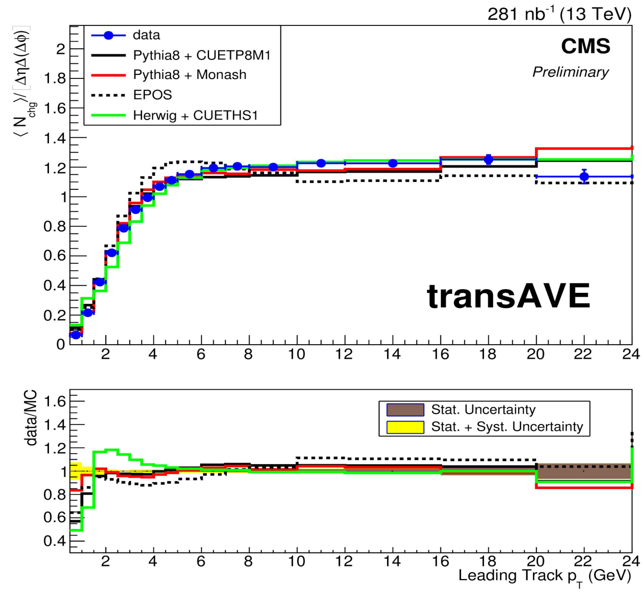


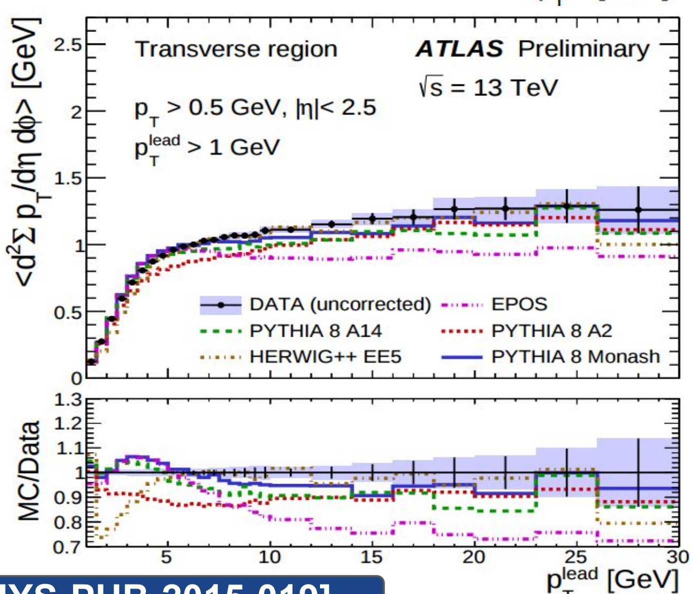
Measurements with *leading particle*

[FSQ-15-007]

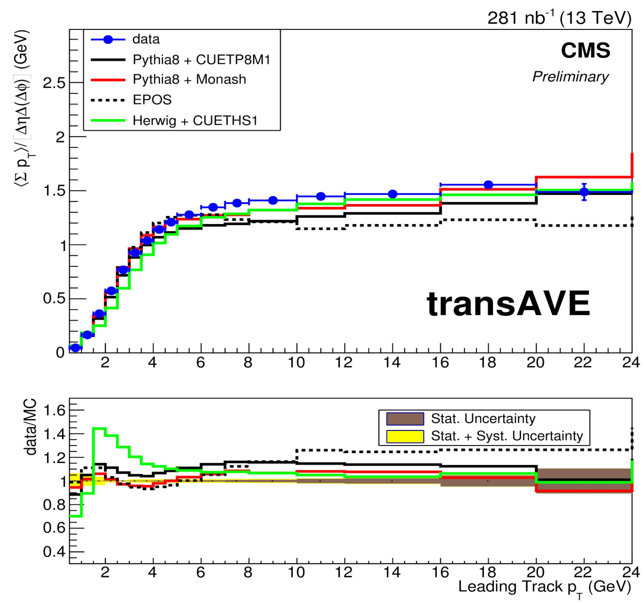


Track density





Energy density



[ATL-PHYS-PUB-2015-019]

Measurements with *leading jet*

Measurements of the transverse activity with leading *jet-particle* are not directly comparable for ATLAS and CMS (different selection strategies).

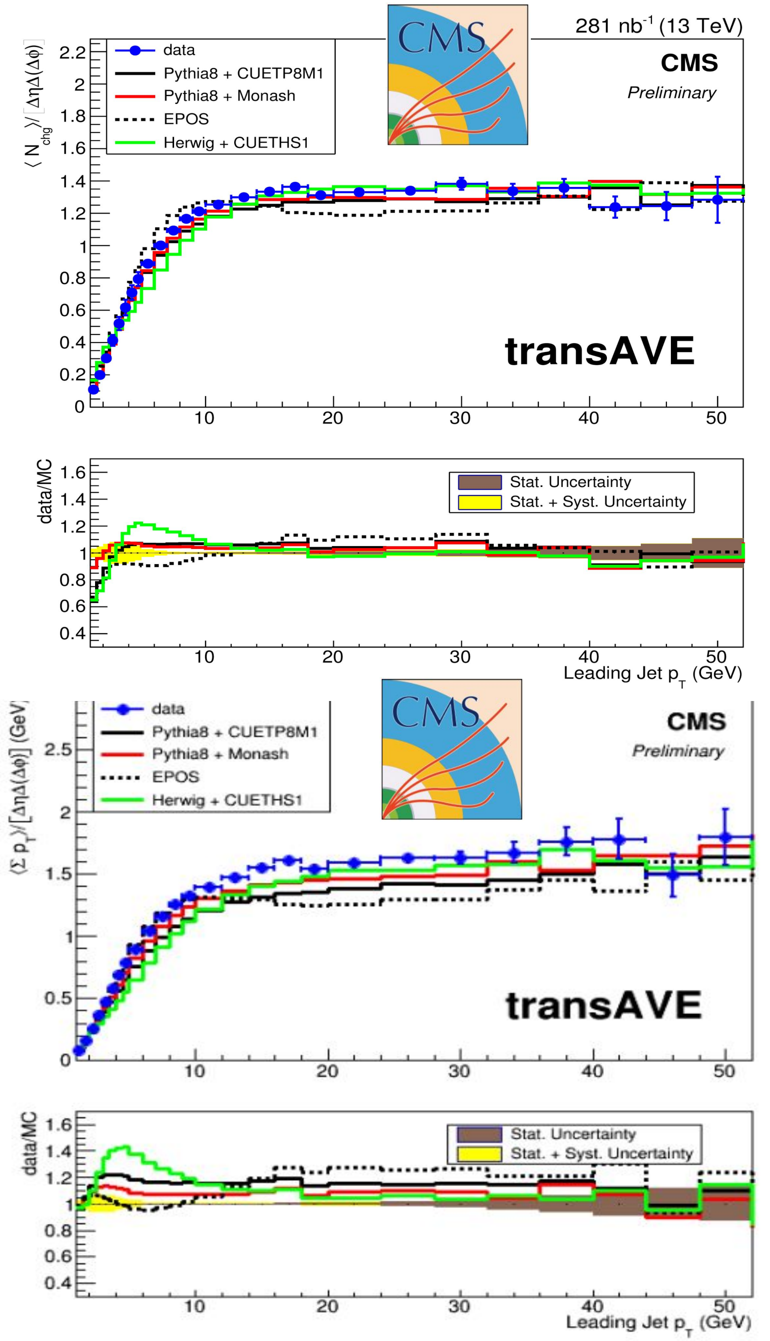
Similar conclusions from comparison with simulation:

Best performing Monash tuning for Pythia8 [EPJC 74 (2014) 3024]

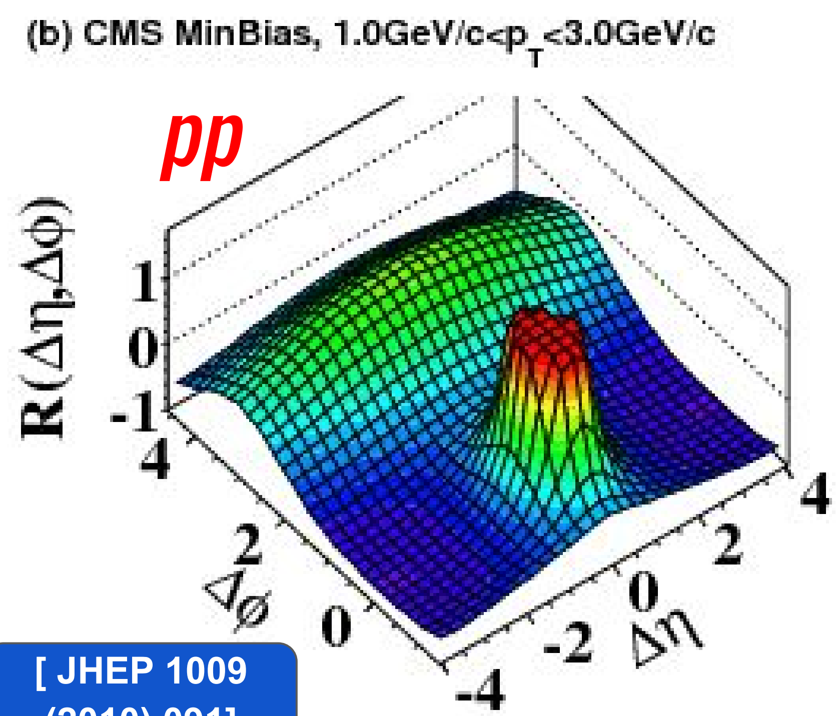
HERWIG++ (CUETHS1) [EPJC 58 (2008) 639] works better for harder events than for softer.

Track density

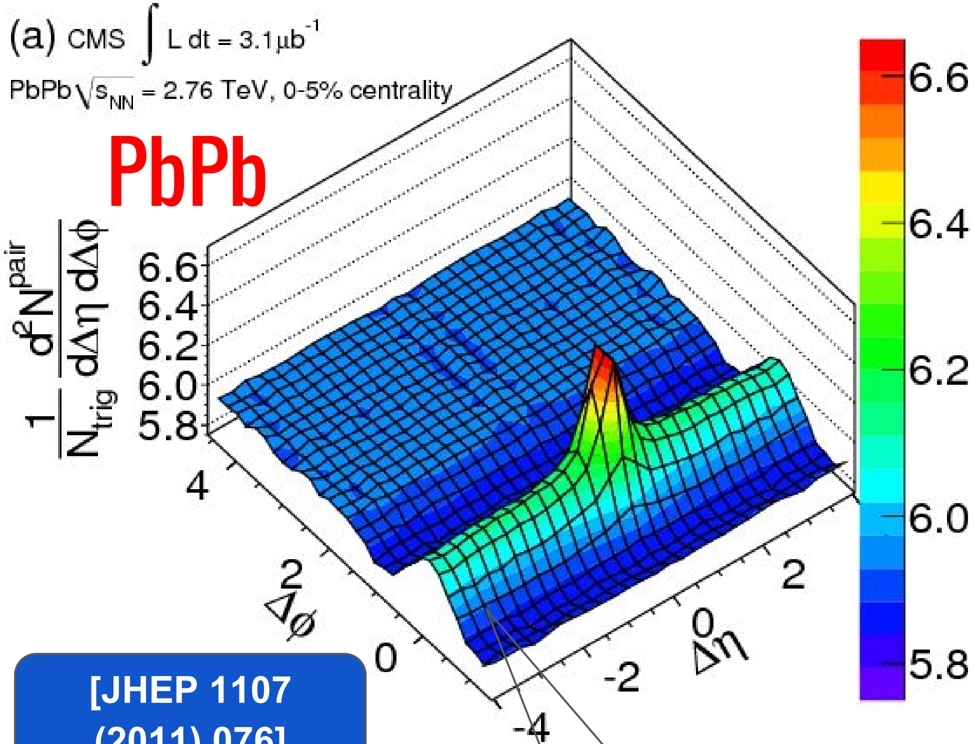
Energy density



Long-range near-side correlations



[JHEP 1009 (2010) 091]



[JHEP 1107 (2011) 076]

The effect was observed also in *p*Pb collisions by CMS and by LHCb (in the forward region!).
CMS observed the effect also in high-multiplicity *pp* collisions in 2013.

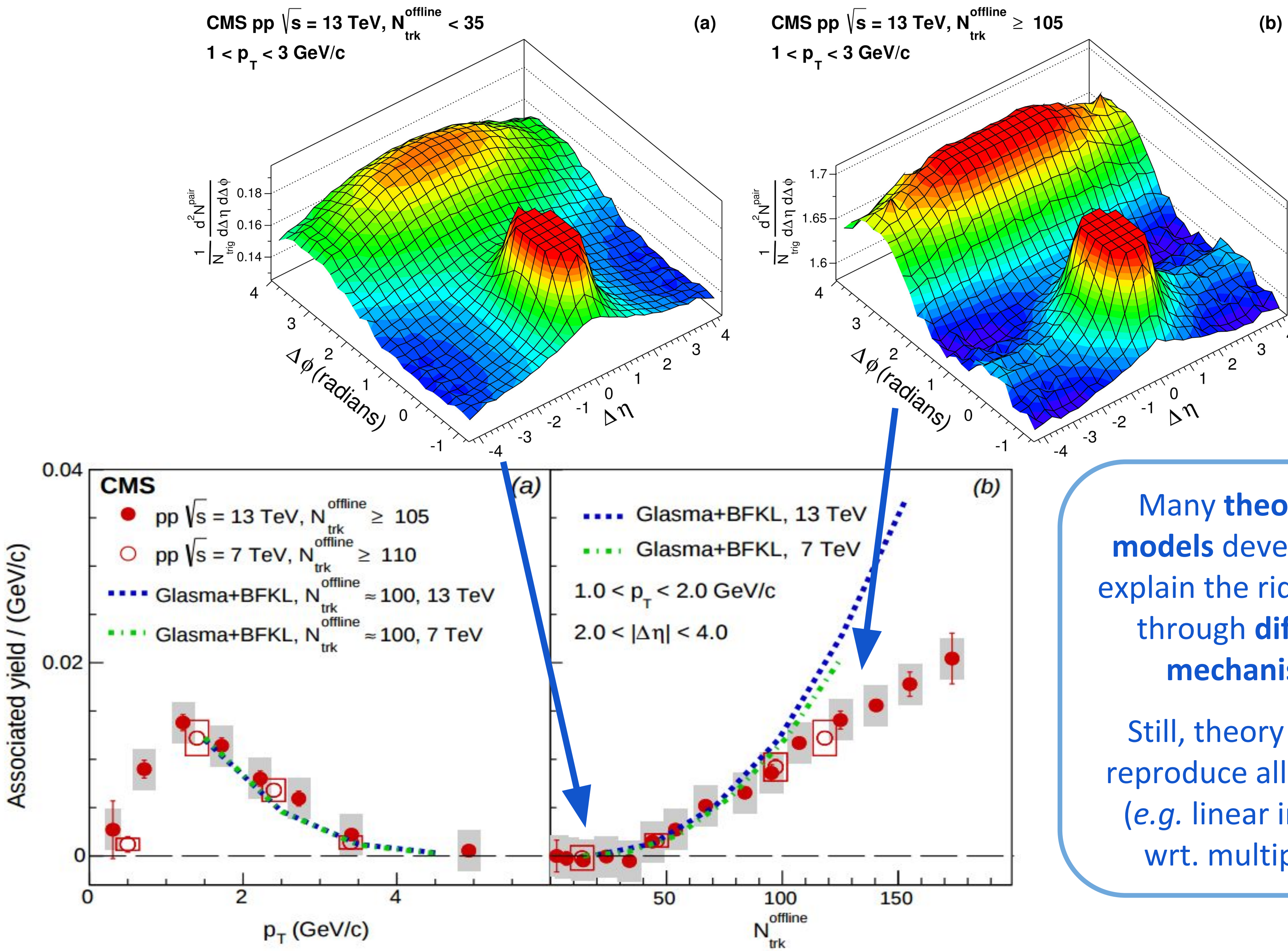
CMS *pPb*:
PLB 718 (2013) 795

LHCb *pPb*:
arXiv:1512.00439

CMS *pp* (8 TeV):
JHEP 1009 (2010) 091

"Ridge"-effect, originally seen only in Ion-Ion collisions.

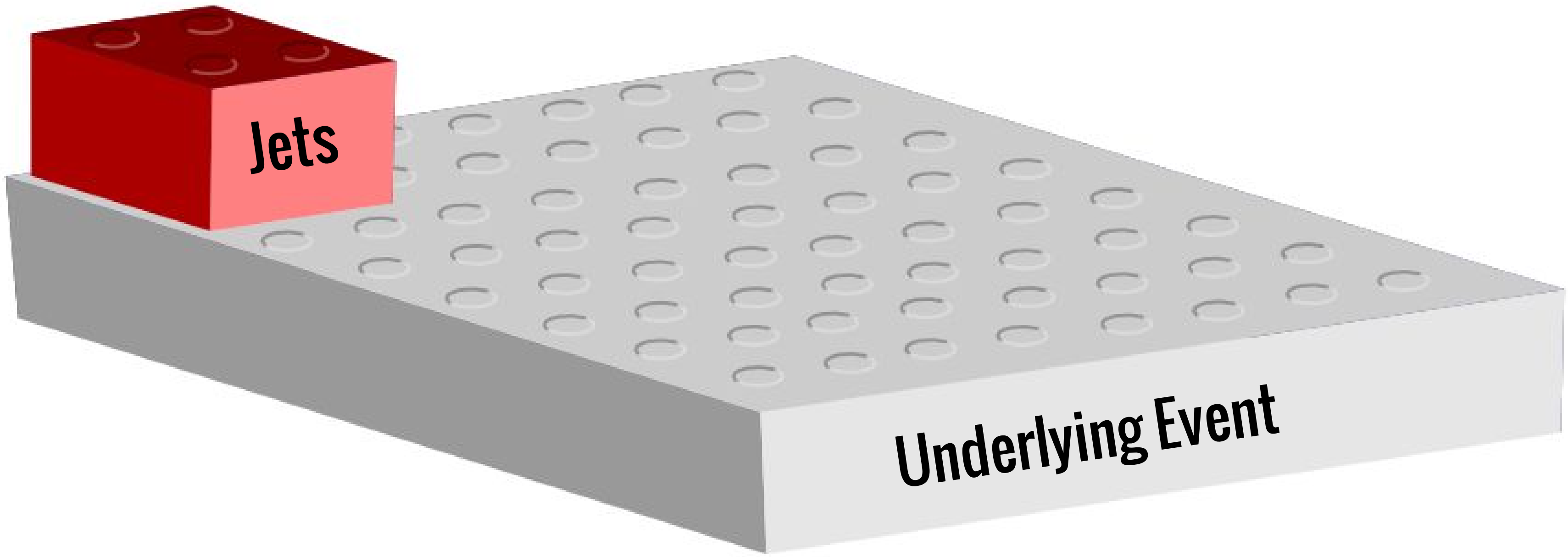
Long-range correlations in *pp* collisions @ √s = 13 TeV



Many **theoretical models** developed to explain the ridge-effect through **different mechanisms**.

Still, theory cannot reproduce all features (*e.g.* linear increase wrt. multiplicity)

Physics with Jets

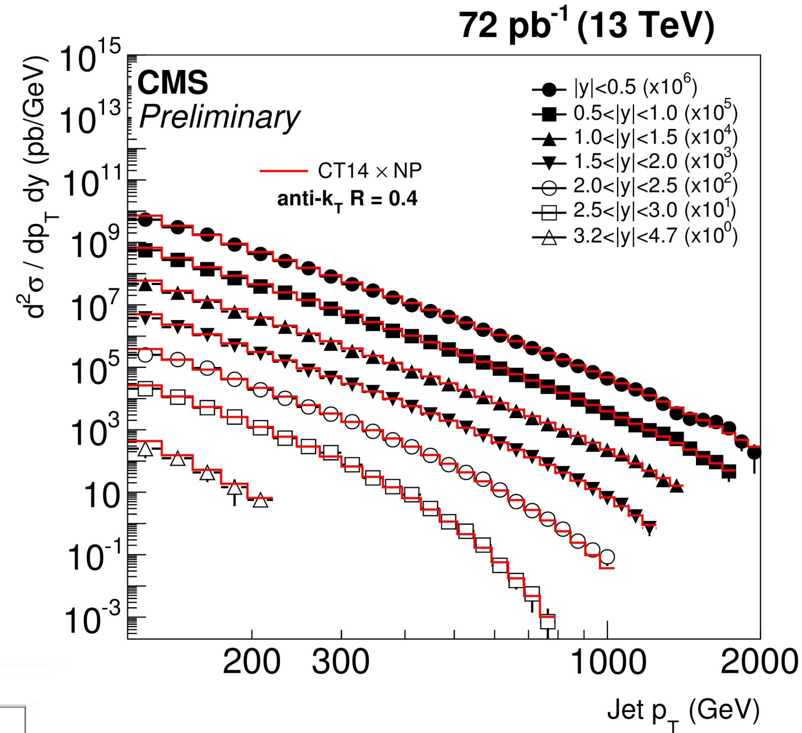


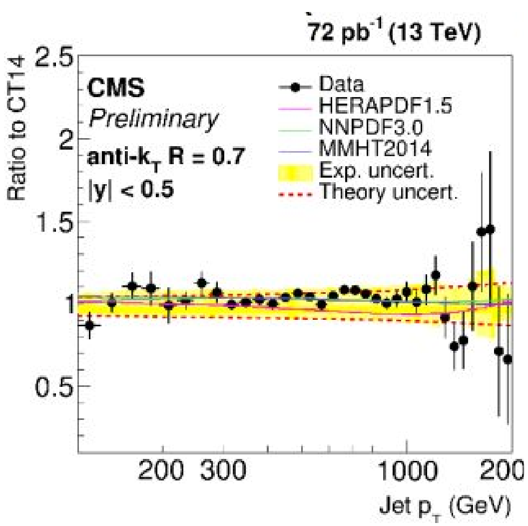
Production cross-section of jets at CMS @ √s = 13 TeV

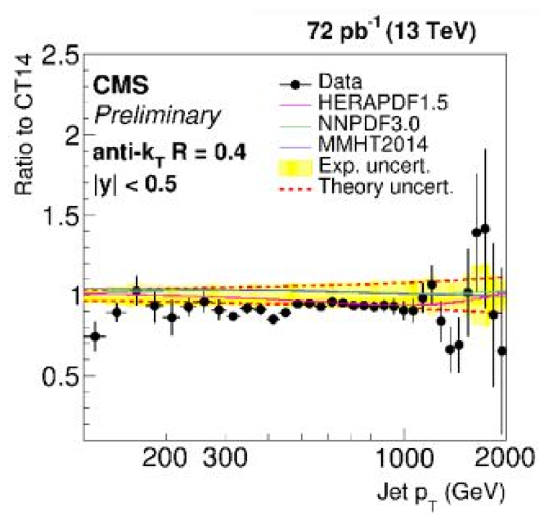
Double-differential cross-section of jet production @ √s = 13 TeV.

Using anti-k_T clusterization with R = 0.4 and 0.7 and comparing to theoretical predictions:

- Pythia8 with PowHeg
- NLOJet++ with CT14 *pdf*







Different behaviour observed for the two radii.

Effects of *soft* (out of the "cone") effects?

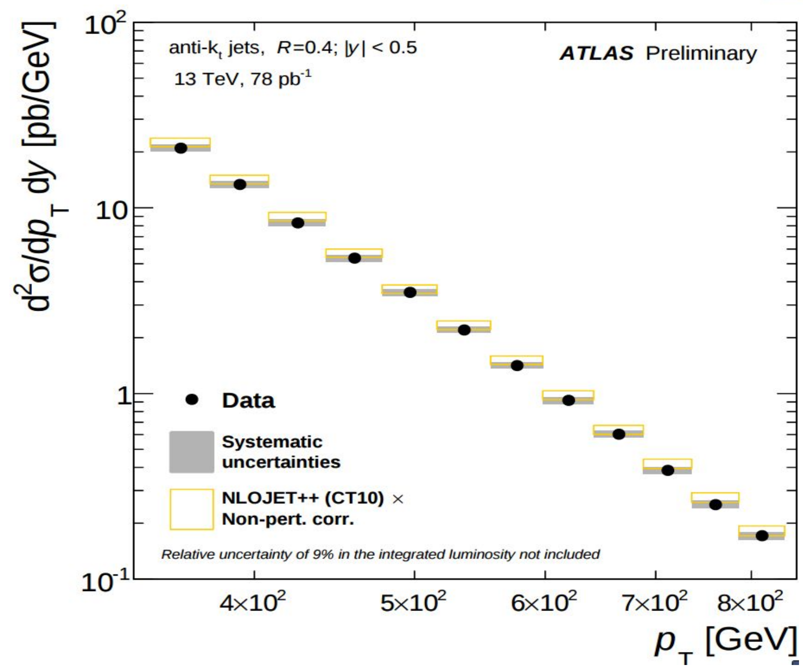
Production cross-section of jets at √s = 13 TeV ATLAS

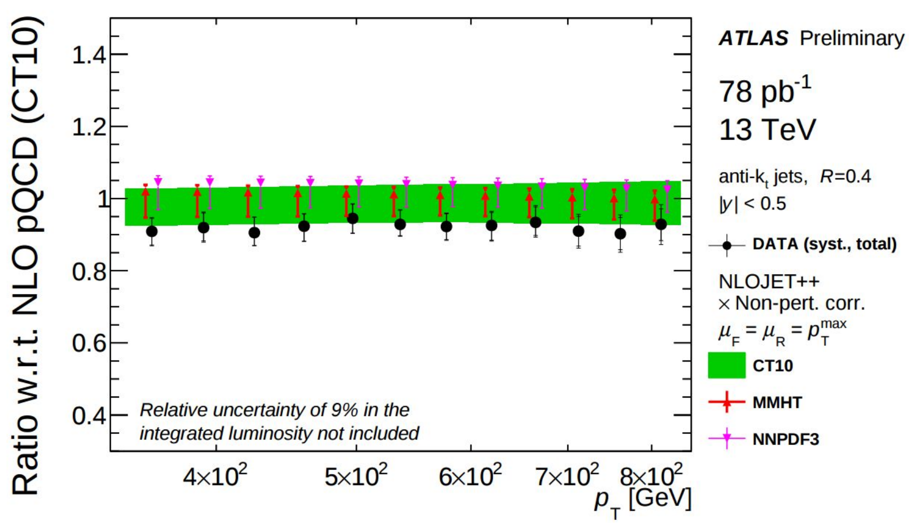
ATLAS measure the production cross-section measurement in the central rapidity bin.

Using anti-k_T factorization with R = 0.4.

The important correlation of the uncertainties makes hard to estimate the compatibility of data with theory.

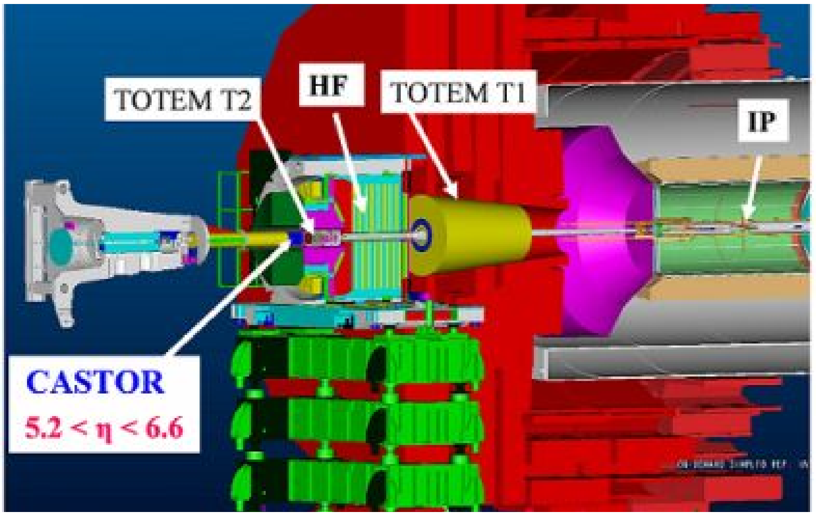
NLOJet++ with NP is used, combined with different *pdf*s.





Very forward production of inclusive jet @ $\sqrt{s}$ = 13 TeV

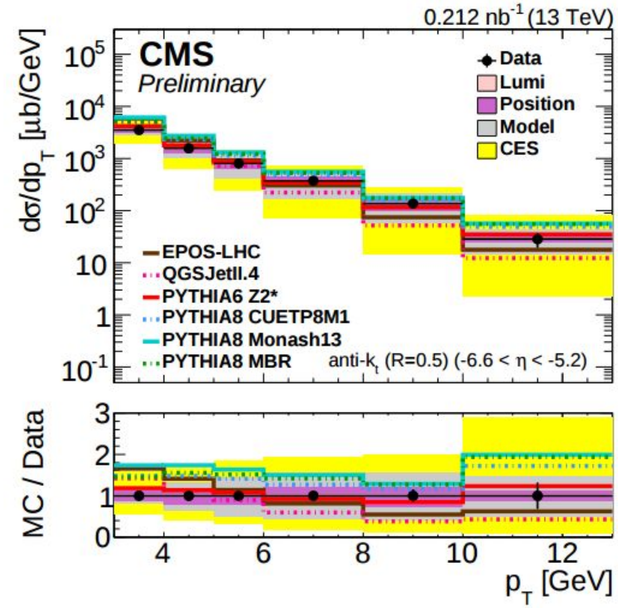
Exploring the forward region using CASTOR calorimeter.

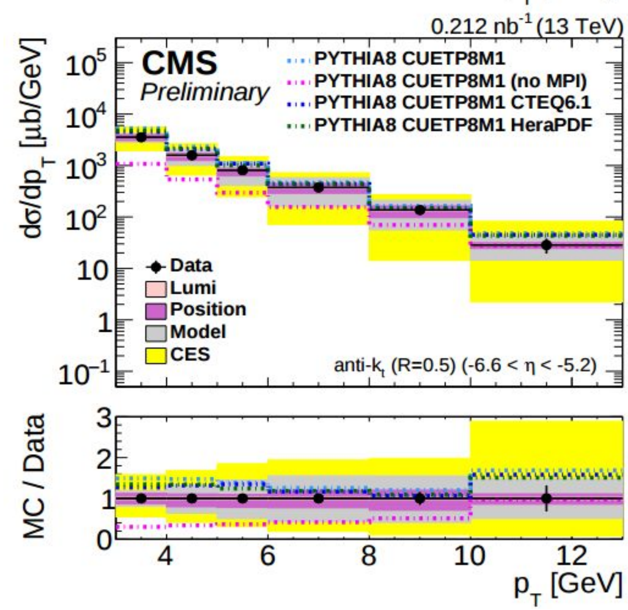


Experimental uncertainty, dominated by CASTOR energy scale, is still large to distinguish between different theoretical models:

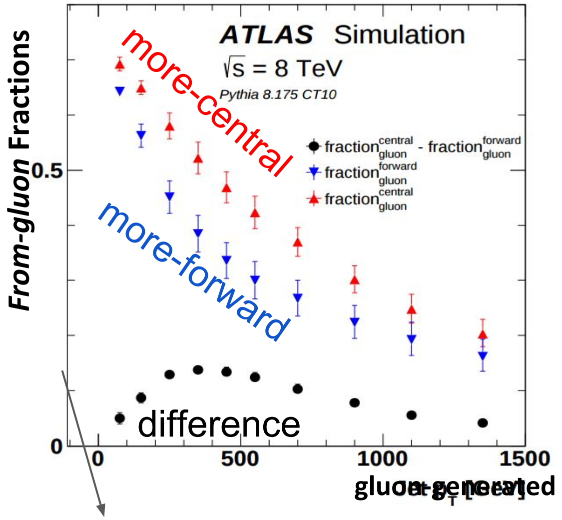
All tested theoretical models found consistent with data!

This measurement has limited sensitivity to *pdf,* but is sensitive to Multi-Parton Interaction.

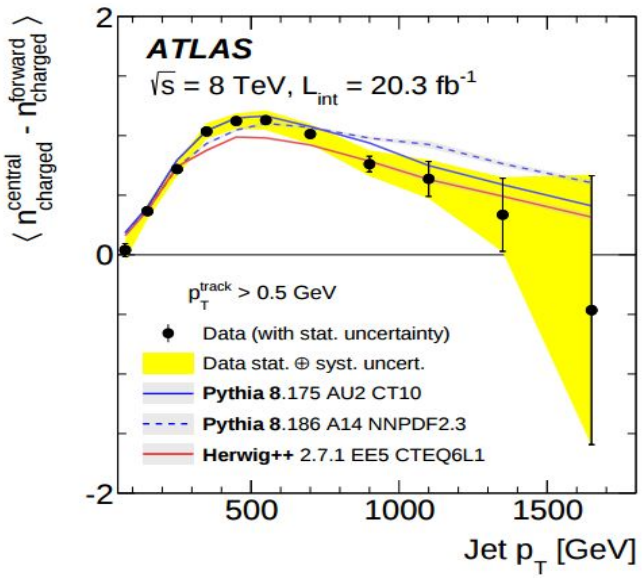


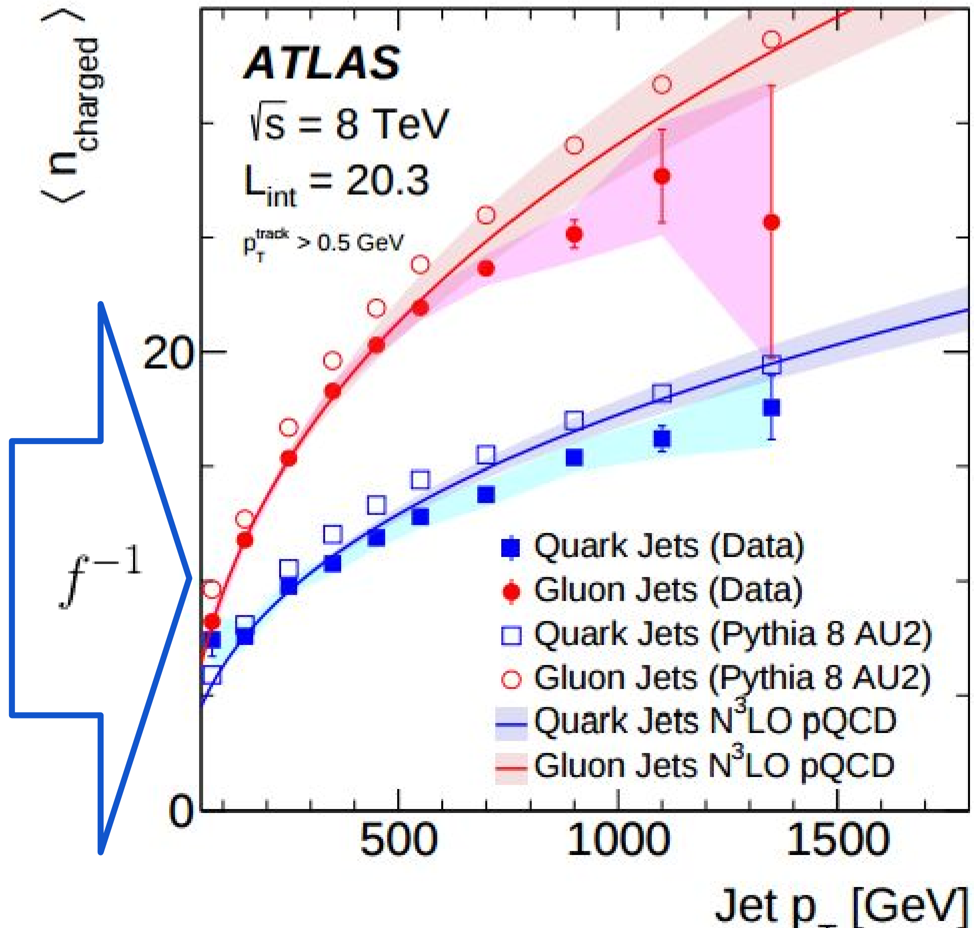


Charged particle multiplicity inside jet @ $\sqrt{s}$ = 8 TeV



$$\begin{pmatrix} \text{central} \\ \text{forward} \end{pmatrix} = \begin{pmatrix} f(g \to c) & [1 - f(g \to c)] \\ f(g \to f) & [1 - f(g \to f)] \end{pmatrix} \begin{pmatrix} \text{from } g \\ \text{from } q \end{pmatrix}$$



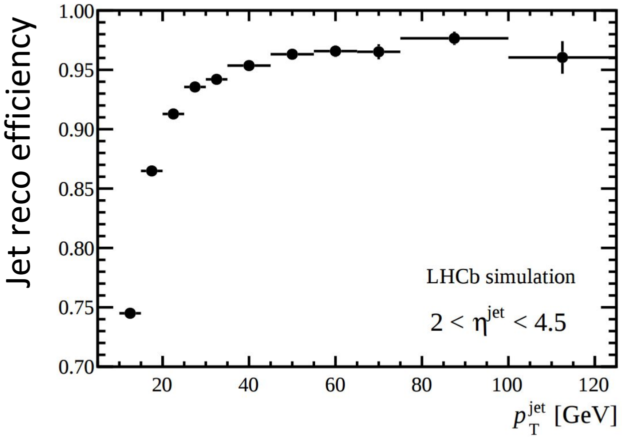


Simulation predicts **systematically larger track multiplicity** for jets.

Exploiting different charged multiplicity of “more-forward” and “more-central” gluon-generated jets, multiplicity of gluon-generated and quark-generated jets is computed.

Jet studies at LHCb in the forward region

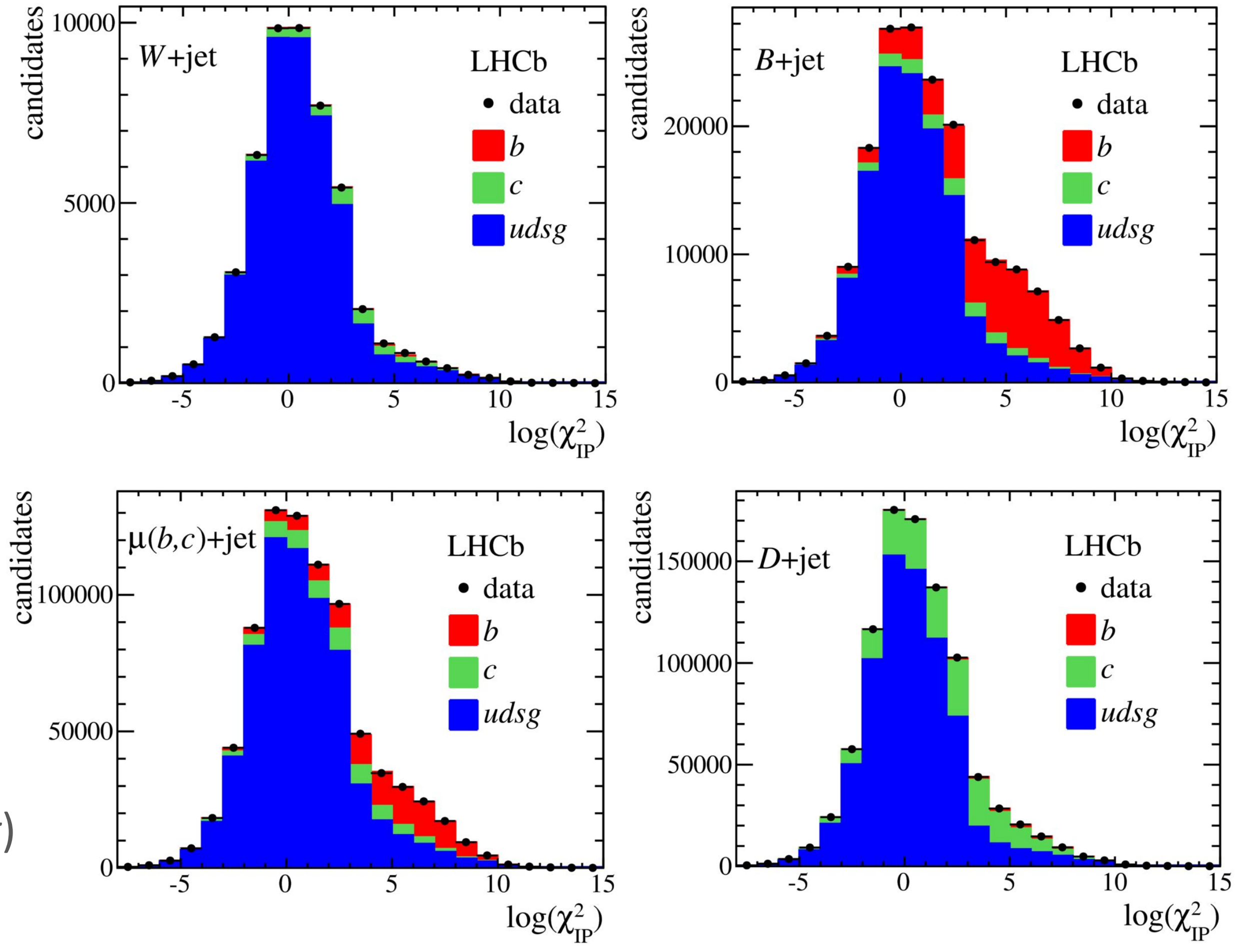
Jet reconstruction using anti-k_T factorization and *FASTJET* algorithm.



Using variable χ^2_{IP} to disentangle HF contributions to jets.

$\chi^2_{IP} = \chi^2_{PV}$ (with t) - χ^2_{PV} (without t)

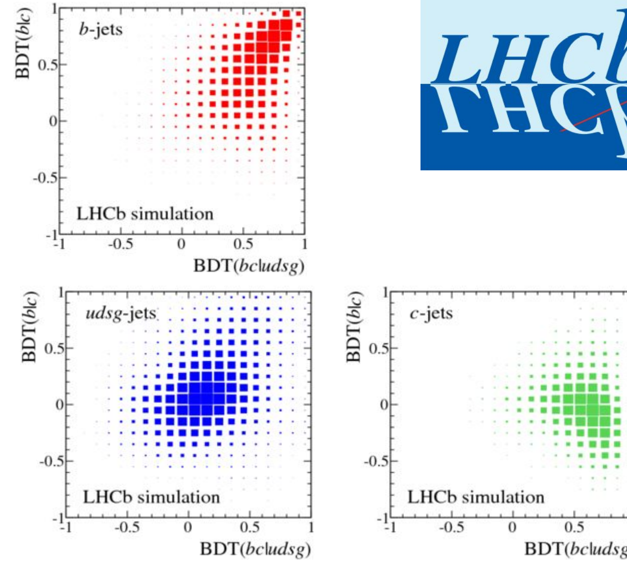
t is the leading track of the jet



Template *pdf*s from simulation,
with resolution corrections from W + jet data.

b-tagging and *c*-tagging at LHCb

Tagging based on Secondary Vertices to enhance purity.

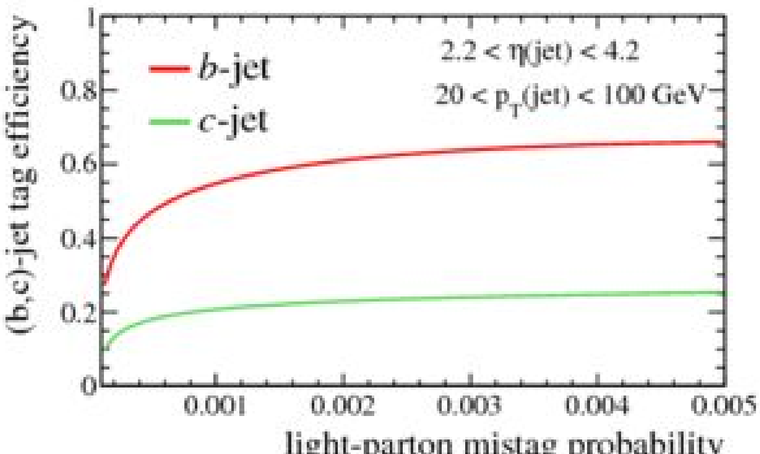


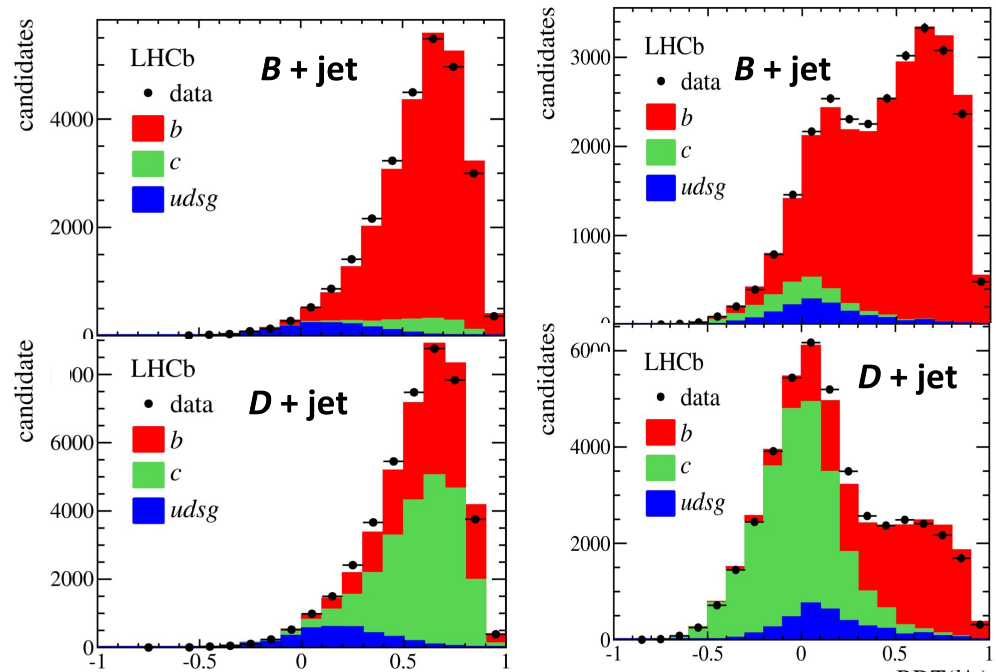
To avoid secondary vertices from strange particles:

- Veto on K_S^0 mass
- Flight-Distance [mm] < 1.5 × p_z [GeV]

Two BDTs based on the SV closest to the PV to distinguish HF from light-parton jets,
and c- from b- jets.

Simulated performance of the SV tagger





BDT(bc|udsg) BDT(b|c)

b-tagging and *c*-tagging at LHCb

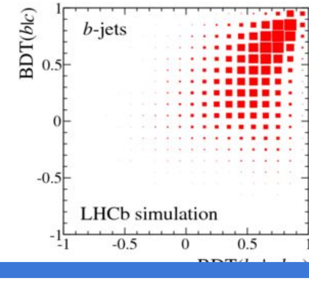
Tagging based on Secondary Vertices to enhance purity.

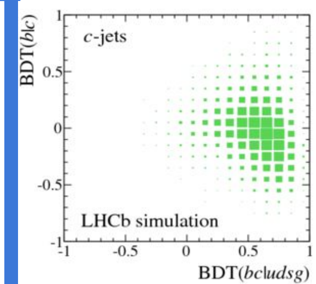
To avoid secondary

- Veto on K_S^0 ma
- Flight-Distance

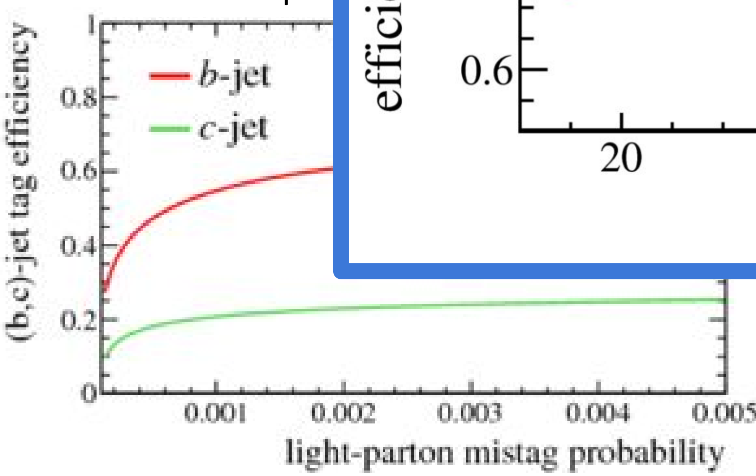
Two BDTs based on

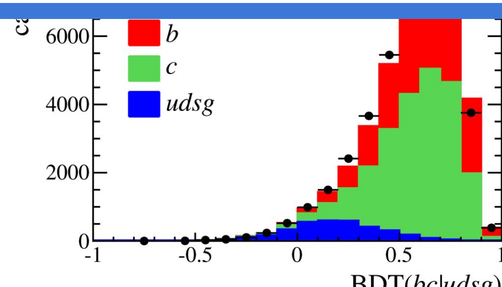
HF from light-parto

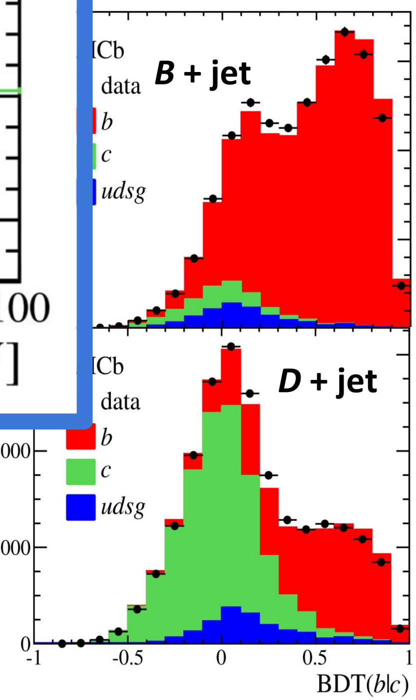


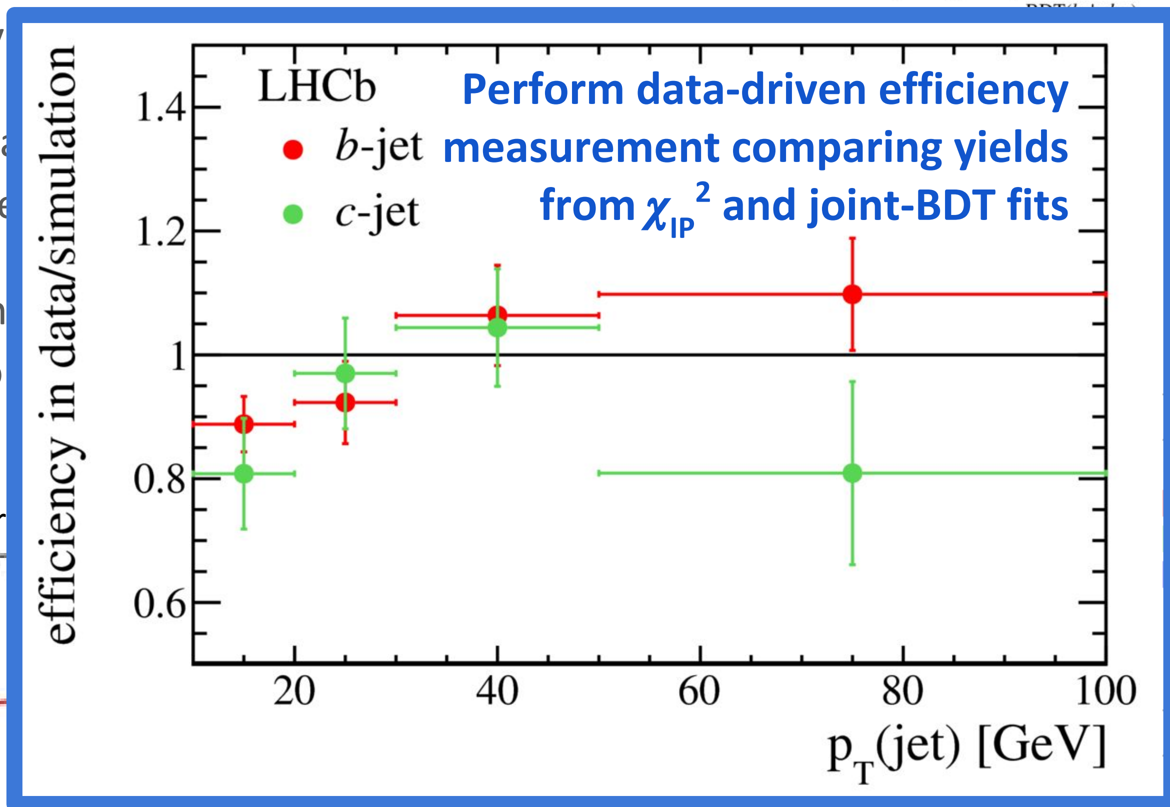


Simulated per

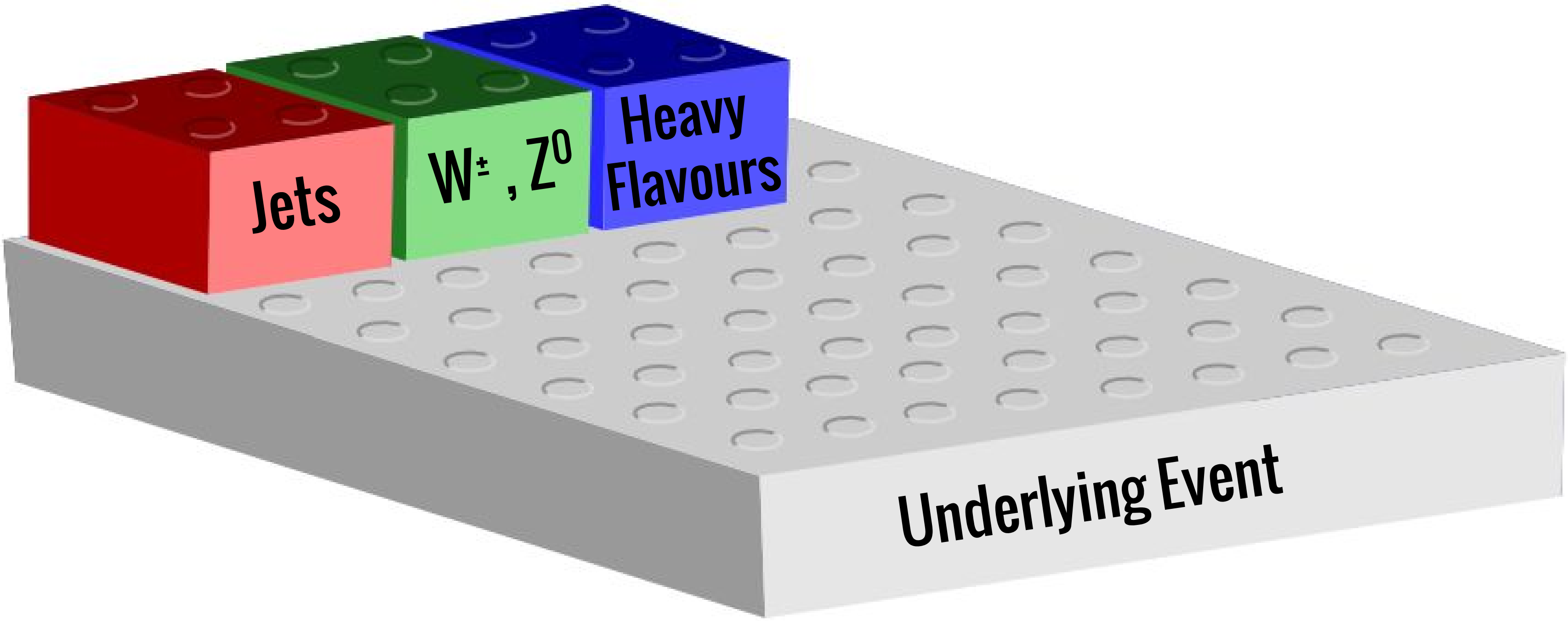




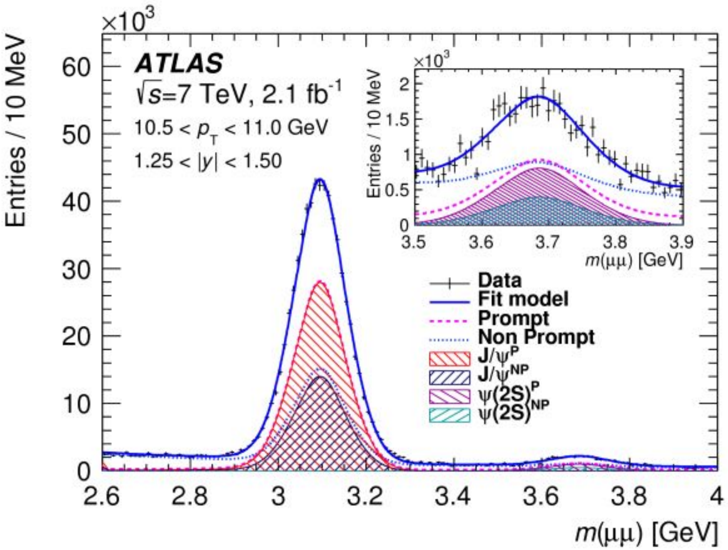


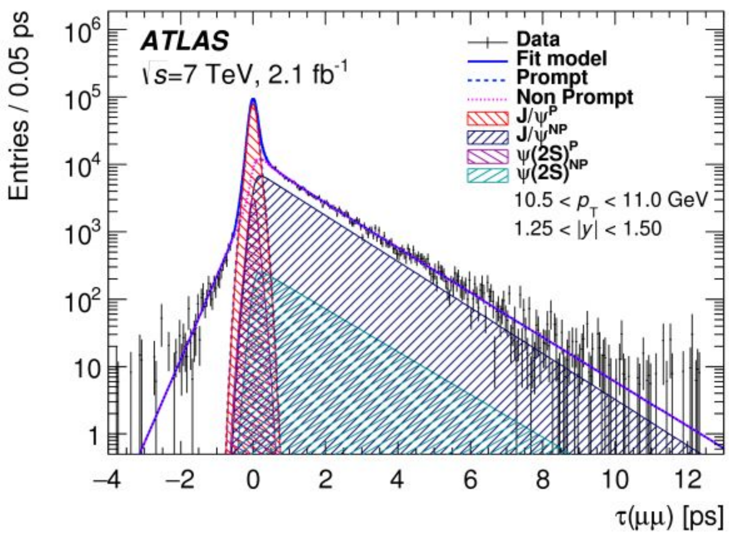


Heavy Flavours



Prompt J/ψ production at 13 TeV





ATLAS-CONF-2015-030

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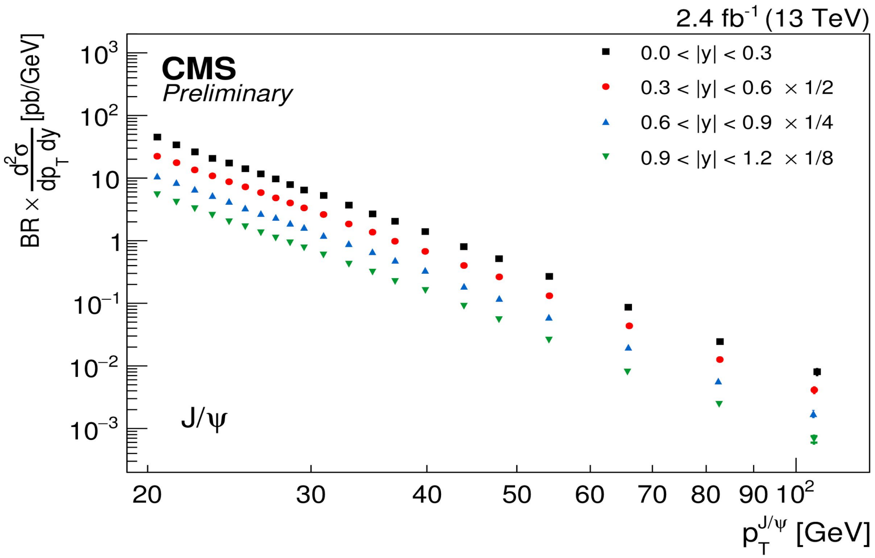
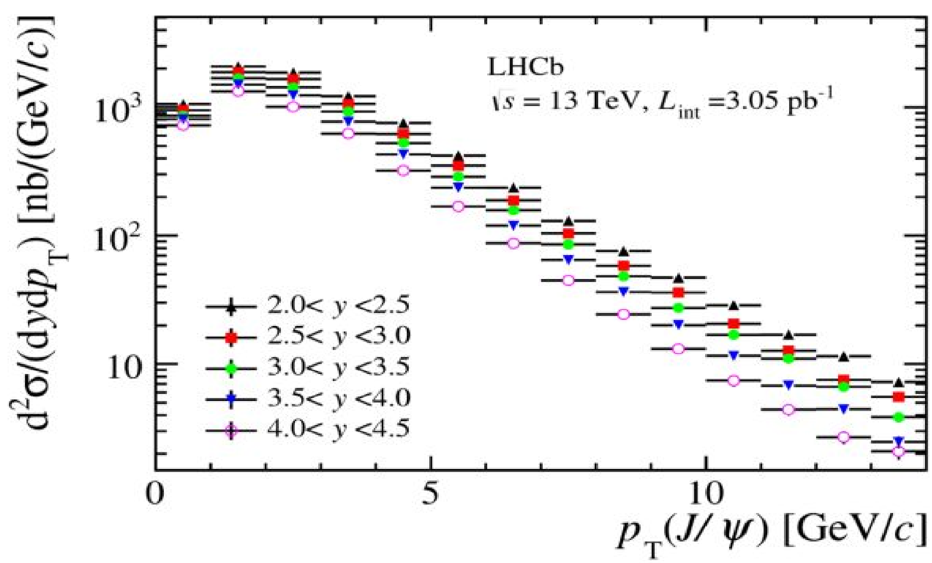
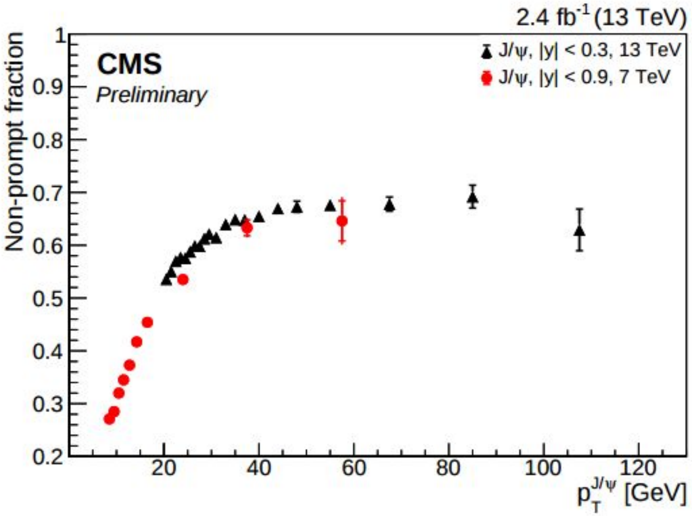




Detached J/ψ as proxy for *b*-hadrons production

Assuming small variation of the *b*-quark **fragmentation functions**, detached J/ψ cross-section measurement allows to compute b-quark production cross-section.



ATLAS-CONF-2015-030

CMS-PAS-BPH-15-005

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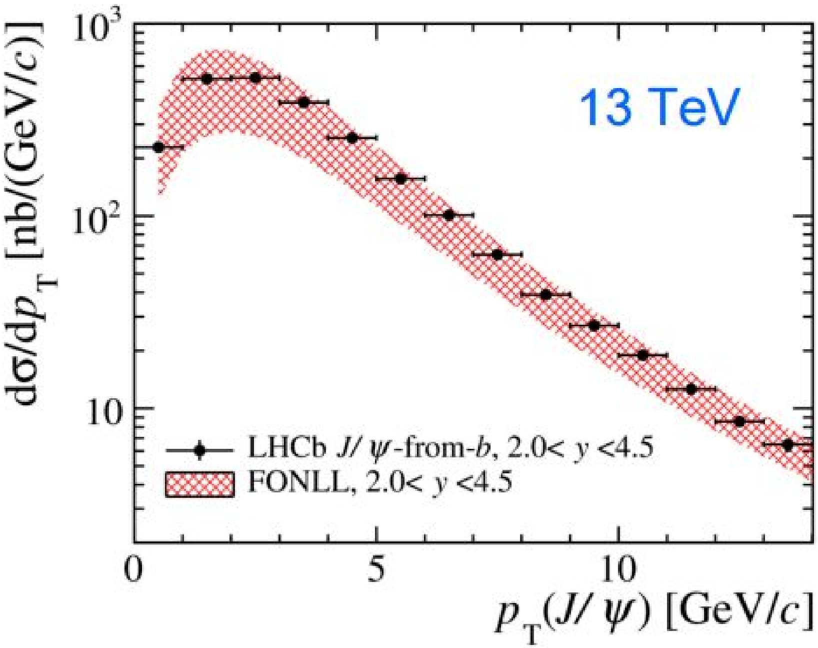
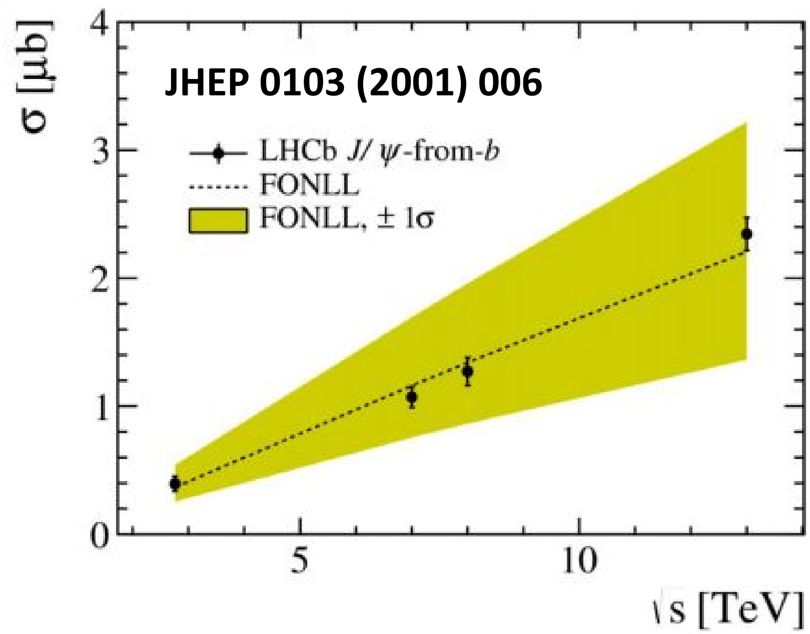
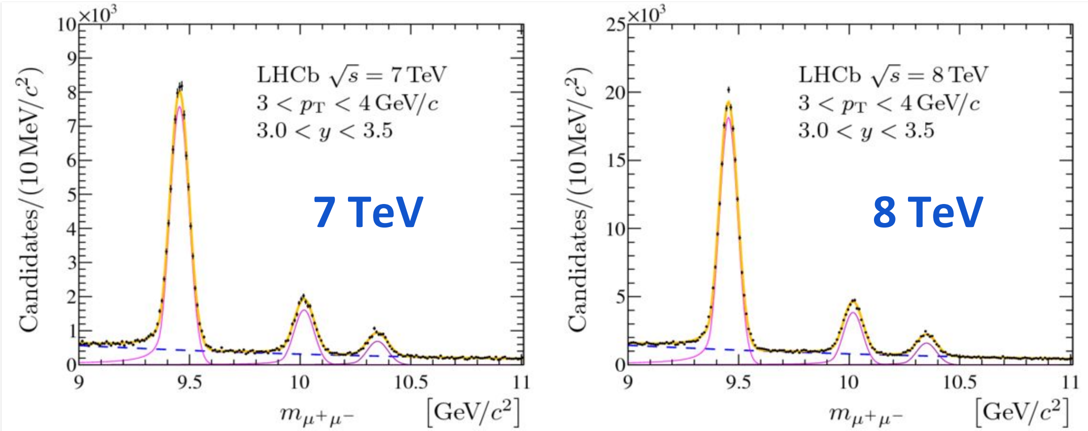
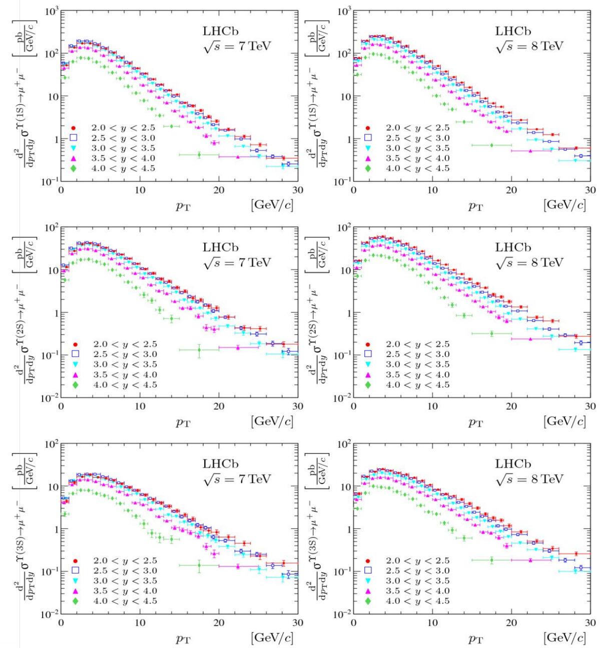


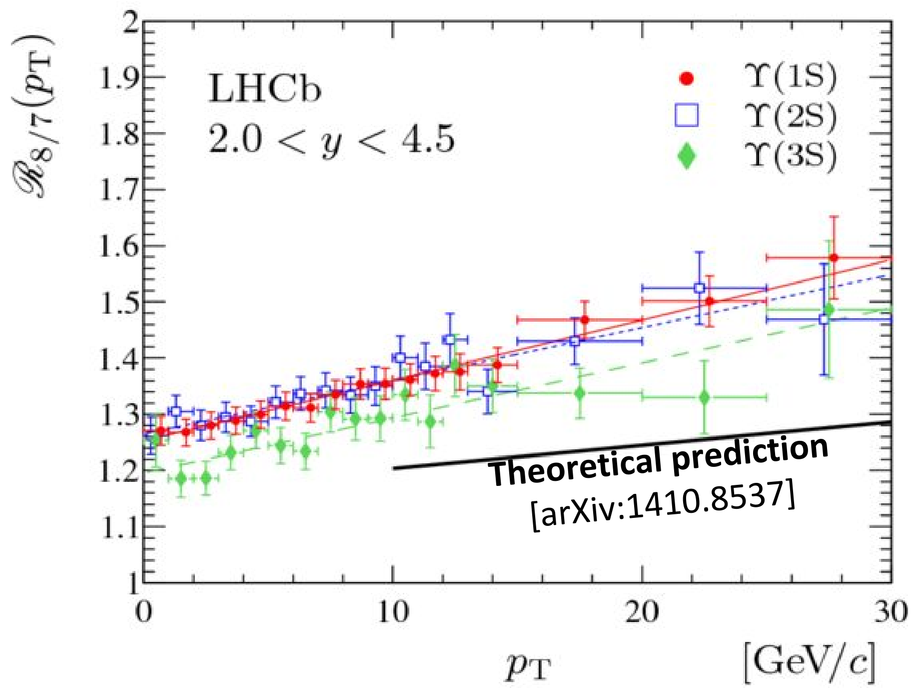


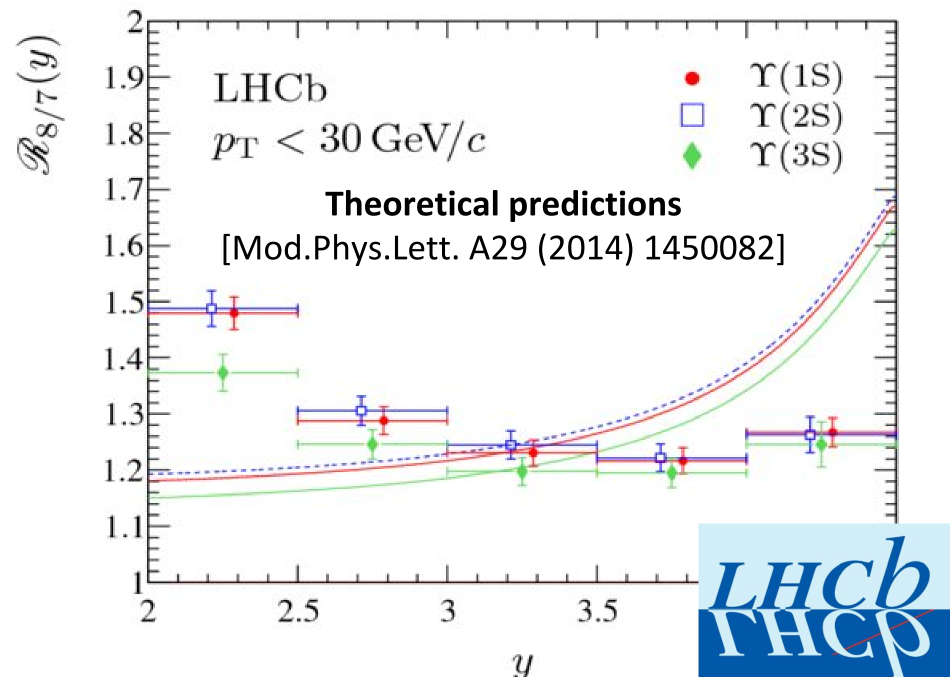
Υ(nS) production at $\sqrt{s}$ = 7 and 8 TeV



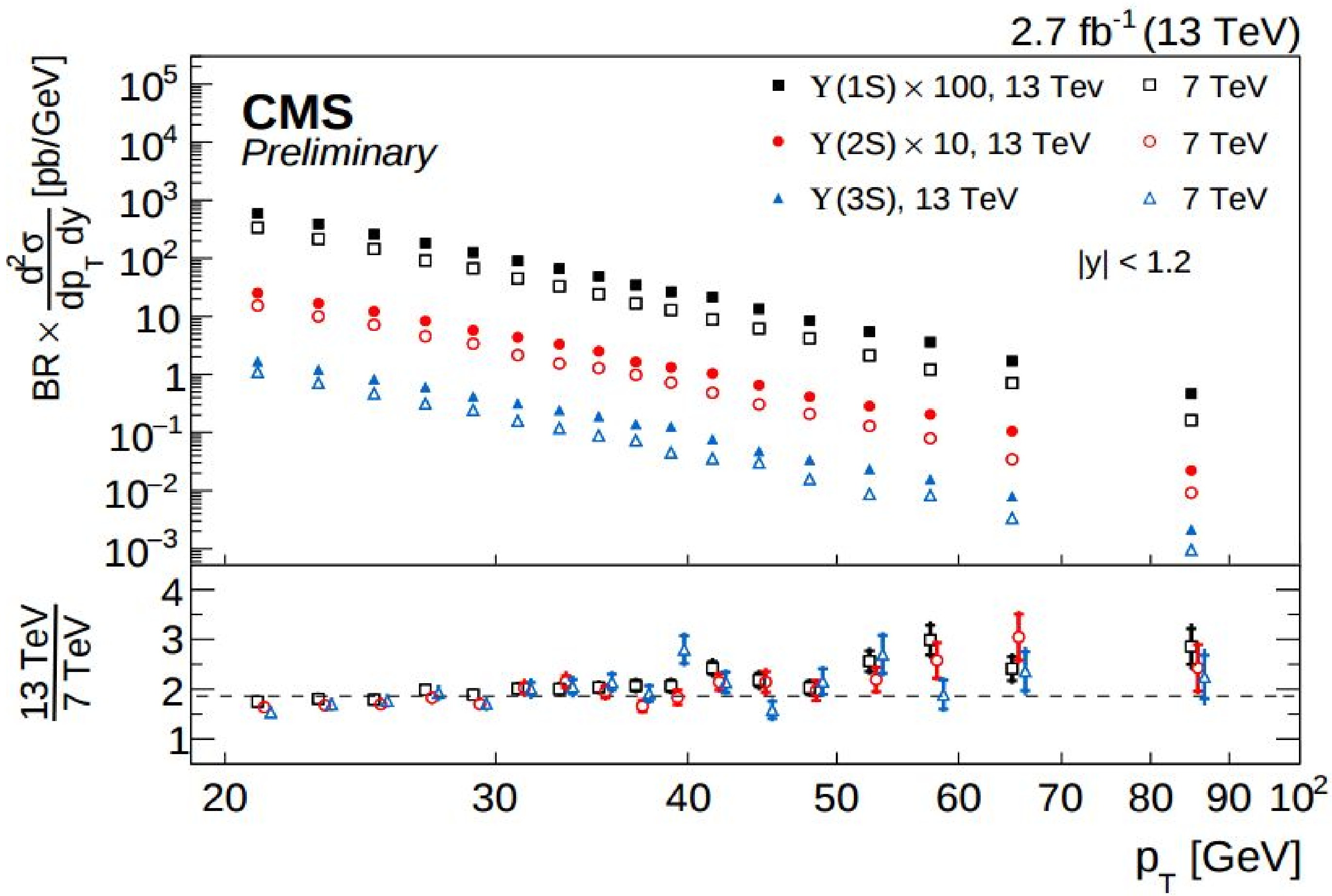


Re-analysis of LHCb, explicitly targeting the ratio measurement confirms unpredicted behaviour.





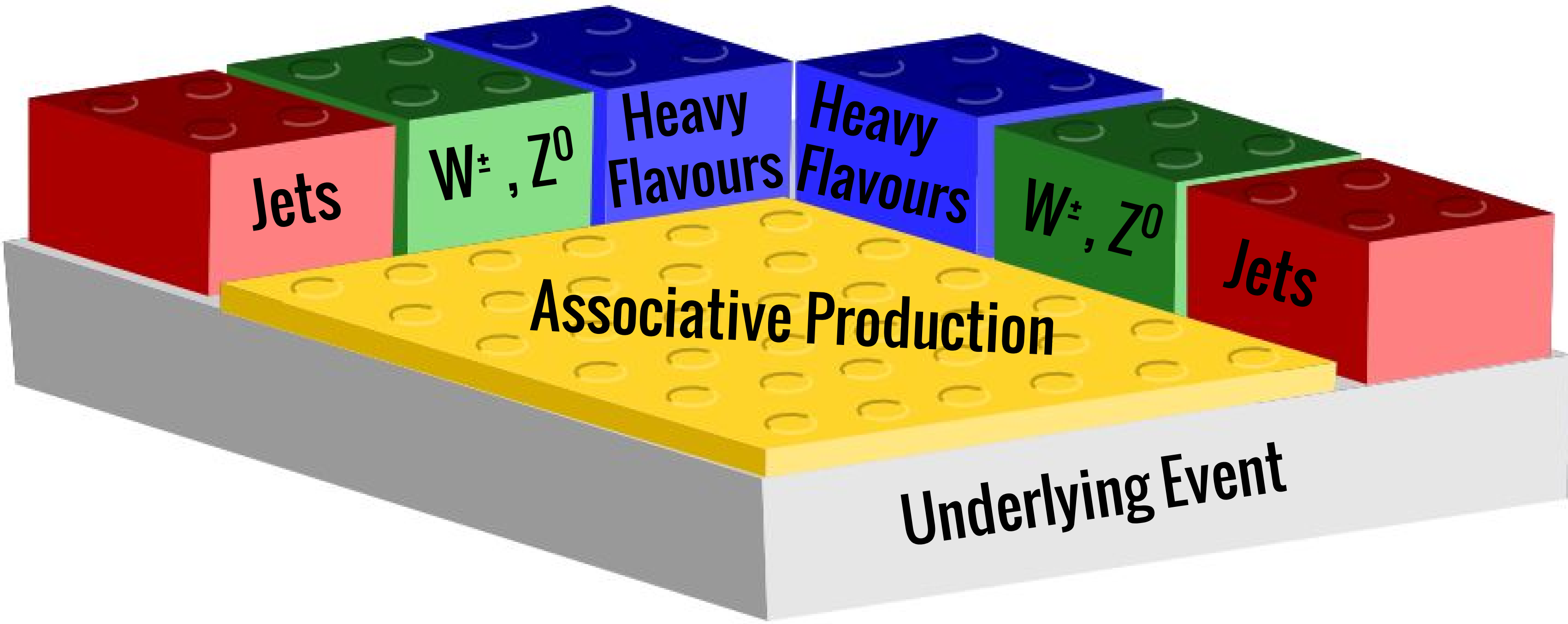
Υ(nS) production at $\sqrt{s}$ = 13 TeV



The Υ cross sections at 13 TeV are factors of 2 to 3 larger wrt. 7 TeV cross sections, changing slowly as a function of dimuon pT.

Order of the increase expected from pdfs and verified sith PYTHIA 8.
A detailed comparison with theory awaits an updated NRQCD calculation for 13 TeV.

Associative production

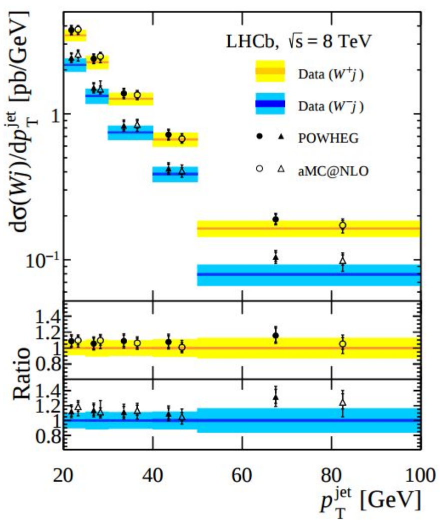


$W^{\pm}/Z^{0}$ + Jet in the forward region

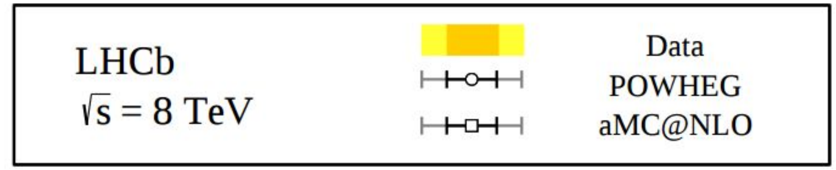
New result: *First time it is presented.*

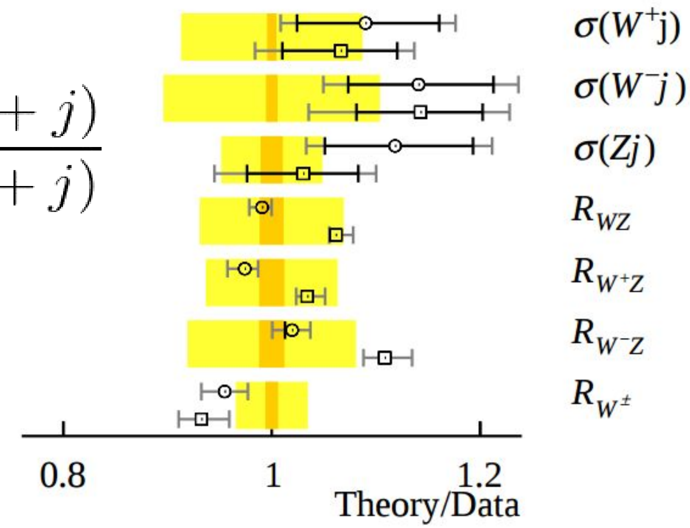
$Z \rightarrow \mu\mu$, $W \rightarrow \mu\nu$, jets with *anti-k_T* factorization.

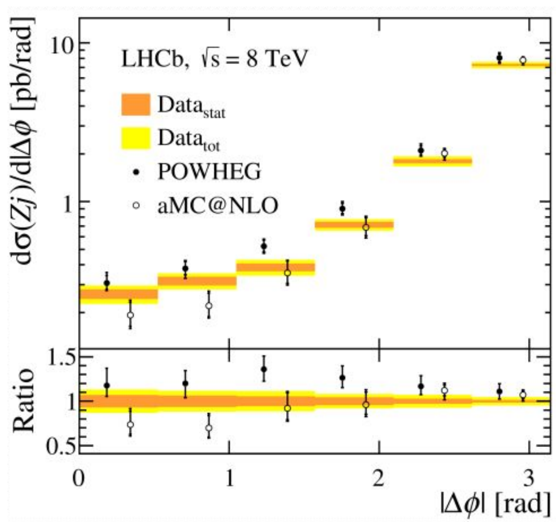
Differential cross-sections measured.

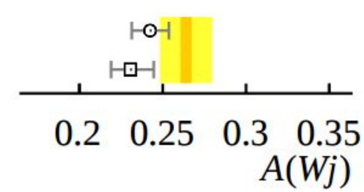


$$R_{ab} = \frac{\sigma(a+j)}{\sigma(b+j)}$$



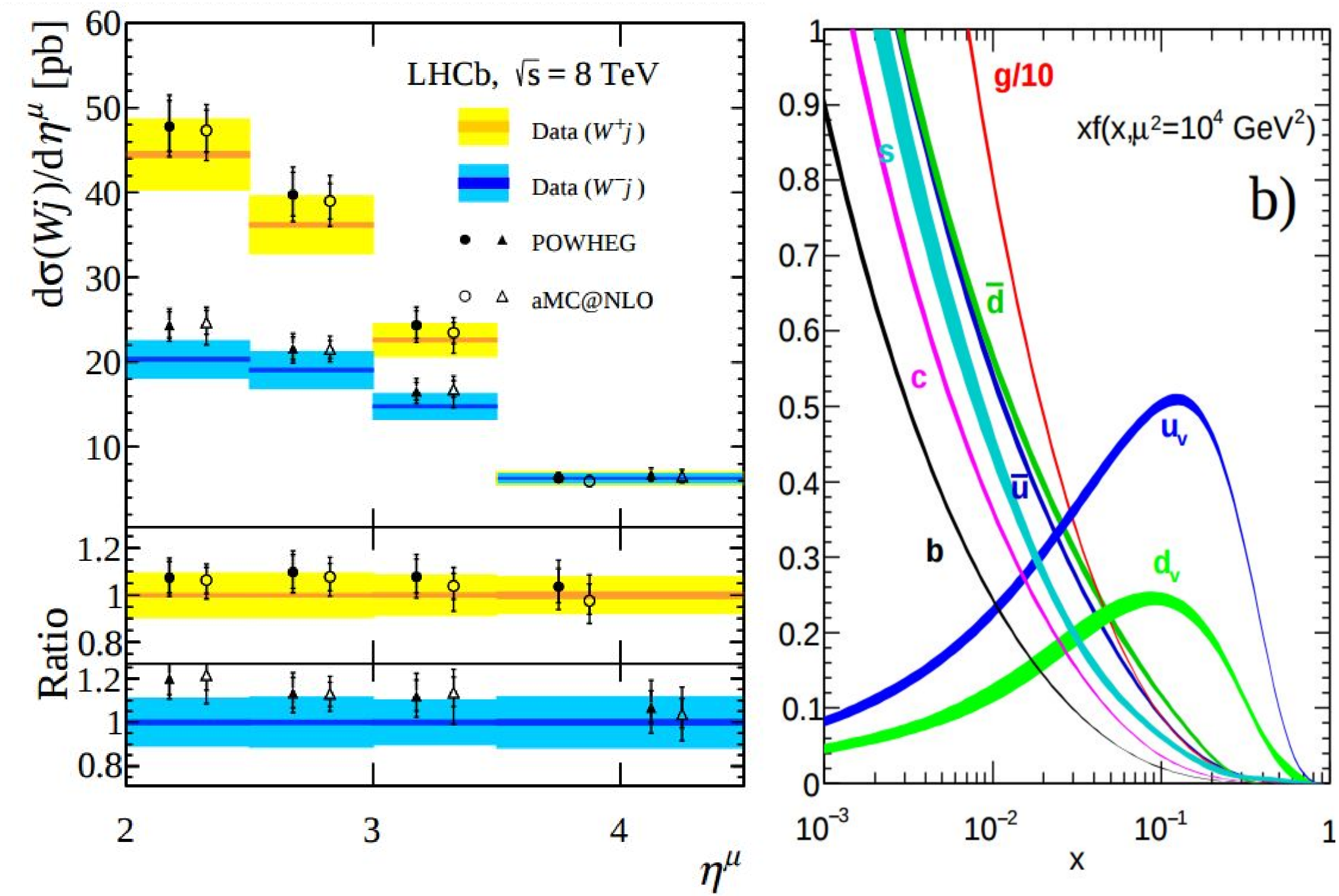






$$A(Wj) \equiv (\sigma_{W^+j} - \sigma_{W^-j})/(\sigma_{W^+j} + \sigma_{W^-j})$$

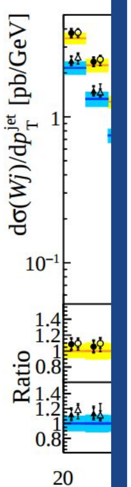
$W^{\pm}/Z^0$ + Jet in the forward region



N

Z

D



$\sigma(W^+j)$

$\sigma(W^-j)$

$\sigma(Zj)$

R_{WZ}

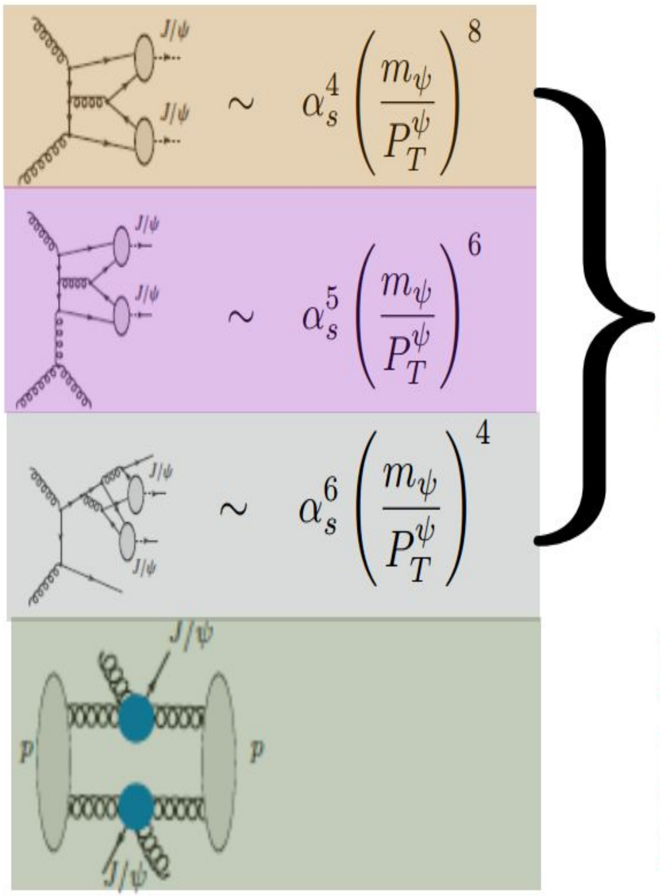
R_{W^+Z}

R_{W^-Z}

$R_{W^\pm}$

$$A(Wj) \equiv (\sigma_{W+j} - \sigma_{W-j})/(\sigma_{W+j} + \sigma_{W-j})$$

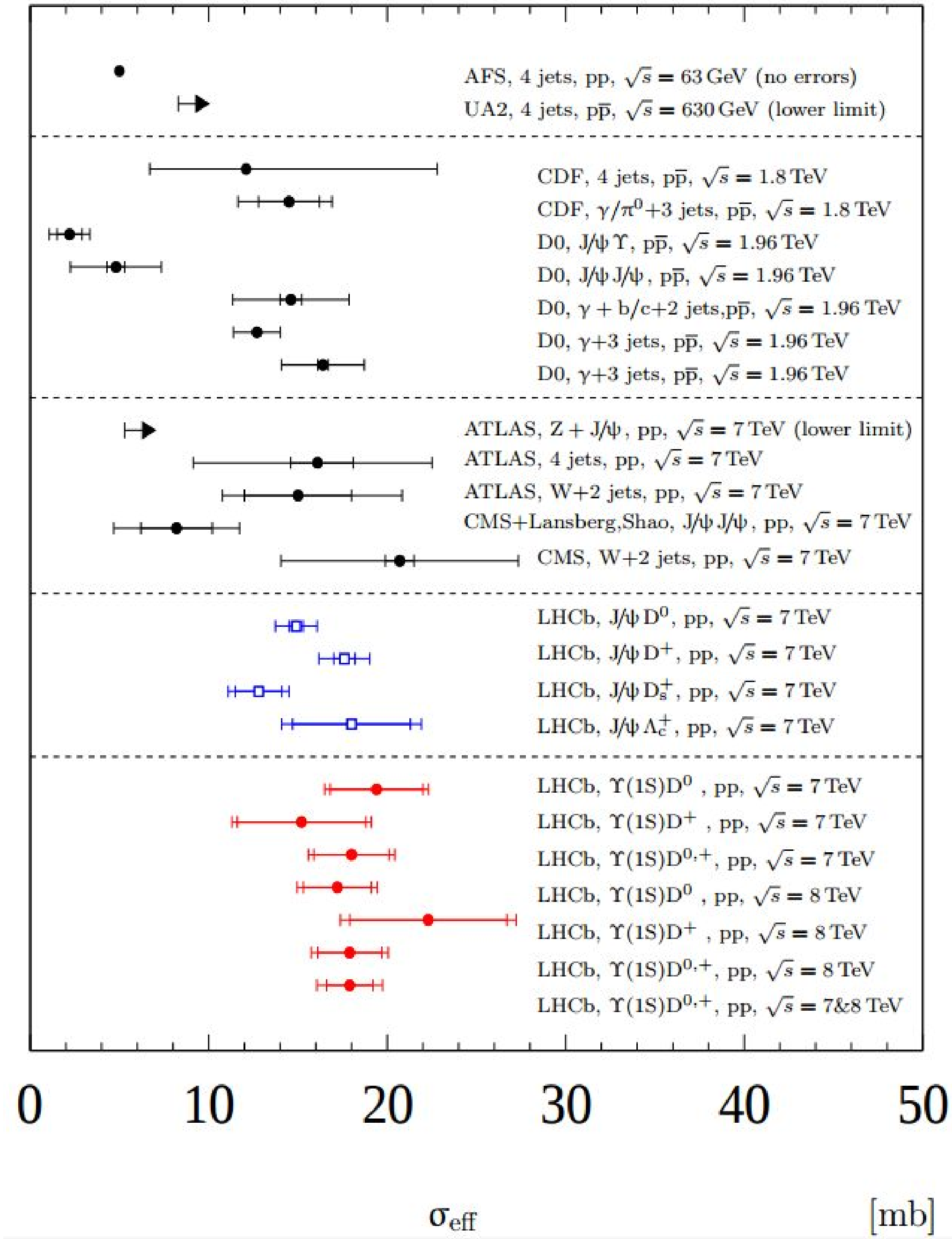
Double Parton Scattering



SPS

DPS

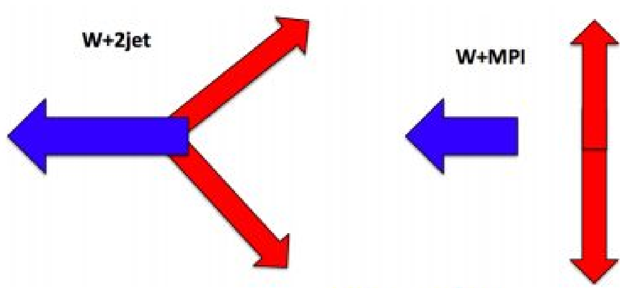
$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{\text{eff}}}$$



Double Parton Scattering at ATLAS

Final state	Publication
$W^\pm + 2$ jets	New J.Phys. 15 (2013) 033038
$W^\pm + J/\psi$ (prompt J/ψ production)	JHEP 1404 (2014) 172
$Z + J/\psi$ (prompt and non-prompt)	Eur.Phys.J. C75 (2015) 229
Four-jet	ATLAS-CONF-2015-058

Schematic representation in the transverse plane

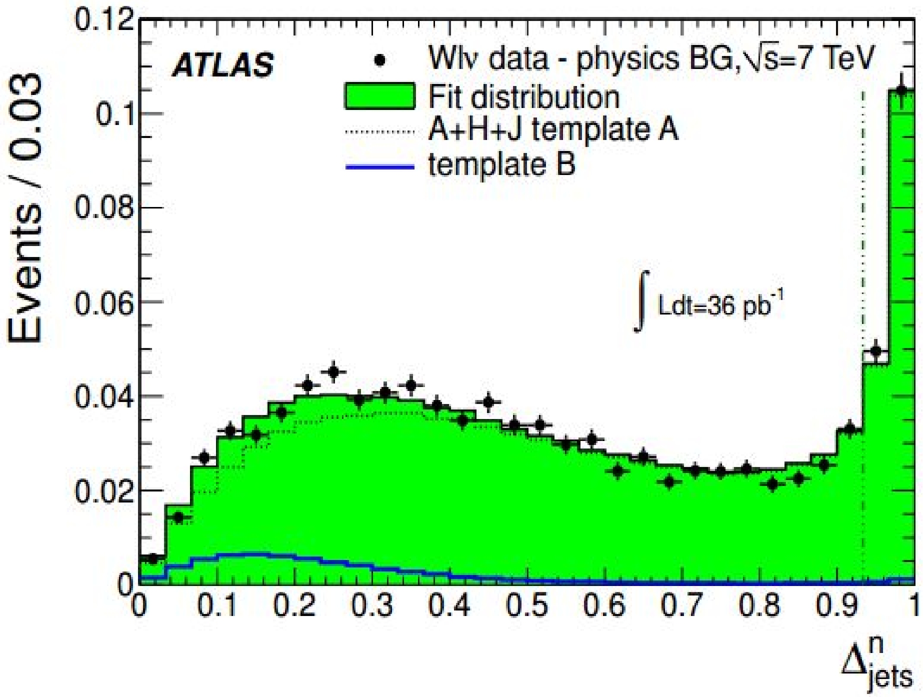


$$\Delta^{\mathrm{n}}_{\mathrm{jets}} = \frac{|\vec{p}_{\mathrm{T}}^{\,J_1} + \vec{p}_{\mathrm{T}}^{\,J_2}|}{|\vec{p}_{\mathrm{T}}^{\,J_1}| + |\vec{p}_{\mathrm{T}}^{\,J_2}|}$$

Results

$$f_{\mathrm{DPS}} = 0.08 \pm 0.01\ (\text{stat.}) \pm 0.02\ (\text{syst.})$$

$$\sigma_{\mathrm{eff}} = 15 \pm 3\ (\text{stat.})^{+5}_{-3}\ (\text{syst.})\ \mathrm{mb}$$



Double Parton Scattering at ATLAS

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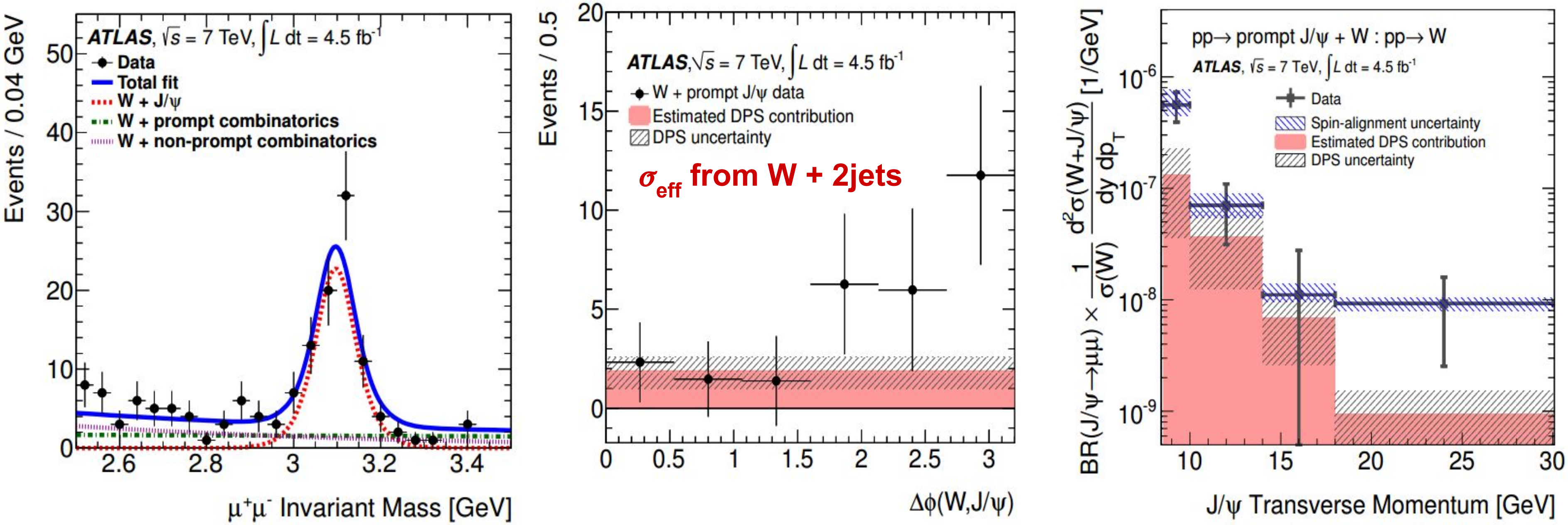

Double Parton Scattering at ATLAS

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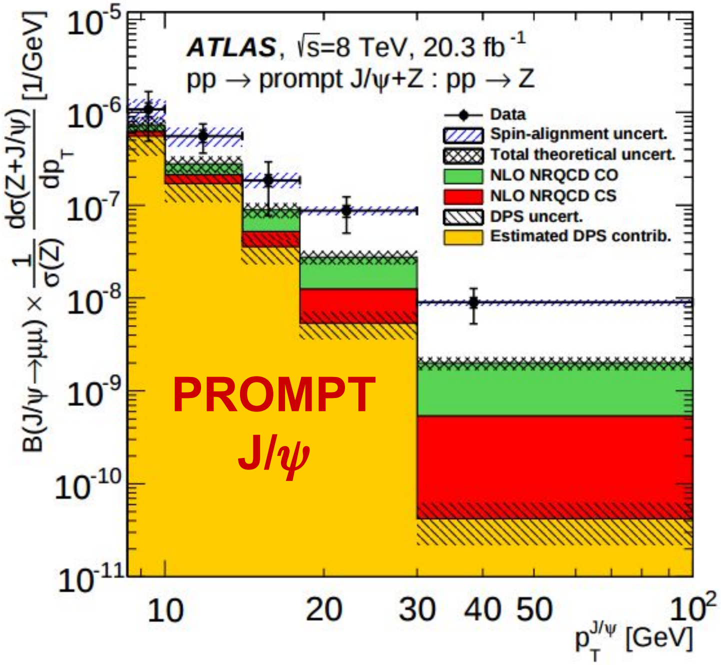
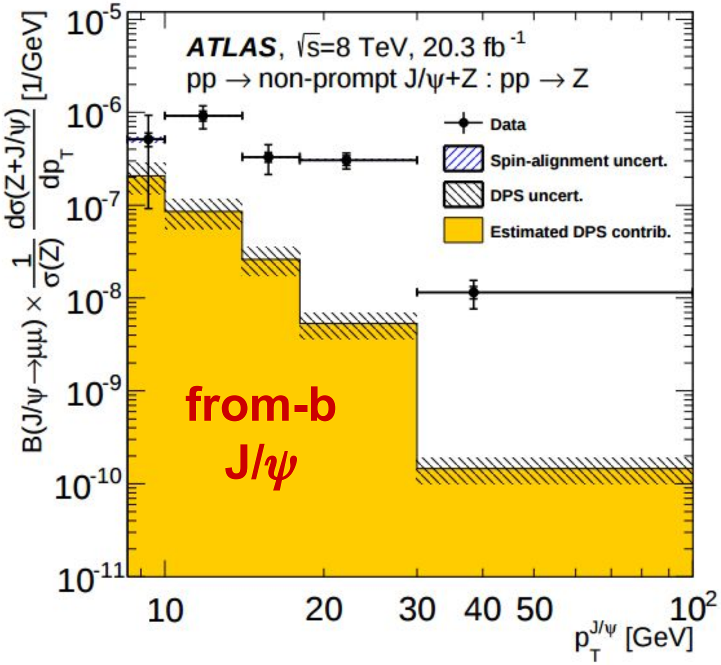
Four-jet	ATLAS-CONF-2015-058

σ_{eff} from W + 2jets





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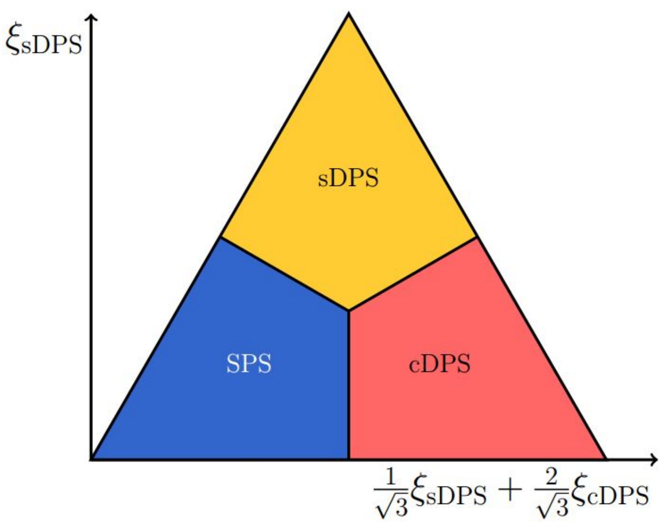
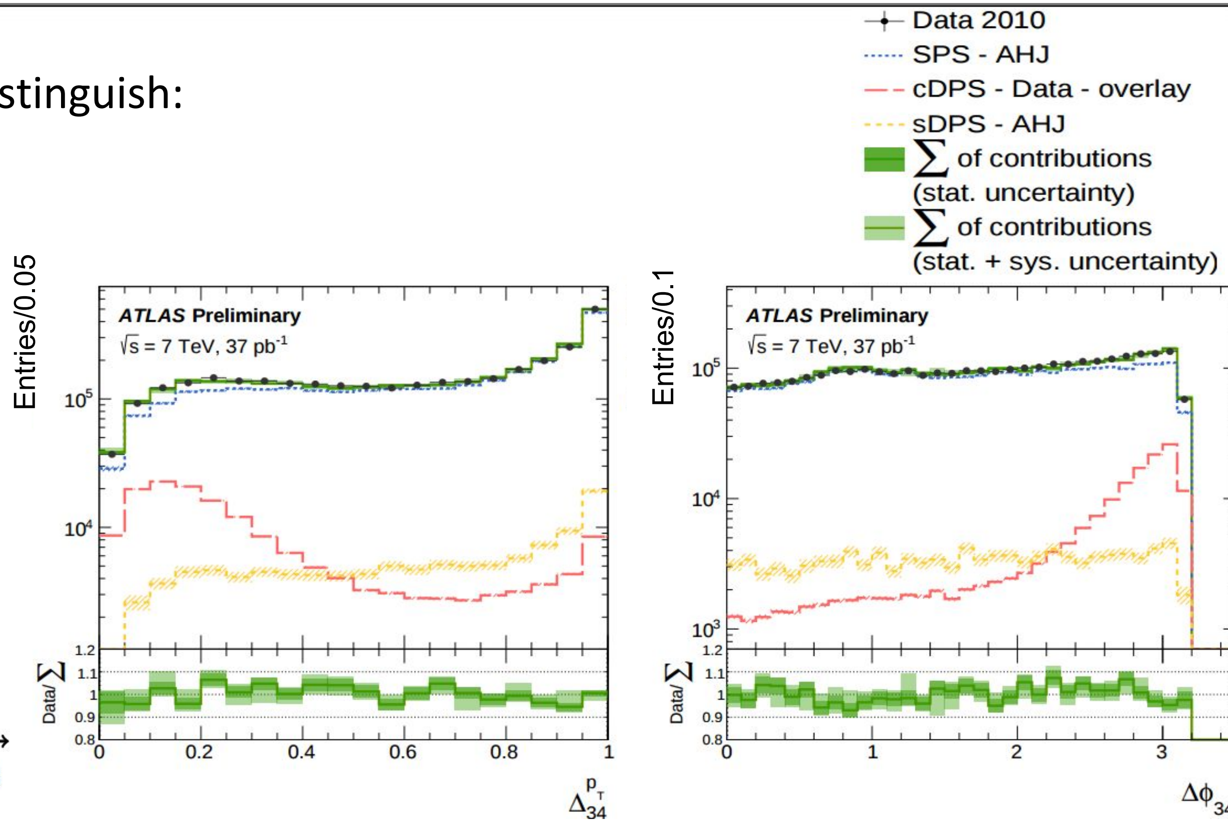
Four-jet	ATLAS-CONF-2015-058

Train on Simulation 2 MVA to distinguish:

- semi-DPS from SPS and
- complete-DPS from SPS.

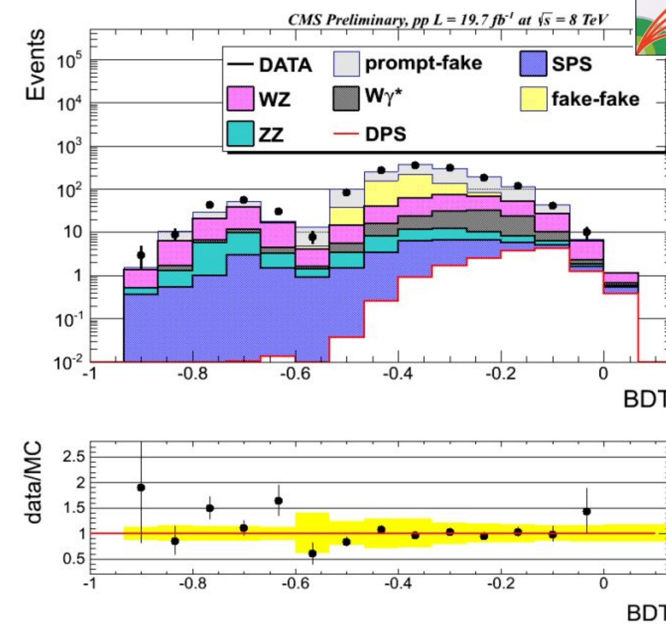


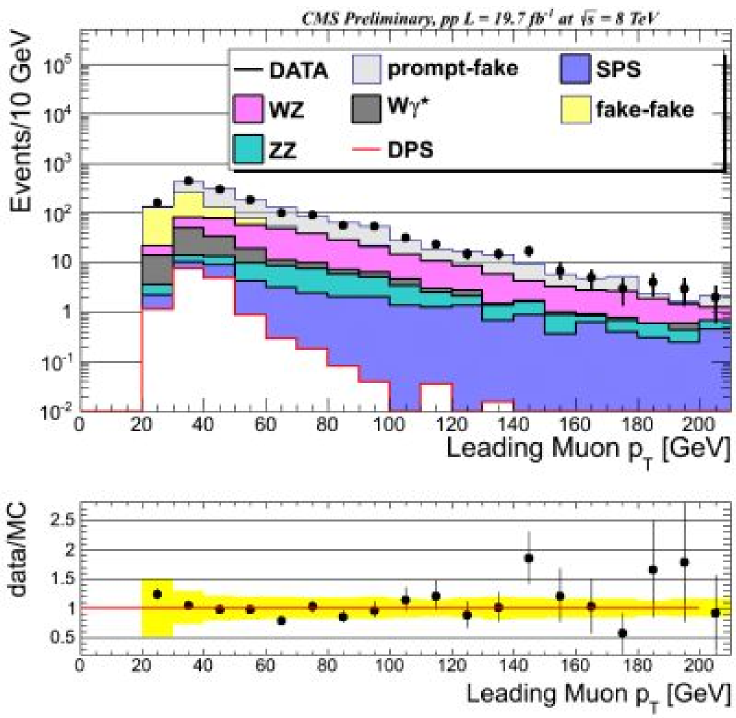


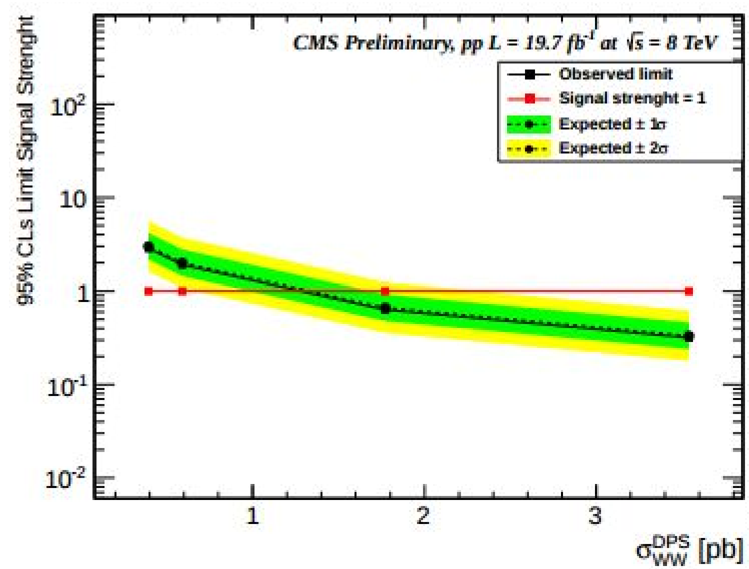
DPS with $W^{\pm}W^{\pm}$ production at CMS

Define a BDT to identify DPS.

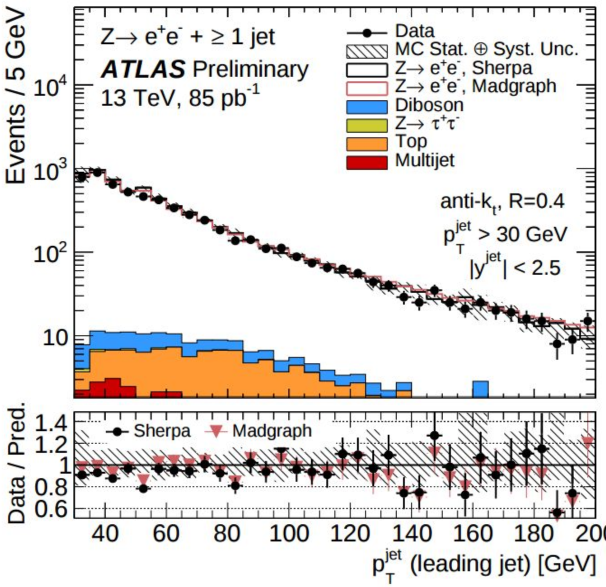
Signal sample: opposite sign DPS MC events
Background sample: mixture of QCD, W + jets, and WZ. Training of QCD and W + jets sample, based on data-driven templates.

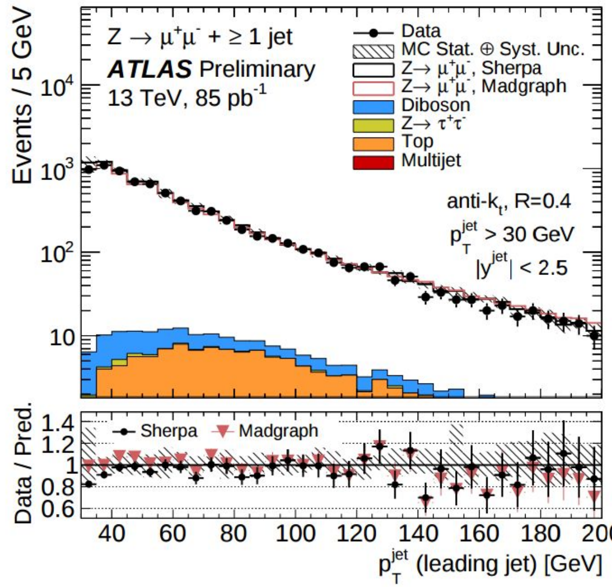


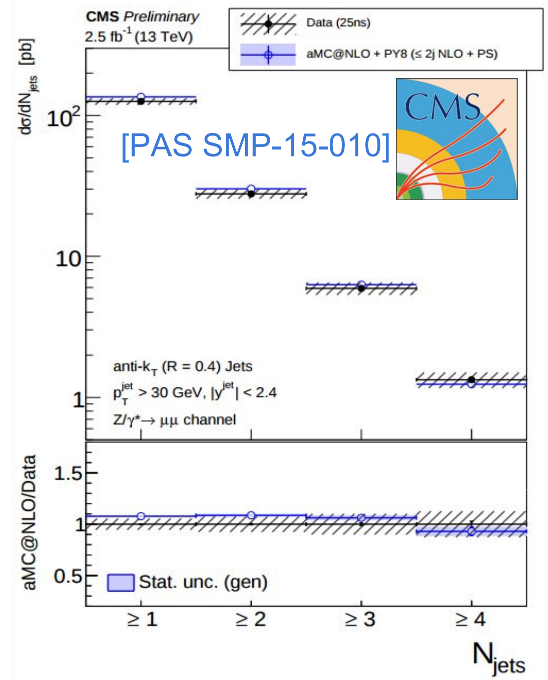




Z + jet cross section at $\sqrt{s}$ = 13 TeV

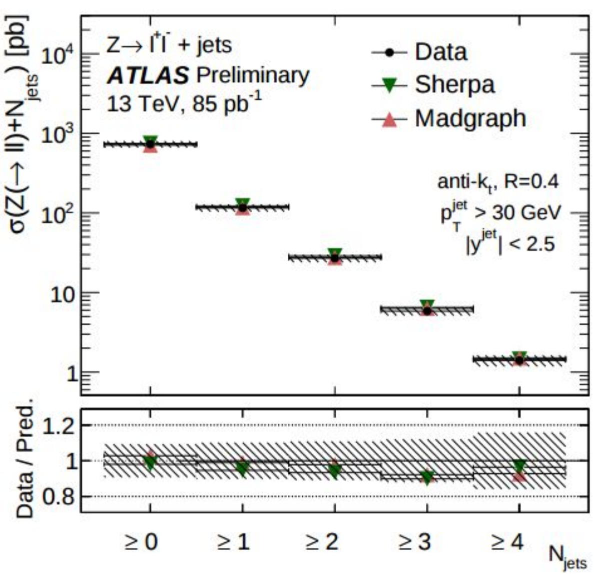


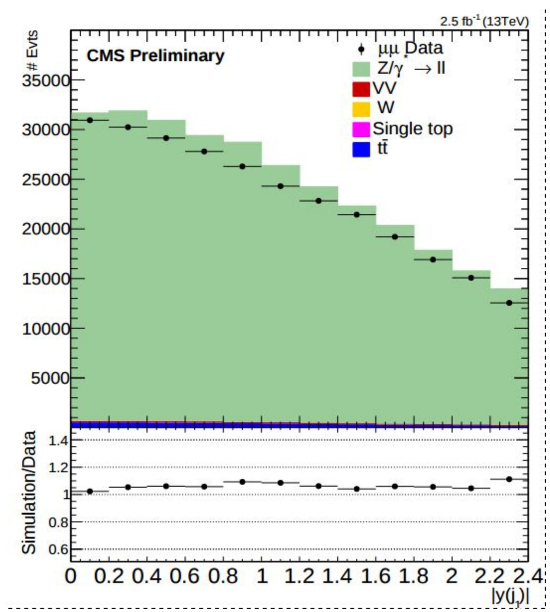


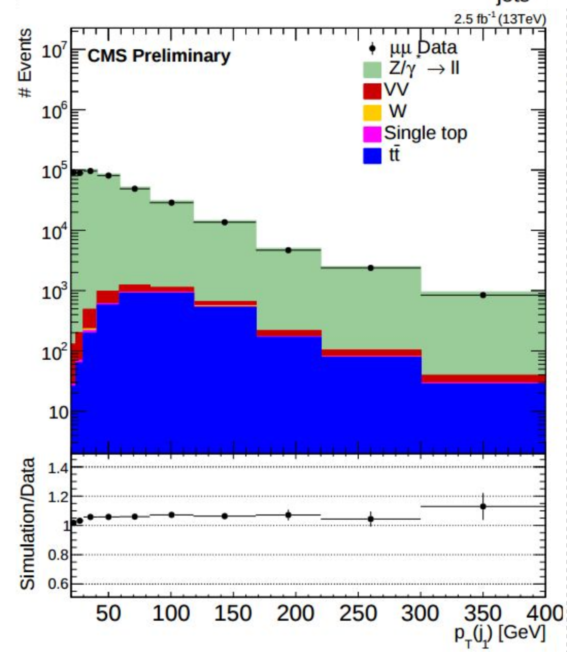


[PAS SMP-15-010]

[ATLAS-CONF-2015-041]







Summary & outlook

Summary

At the beginning of the century, the predictions based on the strong-interaction processes were off of **orders of magnitude** with respect to data.

Today, our understanding of QCD is at level of few percents !

Good understanding of QCD is of crucial relevance for new physics searches.

This is particularly true for *associative production* measurements representing background for rare (or *rare-stuff*) decays.

Crucial **interplay** of several actors to keep *understanding* and *tuning* SM predictions.

Measurements in the forward region at LHCb and in ion ion collisions at ALICE, can provide useful input for measurement at ATLAS and CMS, when properly integrated in theoretical models and Monte Carlo generators.

Outlook

:«A very important parameter of QCD is $\sqrt{s}$»

A new Run of the LHC has just started and has already yielded important results.

Studies on the dependence on energy, and exploitation of the increased luminosity to study rarer processes will shed new light on QCD.

The experiments are being upgraded (e.g. Herschel and SMOG at LHCb, CASTOR at CMS, active since Run2), adding further ingredients to the global picture.

Discussion: 13TeV can provide more...

In many other studies 13TeV data can bring a lot, so difficult not to forget anything...

A list of some of the most important follows and more information in backup:

++ **PDF studies and alpha_s measurement**: e.g. see jet differential xsec

++ **Multi-jet studies (wider phase space)**

++ **V+HF, V+jet ("heavier" theory tests)**

++ **Parton correlation and DPS (dPDF(?)):** same sign diboson probe, MPI √s dependence

++ **Associative production of quarkonia: J/ψ J/ψ , J/ψ $\psi(2S)$, J/ψ χ_c**

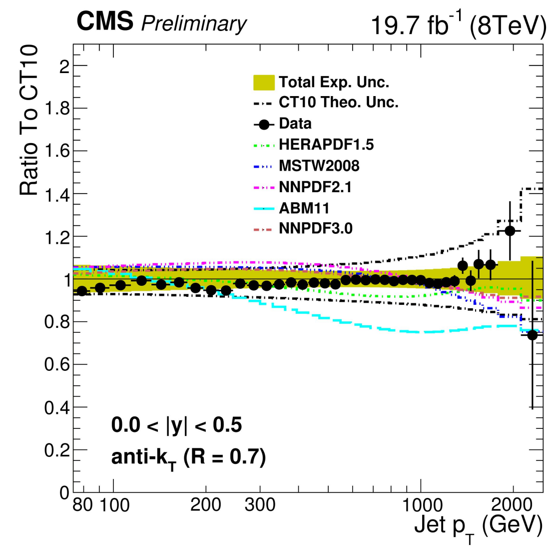

The End

Double-differential inclusive jet cross section

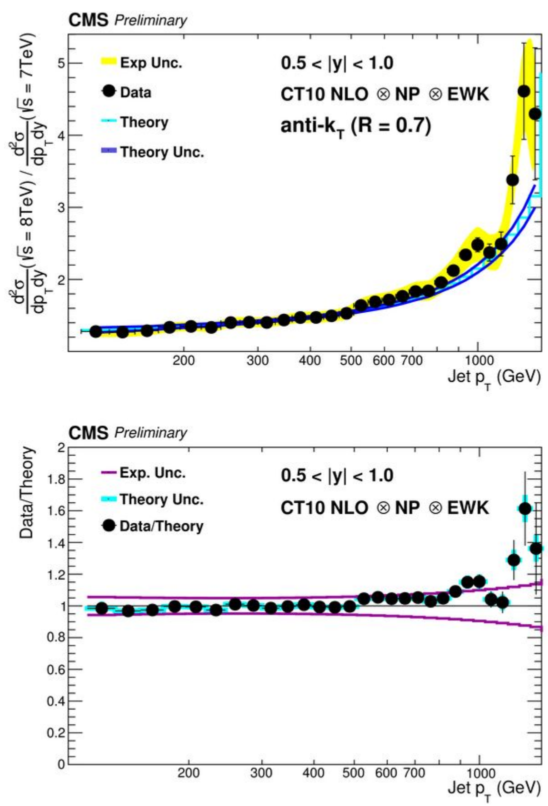
PDF studies and Alpha_s measurement already achieved on RunI.

Same studies with new data at 13 TeV can be extremely important, bringing more information, along with the cross section ratio b/w different energies.

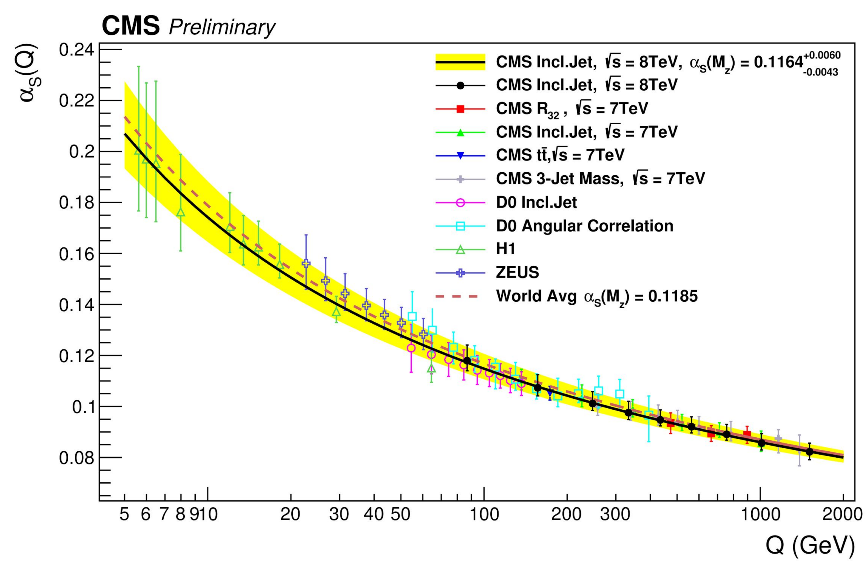
PDF tests



xsec
Ratio
7/8TeV



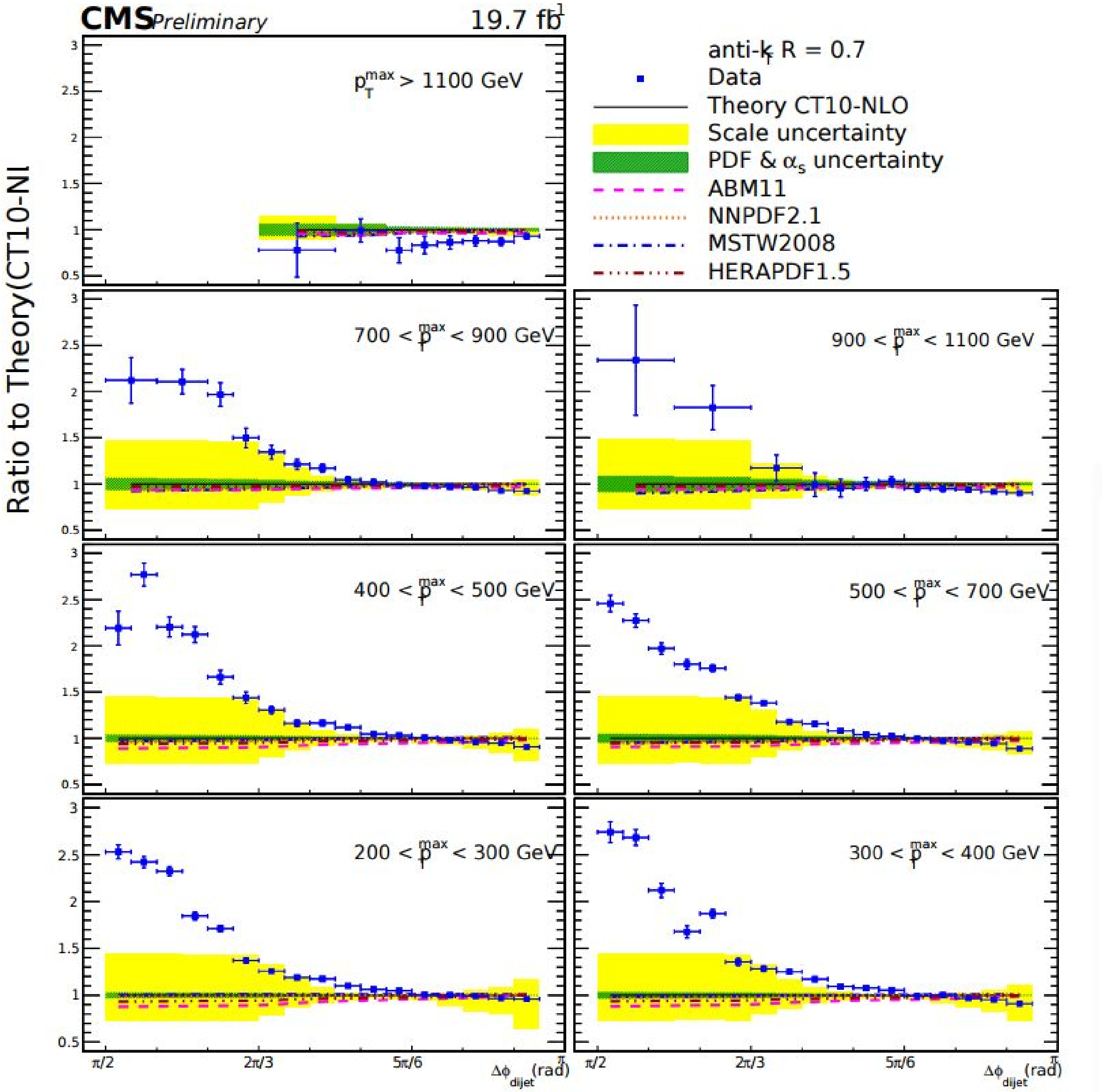
Alpha_s



Multi-jet studies

Measurement of dijet azimuthal decorrelations

This is a clear example on how at 13TeV the pT range and the accuracy of such a study can be greatly improved.

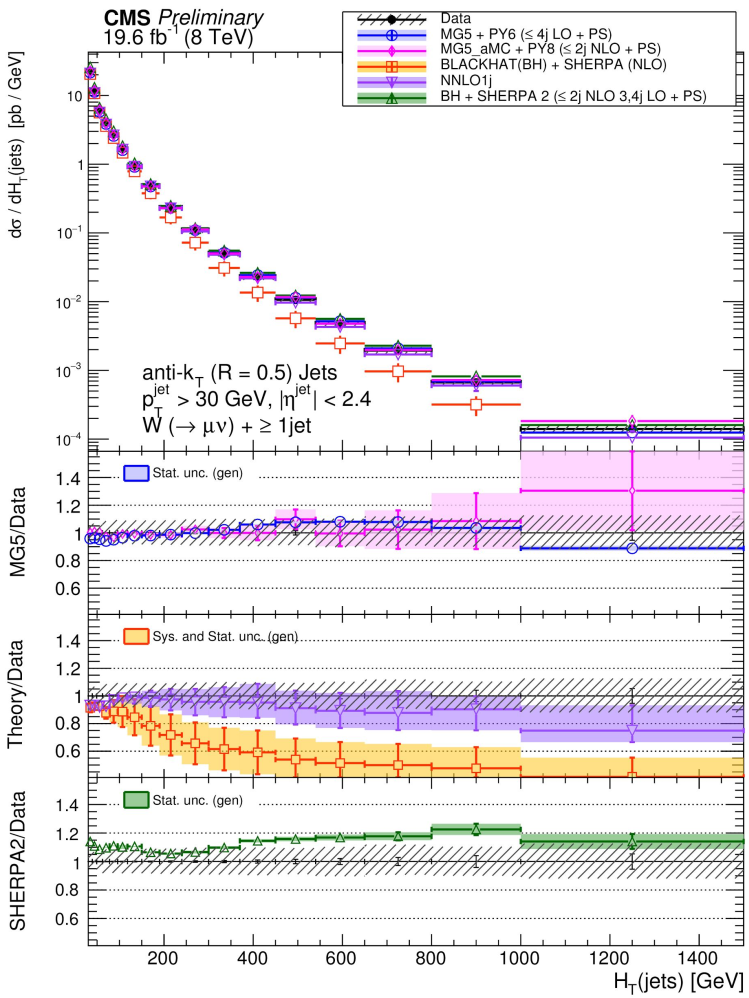


V+jets

e.g. Differential cross section measurements of W bosons produced in association with jets

In figure only one of the several measurement already performed at 8TeV.

13TeV data can directly extend all the results.

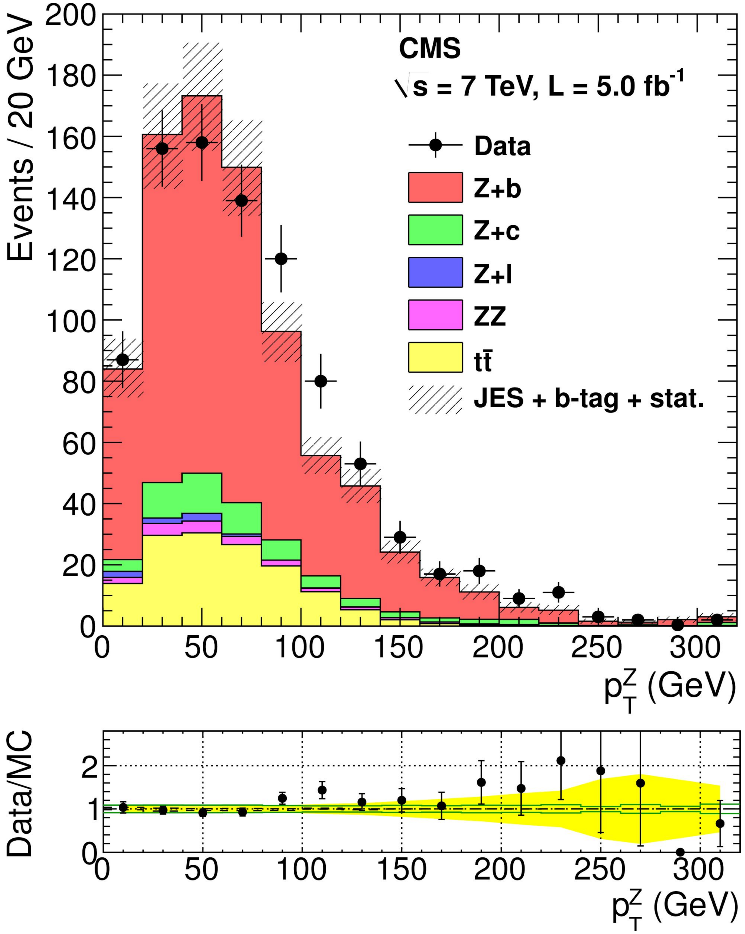


V+HF

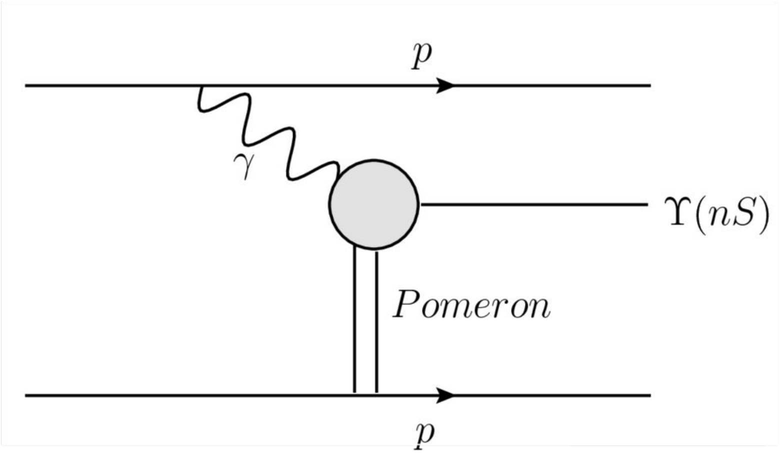
E.g.Measurement of the production cross sections for a Z boson and one or more b jets

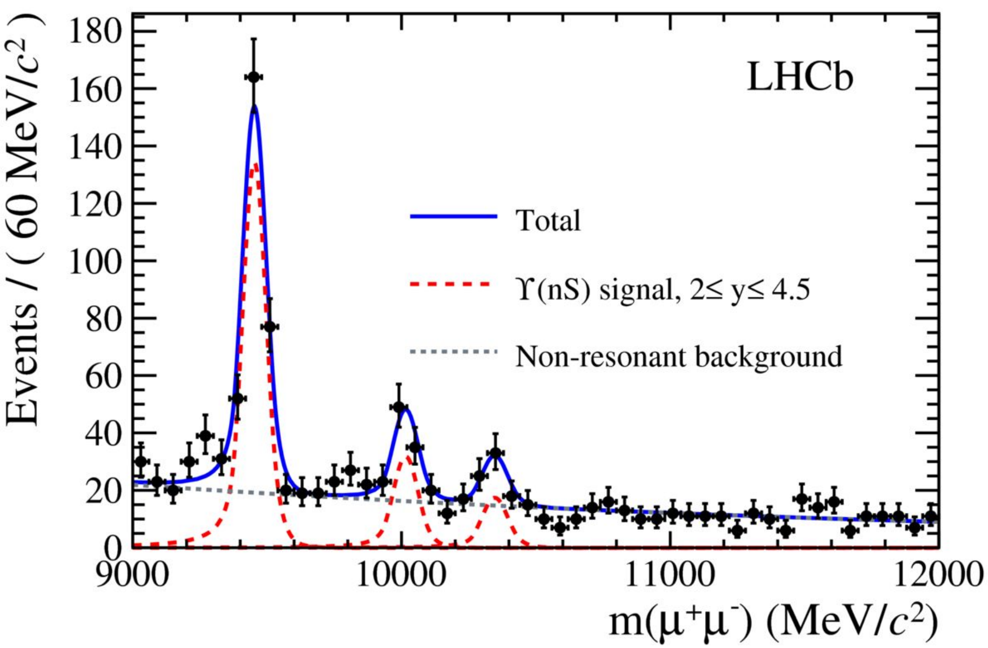
In figure only one of the several measurement already performed at 7TeV.

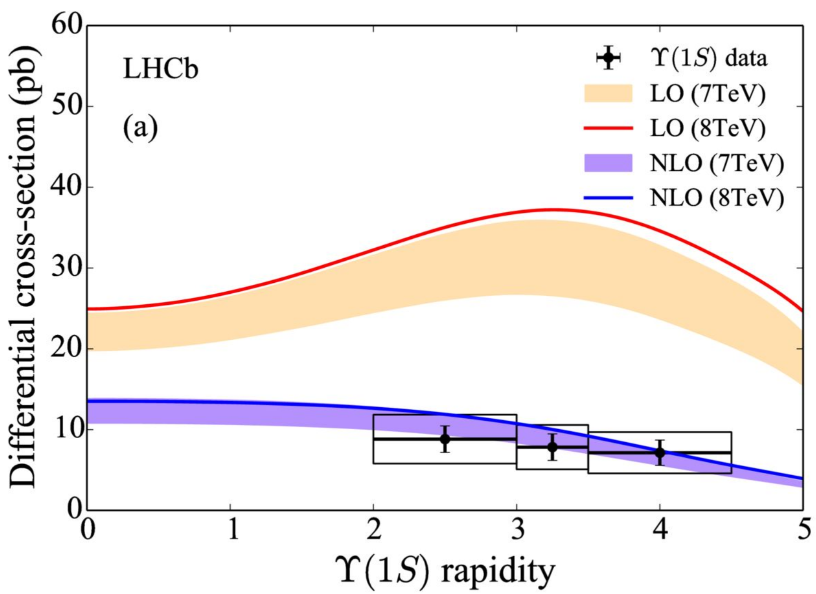
13TeV data can increase the accuracy and the energy range of all this kind of approach.



Central Exclusive Production of Υ(nS)



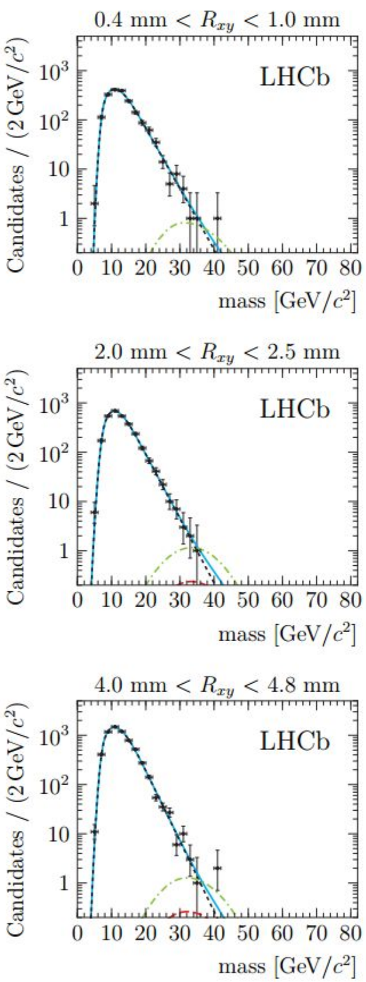


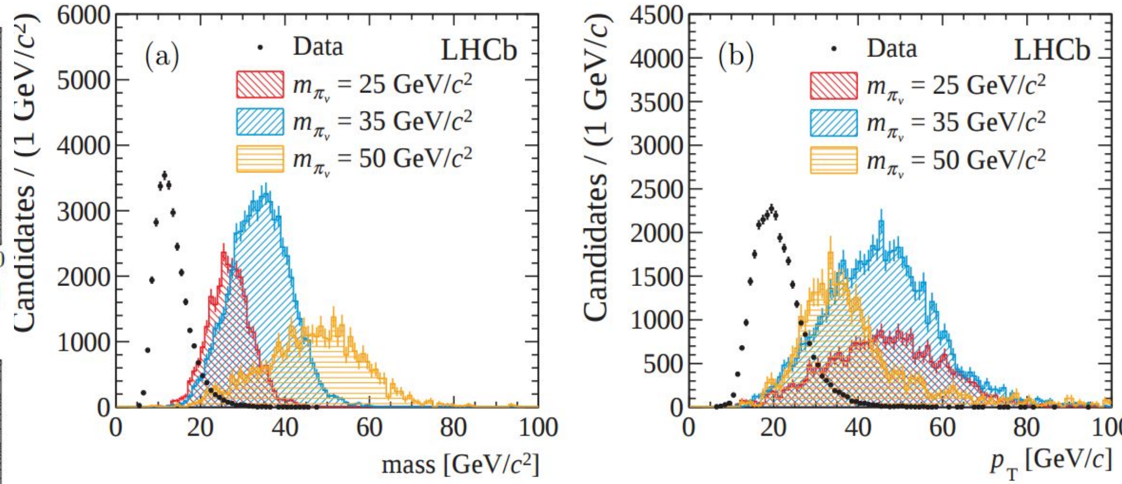


A recent LHCb measurement of the Υ (nS) cross-section in events with no reconstructed primary vertex (CEP) is statistically limited to resolve 7 to 8 TeV differences.

Search for $\pi_v \rightarrow$ dijet with $\sqrt{s}$ = 7 TeV (2011 data)

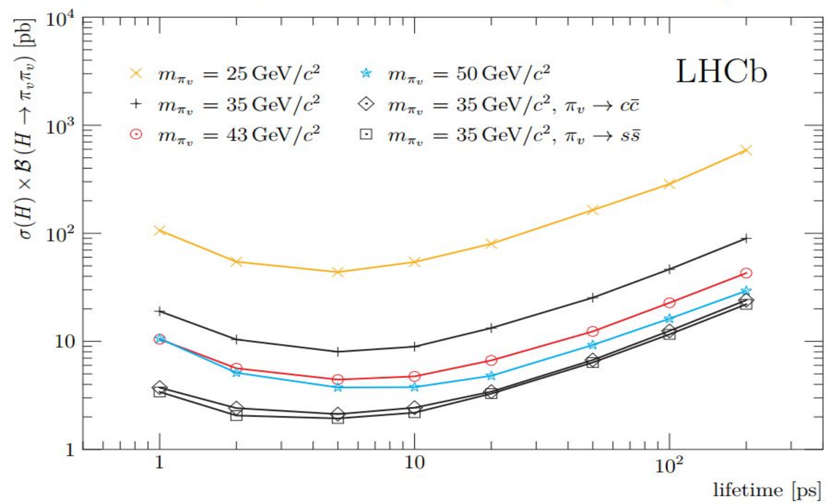
Massive neutral particles produced in higgs decays ($H \rightarrow \pi_v \pi_v$) and decaying to two jets are predicted from several models (*e.g.* SUSY [1306.5773], Hidden Valley [0712.2041]).





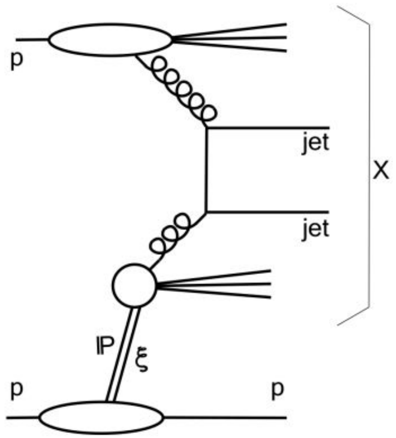
Physics with jets at LHCb can explore regions not covered by GPD

→ further studies in the next years.



[PLB 754 (2016) 214]

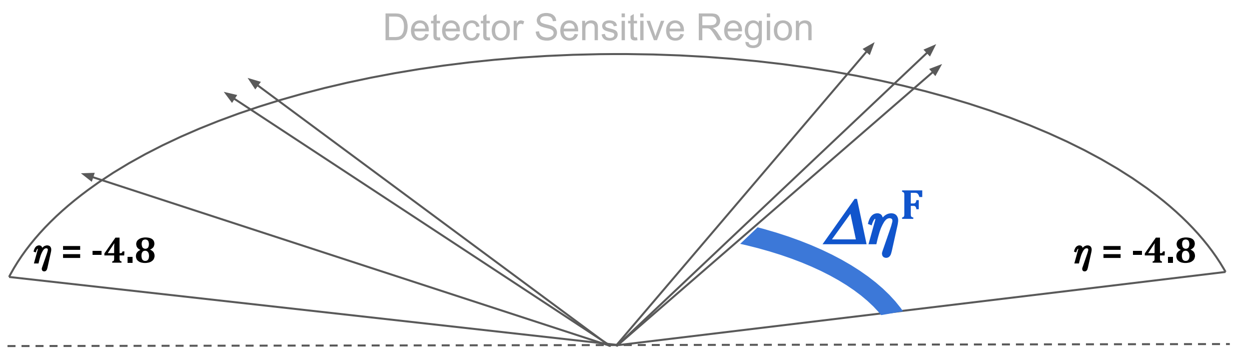
Diffractive di-jets at ATLAS @ √s = 7 TeV

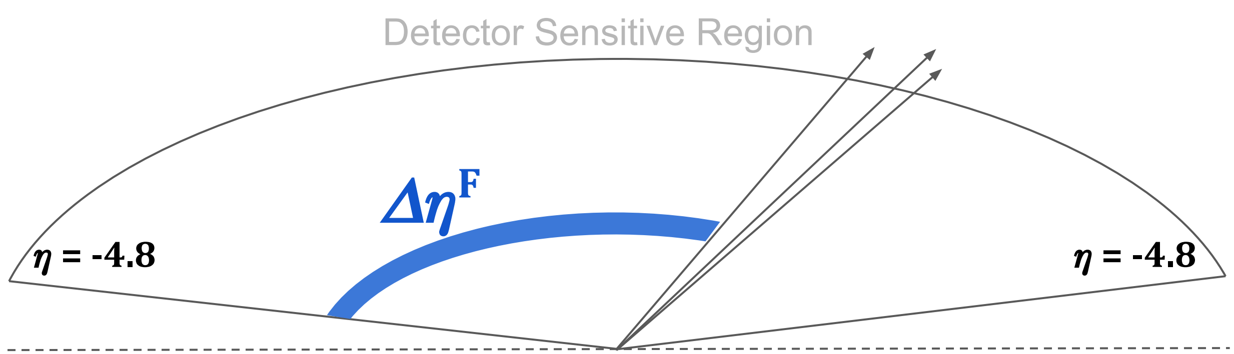


$$\tilde{\xi} \simeq M_X^2/s = \sum p_T e^{\pm\eta}/\sqrt{s}$$

ξ: fractional momentum loss of the proton assuming single diffractive dissociation

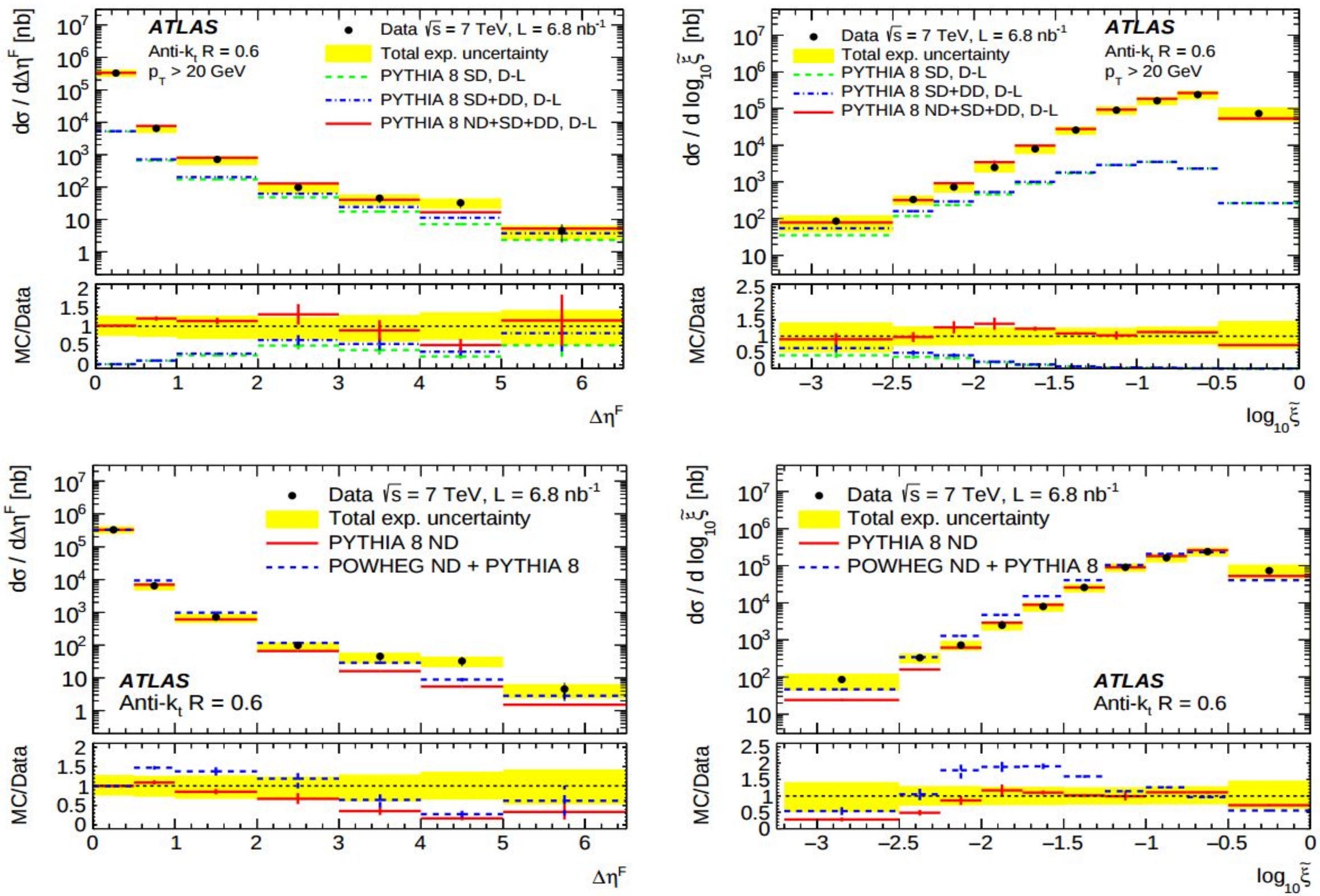
Diffractive collisions producing jets in the final state feature a large «*rapidity gap*»





Diffractive di-jets at ATLAS @ √s = 7 TeV

Non-diffractive contribution is the dominant one, but single dissociation and double dissociation contributions are also necessary to achieve good agreement with data.



Mueller Navelet di-jets at CMS @ 7 TeV

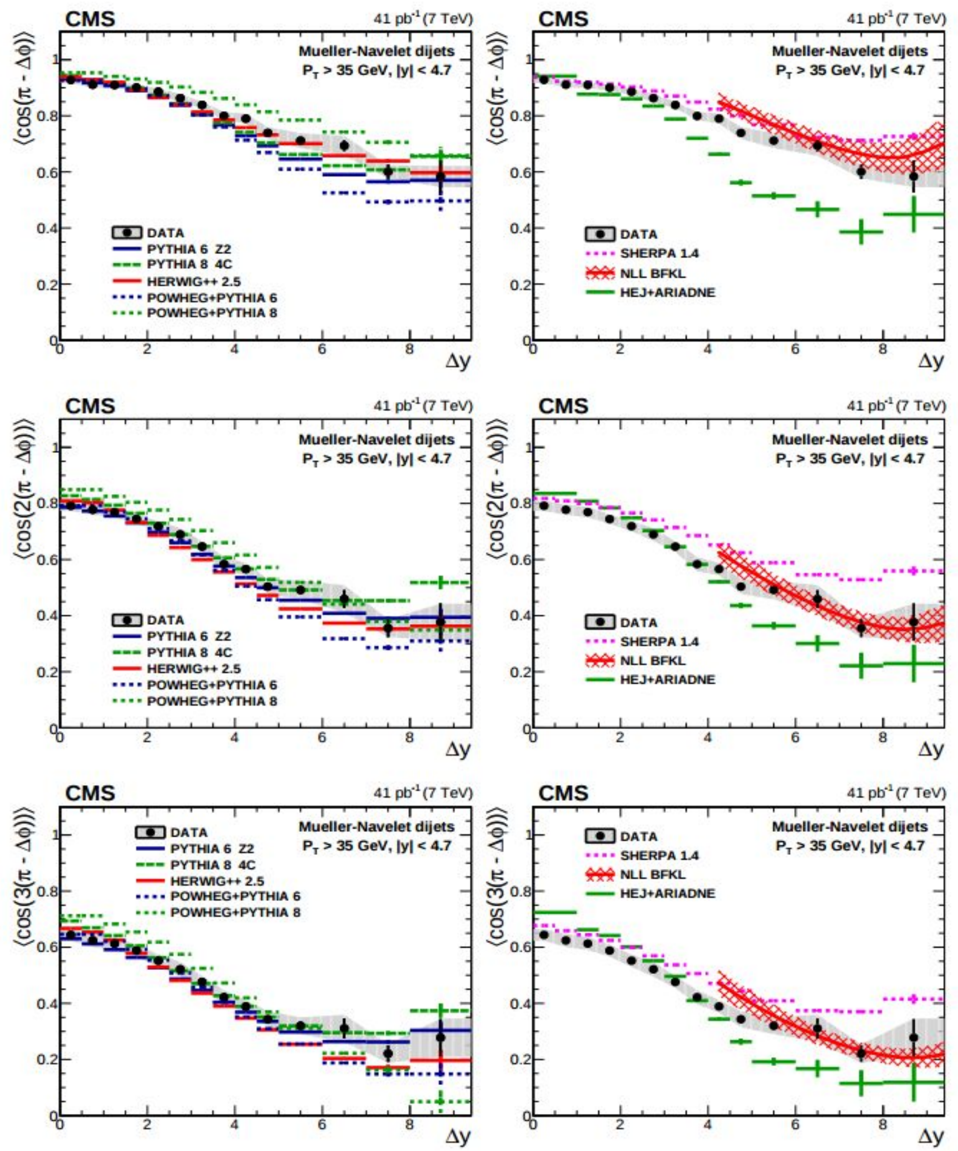
Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) successfully described *parton evolution* in a number of applications.

For asymptotic domain $p_T << \sqrt{s}/2$, Balitsky–Fadin–Kuraev–Lipatov (BFKL) equation is better justified, but never tested in the LHC regime.

For low-p_T jets with large $\Delta\eta$ predictions of DGLAP and BFKL are different.

We define the observables C_n as Fourier coefficients of the $\Delta\phi$-differential cross-section:

$$\frac{1}{\sigma}\frac{d\sigma}{d(\Delta\phi)}(\Delta y, p_{\mathrm{Tmin}}) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} C_n(\Delta y, p_{\mathrm{Tmin}})\,\cos(n(\pi - \Delta\phi))\right].$$



MC generator HEJ+ARIADNE based on BFKL equations describes data fairly.

NLL analytical predictions found as accurate as POWHEG + PYTHIA.

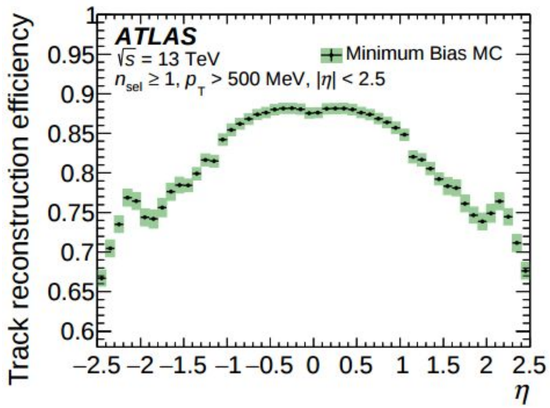
Charged tracks distributions @ √s = 13 TeV

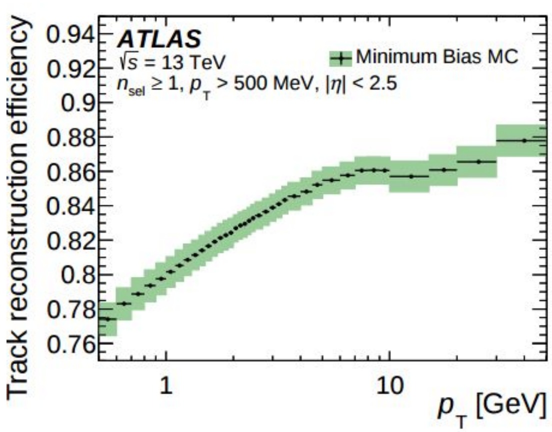
9 million events, corresponding to 170 μb^{-1} (using a special fill of the LHC).

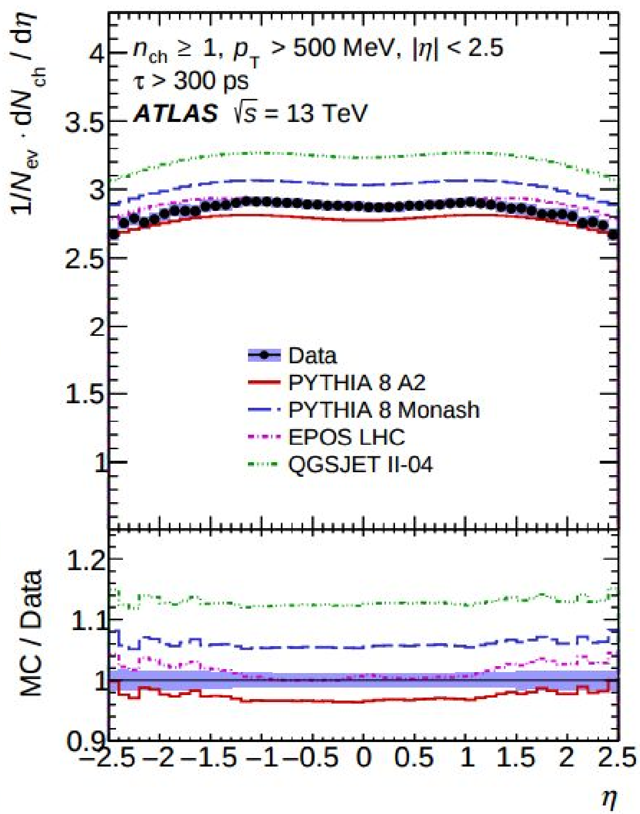
Hyperons excluded because of small reconstruction efficiency.

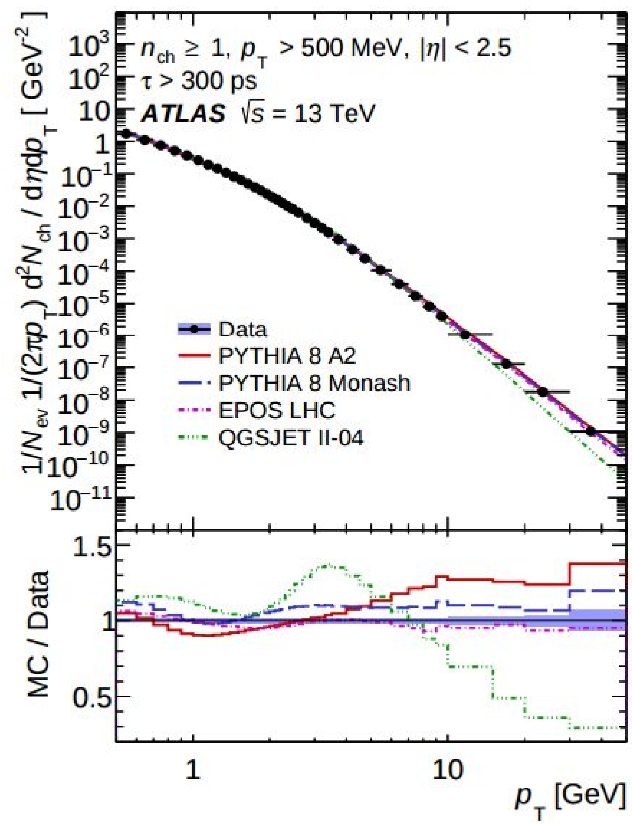
Results are compared with various MC generators. Good agreement found with EPOS.

Efficiency corrections



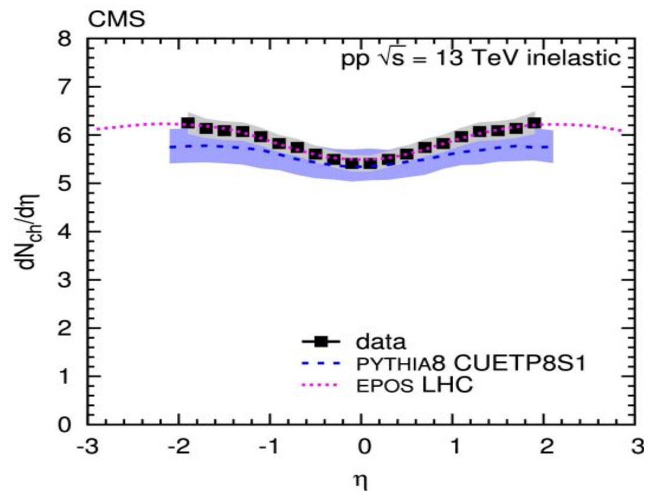


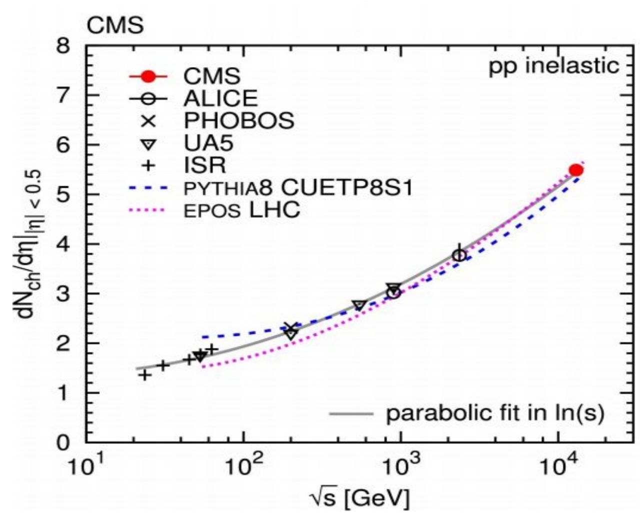


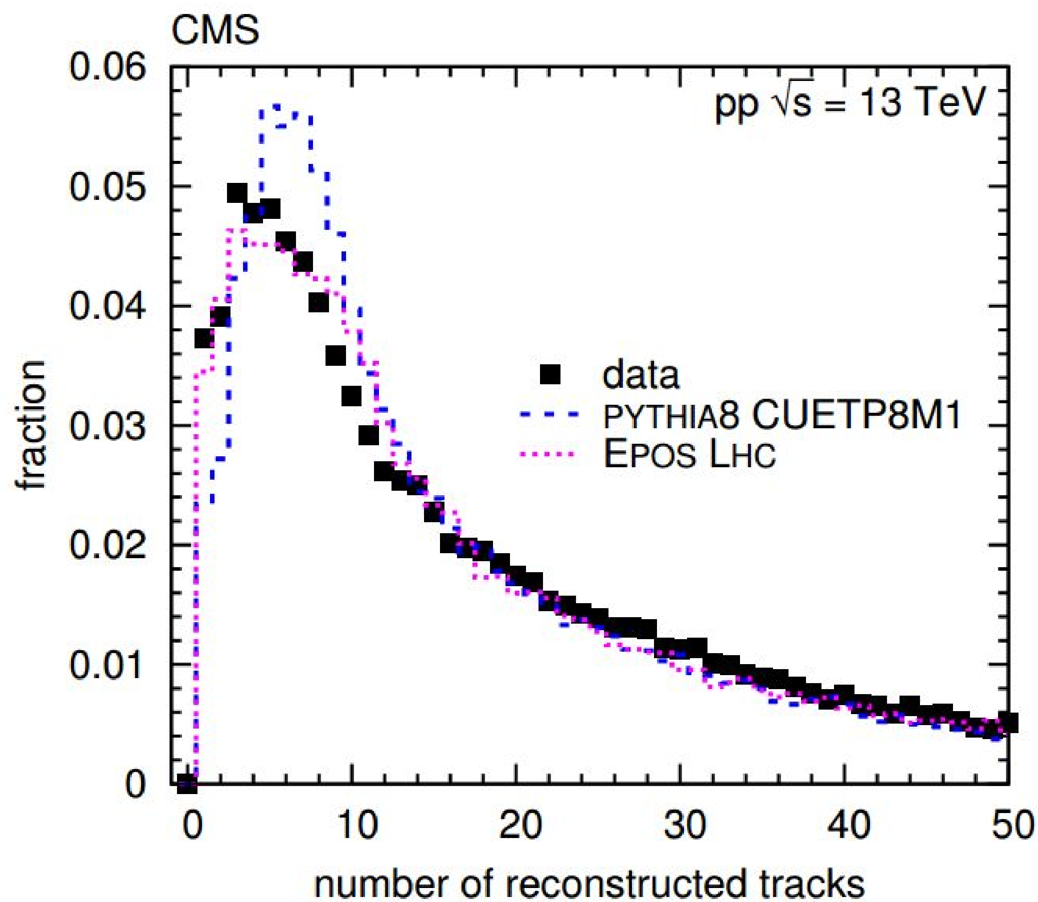


Pseudorapidity distribution at 0 T @ √s = 13 TeV

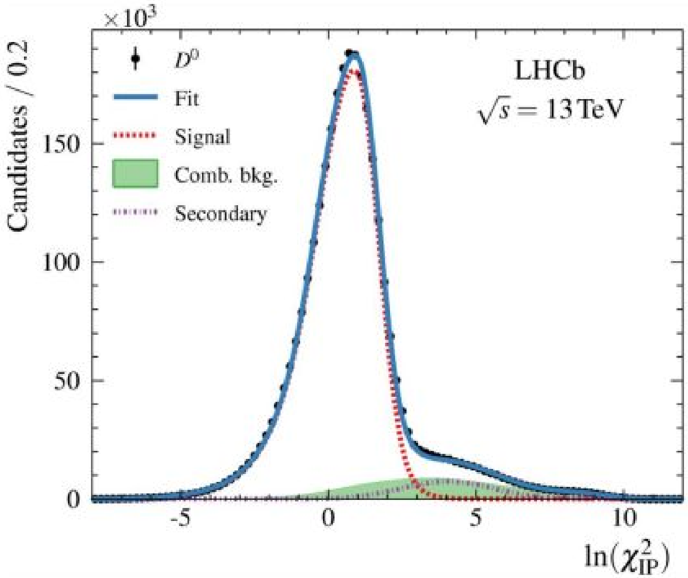
CMS measurement, without minimum p_T (no magnetic field), confirms EPOS LHC is well behaved. Data corrected for lepton fraction.
11.5 million events, collected in special run of the LHC.







Charm Production cross-section at LHCb $\sqrt{s}$ = 13 TeV



$$\chi^2_{\rm IP} = \chi^2_{\rm PV}(\text{w/ track}) - \chi^2_{\rm PV}(\text{w/o track})$$

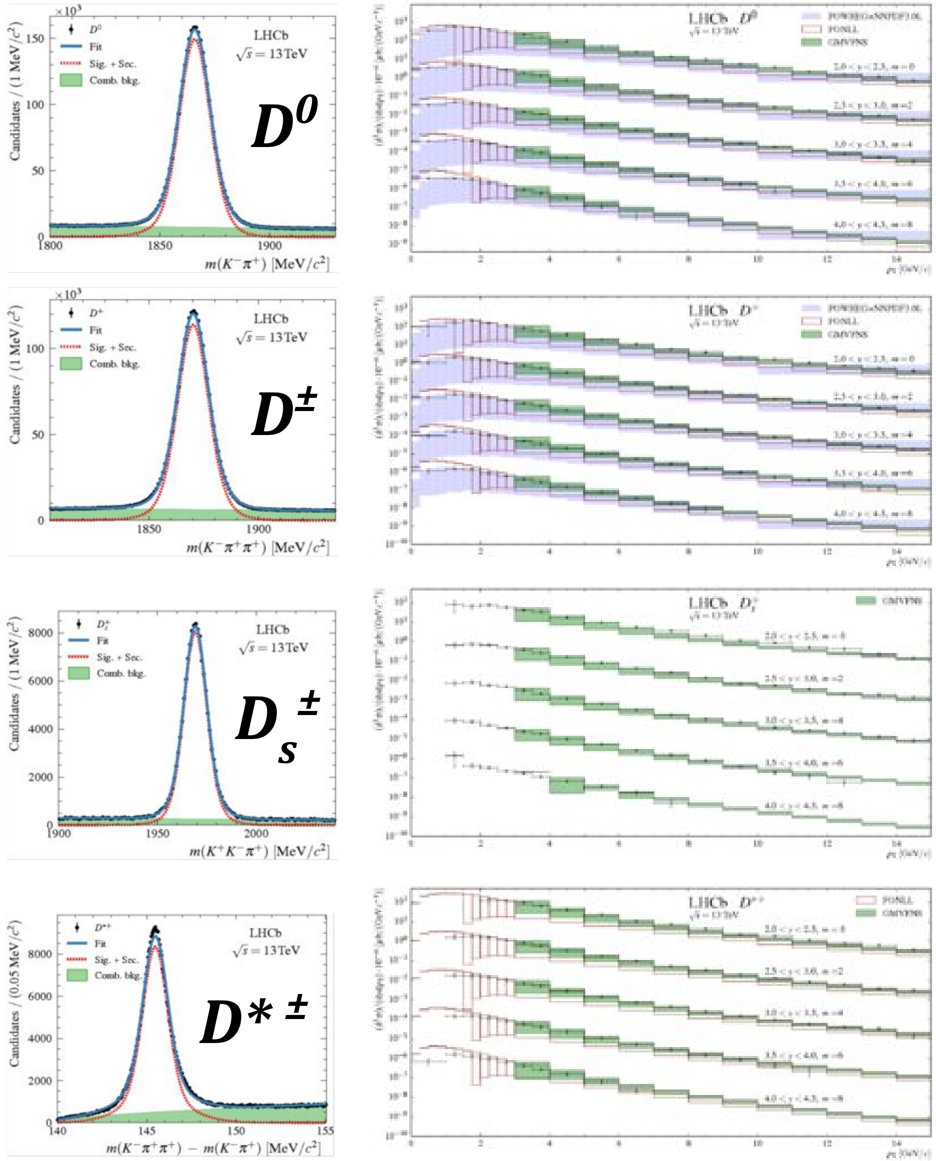
used to remove *from-b* contributions.

$$\sigma(pp \to D^0 X) = 2460 \pm\ 3 \pm 130\ \mu\text{b}$$

$$\sigma(pp \to D^+ X) = 1000 \pm\ 3 \pm 110\ \mu\text{b}$$

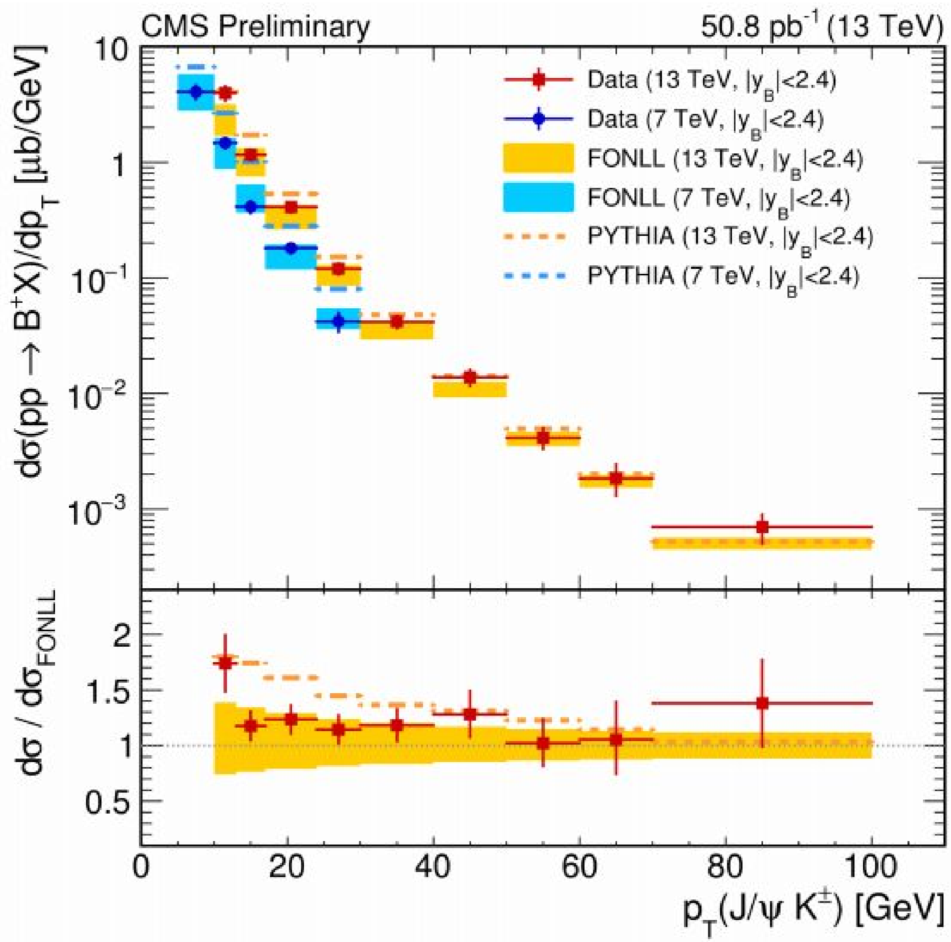
$$\sigma(pp \to D_s^+ X) = 460 \pm 13 \pm 100\ \mu\text{b}$$

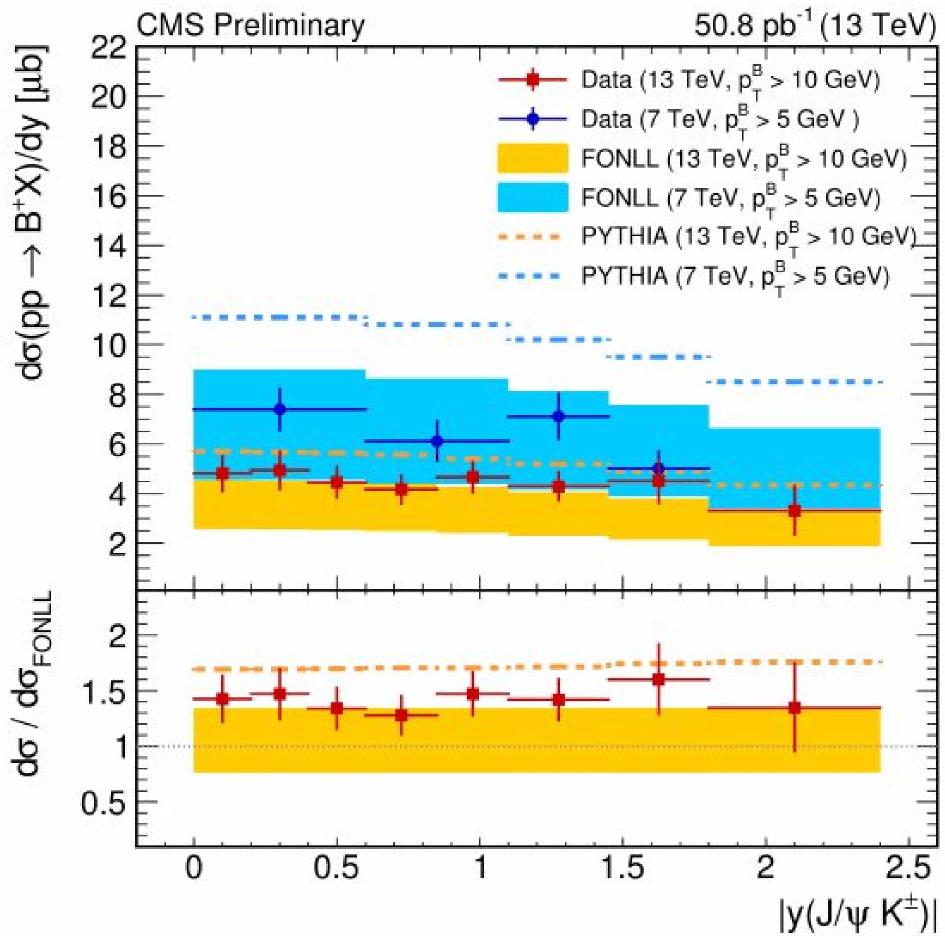
$$\sigma(pp \to D^{*+} X) = 880 \pm\ 5 \pm 140\ \mu\text{b}$$



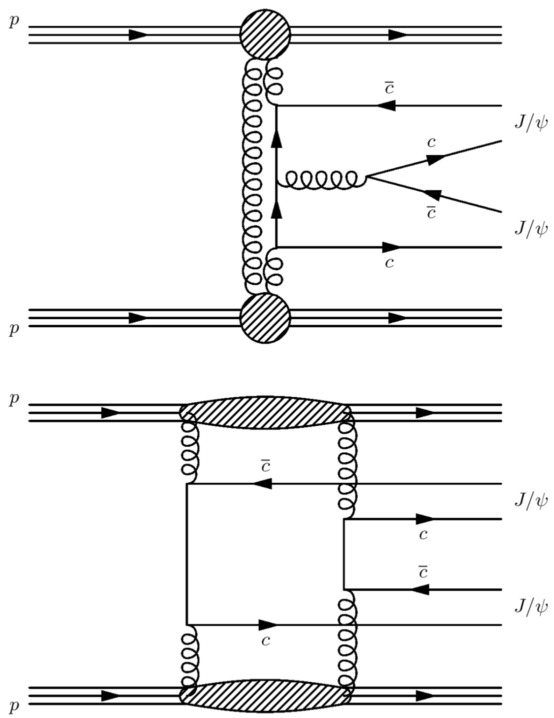
B^+ production cross-section @ $\sqrt{s}$ = 13 TeV

To test that the evolution of the fragmentation functions it is important to measure the production cross-section of various *b*-hadrons specifically.
Measurement found in agreement with predictions from FONLL.





CEP of J/ψ pairs: where DPS is forbidden



$$\sigma^{J/\psi J/\psi} = 58 \pm 10(\text{stat}) \pm 6(\text{syst})\ \text{pb},$$
$$\sigma^{J/\psi\psi(2S)} = 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\ \text{pb},$$

Very preliminary theoretical calculations are in agreement with the measured σ