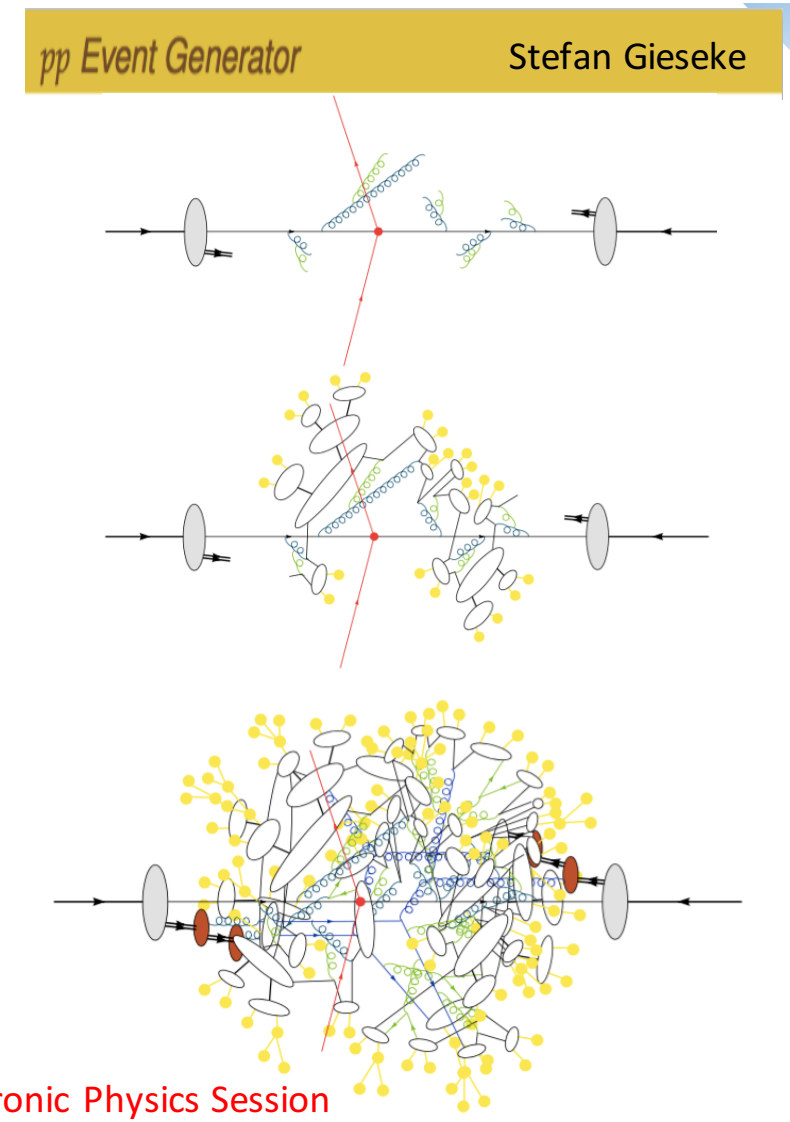
Strong Interactions

Halina Abramowicz
Tel Aviv University



From soft to hard (biased selection)

- Cross sections
- Diffractive scattering - Exclusive processes
- Parton distribution functions - PDFs
- Underlying event properties
- Double parton scattering
- Jet production
- Prompt photon production
- W,Z and jets

Follow up in excellent mini-reviews in the Strong Interactions and Hadronic Physics Session

Motivation

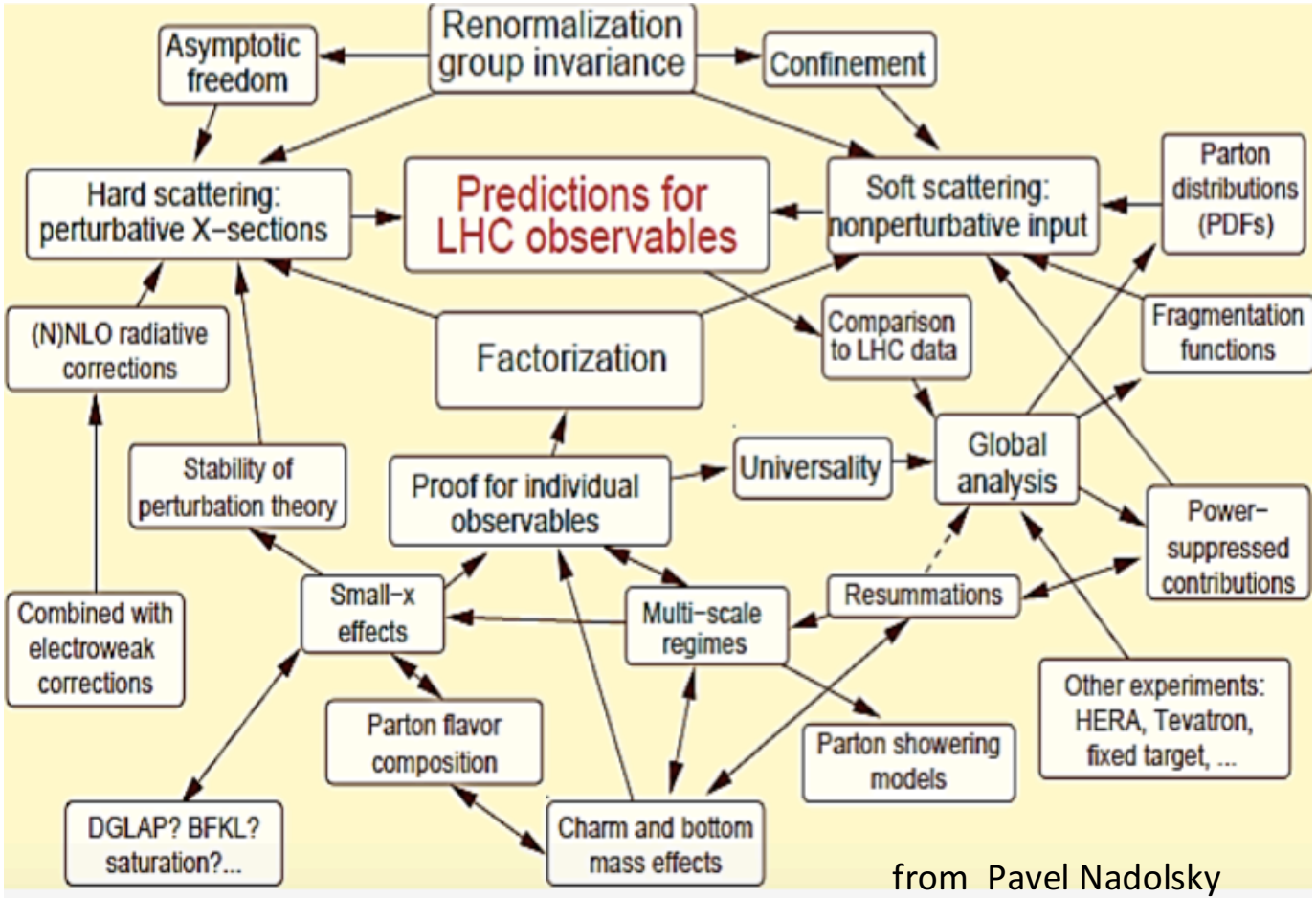
It is all about understanding QCD

- proton structure
- confinement
- origin of mass
- dense matter
- ….

and controlling QCD

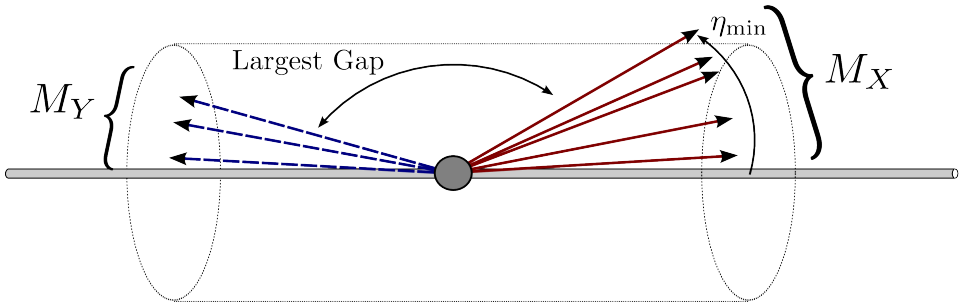
- to make precision predictions
- to provide input to cosmic ray physics
- ….

What it takes to get SM for LHC



from Pavel Nadolsky

Inelastic cross section

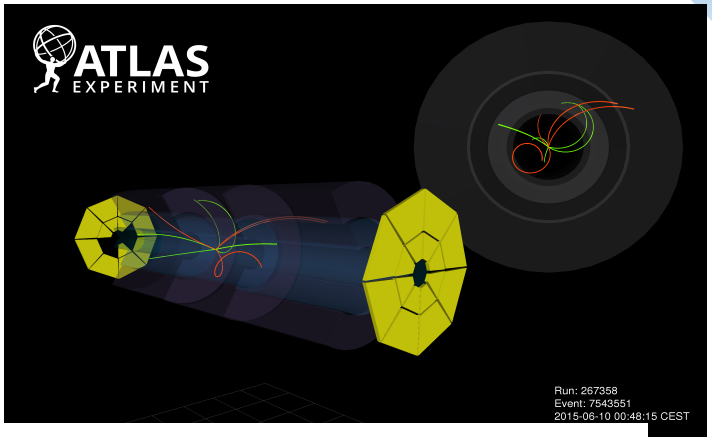


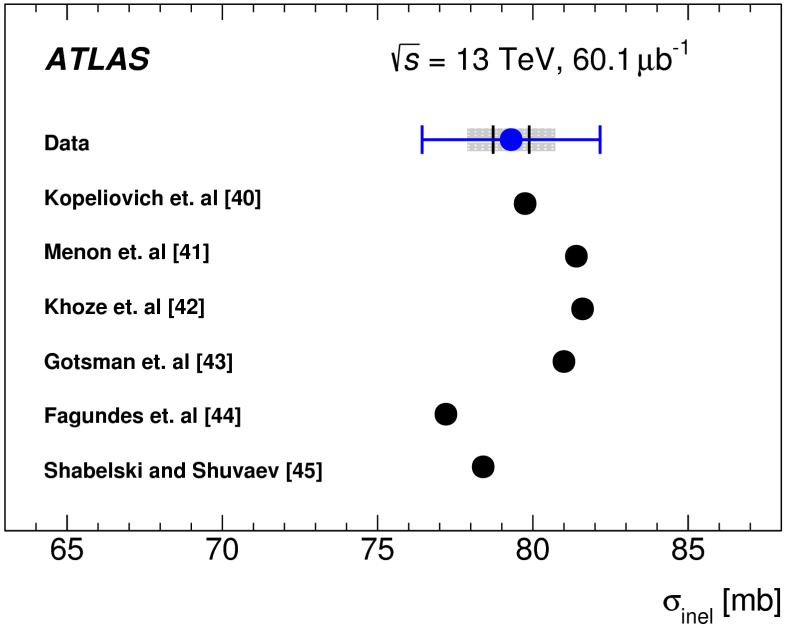
ATLAS – MBTS coverage 2.07<|η|<3.86;
M_X M_y >13 GeV
arXiv:1606.02625 (JHEP)

CMS – HF coverage 3.0<|η|<5.2 and
CASTOR -6.6<η<-5.2;
M_X>4.1 GeV M_y>13 GeV
CMS PAS FSQ-15-005

ATLAS
79.3 ± 0.6 (exp) ± 1.3 (lum) ± 2.5 (ext) mb

CMS preliminary
71.3 ± 0.5 (exp) ± 2.1 (lum) ± 2.7 (ext) mb



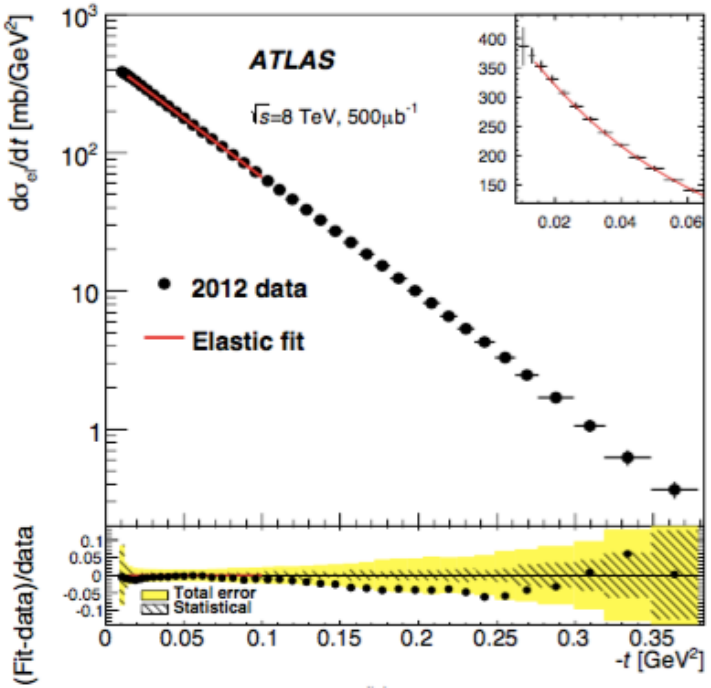


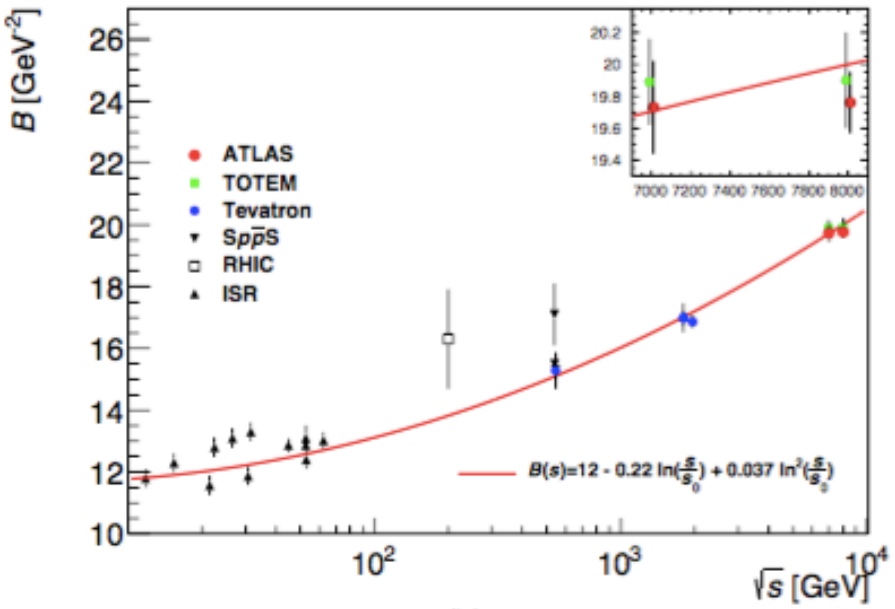
Elastic and total cross section

ATLAS – based on the optical theorem

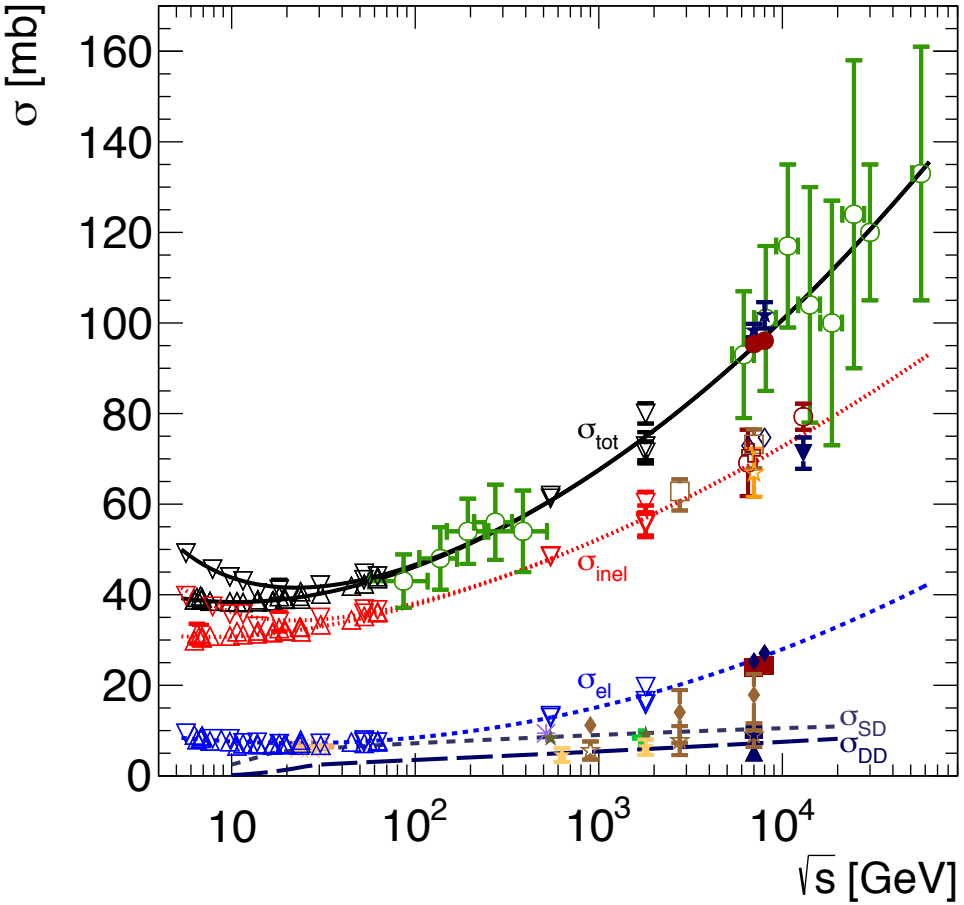
arXiv:1607.06605 (PLB)

$$\sigma_{\text{tot}}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2}\left.\frac{d\sigma_{\text{el}}}{dt}\right|_{t\to 0} \qquad \sigma_{\text{el}} = \frac{\sigma_{\text{tot}}^2}{B}\frac{1+\rho^2}{16\pi(\hbar c)^2}$$





Compilation of cross sections as a function of $\sqrt{s}$



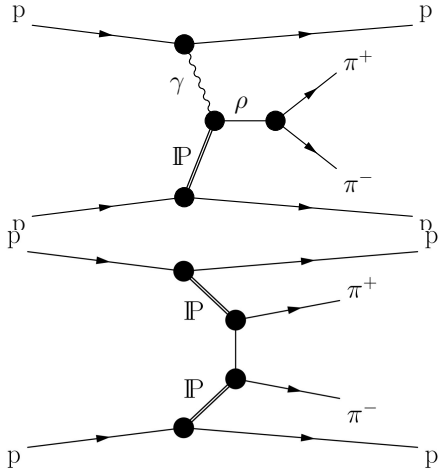
- Cosmic rays σ_{tot}
- TOTEM σ_{tot}
- ATLAS (ALFA, σ_{tot})
- ATLAS (ALFA, σ_{el})
- TOTEM σ_{el}
- ATLAS σ_{inel}
- CMS Preliminary σ_{inel}
- TOTEM σ_{inel}
- ALICE σ_{inel}
- LHCb σ_{inel}
- ATLAS (ALFA, σ_{inel})
- CMS σ_{SD}
- ALICE σ_{SD}
- E710 σ_{SD}
- UA4 σ_{SD}
- CDF σ_{SD}
- Armitage et al. (ISR, σ_{SD})
- CHLM (ISR, σ_{SD})
- CMS σ_{DD}
- ALICE σ_{DD}
- CDF σ_{DD}
- Lower energy pp
- Lower energy $p\bar{p}$

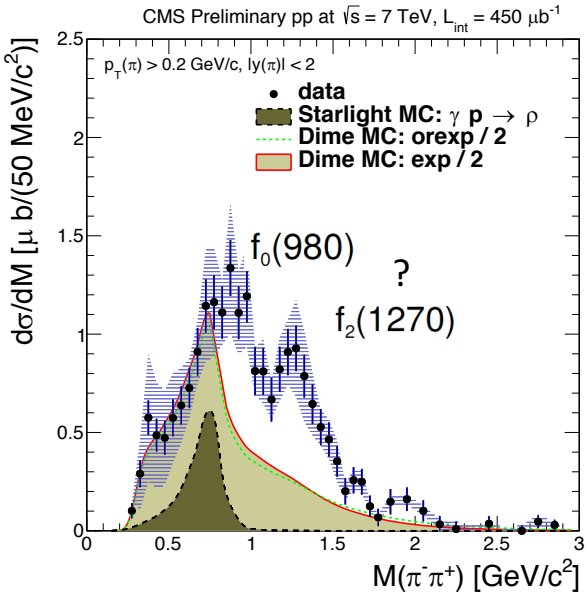
- COMPETE HPR1R2
- $12.7 - 1.75\ln(s) + 0.14\ln^2(s)$
- $\sigma_{inel} = \sigma_{tot} - \sigma_{el}$
- Pythia 8 MBR (SD, ε=1.04)
- Pythia 8 MBR (DD, ε=1.04)

No surprises

Pomeron and exclusive processes

CMS-PAS-FSQ-12-004

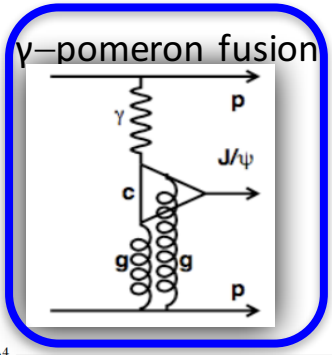


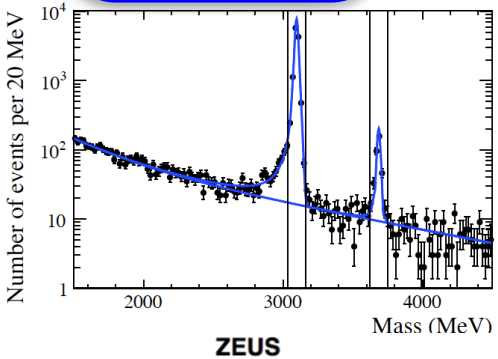


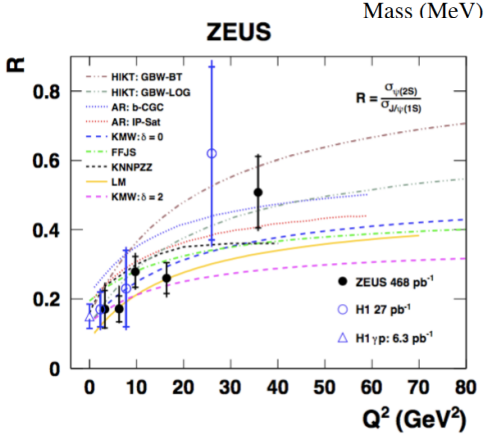
LHCb-CONF-2016-007-001

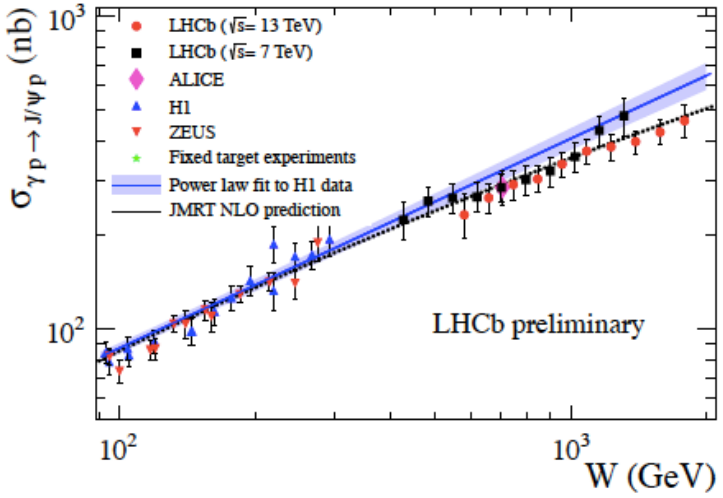
Nucl.Phys. B909 (2016) 934

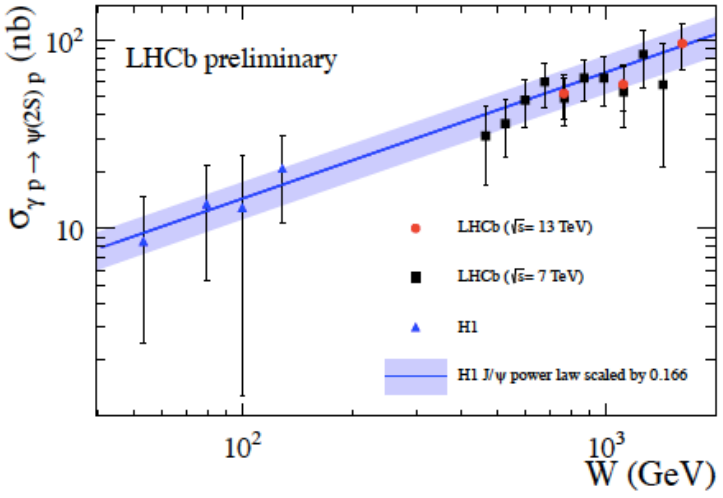
γ–pomeron fusion



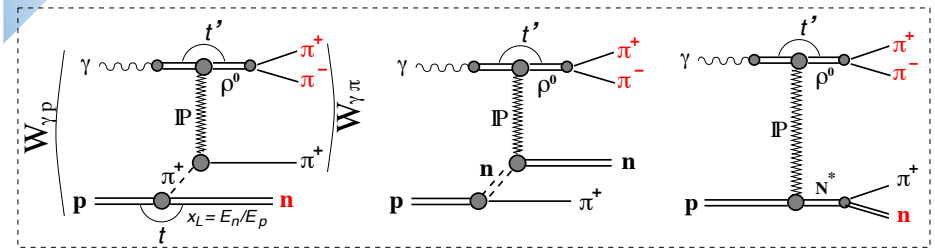


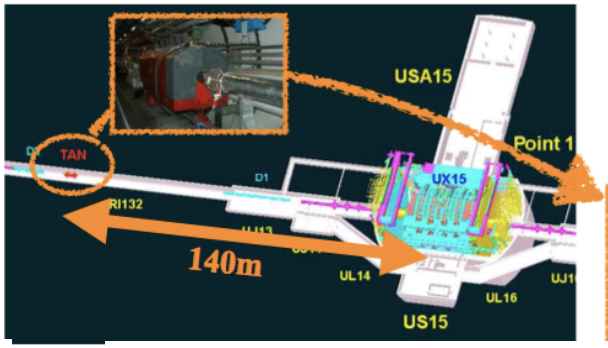


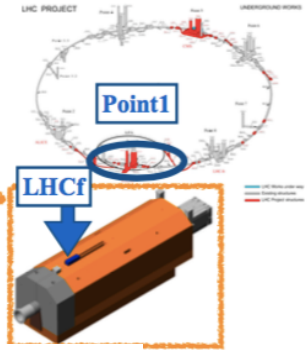




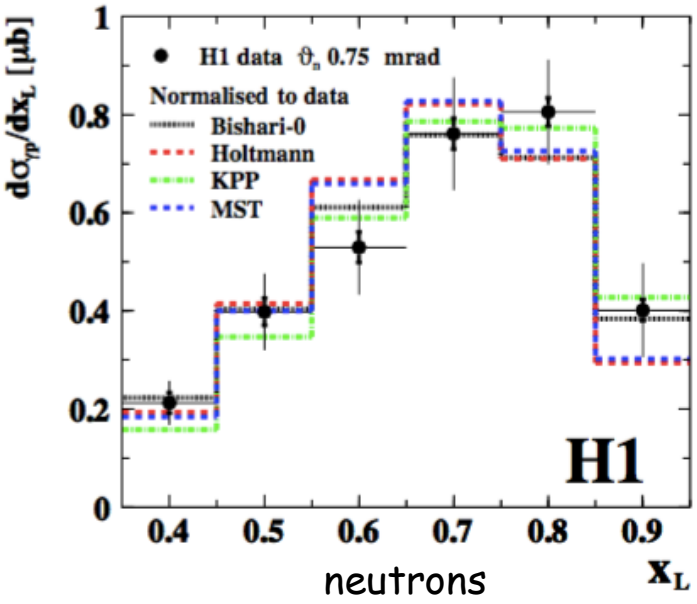
Exclusive production and forward physics

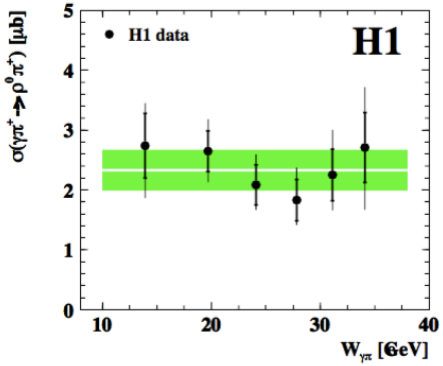






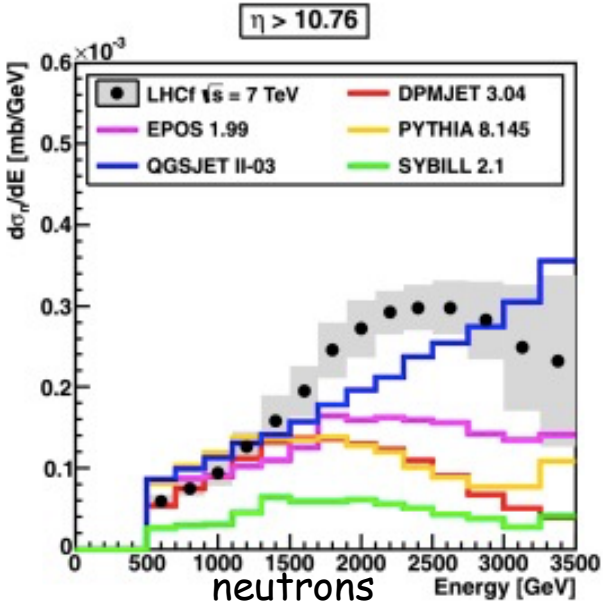
Eur.Phys.J. C76 (2016) 41





About half of what might be expected from γp and additive quark model

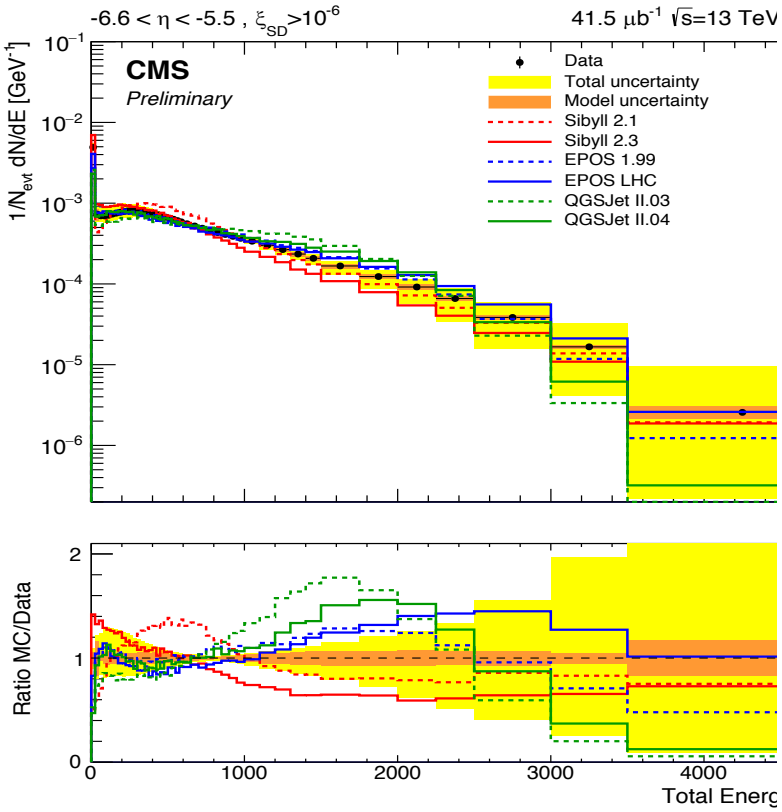
Phys.Lett. B750 (2015) 360



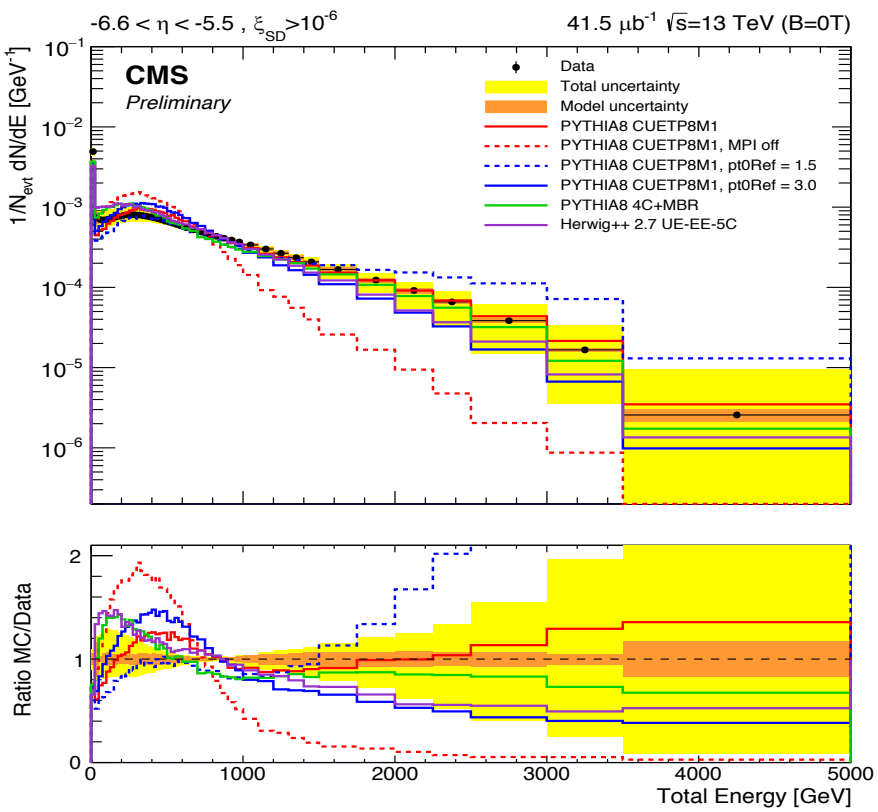
Event characteristics – forward region (13 TeV)

CMS PAS FSQ-16-002

Cosmic ray models



Variations of PYTHIA and HERWIG++

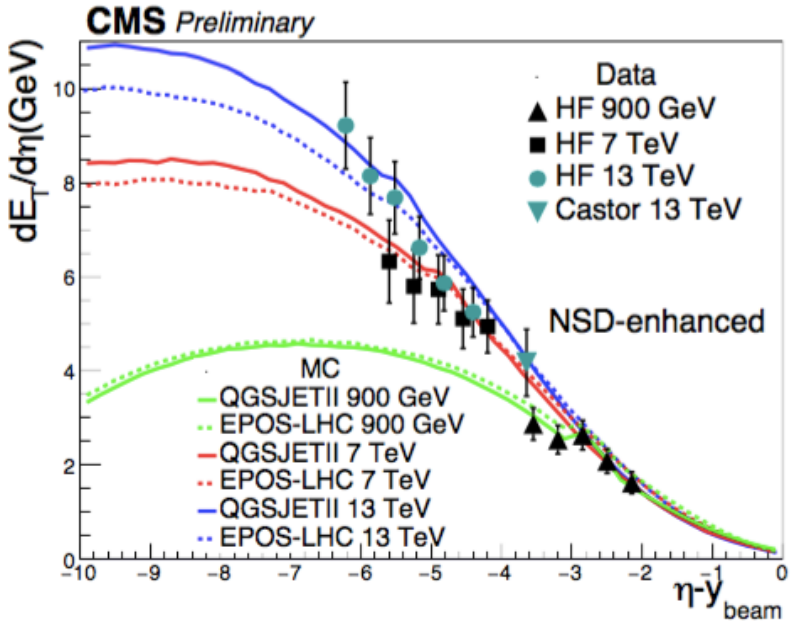


Energy deposited in -6.6<η<-5.2

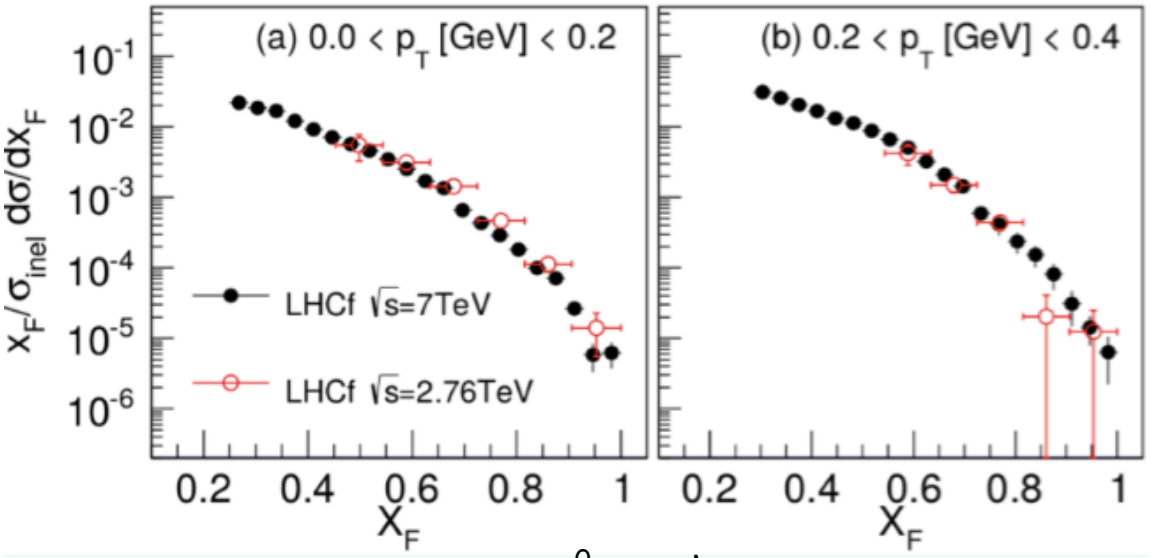
Event characteristics – forward region

Feynman's scaling – limiting fragmentation

CMS PAS FSQ-15-006



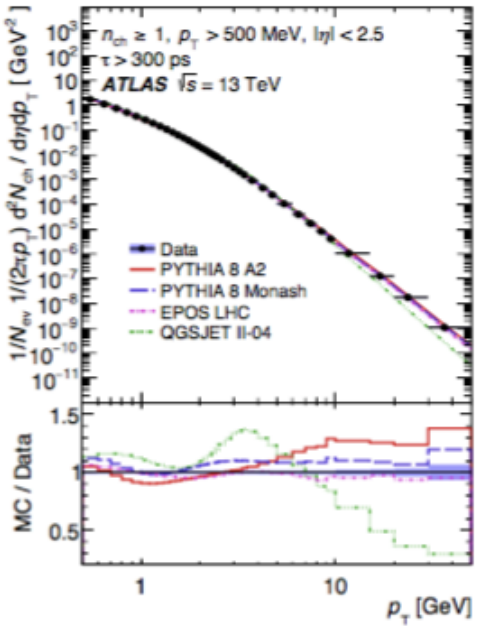
arXiv:1507.08765



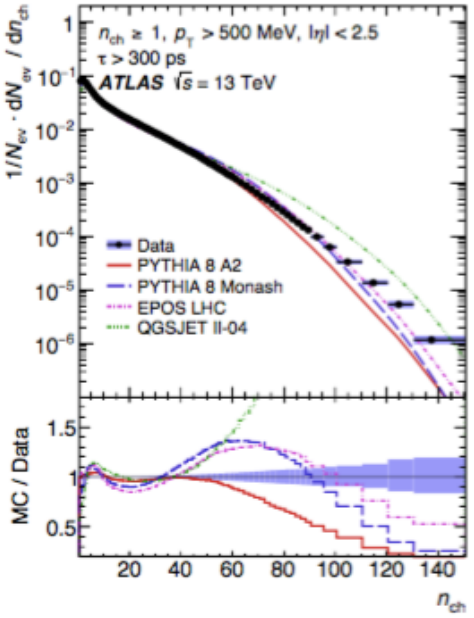
$x_F \equiv 2p_z/\sqrt{s}$

π^0 spectrum

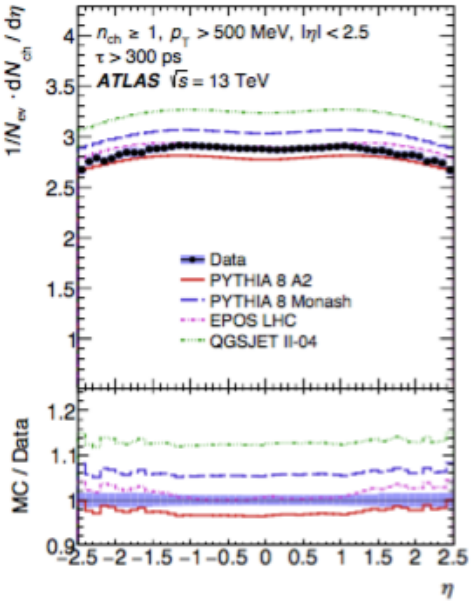
Event characteristics – central region (13 TeV)



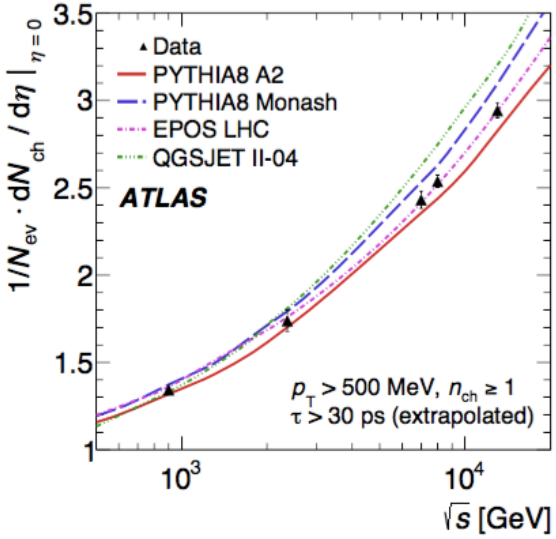
Transverse momentum

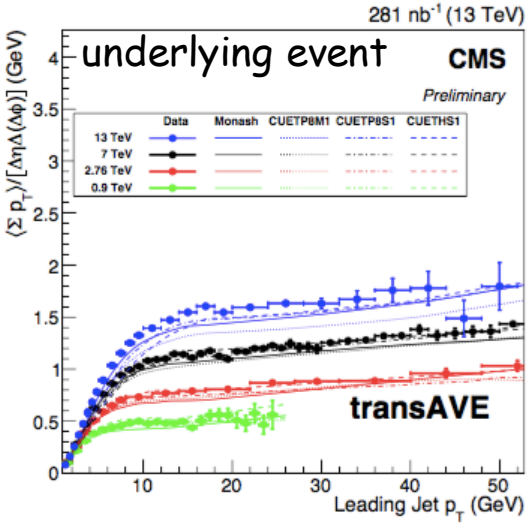


Charged multiplicity



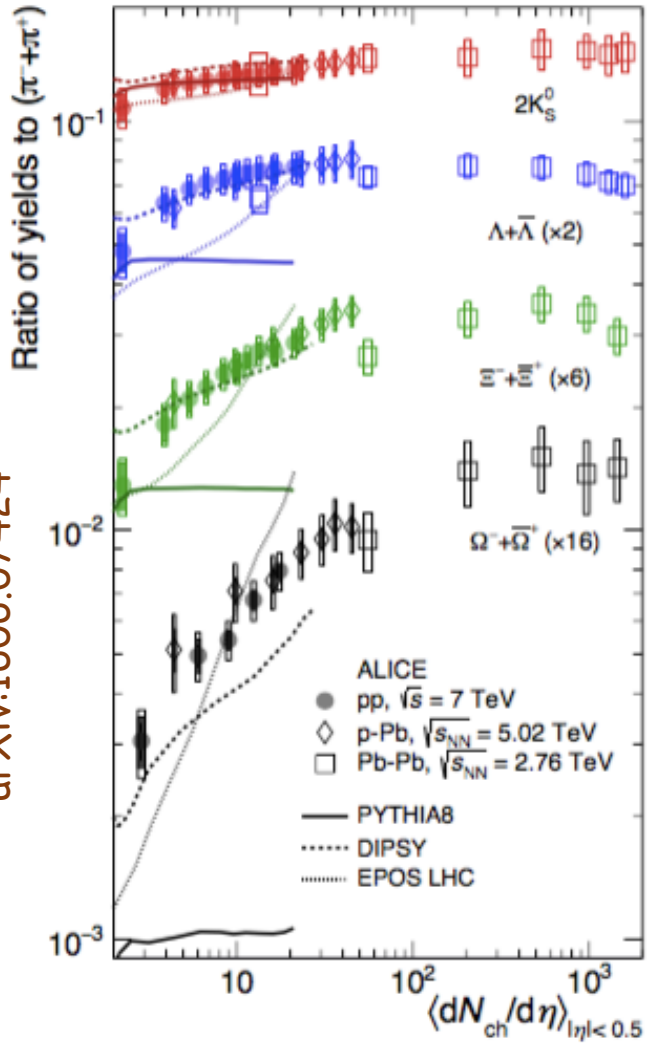
Pseudorapidity



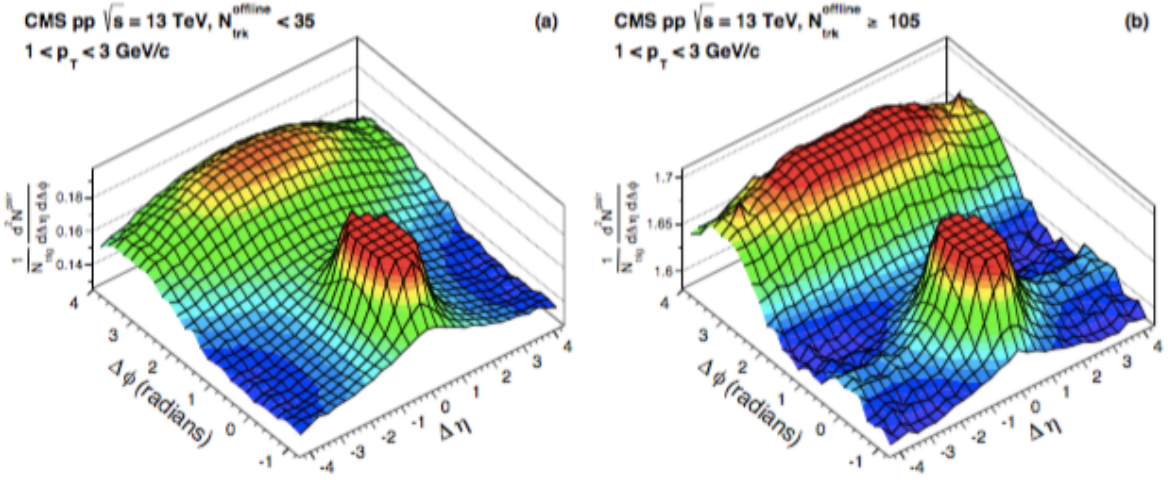


ATLAS – Phys.Lett. B758 (2016) 67
– Eur.Phys.J. C76 (2016) 403
CMS – CMS-PAS-FSQ-15-007

Event characteristics – surprises



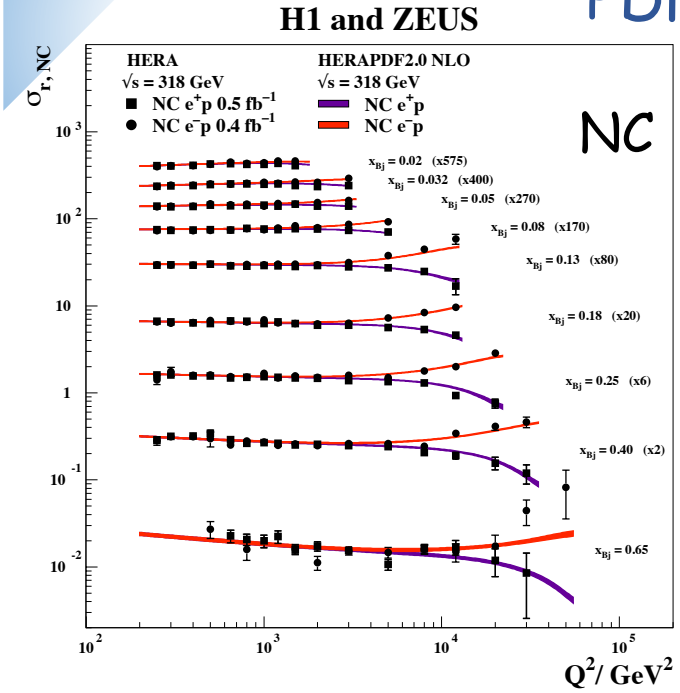
arXiv:1606.07424

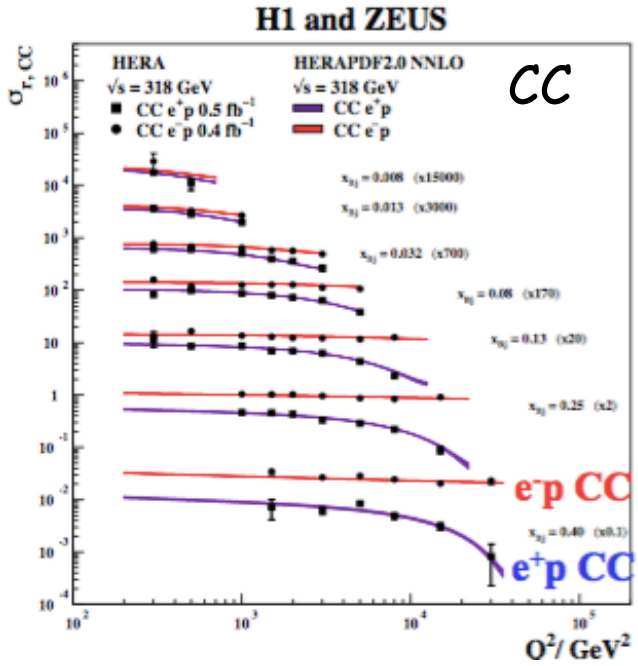


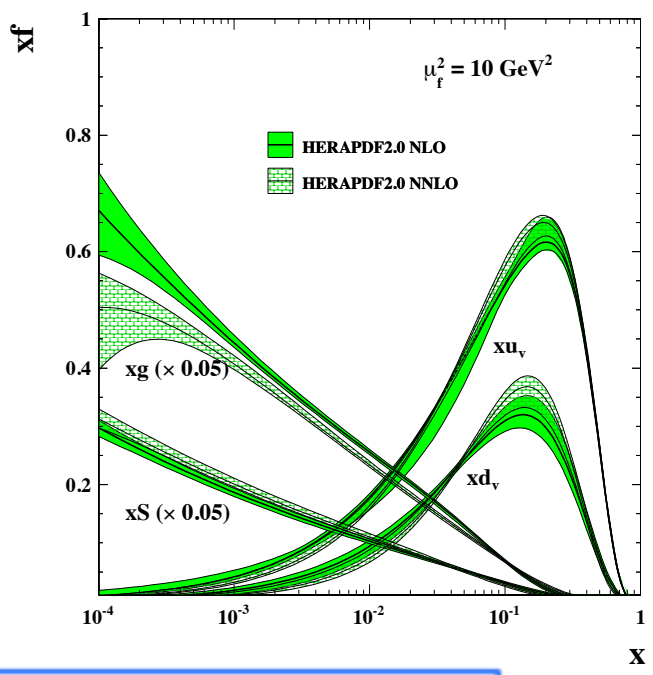
The 2D $(\Delta\eta, \Delta\phi)$ two-particle correlation functions in pp collisions at $\sqrt{s} = 13$ TeV

Phys.Rev.Lett. 116 (2016) 172302

PDFs – latest HERA release







→ available at www.desy.de/h1zeus/herapdf20/ and on LHAPDF:

Eur.Phys.J. C75 (2015) 580

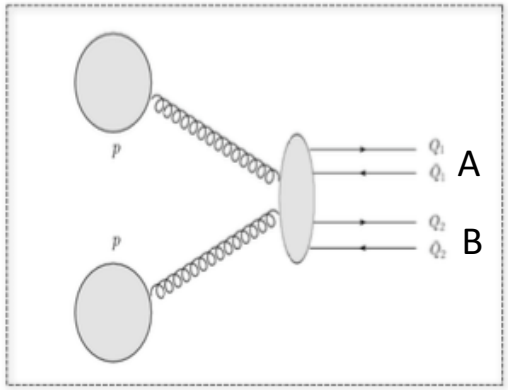
HERAPDF2.0 at NLO and NNLO
also with a scan of $\alpha_s(M^2_Z)$ from 0.110 to 0.130 in steps of 0.001

additional PDF sets :
- HERAPDF2.0HiQ2 at NLO and NNLO - Q^2_{min}=10 GeV²
- HERAPDF2.0AG at LO, NLO and NNLO - alternative gluon parameterisation (strictly positive)
- HERAPDF2.0FF3A and FF3B - fixed flavor number schemes at NLO

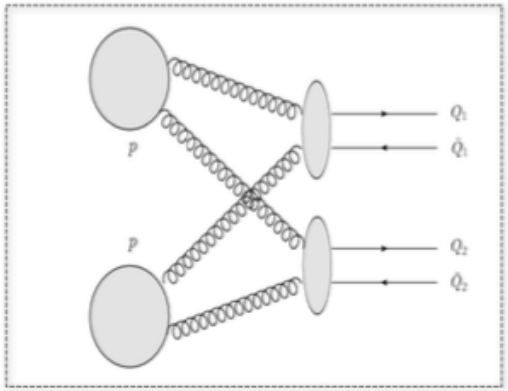
Multi-parton interactions

Inherent method to generate the minimum bias and underlying event activities

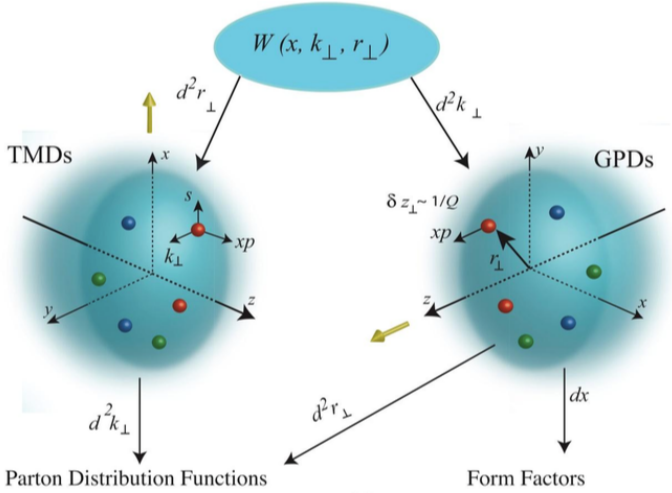
Single Parton Scattering (SPS)
• one hard parton-parton scatter



Double Parton Scattering (DPS)
• two hard scatters within same protons



Need 3D picture



$$\sigma_{\rm DPS}^{\rm AB} = \frac{m}{2}\frac{\sigma_{\rm SPS}^{A}\sigma_{\rm SPS}^{B}}{\sigma_{\rm eff}},$$

$$\sigma_{\rm eff} = \left[\int d^2b\,(T(\mathbf{b}))^2\right]^{-1},$$

T(b) is the overlap function that characterizes the transverse area occupied by the interacting partons

The smaller the σ_{eff} the larger the probability of DPS – highly packed partons

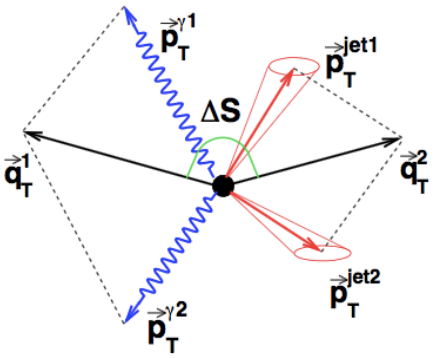
Double-parton scattering

D0 final state 2γ+2jets at 1.96 TeV

$$\sigma_{\text{eff}} = 19.3 \pm 1.4(\text{stat}) \pm 7.8(\text{syst})\text{mb}.$$

f_{DPS}= 0.213 ± 0.061(stat) ± 0.028(syst)

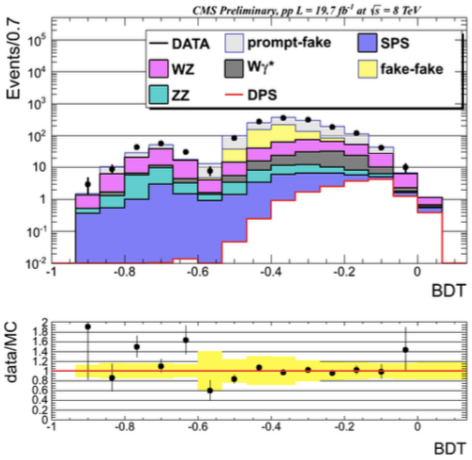
Phys.Rev. D93 (2016) 052008



CMS final state $W^{\pm}W^{\pm}$ at 8 TeV (preliminary)

σ_{eff} > 5.91 mb (95% CL)

CMS PAS FSQ-13-001



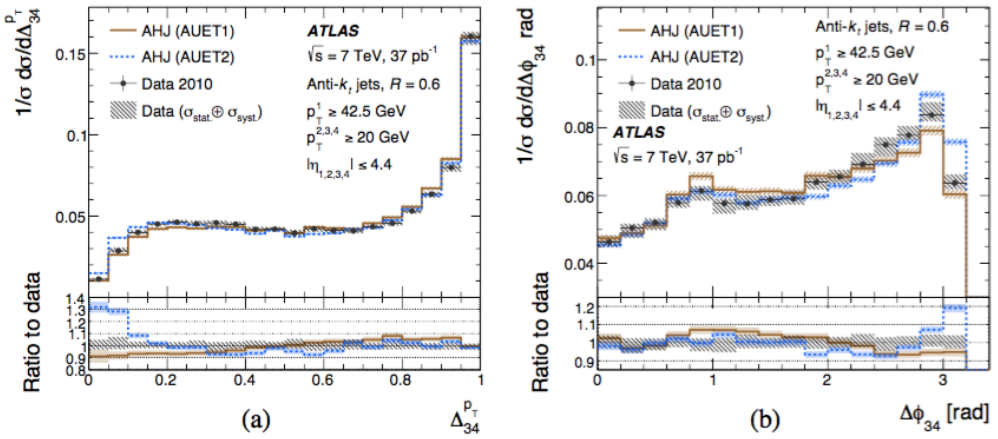
Double-parton scattering

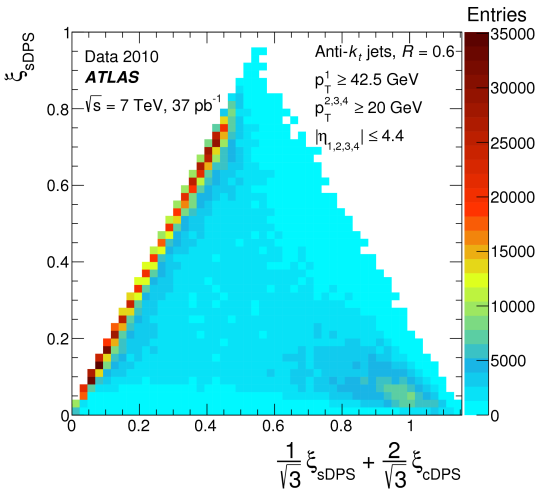
ATLAS in 4jets at 7 TeV

arXiv:1608.00852

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

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



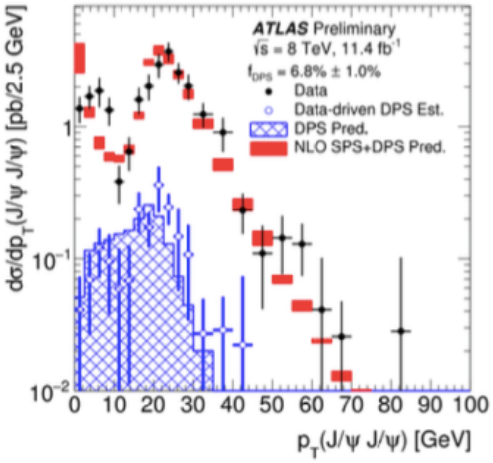


ATLAS in $J/\psi J/\psi$ at 8 TeV (preliminary)

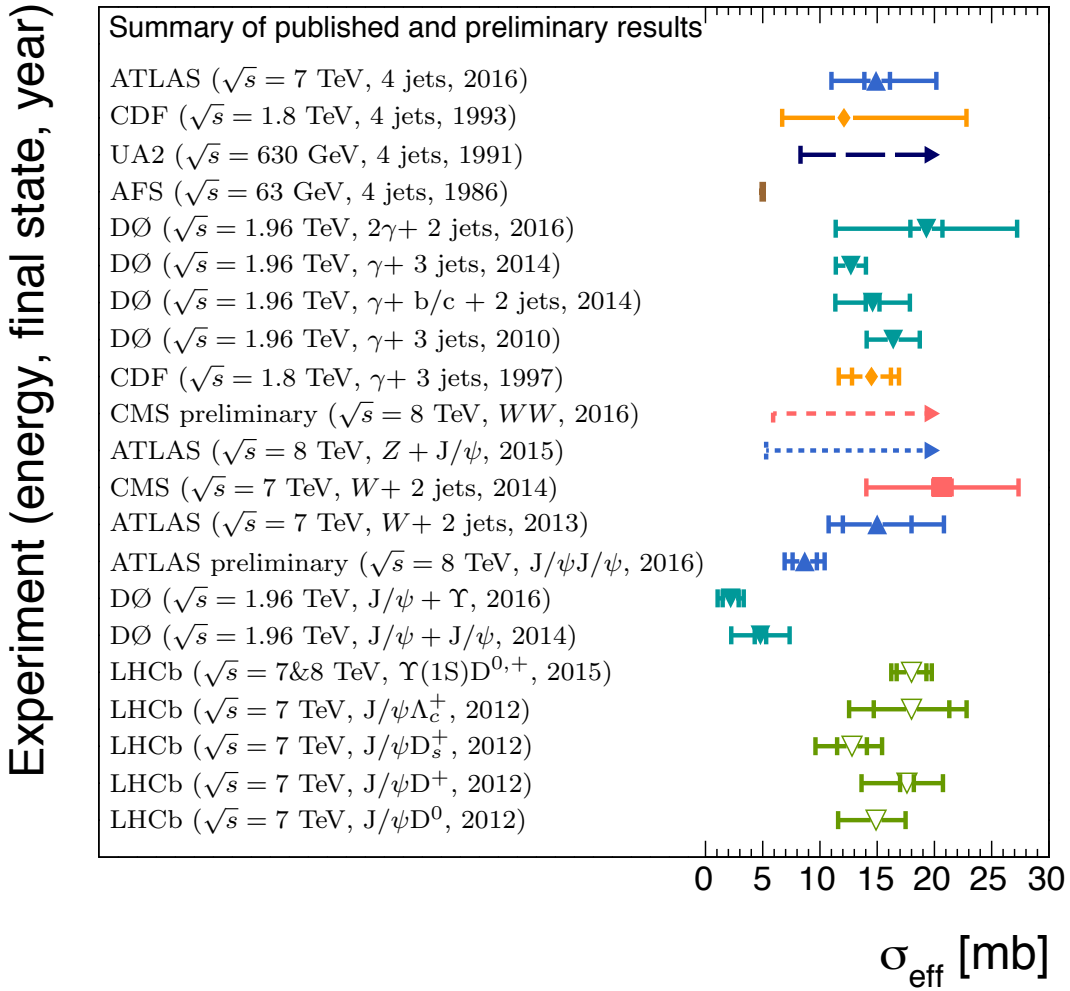
$$\sigma_{\text{eff}} = 8.7 \pm 1.1\ (\text{stat}) \pm 1.4\ (\text{syst}) \pm 0.1\ (\text{BF}) \pm 0.3\ (\text{lumi})\ \text{mb}$$

$$f_{\text{DPS}} = 6.6 \pm 0.8\ (\text{stat}) \pm 0.2\ (\text{syst})\%$$

ATLAS-CONF-2016-047



Double-parton scattering

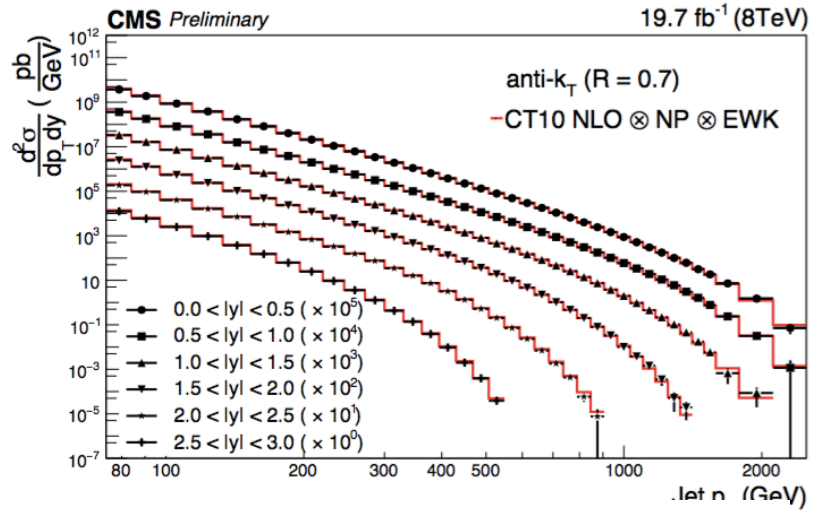


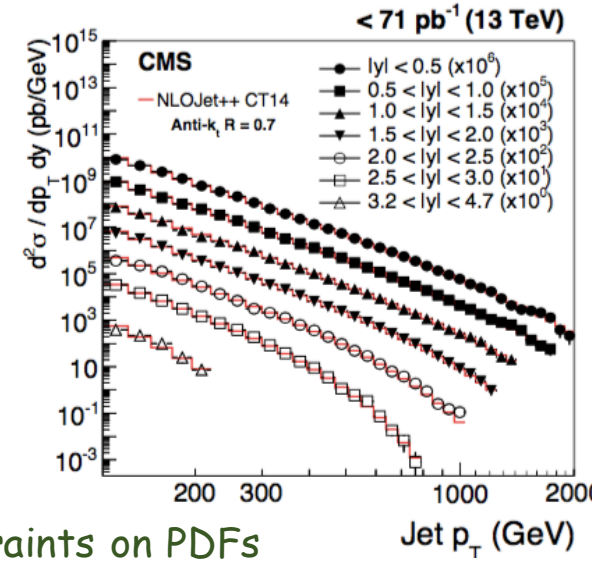
- $\sigma_{eff} < \sigma_{inel}$
- $\sigma_{eff} < 30$ mb expected from gluon form-factor
- non-universal?

Potential source of information about 3D proton

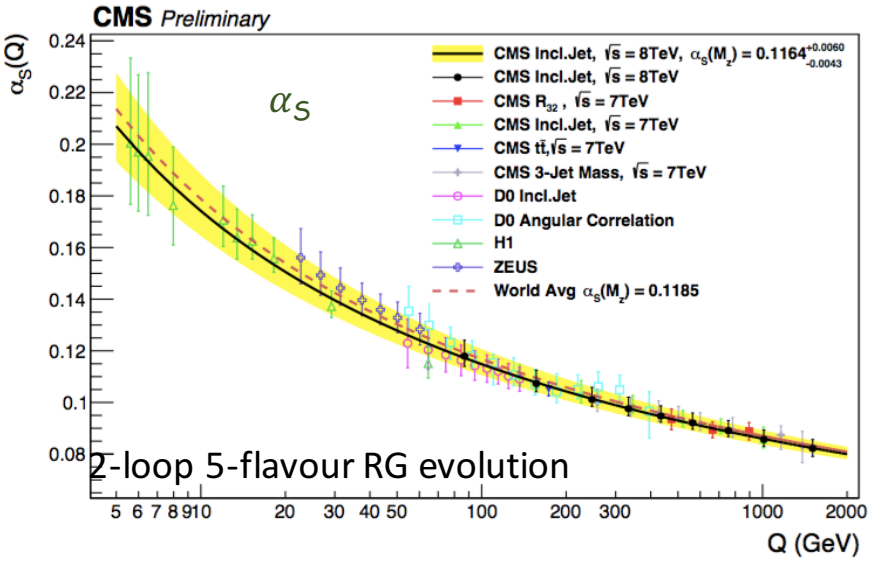
pQCD stress test - jet production

CMS-PAS-SMP-14-001



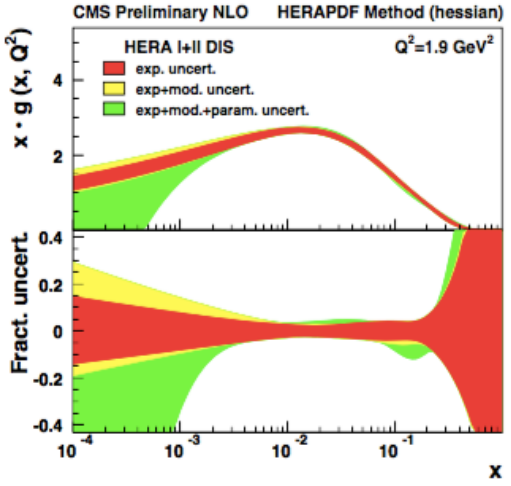


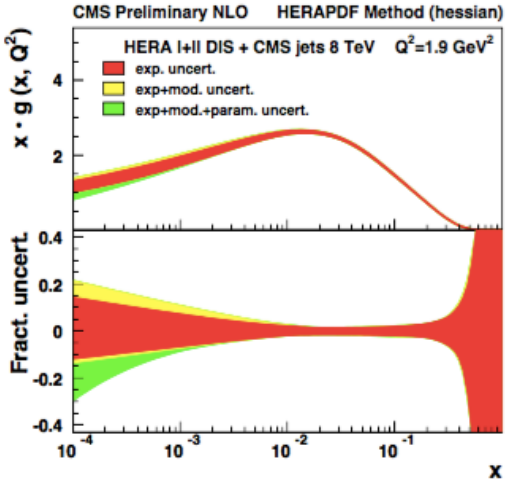
arXiv:1605.04436 (EPJC)



2-loop 5-flavour RG evolution

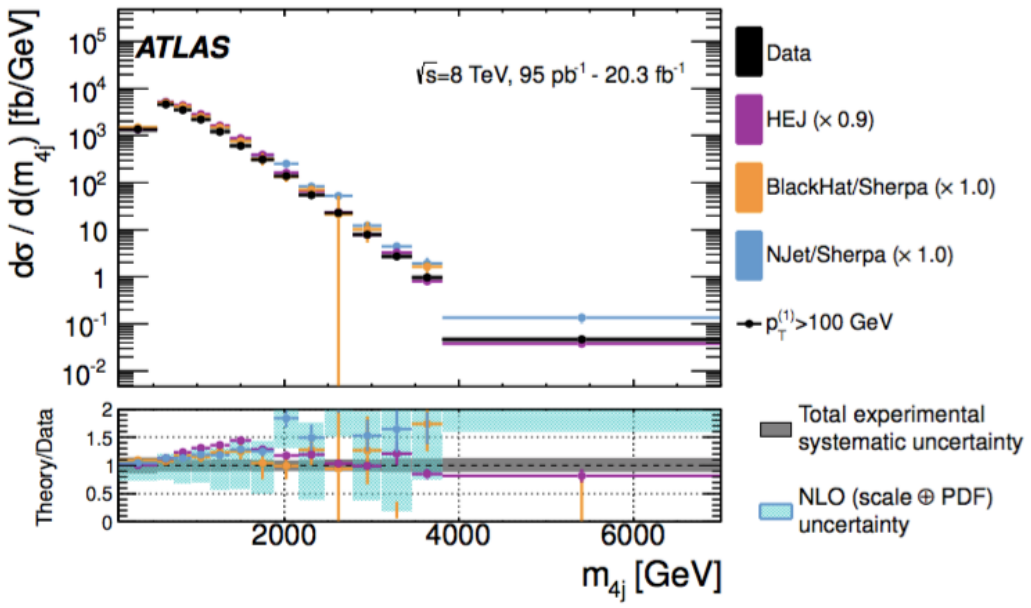
Constraints on PDFs





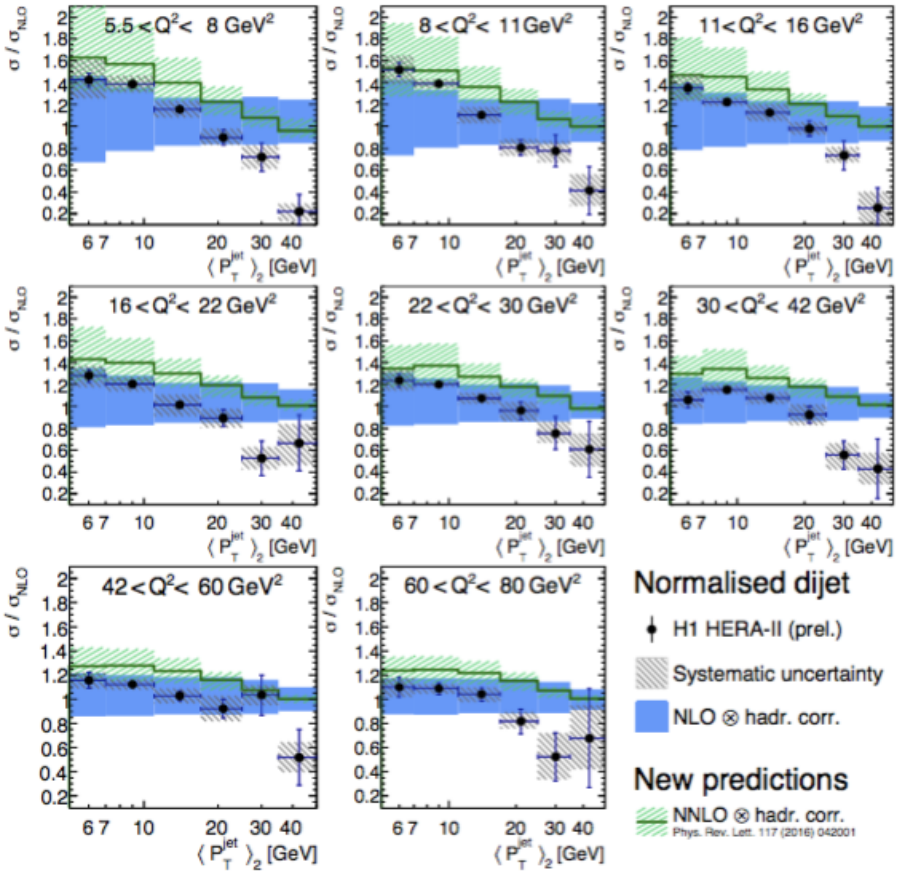
pQCD stress test - multijet production

JHEP 1512 (2015) 105



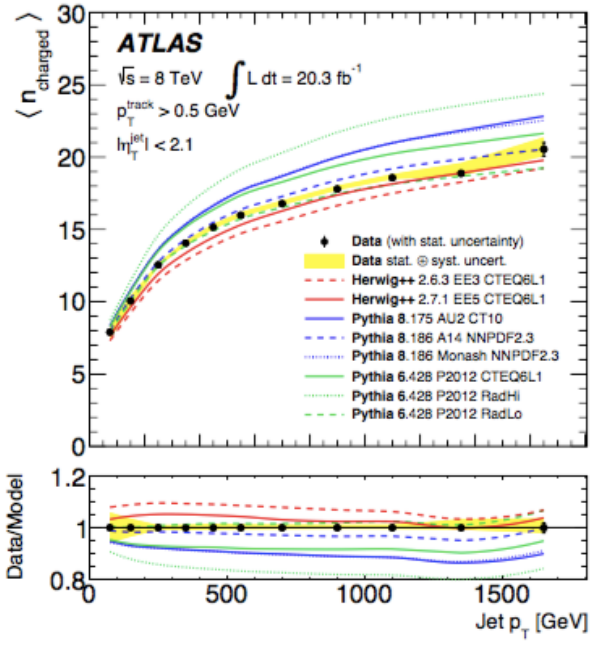
Multi-leg/multi-scale final states still not fully under control

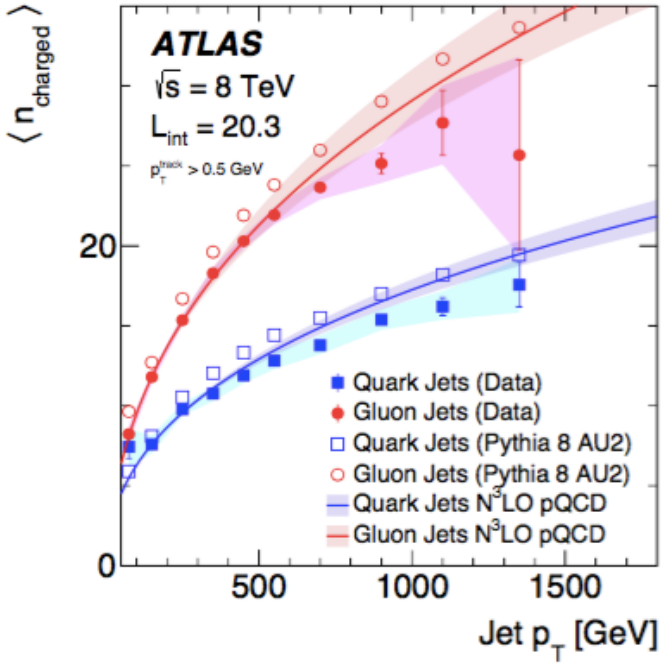
H1prelim-16-061



Properties of jets in dijets

Charged multiplicity Eur.Phys.J. C76 (2016) 322

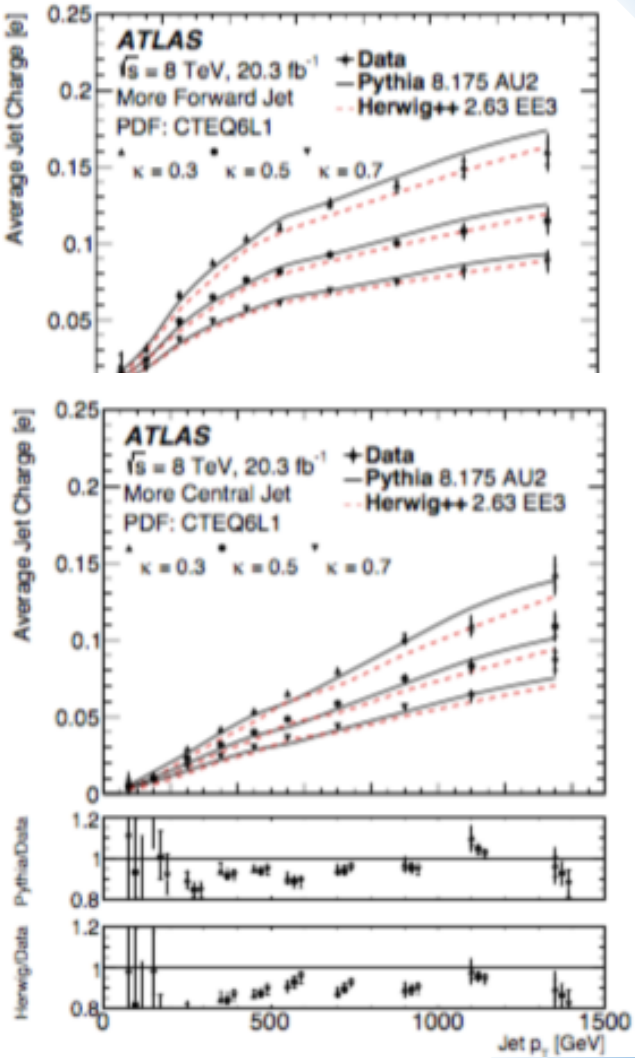




$$\langle n^{f}_{\text{charged}}\rangle = f^{f}_{q}\langle n^{q}_{\text{charged}}\rangle + f^{f}_{g}\langle n^{g}_{\text{charged}}\rangle$$
$$\langle n^{c}_{\text{charged}}\rangle = f^{c}_{q}\langle n^{q}_{\text{charged}}\rangle + f^{c}_{g}\langle n^{g}_{\text{charged}}\rangle.$$

$$Q_J = \frac{1}{(p_{\mathrm{T}\,J})^{\kappa}} \sum_{i \in Tracks} q_i \times (p_{\mathrm{T,i}})^{\kappa}$$

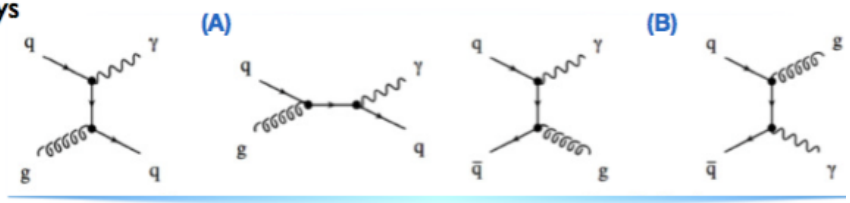
Phys.Rev. D93 (2016) 052003



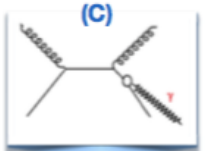
pQCD readiness for prompt photons

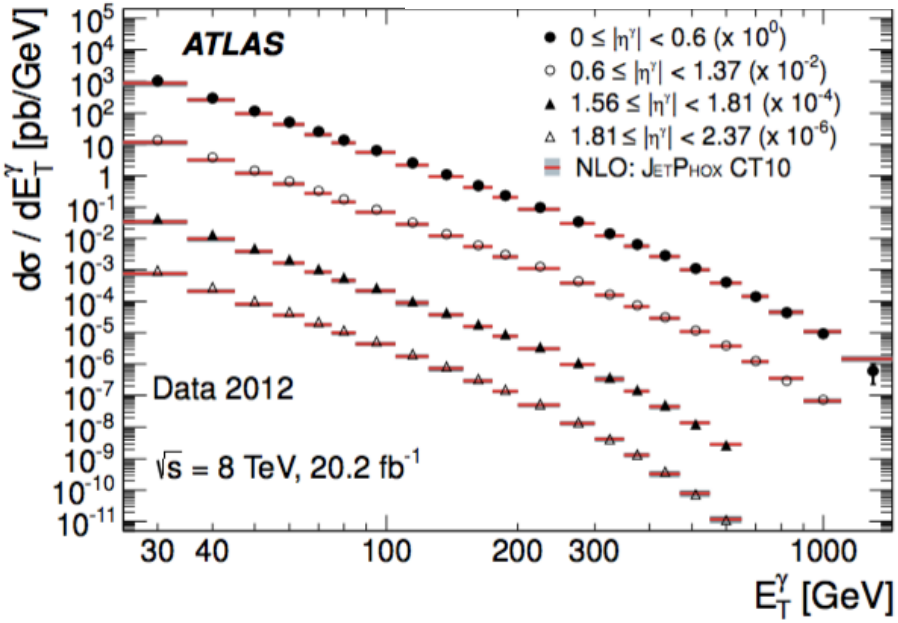
PROMPT PHOTONS:
not from hadron decays

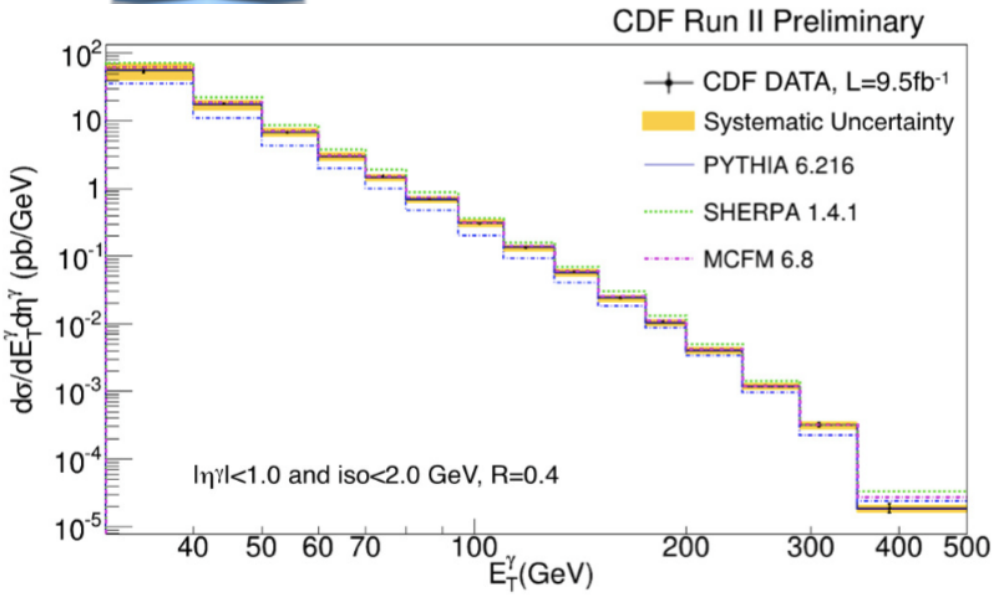
- **Direct photon**
  - A. **Compton**
  - B. **Annihilation**



- **Fragmentation photon** (C)
  BUT suppressed with isolation





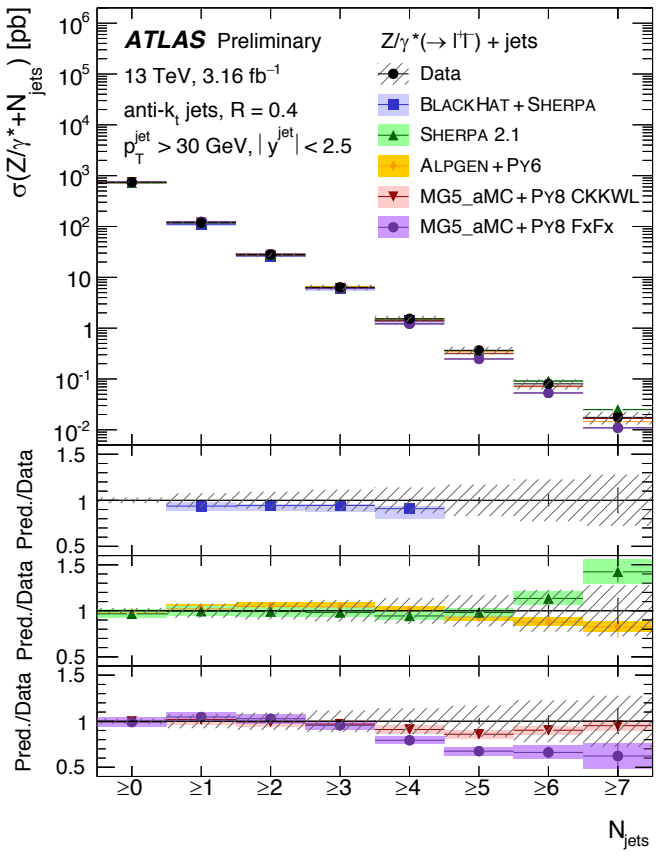


JHEP 1608 (2016) 005

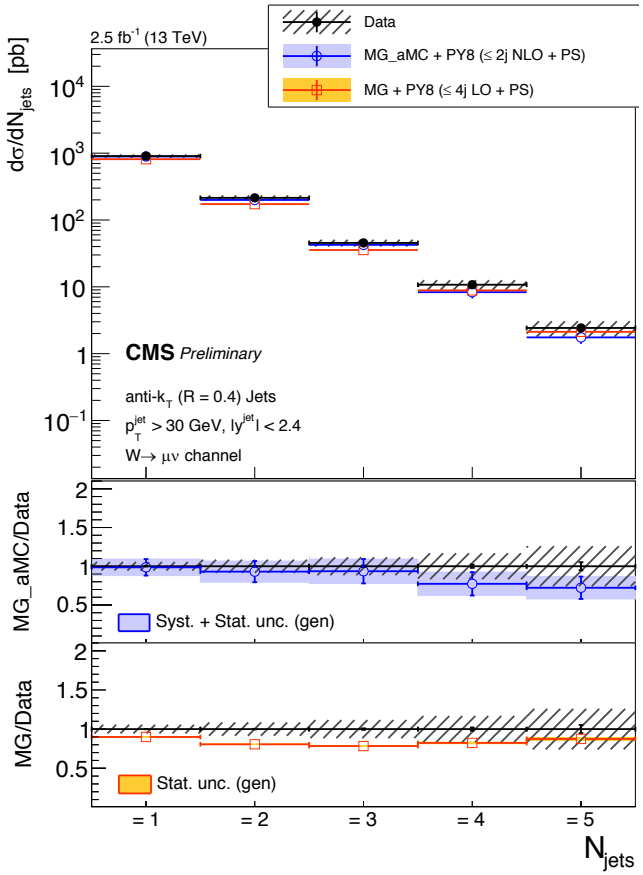
CDF-note-11180

W/Z + jets

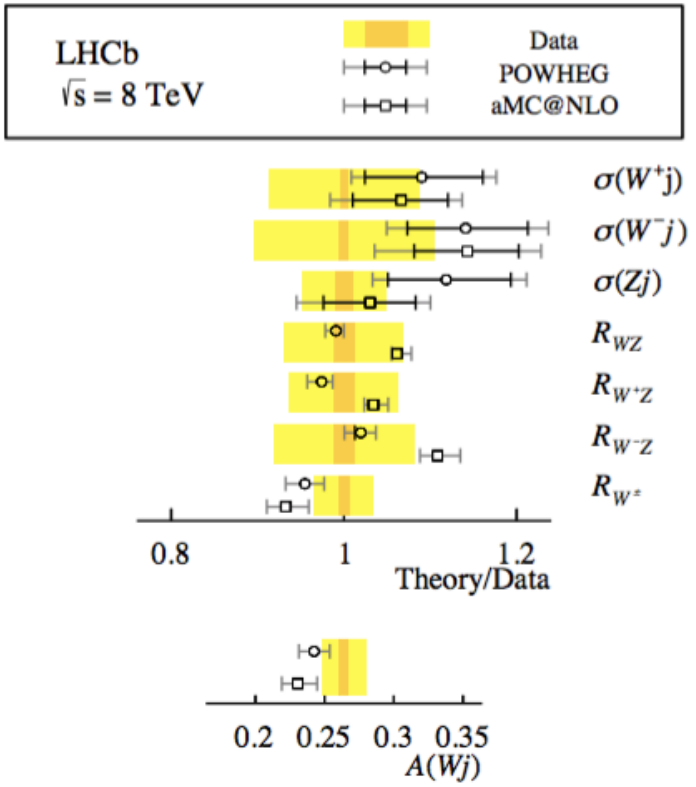
ATLAS-CONF-2016-046



CMS-PAS-SMP-16-005



JHEP 1605 (2016) 131



Jet: anti-k_T R=0.5 $2.2 \le \eta \le 4.2$, p_T>20 GeV

Good description for low jet multiplicity (including c and b jets)

Higher jet multiplicities require more work

Summary

- Given the complexity of the final states,
  all in all a good description of main event characteristics achieved

- Certain regions of phase space still poorly controlled, ex. – forward energy flow, high multiplicities

- PDFs – HERA data an anchor but not sufficient for low or high x or 3D picture of proton – JLAB might be too low s; next opportunity EIC/eRHIC

- The role/impact of collective effects not understood

- Main concern – lack of precise SM expectations may hinder searches for BSM physics unless the new physics is spectacular….

Backup

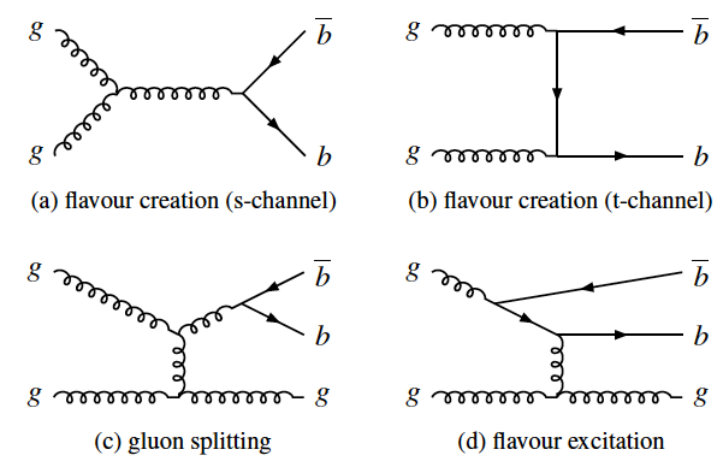
heavy flavour jets: b-bbar dijets

- **b-quark pair production:**
- mixture of production diagrams
- tests QCD heavy flavour calcs.

ATLAS EXPERIMENT arXiv:1607.08430

- two jets pt > 20 GeV, $|\eta| < 2.5$, both tagged as b-jets
- pt1 > 270 GeV
  enhances gluon splitting and flavour excitation relative to flavour creation c.f. previous analyses
- cross sections differential in several observables: m_{bb}, pt_{bb}, $y_B = ½ |y_1+y_2|$, $y^* = ½ |y_1-y_2|$, $\Delta\Phi$, ΔR

LO Feynman diagrams for b-bbar production



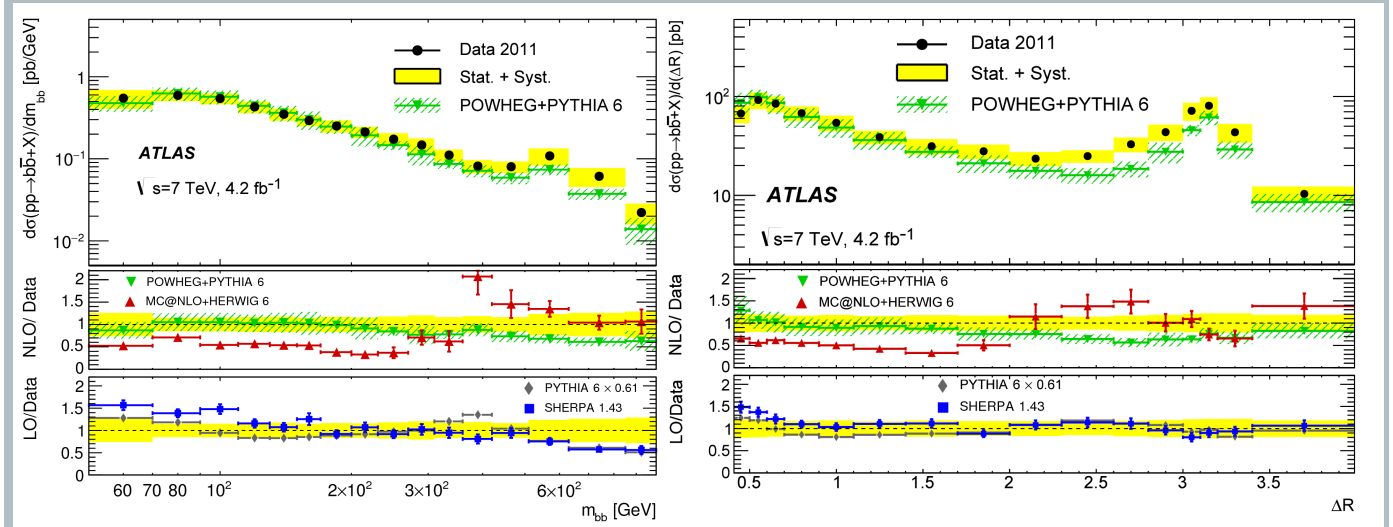
different ranges of measured observables probe different production mechanisms

b-jets

heavy flavour jets: b-bbar dijets

- **compared to LO and NLO MCs**
- reasonable agreement with Powheg+PYTHIA6
- MC@NLO shows significant deviations in all variables
- LO MCs generally reproduce shape of data for most observables (though some bins deviate)

arXiv:1607.08430



(significant contribution from flavour creation for m_{bb} > 550 GeV and $\Delta R \cong 3$)

21