Experimental Results on QCD What's Next?

Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
Davis University USA

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Nobel Symposium on LHC results

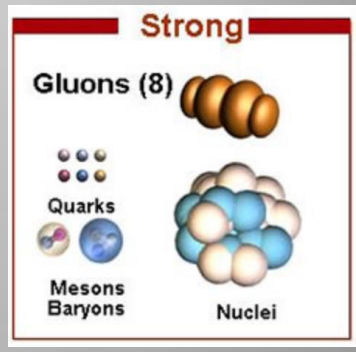
QCD

QCD plays a major role in basically every topic under discussion at this Symposium. For precision physics, or discovery physics we need to understand the role of QCD corrections: QCD is all around us at the LHC

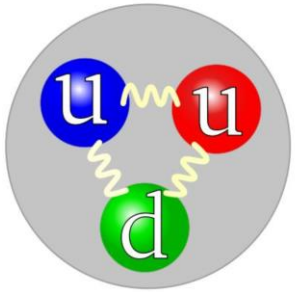
Quantum chromodynamics

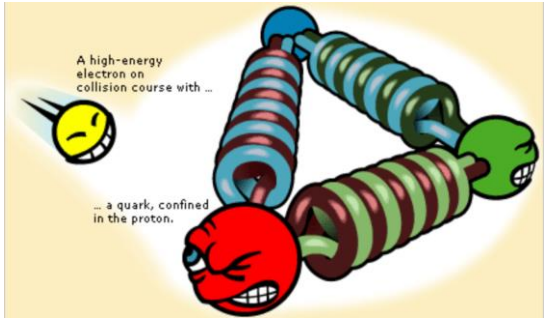
From Wikipedia, the free encyclopedia

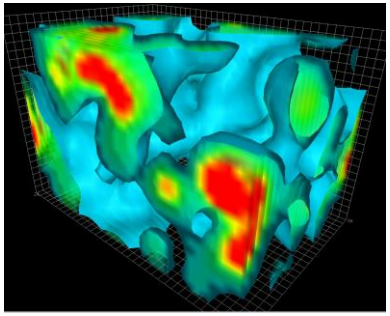
In theoretical physics, **quantum chromodynamics** (**QCD**) is a theory of the strong interaction (color force), a fundamental force describing the interactions between quarks and gluons which make up hadrons (such as the proton, neutron or pion). It is the study of the **SU**(3) Yang–Mills theory of color-charged fermions (the quarks). QCD is a quantum field theory of a special kind called a non-abelian gauge theory, consisting of a 'color field' mediated by a set of exchange particles (the gluons). The theory is an important part of the Standard Model of particle physics. A huge body of experimental evidence for QCD has been gathered over the years.



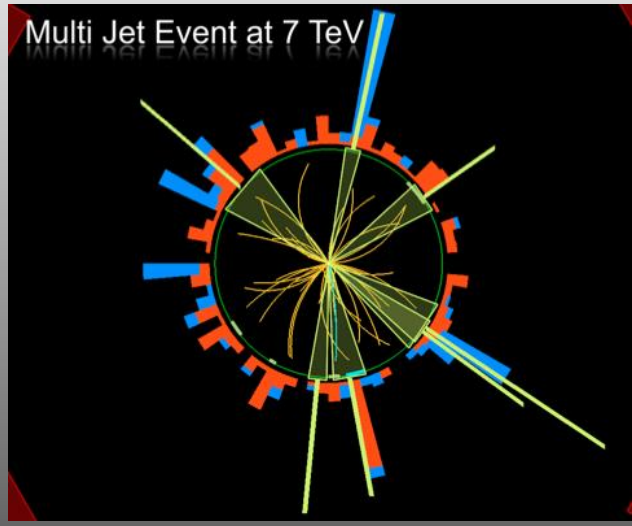
$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F_a^{\mu\nu} F^a_{\mu\nu} + \sum_f \bar{\psi}_i^{(f)} \left(i \not{D}_{ij} - m_f \delta_{ij} \right) \psi_j^{(f)}$$







Topics in this Presentation



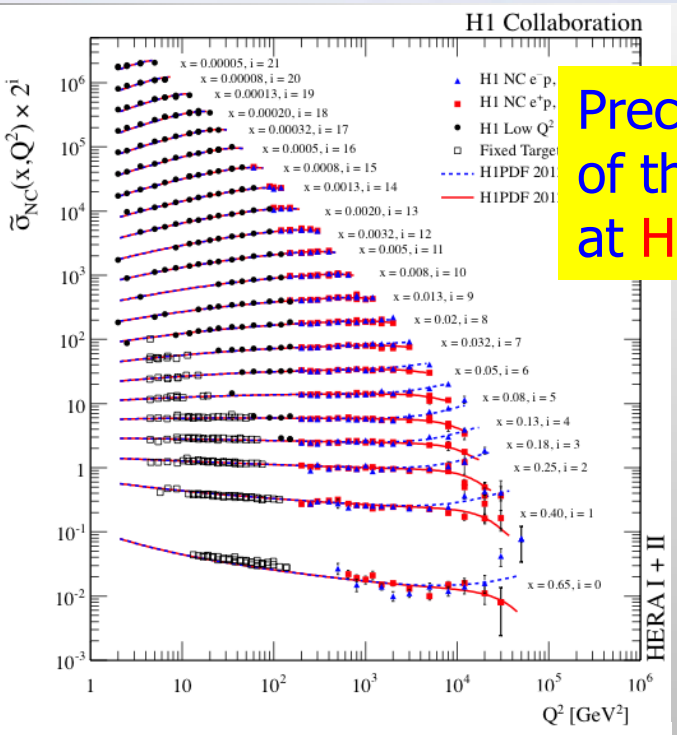
- Soft QCD Dynamics
  - Particle production & fragmentation
  - Correlations, possible new effects
  - Forward energy measurements
- Diffractions, events with rapidity gaps
  - Elastic, diffractive and total cross sections
  - Exclusive Higgs production?
- Perturbative QCD
  - Jet production
  - Jet substructure
  - Extraction of α_s
  - The structure of the proton
  - Low-x studies

6 out of 7 LHC experiments publish data on QCD topics…

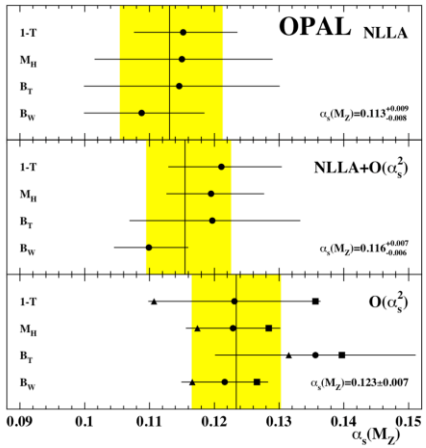
LHCb TOTEM ALICE LHCf ATLAS CMS

QCD at Recent Colliders

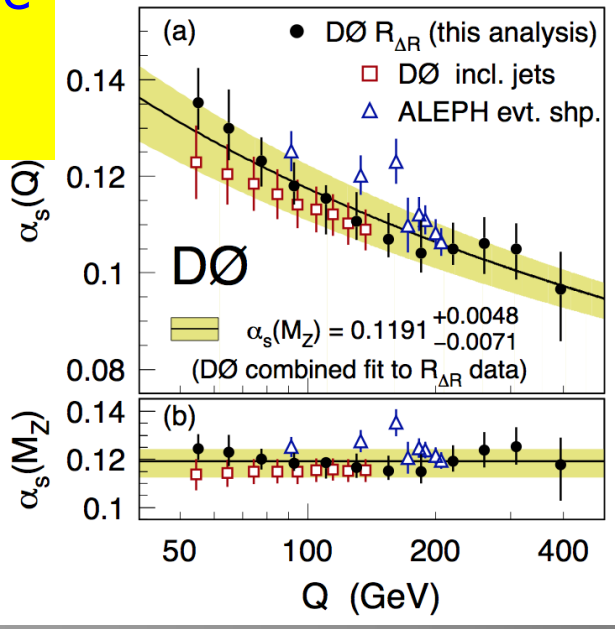
Precision measurements of the proton structure at HERA



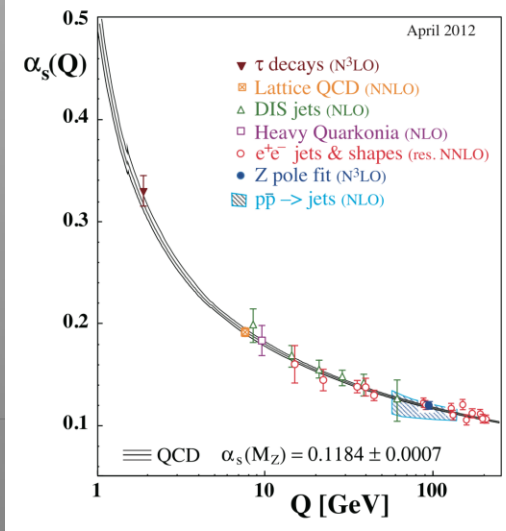
Precision measurements at the Z factory LEP



QCD studies at the hadron collider Tevatron



Summary on α_s Results

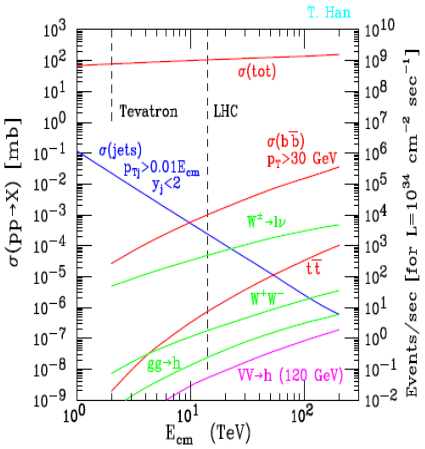


Soft QCD Dynamics

Understanding Soft Collisions

Most collisions at the LHC do not involve a hard scattering scale: these are so called soft collisions. They make up most of a "minimum bias" event sample

Scattering cross sections for various SM processes:

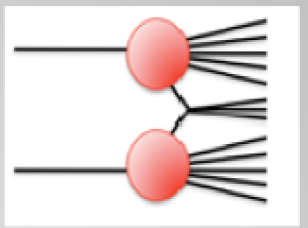


- Detailed studies of multi-particle production in pp
- Monte Carlos tunes, eg for describing the pile-up

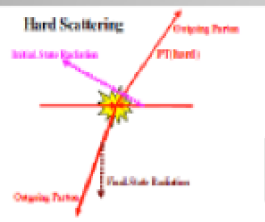
Pile-up 2012!!
Much more in 2015+

Event Types and Underlying Event

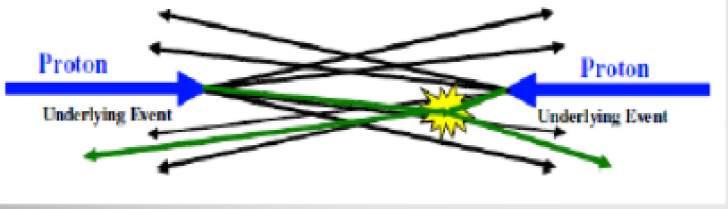
$$\sigma_{tot} = \sigma_{EL} + \sigma_{SD} + \sigma_{DD} + \sigma_{ND/HC}$$

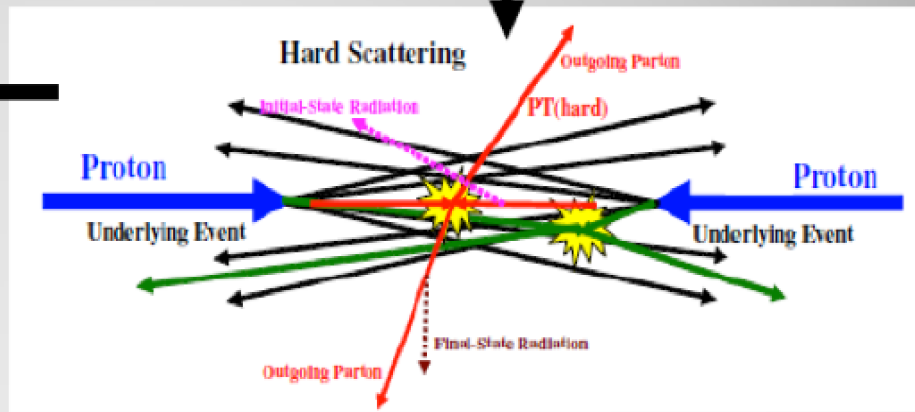


- Elastic Scattering
- Single diffraction
- Double diffraction
- Non-diffraction



Hard Scattering Component





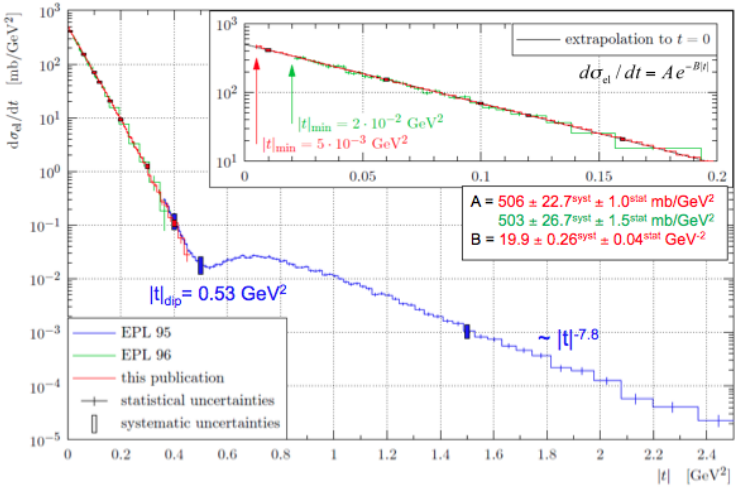
…Not always easy to classify individual events

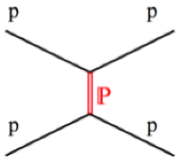
Elastic/Total pp Cross Section

TOTEM = Roman Pots + Forward Detectors
TOTEM uses the same IP as CMS (IP5)

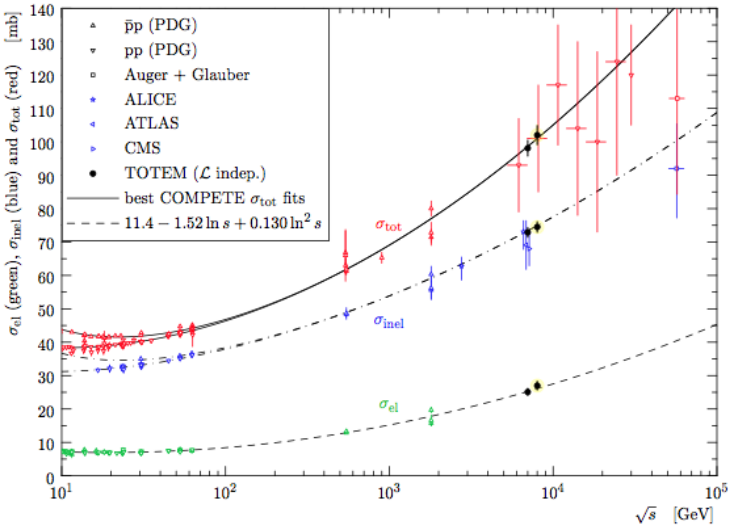
EPL 101 21004 (2003)

7 TeV elastic differential cross section





8TeV cross sections



$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{dN_{el}/dt\big|_0}{N_{el} + N_{inel}}$$

$$\sigma_{tot} = (101.7 \pm 2.9)mb$$

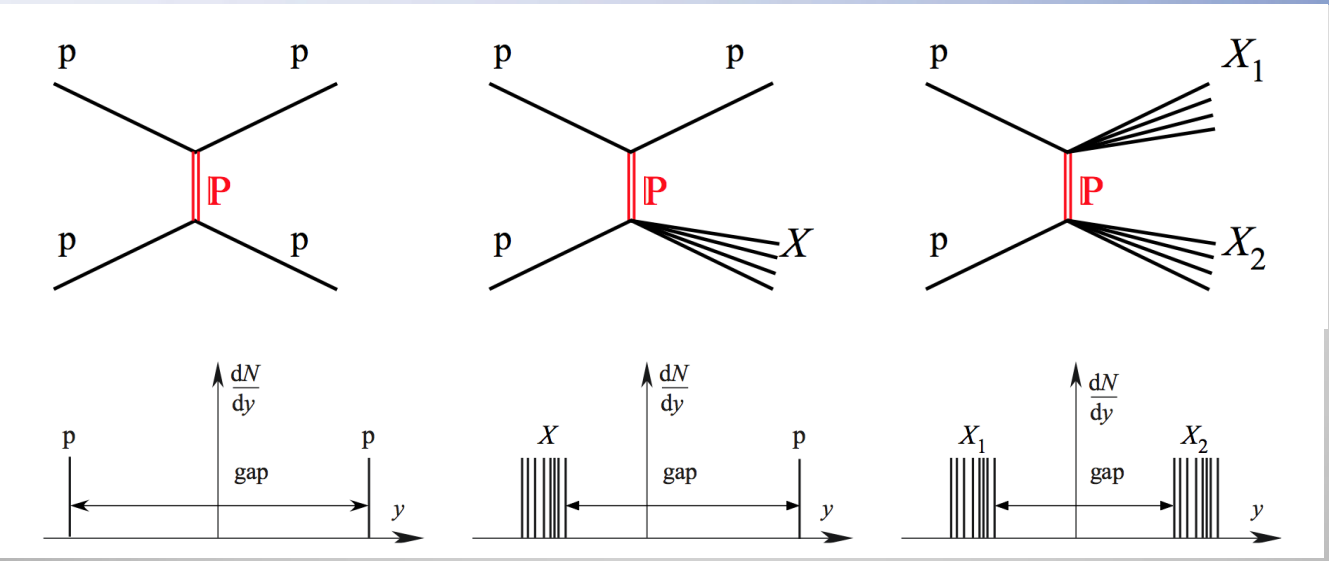
$$\sigma_{inel} = (74.7 \pm 1.7)mb$$

$$\sigma_{el} = (27.1 \pm 1.4)mb$$

Future: •High beta measurements for Coulomb-Nuclear interference, ALFA

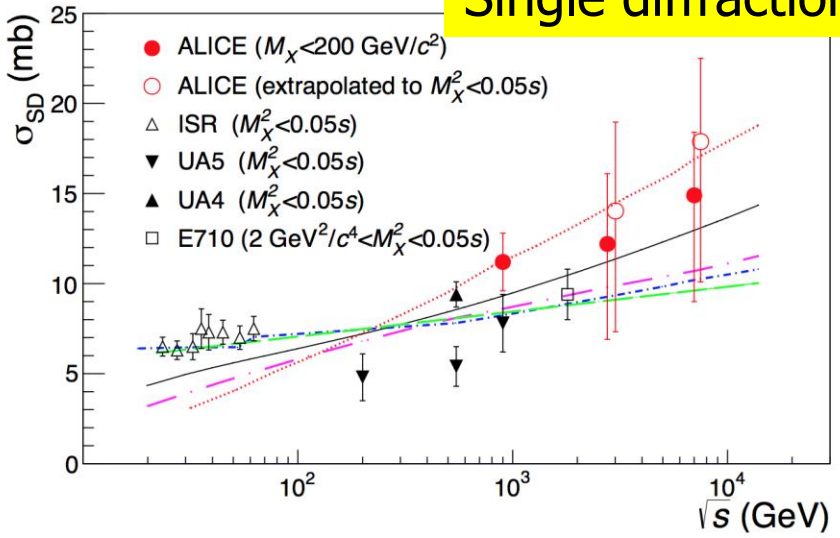
Q1: More precise EL/TOTAL data needed at lower energies, ie 2 TeV?

Diffractive Cross Sections

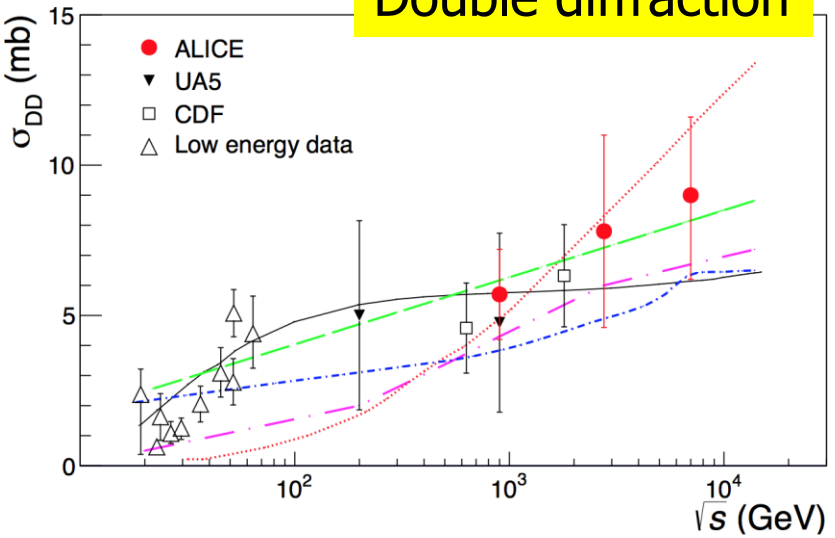


arXiv:1208.4968

Single diffraction



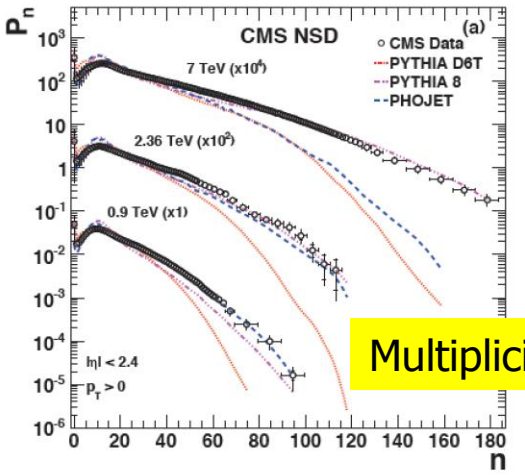
Double diffraction



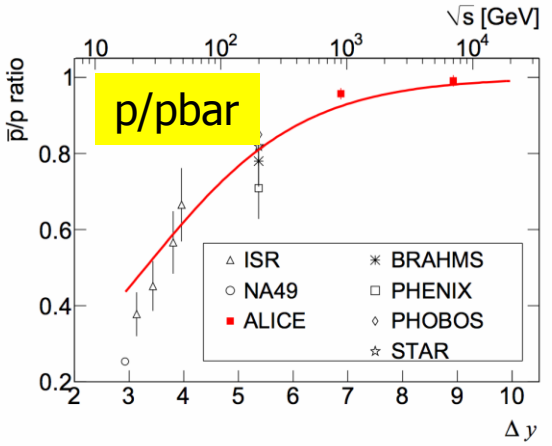
Q2: Importance of precise SD and DD measurements? (needs special run@HE)

Understanding Particle Production

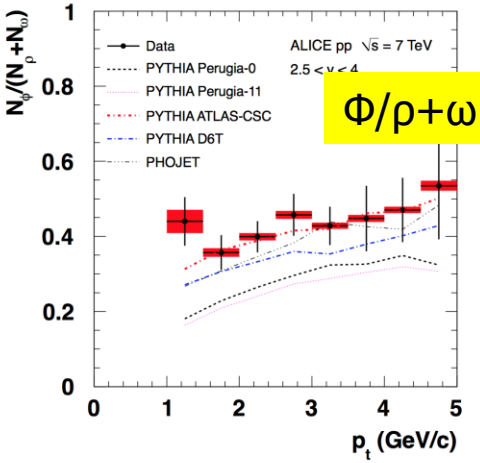
- Single particles, multiplicities etc. vs phenomenological models…
- LHC detectors are excellent and complementary for such studies



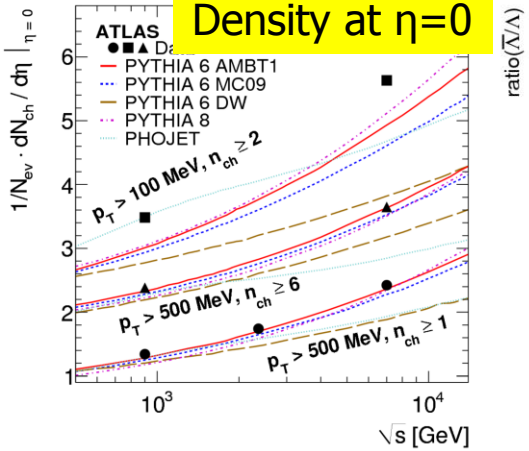
Multiplicities



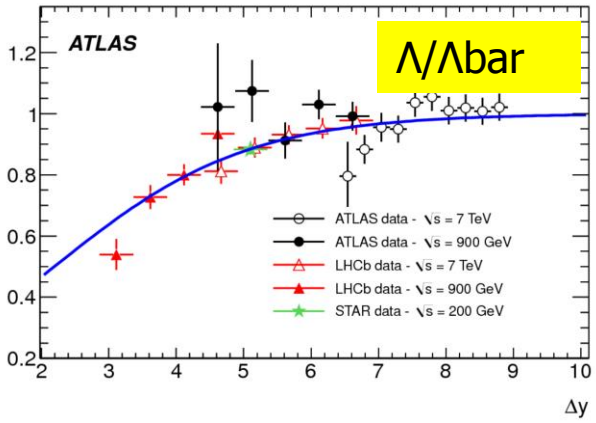
p/pbar



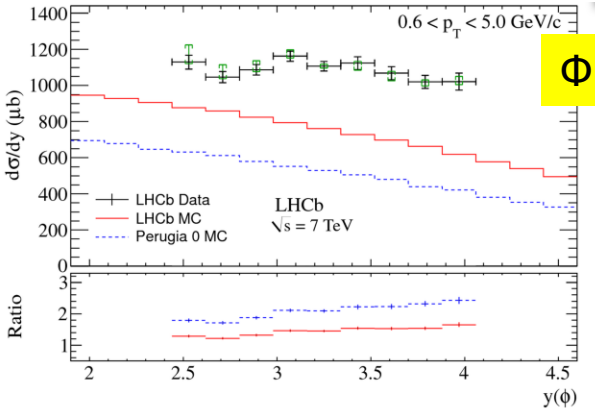
Φ/ρ+ω



Density at η=0



Λ/Λbar

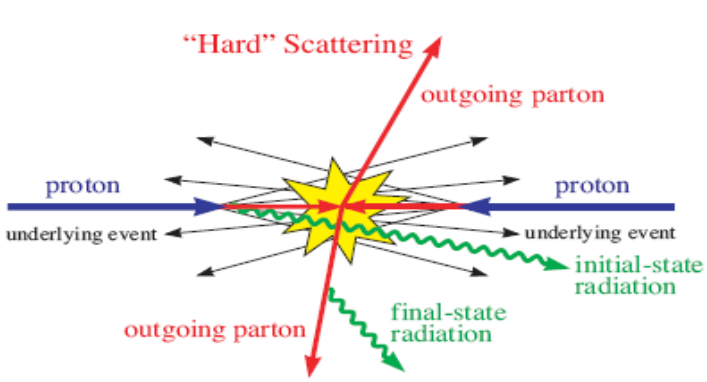


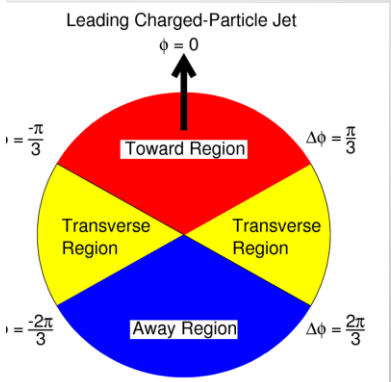
Φ

Q3: Should we organize a (or a few) more Universal Tunes of the MCs?

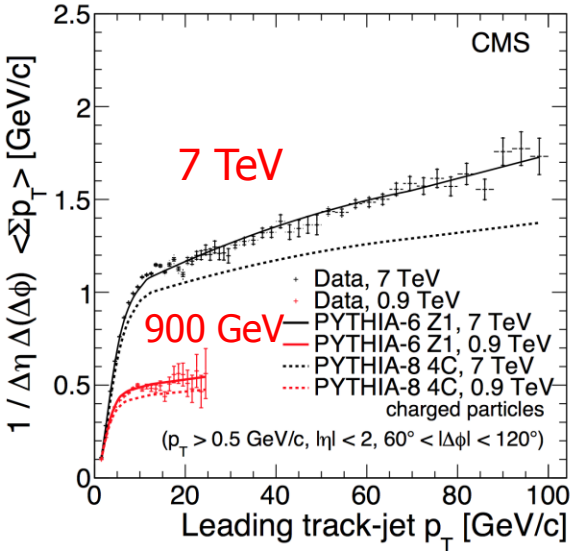
Underlying Event Studies

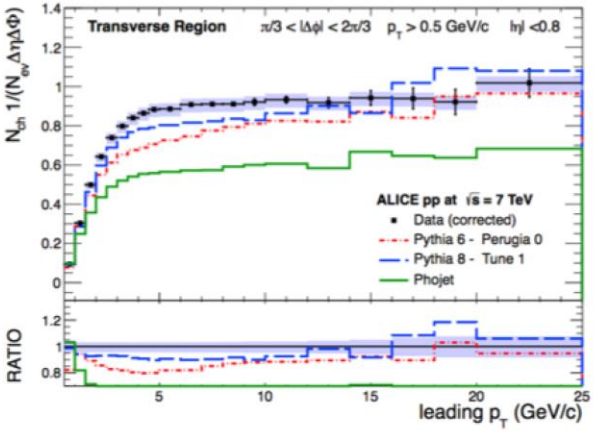
An important systematic effect for precision measurements, eg top mass
All central detectors have made measurements in the 'transverse' region:

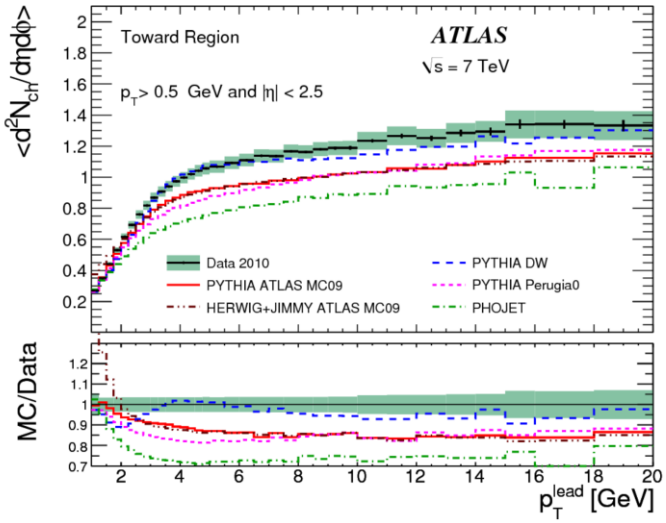




Measure the particle flow in transverse region as function of the hard scale





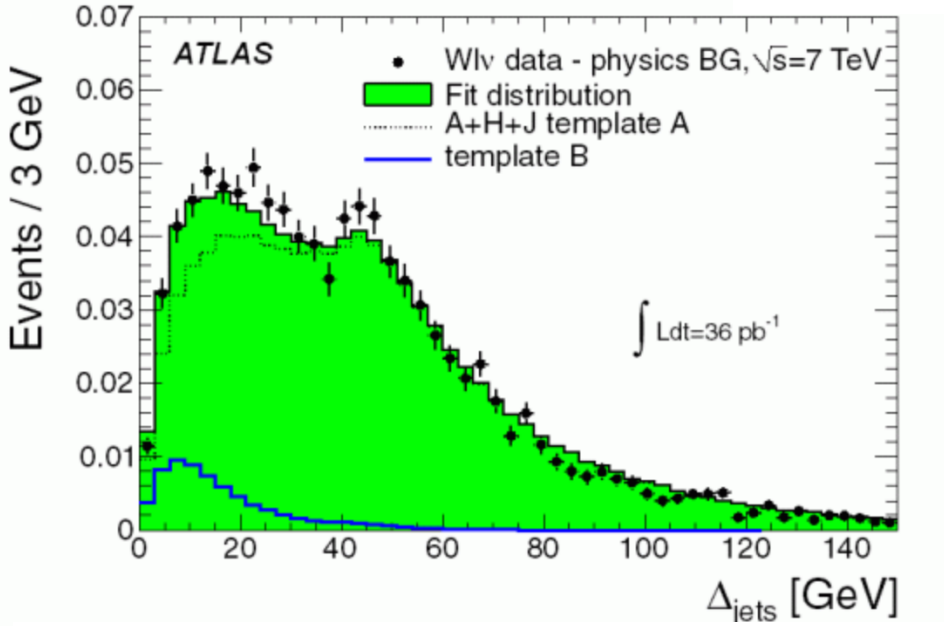


Q3: Should we organize a (or a few) more Universal Tunes of the MCs (bis)?

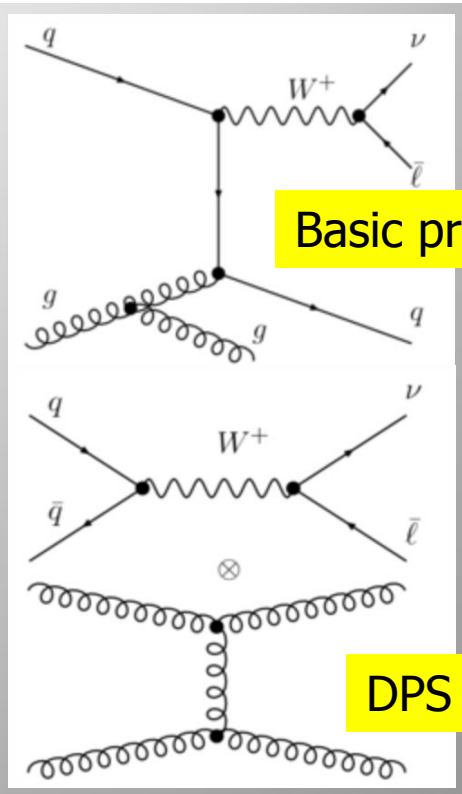
Double Parton Scattering

Example: angular correlations study of W+ 2jet events: The fraction of the cross section attributed to DPS= 0.08 ± 0.01 (stat.) ± 0.02 (sys.)

arXiv:1301.6872



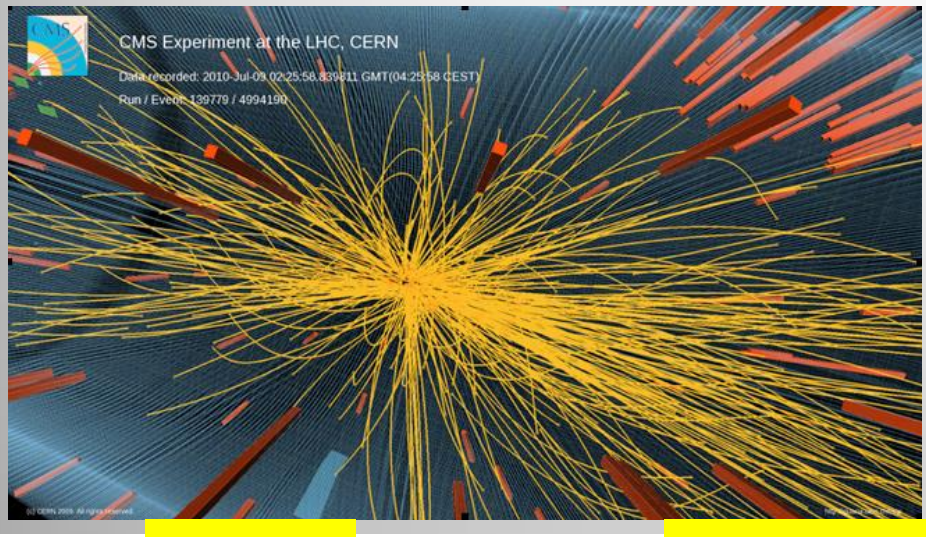
Difference between the transverse momenta of the two jets (p_T > 20 GeV)



DPS can be important for searches where after cuts only a few events remain…

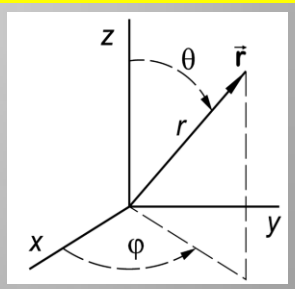
Q4: How well do we control DPS at the LHC energies?

Correlations Between Produced Particles



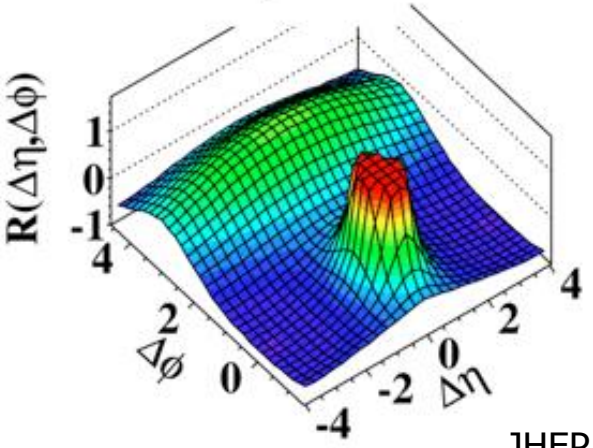
- Select high multiplicity events
- Study the correlation between two charged particles in the angles φ (transverse): Δφ and θ (longitudinal): Δθ

$\eta = -\ln \tan\theta/2$



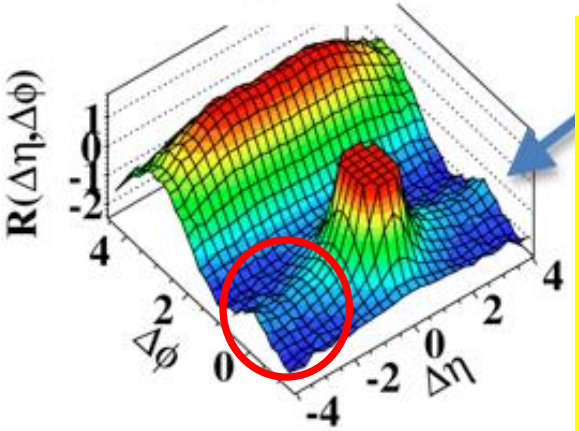
All events

MinBias, 1.0GeV/c<p_T<3.0GeV/c



High multiplicity events

N>110, 1.0GeV/c<p_T<3.0GeV/c



JHEP 1009 (2010) 091

A new phenomenon in the 'stronge force'?

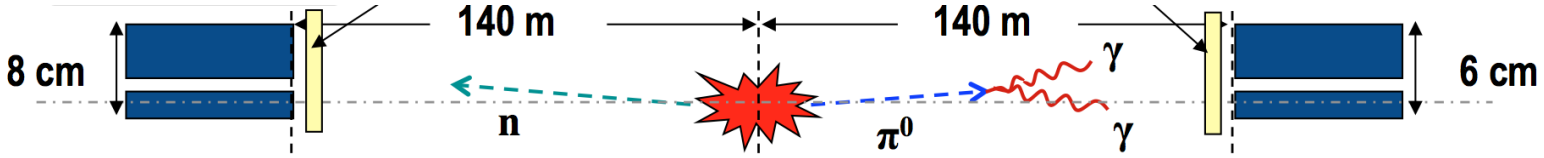
- Multiple interactions?
- Glass condensates?
- Hydrodynamic models?

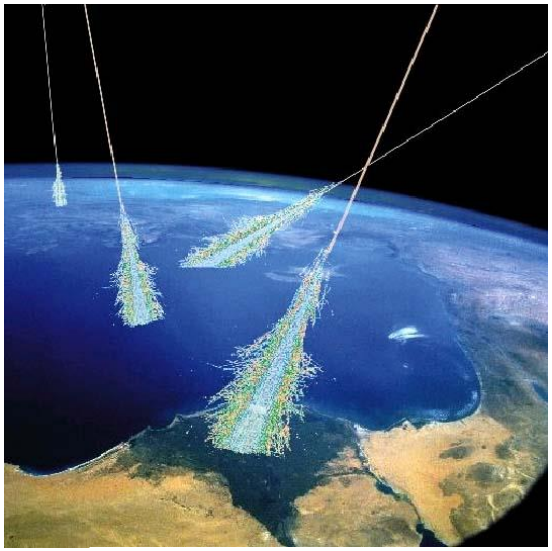
…

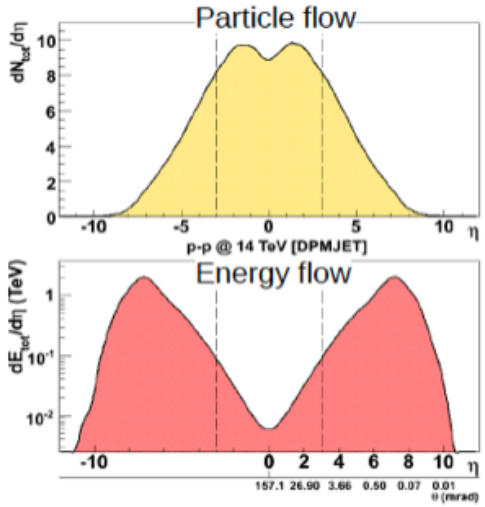
Q5: Understanding the "Ridge" in pp collisions? New/additional measurements?

Forward Particles Measurements

- LHCf uses the same Interaction Point as ATLAS (IP1)
- LHCf has forward detectors at zero degrees seen from the IP (140 away from the IP): Measure the forward photons/pions for cosmic ray studies







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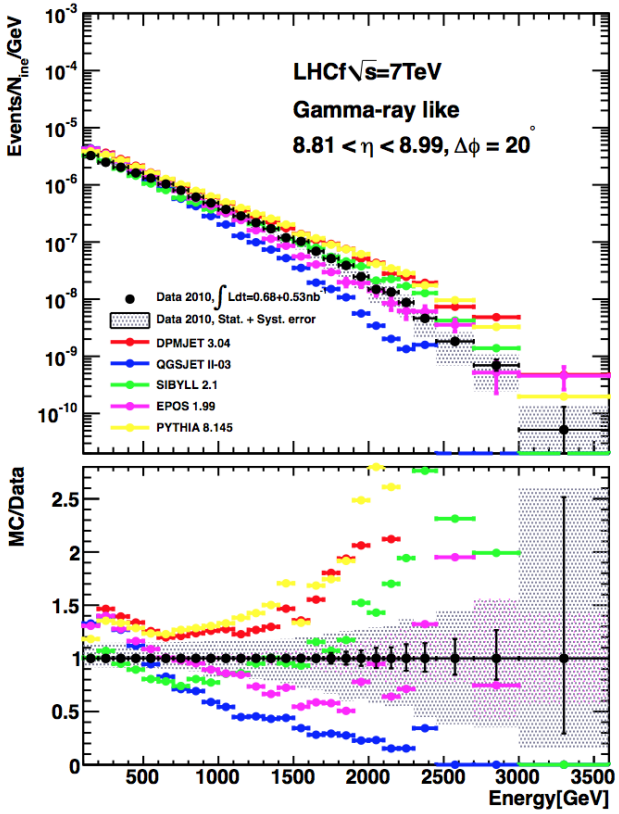


Forward gamma measurement compared to Monte Carlos for Cosmic Ray studies

No model reproduces the data well !!

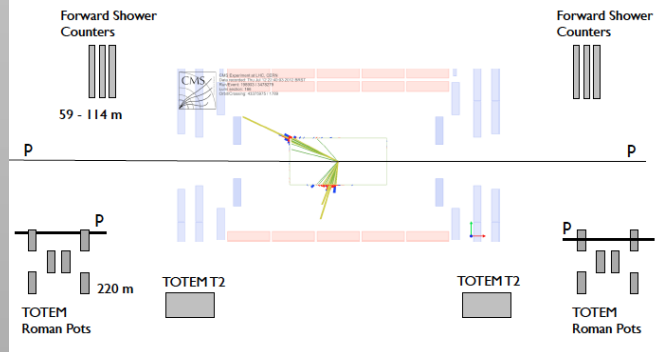
Q6: LHC data connection with cosmic rays?

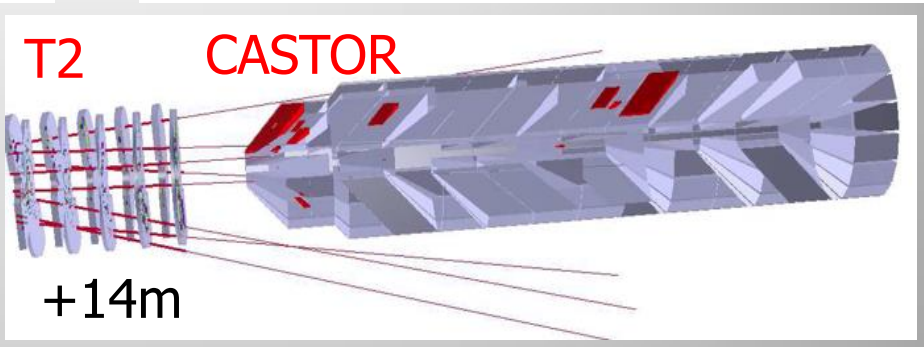
Future Option: CMS + TOTEM?

Since end of 2011: "Common data taking of CMS with TOTEM"

RP (TOTEM) + Central Di-jet (CMS)

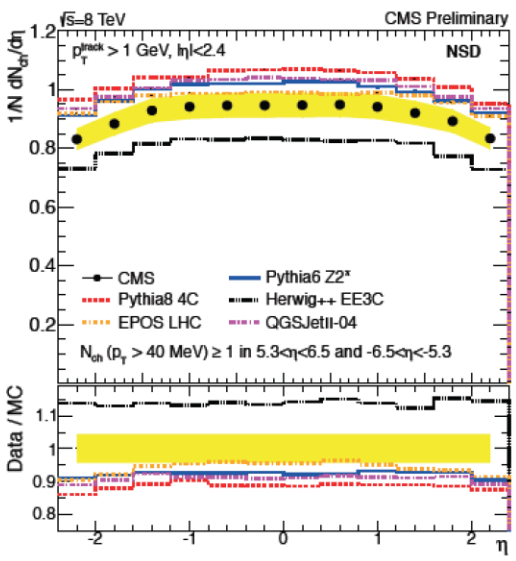
T2 (TOTEM) + CASTOR (CMS)

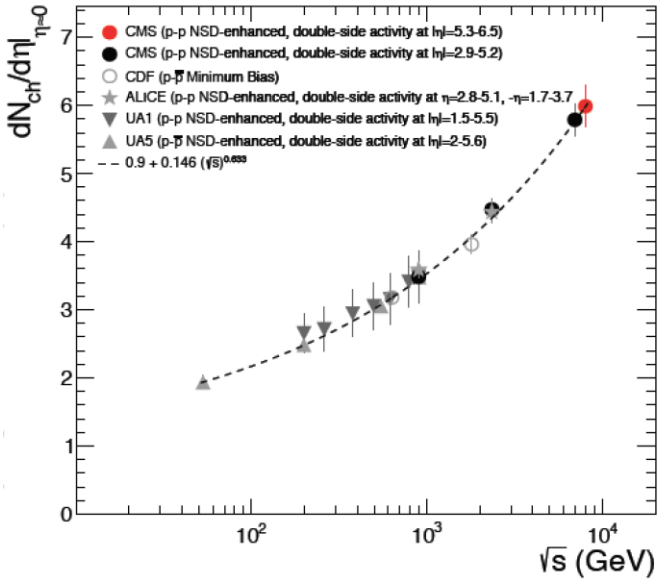


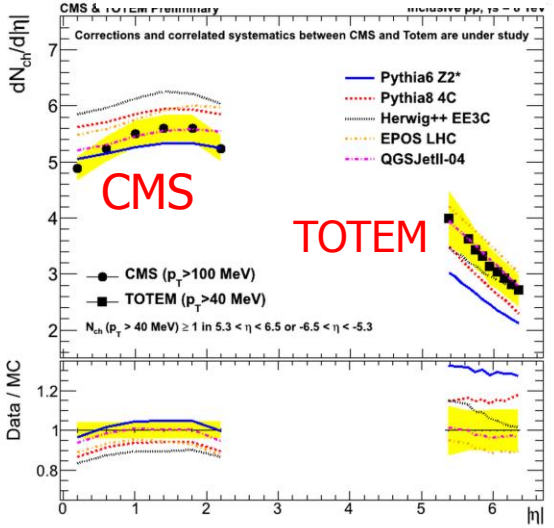


CMS central energy flow with TOTEM T2 tag

CMS PAS FSQ-12-026

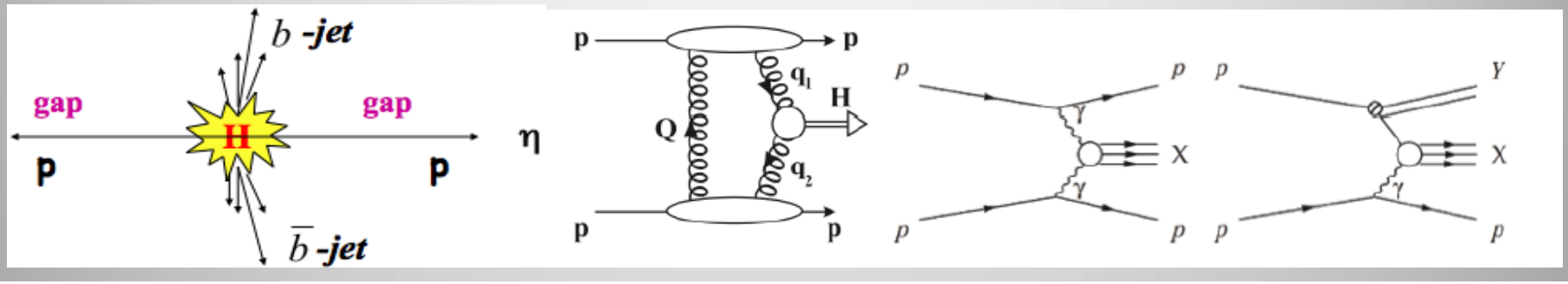




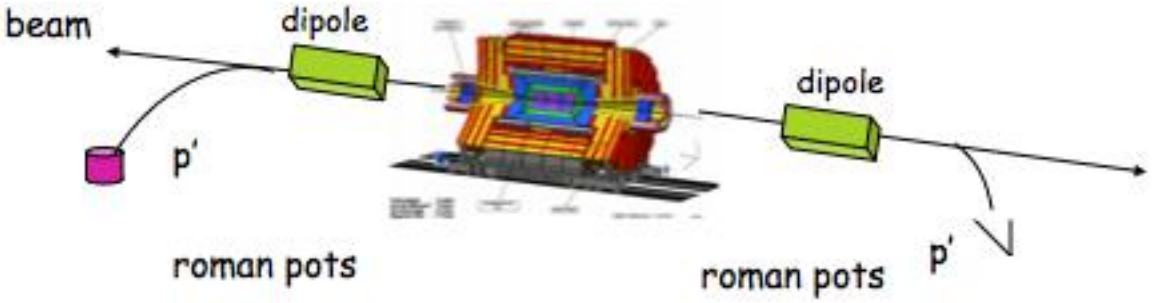


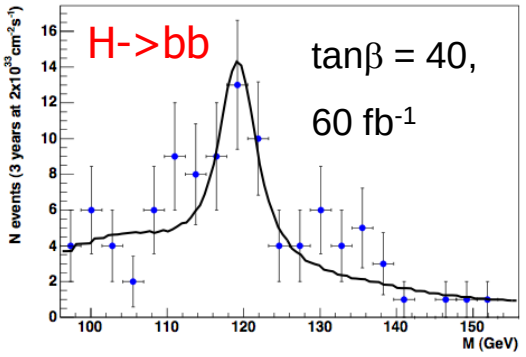
Exclusive Higgs Production

High Precision Spectrometer at 240/420m from the interaction point



$$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$$ ΔM = O(1.0-2.0) GeV



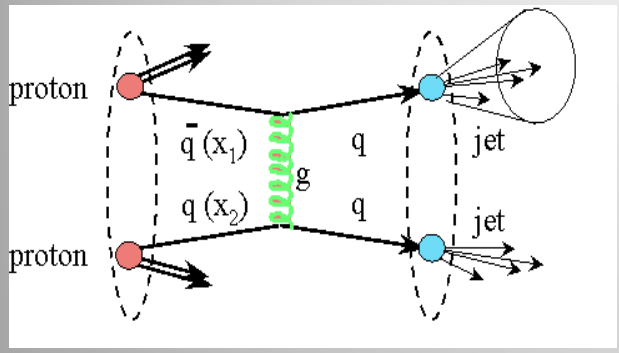


- H->bb decay with suppressed background
- Cross section ~ 10 fb (SM) to ~ 100 fb (MSSM)
- Mass resolution ~ 1-2% via protons
- CP analyzer via azimuthal pp correlations

Needs detectors at 240/420m
Discussed in ATLAS & CMS

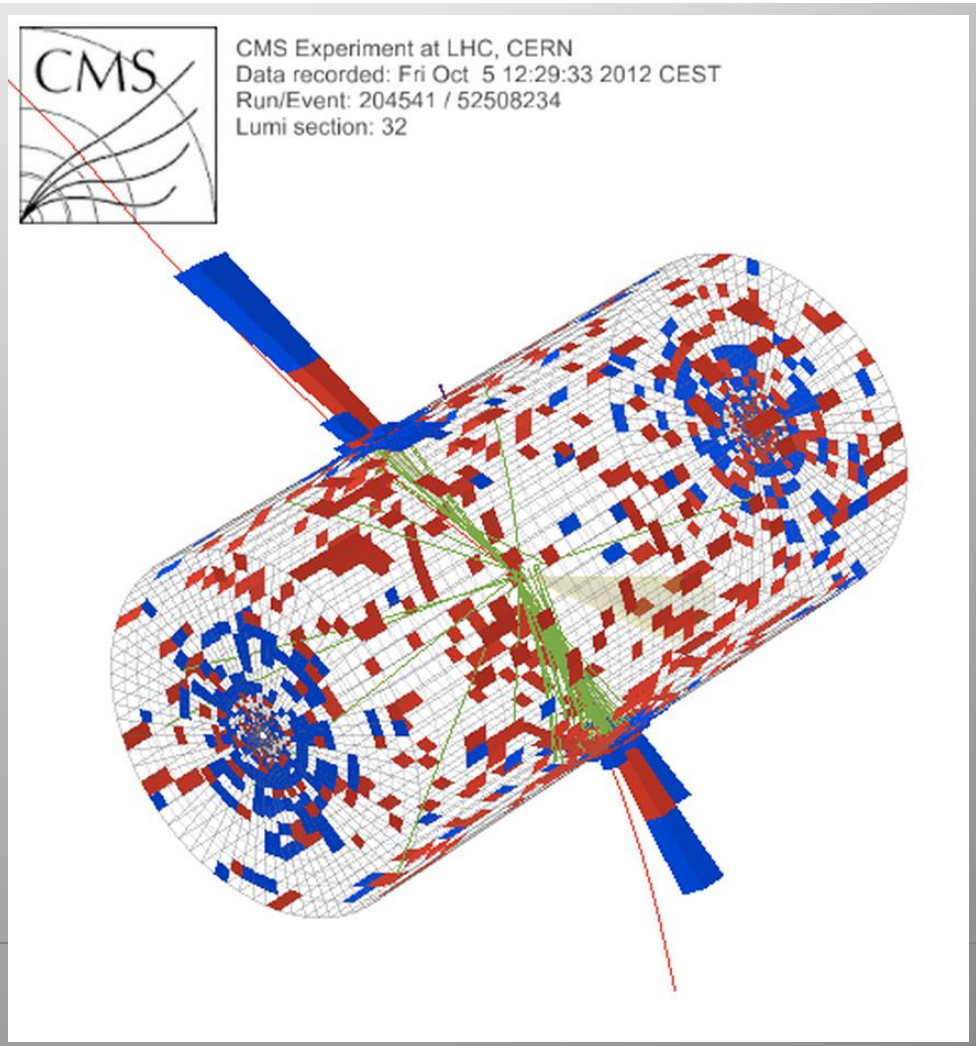
Hard Scattering
Perturbative QCD

Strong Interaction: Jets Production!



Study the strong force using jet production

Di-jet invariant mass = 5.15 TeV (R=1.1 jets)



Jets of particles emerge after a high energy parton-parton scattering

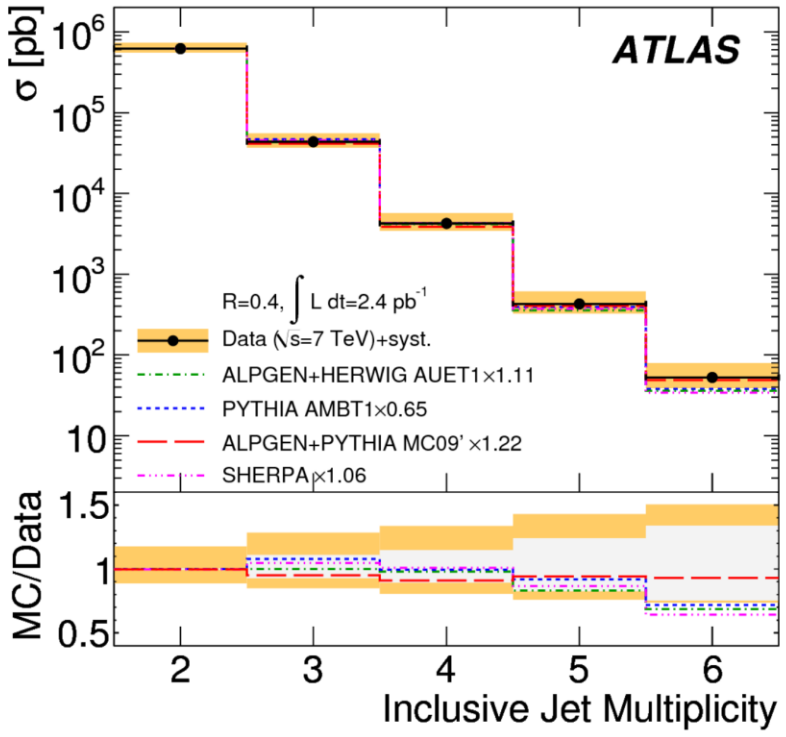
In this event more than 60% of the full proton-proton energy ends up in jets

Early Measurements of Multi-jets

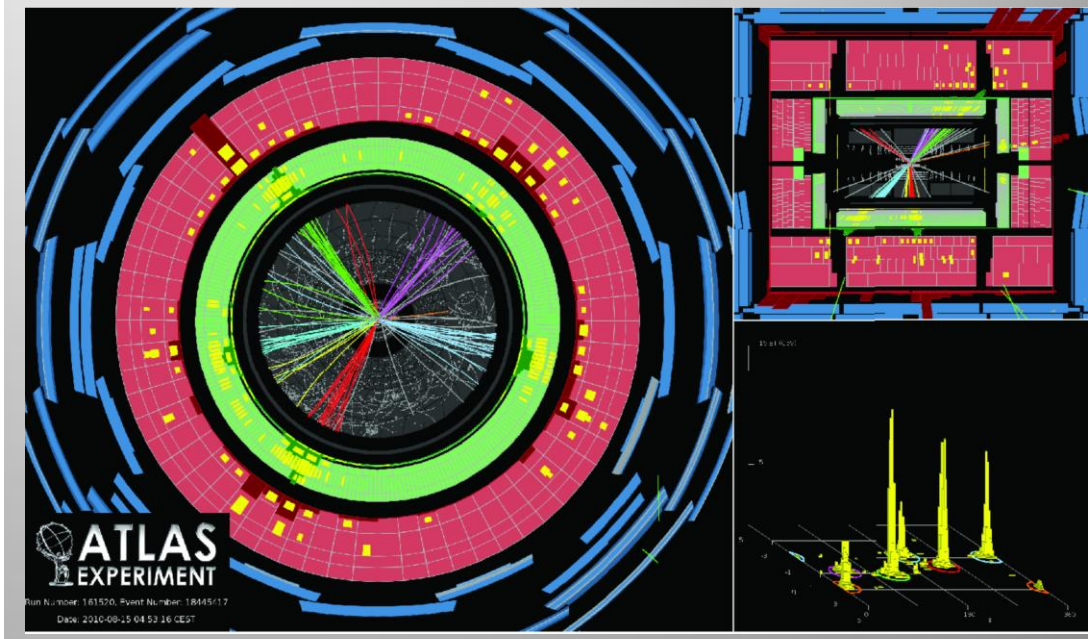
Early 2010 data…

Jet Multiplicity distribution

Eur.Phys.J. C71 (2011) 1763



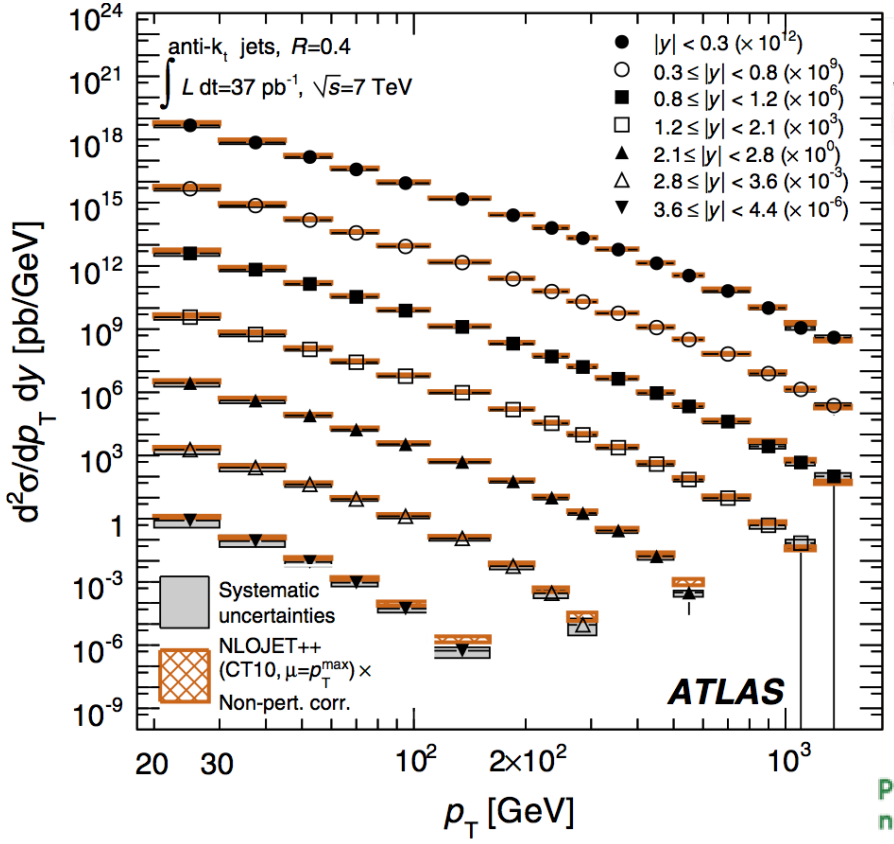
A six jet event



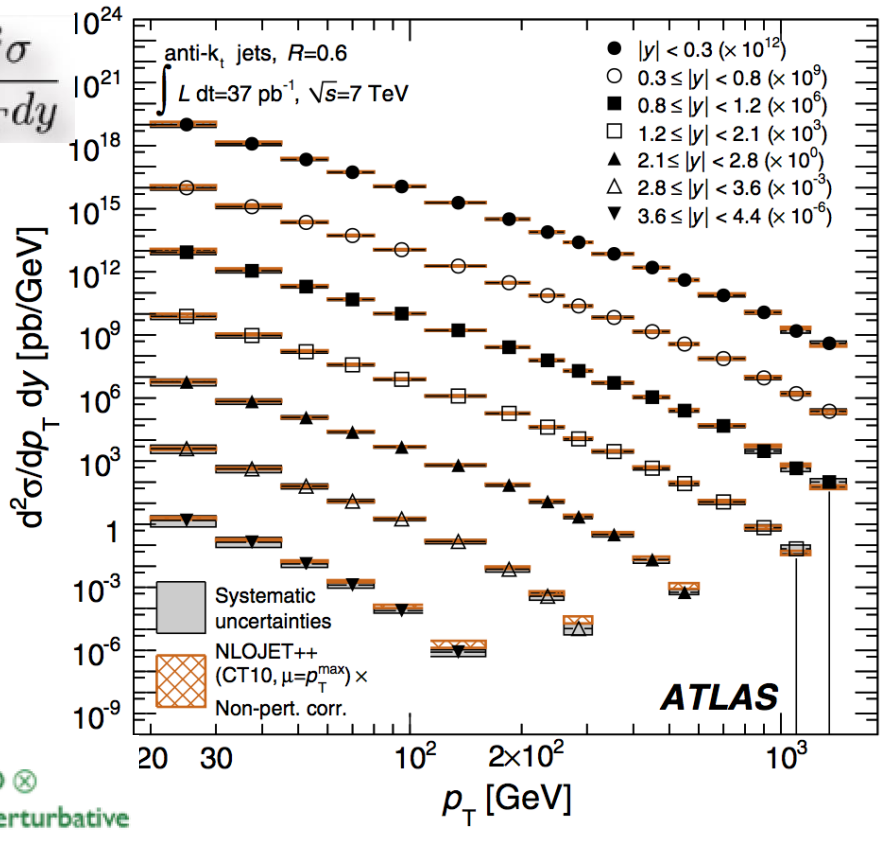
Multi-jet distribution in good agreement with theory - LO matrix elements plus matched parton showers - apart from normalization

Inclusive Jet Production (7 TeV)

Phys.Rev. D86 (2012) 014022



$$\frac{d^2\sigma}{dp_T dy}$$



pQCD ⊗ non-perturbative corrections

Agreement with NLO calculations over the full range, up to 2 TeV jets

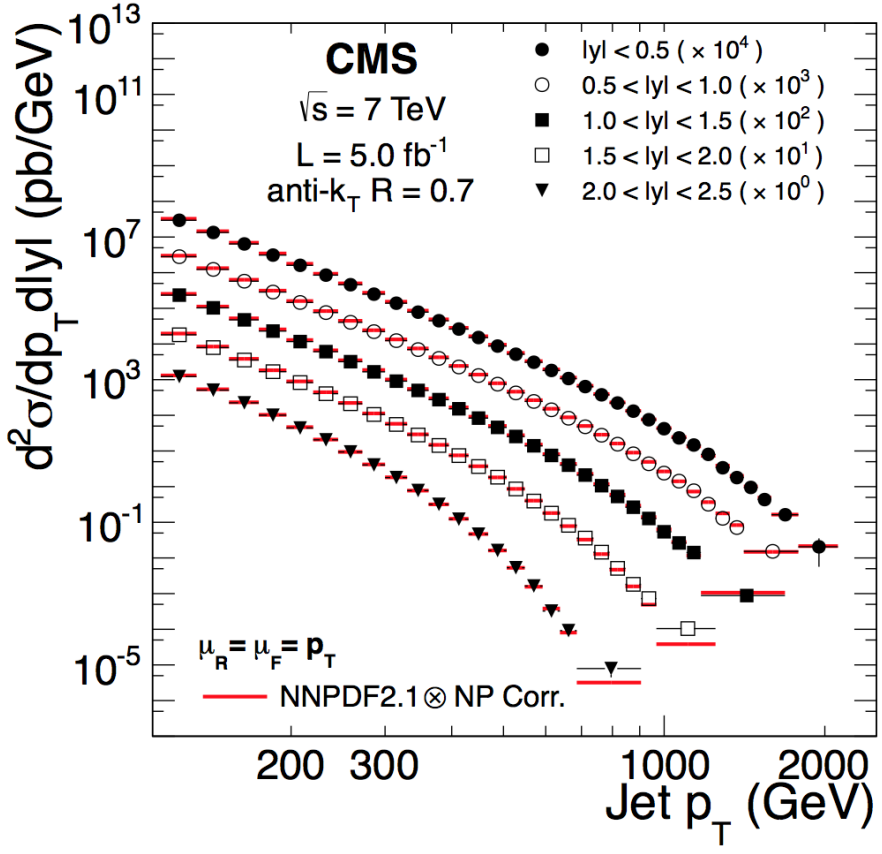
The anti-kT jet algorithm is used in most studies. The 'cone' chosen for this algorithm is different for ATLAS and CMS -> no direct comparison possible

ATLAS uses R=0.4 and R=0.6

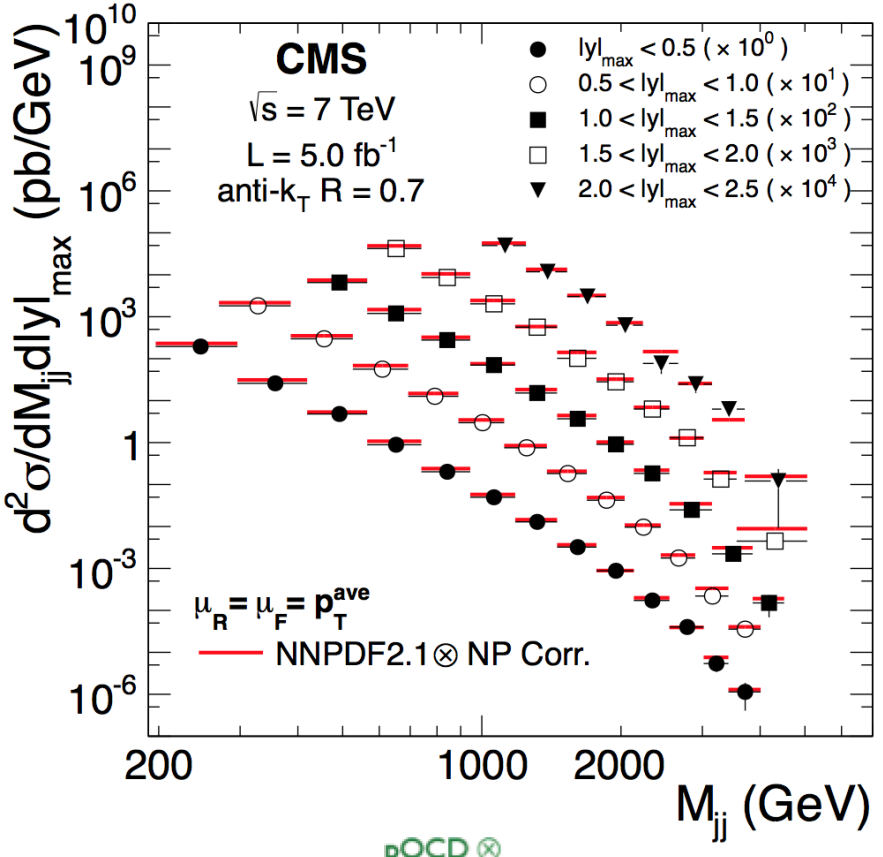
Inclusive Jet Production (7 TeV)

arXiv:1212.6660

$$\frac{d^2\sigma}{dp_T dy}$$



$$\frac{d^2\sigma}{dM_{JJ}d[|y|_{max}, y^*]}$$



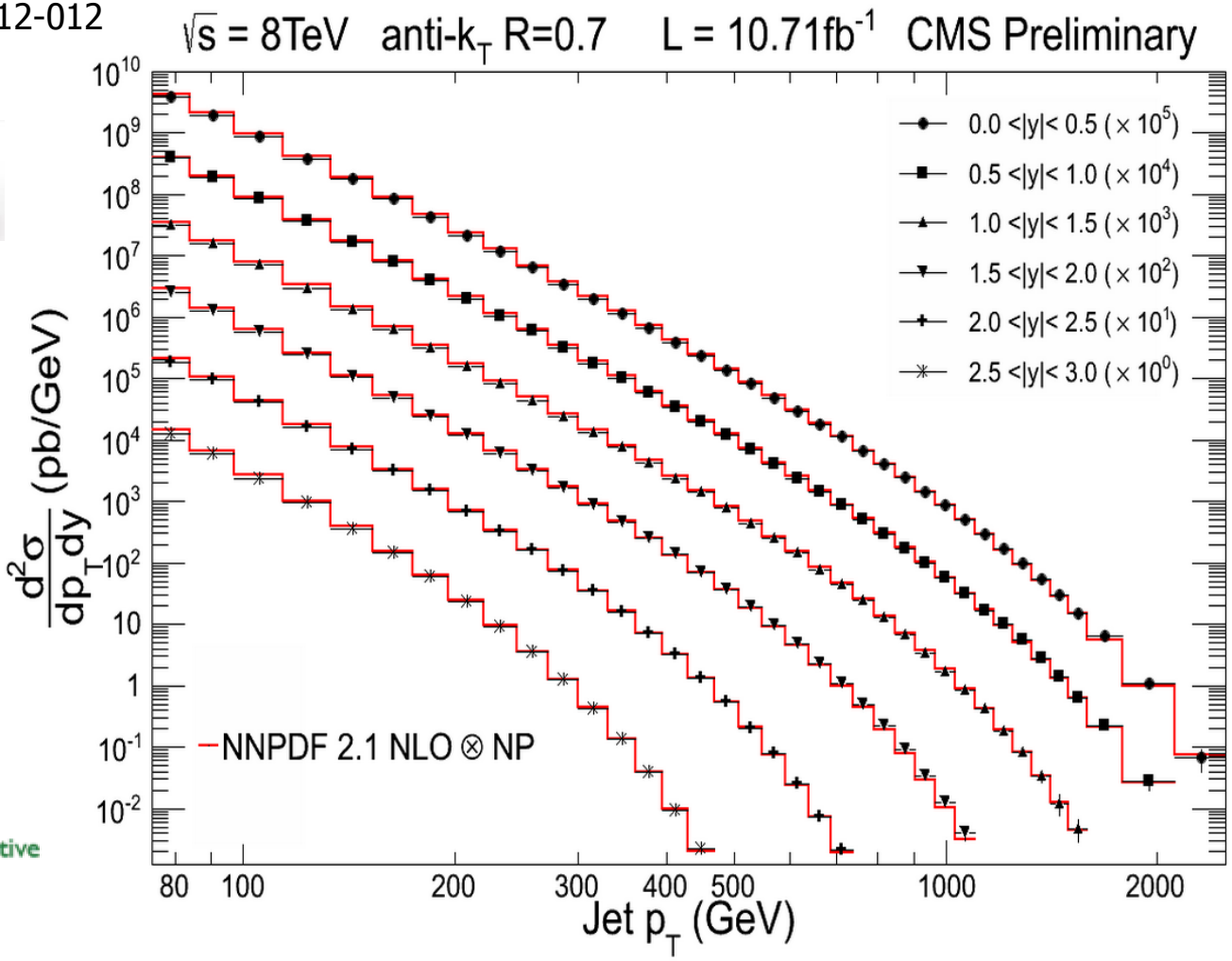
pQCD ⊗ non-perturbative corrections

...and CMS uses R=0.5 and R=0.7...

Q7: Can we convince the experiments to use the same R in future studies...?

Inclusive Jet Production (8 TeV)

CMS-PAS-SMP-12-012



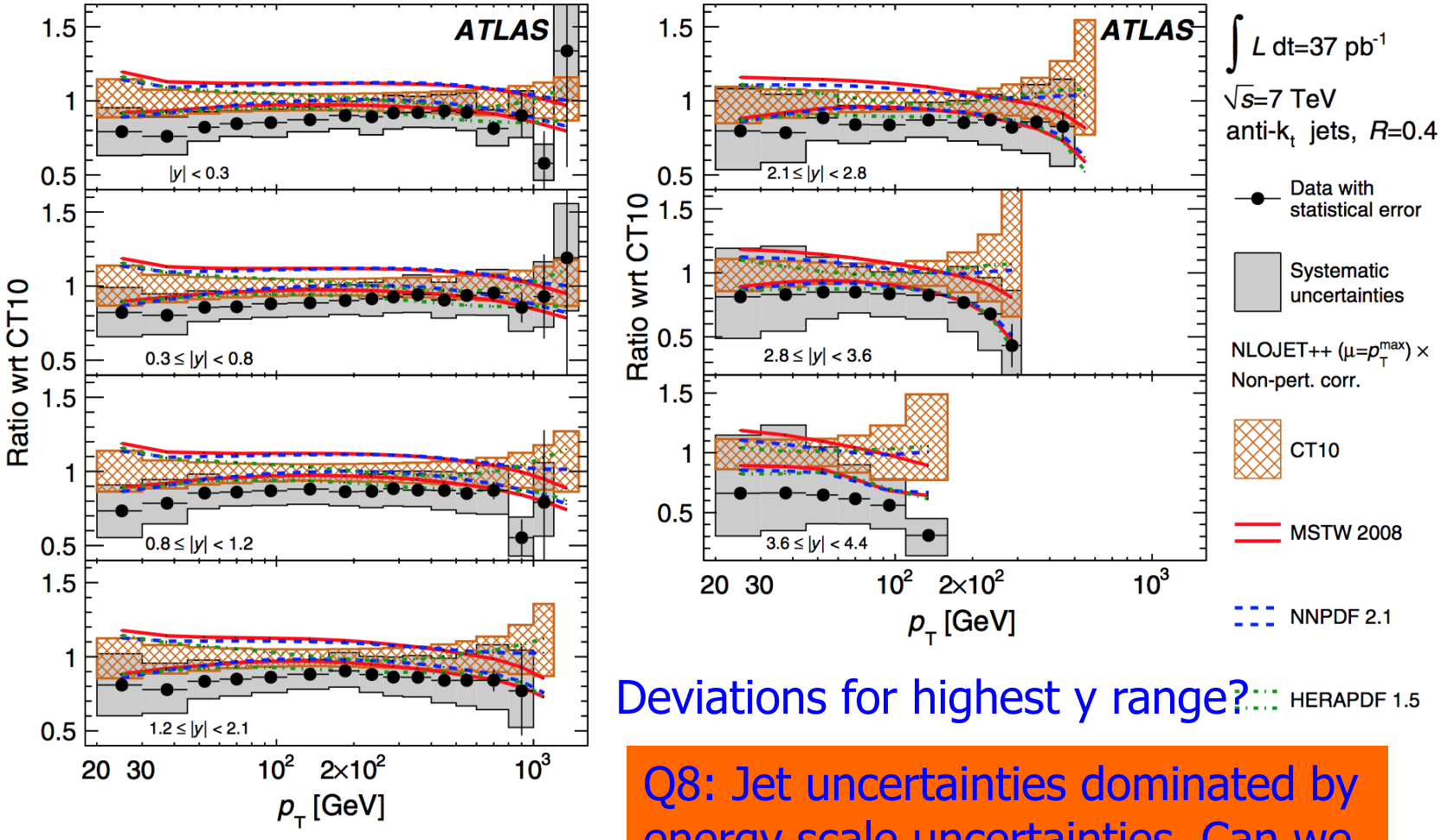
$$\frac{d^2\sigma}{dp_T dy}$$

pQCD ⊗
non-perturbative
corrections

Agreement with NLO calculations over the full range, up to and beyond 2 TeV jets

Inclusive Jet Production

Comparison with NLO calculations with the data in some detail, for different proton structure function parameterizations.

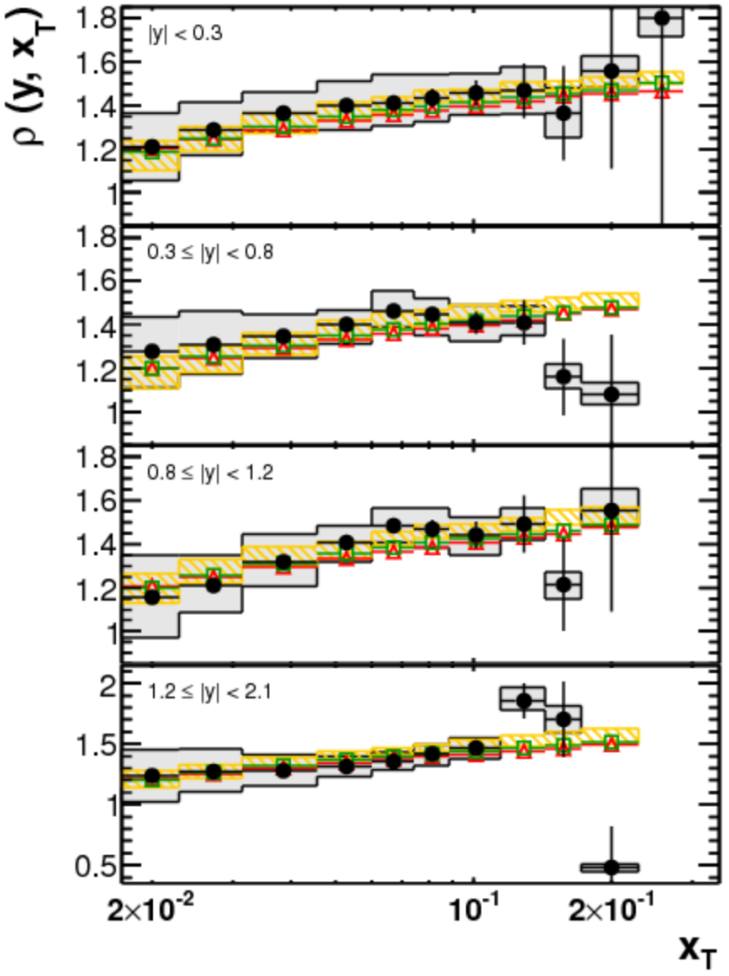


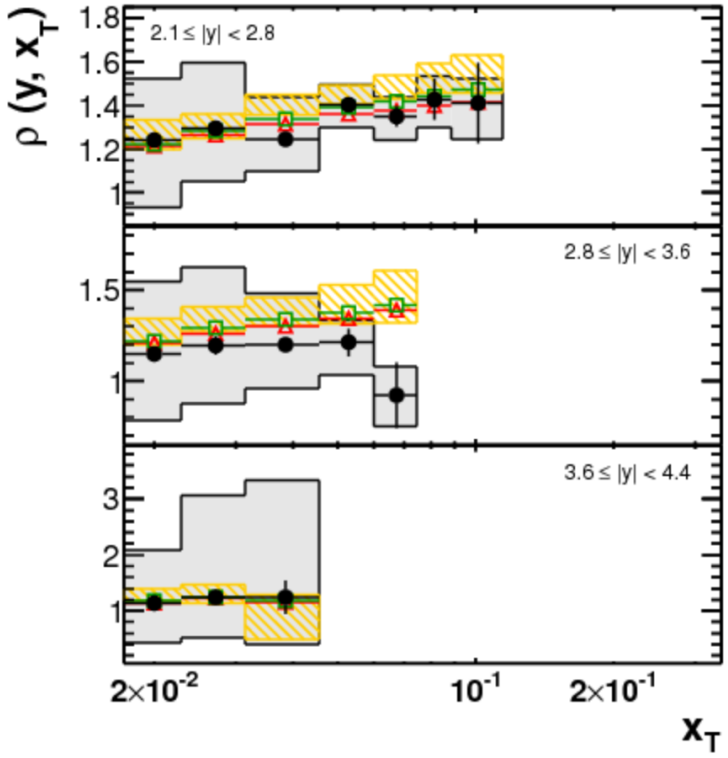
Deviations for highest y range?

Q8: Jet uncertainties dominated by energy scale uncertainties. Can we improve experimentally?

Jets Measurements at Two Energies

Data from proton-proton collisions at 2.76 TeV and 7 TeV





ATLAS

$\int L\,dt = 0.20\ \text{pb}^{-1}$

$\rho = \left[\frac{2.76\text{TeV}}{7\text{TeV}}\right]^3 \frac{\sigma_{\text{jet}}^{2.76\text{TeV}}}{\sigma_{\text{jet}}^{7\text{TeV}}}$

anti-k_t R = 0.4

- Data with statistical uncertainty
- Systematic uncertainties
- NLO pQCD ⊗ non-pert. corr. (CT10, $\mu=p_T^{max}$)
- POWHEG ⊗ PYTHIA tune AUET2B (CT10, $\mu=p_T^{Born}$)
- POWHEG ⊗ PYTHIA tune Perugia 2011 (CT10, $\mu=p_T^{Born}$)

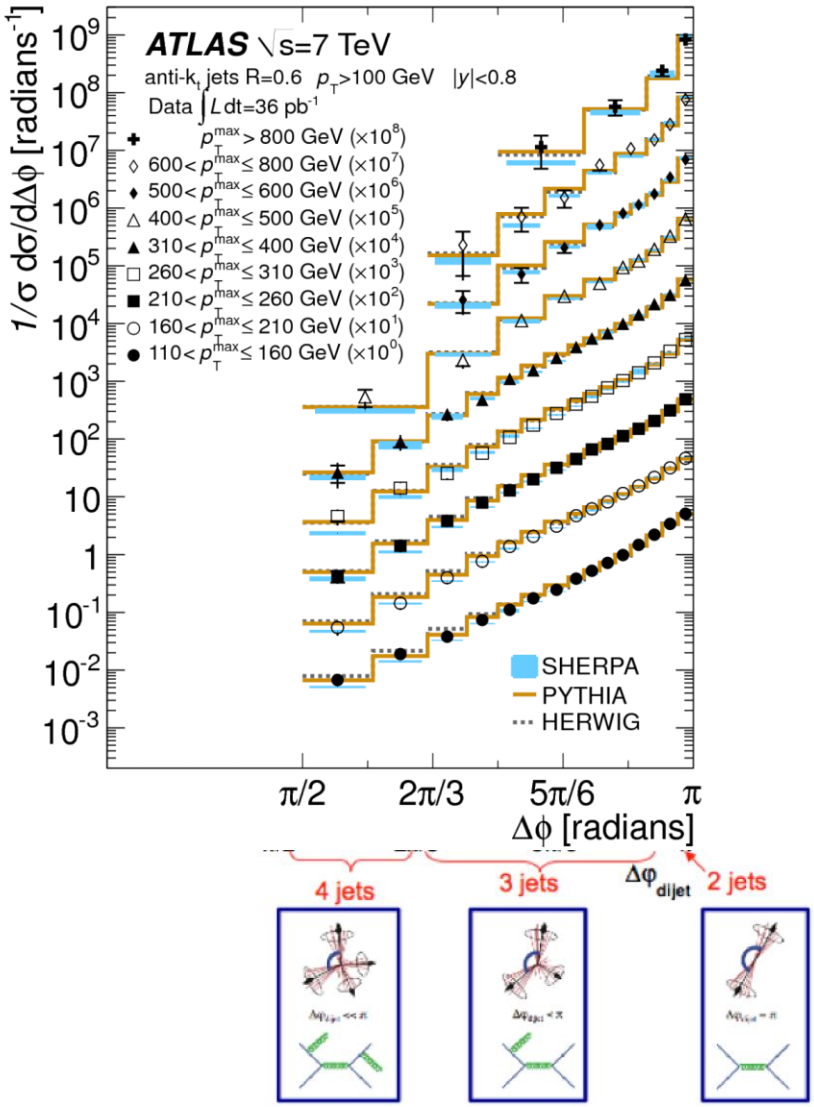
$$x_T = 2p_T/\sqrt{s}$$

arXiv:1304.4739

Some systematics ~ cancel in the ratio

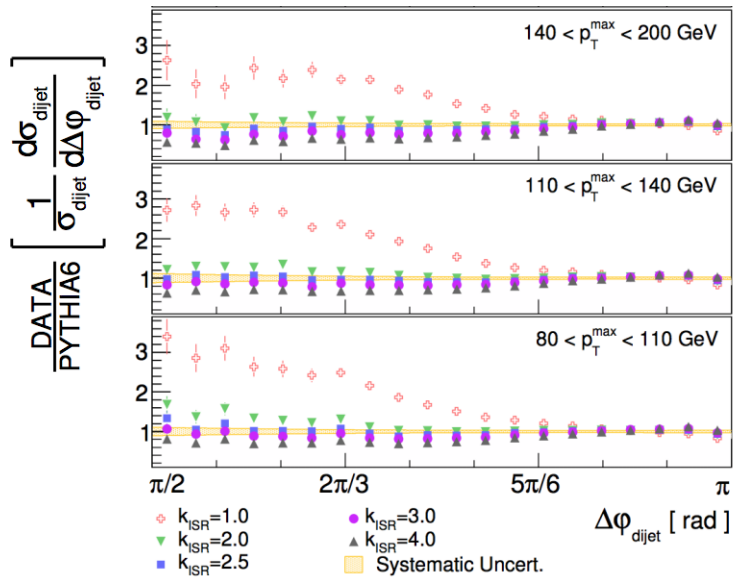
Azimuthal Correlations Between Jets

PRL 106 (2011) 172002



Azimuthal correlations between the two most leading jets are sensitive to the QCD radiation in the event, both initial and final rad.

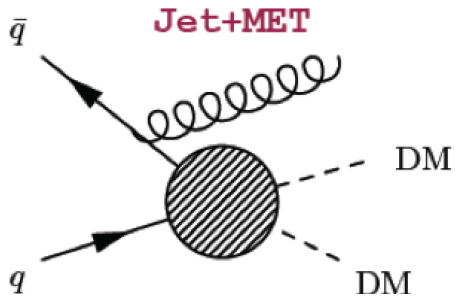
PRL 106 (2011) 172002



Initial state radiation (ISR) became very important for certain searches at the LHC!!

The Dark Matter Connection

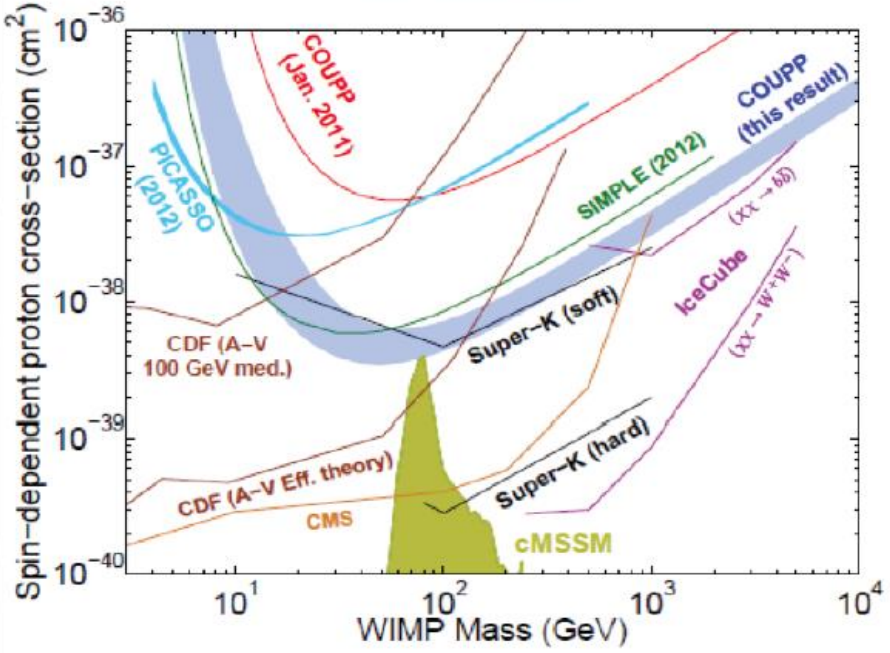
Searches for mono-jets (mono-photons) can be used for
Direct searches for Dark Matter (DM)
-> Spin dependent and spin independent cross sections of DM with matter



Effective contact interaction approach

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

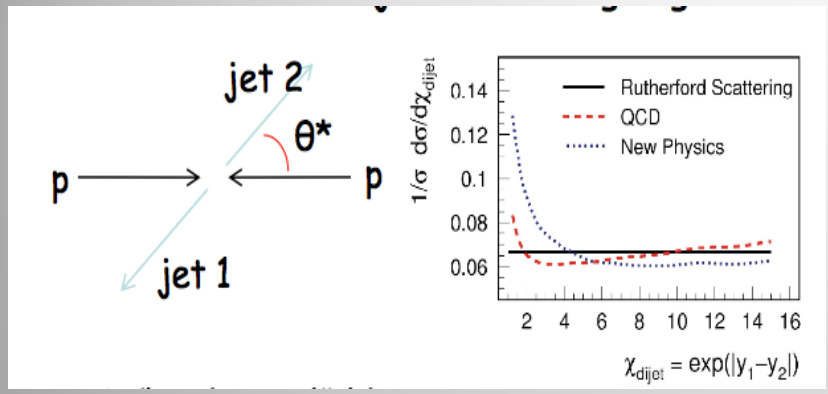


Collider searches are very competitive!!

Similarly some SUSY searches with compressed spectra rely on ISR, for the for trigger: AMSB with semi-stable gauginos arxiv:1202.4847 (ATLAS)

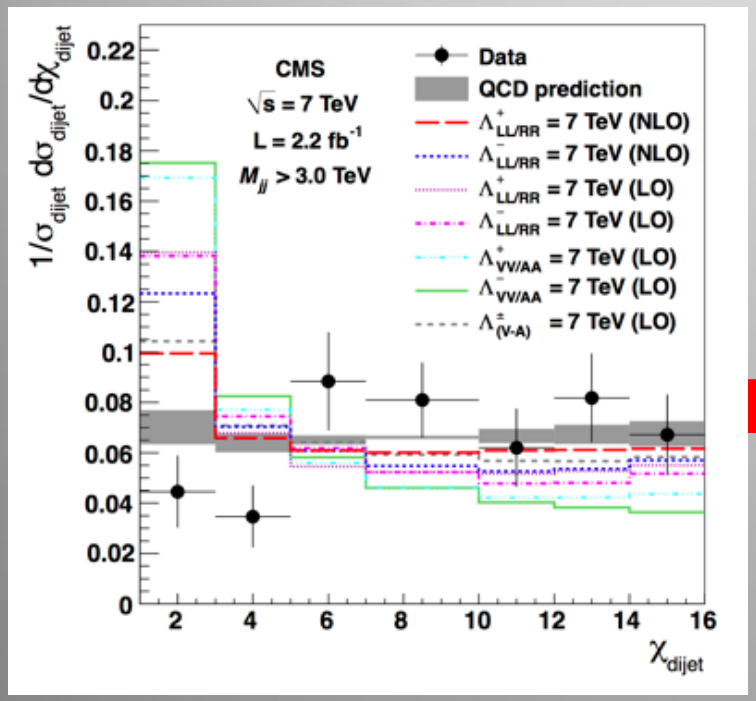
Q9: Do we control ISR well enough so that we can rely on it for searches?

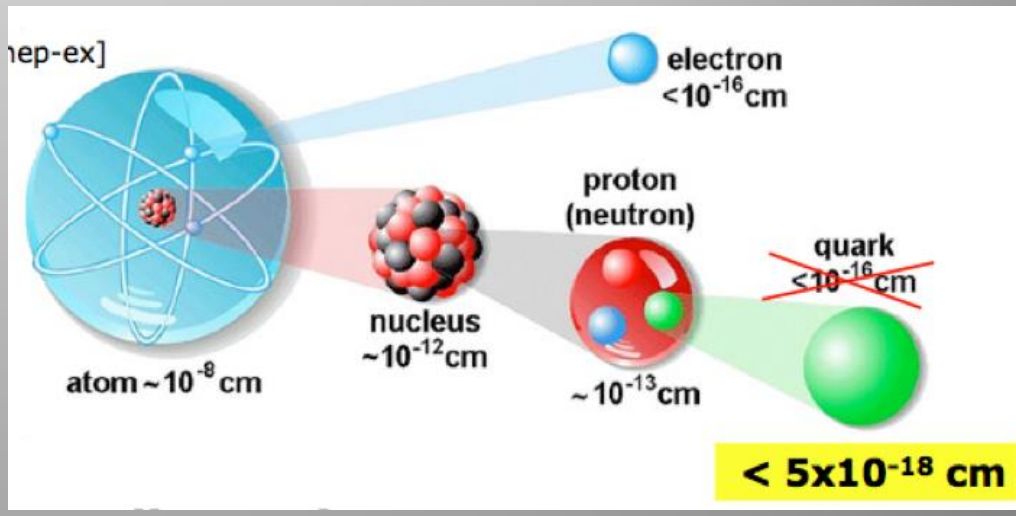
Are Quarks Elementary Particles?



Measurement of the production angle of the jet with respect to the beam
→ High Energy Rutherford Experiment

$$\chi = \exp(2y^*)$$
$$= \exp(|y_1 - y_2|) = \frac{1 + |\cos\Theta^*|}{1 - |\cos\Theta^*|}$$

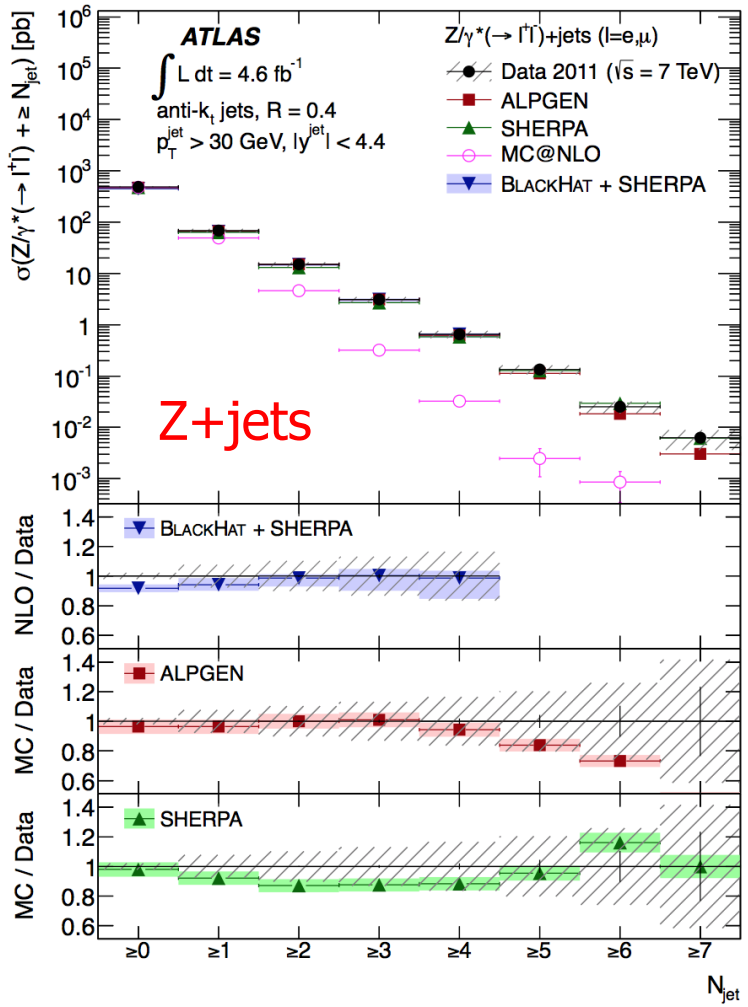




Quarks remain elementary particles after these measurements

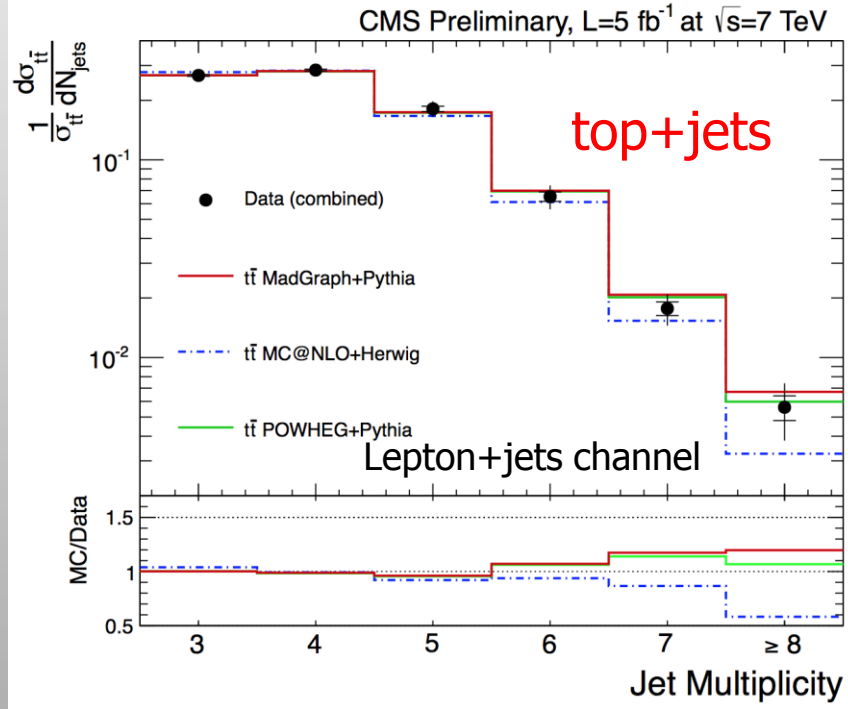
Vector Boson+Jets and Top+Jets

arXiv:1304.7098



High statistics and precision at the LHC allows for W/Z+jets and top+jets studies

CMS-PAS-12-018



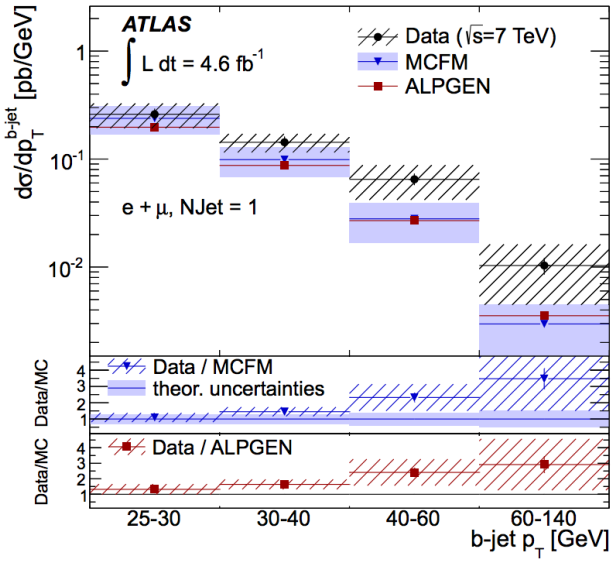
Good description by theory for both processes

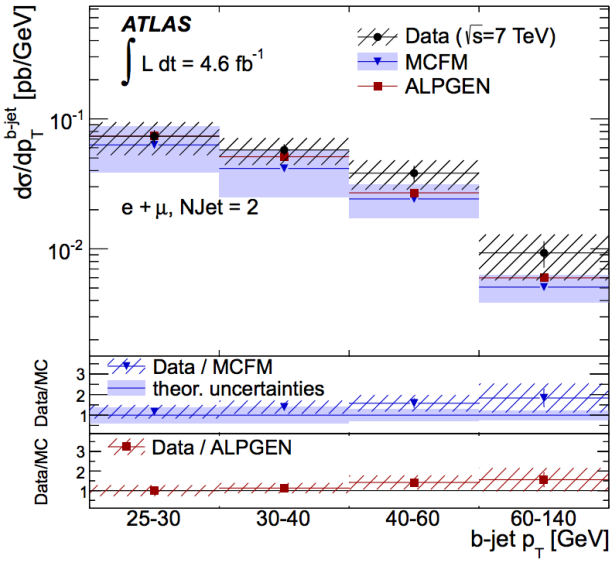
Important backgrounds for searches, eg for SUSY searches

Z,W + b-jet Production

W+b jets

arXiv:1302.2929





Excellent b-tagging in the experiments allows for further more sophisticated measurements such as associated b-jet production

Also Z+b results

W+1 b-jet cross section on the high side
W+2 b-jets cross section agrees with prediction

Gluon splitting issues?

Z+b jets

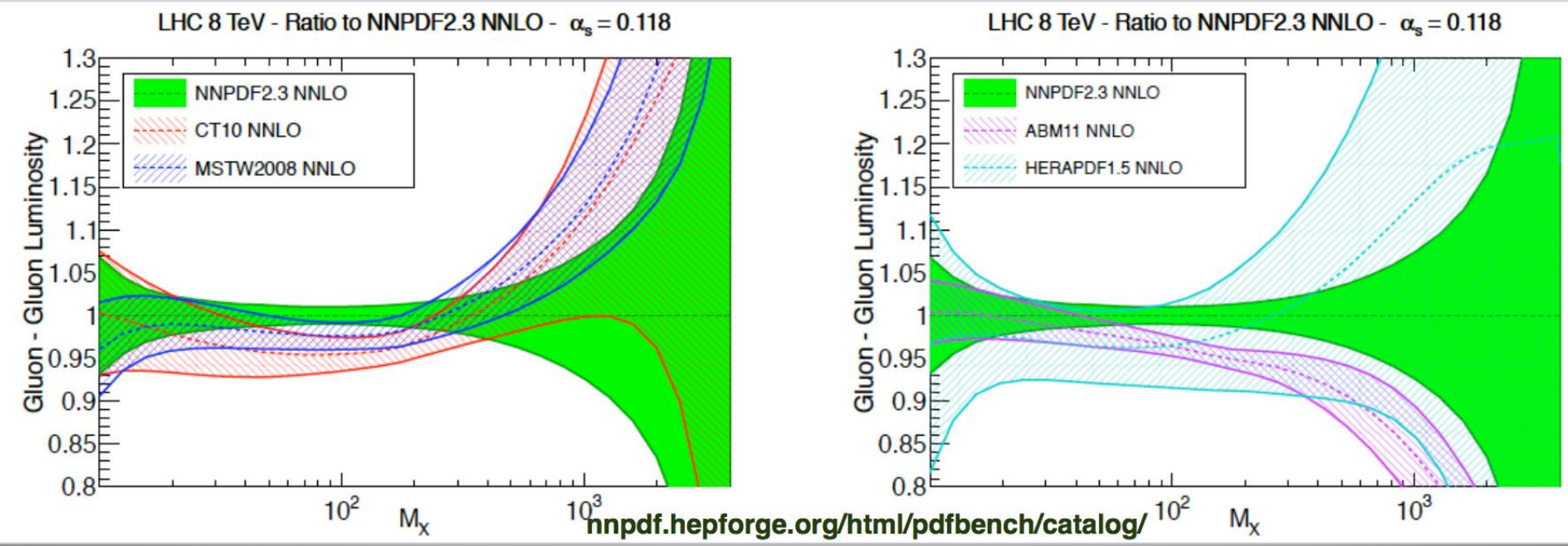
CMS-PAS-SMP-13-004

Multiplicity bin	Measured	MadGraph 5F	MadGraph 4F
$\sigma(Z(\ell\ell)+1b)$ (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.02	3.11 ± 0.03
$\sigma(Z(\ell\ell)+2b)$ (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.01	0.38 ± 0.01

CMS preliminary

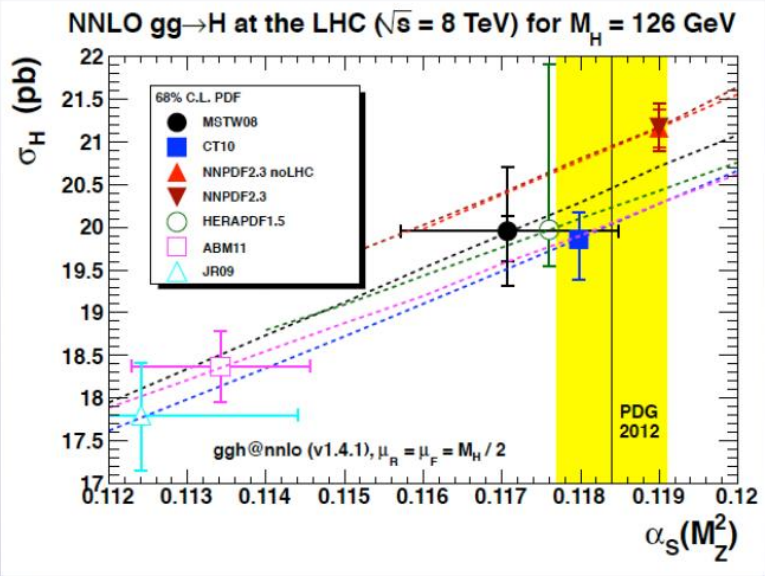
Parton Distributions

- Parton distributions (PDFs) are an essential ingredient of the LHC program
- Several PDFs available at NNLO: ABM, MSTW, CT, NNPDF, HERAPDF,…
- Studied within the experiments in PDF groups, and across experiments with the fitters in PDF4LHC

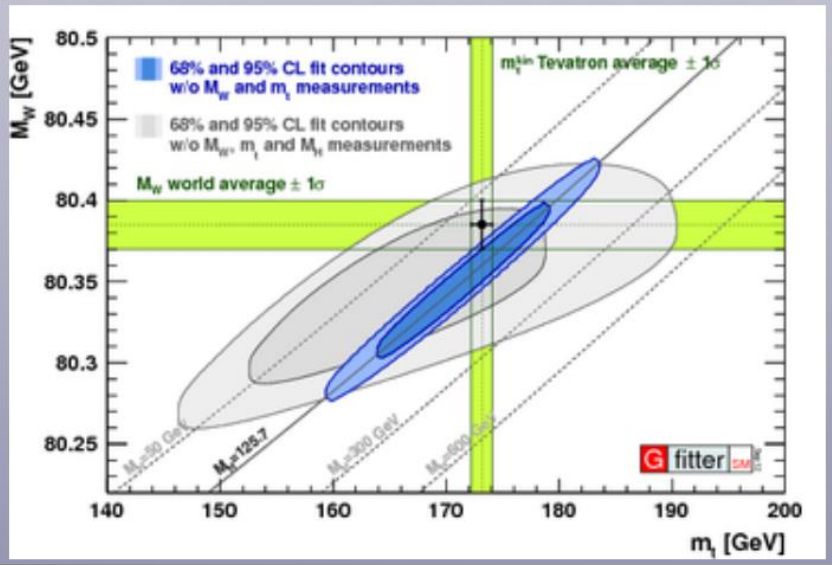


PDFs groups provide central values and error envelopes that differ
-> different choice of data used as input, different TH treatment especially for heavy flavors,...

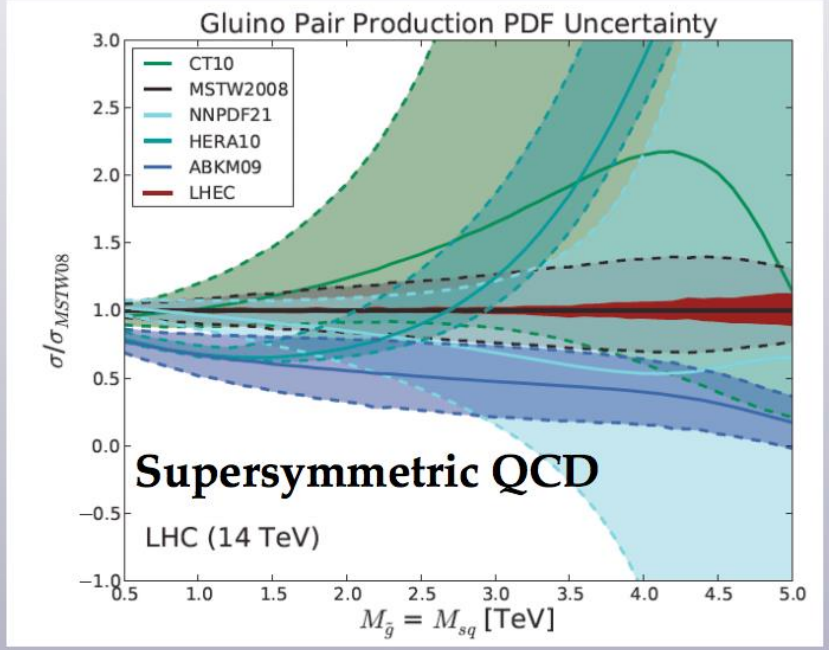
PDF Precision Impact LHC Physics



1) PDFs fundamental limit for Higgs boson characterization in terms of couplings



2) Very large PDF uncertainties (>100%) for new heavy particle production

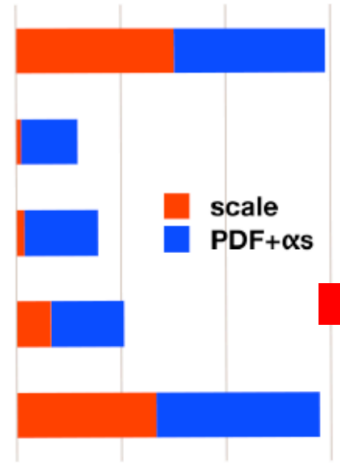


J. Rojo DIS'13

3) PDFs dominant systematic for precision measurements, like W boson mass, that test internal consistency of the Standard Model

PDF Precision

		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%



J. Campbell, ICHEP12

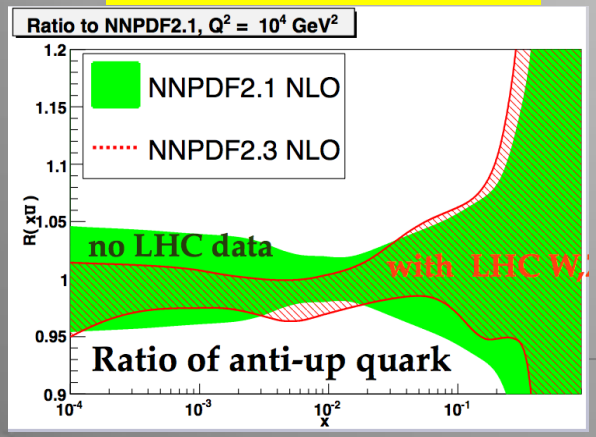
1) PDFs fundamental limit for Higgs boson characterization in terms of couplings

Precision on Higgs cross section from PDFs (and α_s)

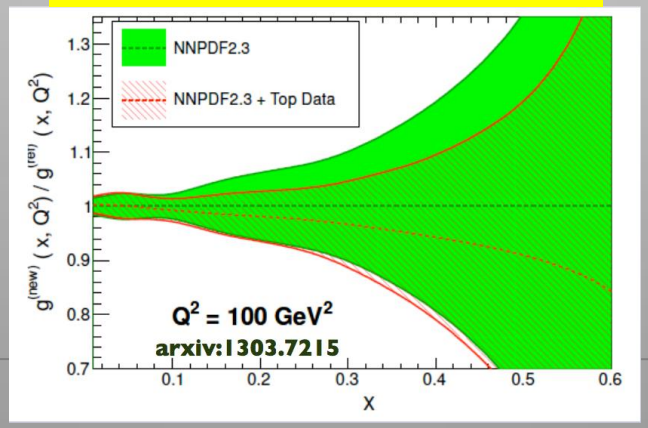
Q10: What is the ultimate precision on PDFs? Now and in future?

Include LHC data!
(wish list in appendix)

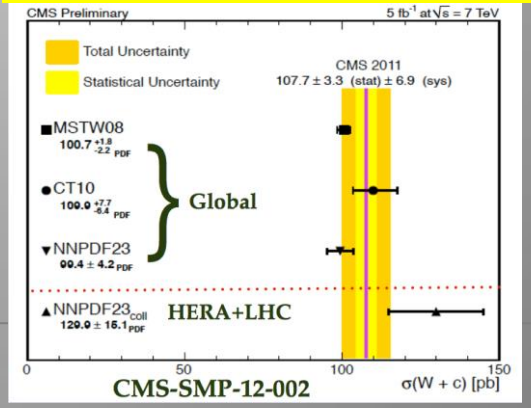
W, Z data included



Top quark data included

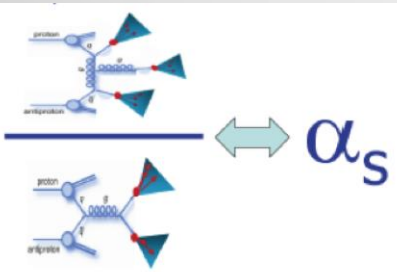


W+c data to tag s-quark
->strangeness supp. ~0.5



3-jet to 2-jet Cross Section Ratios

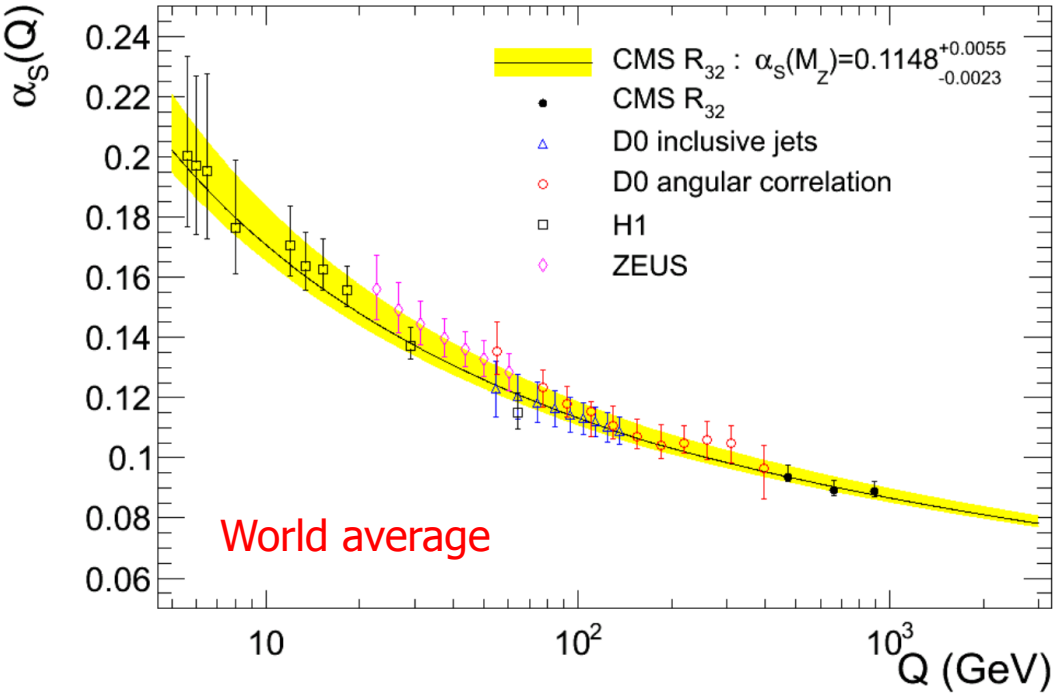
This measurement is sensitive to the fundamental QCD parameter α_s
Di-jets within the range of 420 - 1390 GeV, p_T of all jets larger than 150 GeV



$$R_{32} = \frac{d\sigma_{3+}/dp_T}{d\sigma_{2+}/dp_T} \propto \alpha_s(Q)$$

$$Q = \langle p_{T1,2} \rangle = \frac{p_{T1} + p_{T2}}{2}$$

$\langle p_{T1,2} \rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$
420–600	474	$0.1147\,^{+0.0061}_{-0.0021}$	$0.0936\,^{+0.0040}_{-0.0014}$
600–800	664	$0.1132\,^{+0.0050}_{-0.0031}$	$0.0894\,^{+0.0031}_{-0.0019}$
800–1390	896	$0.1170\,^{+0.0058}_{-0.0032}$	$0.0889\,^{+0.0033}_{-0.0018}$



$$\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\text{exp.}) \pm 0.0018\,(\text{PDF})^{+0.0050}_{-0.0000}\,(\text{scale}) = 0.1148\,^{+0.0055}_{-0.0023}$$ arXiv:1304.7498

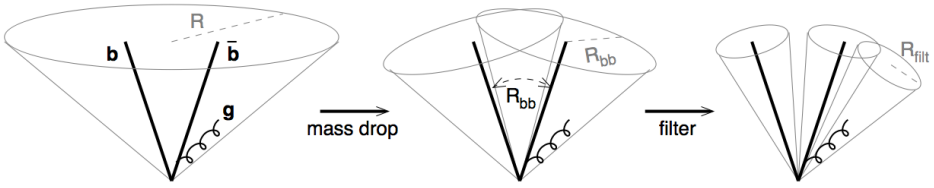
ATLAS prelim: $\alpha_s(M_Z) = 0.111 \pm 0.006(\text{exp.})\,^{+0.016}_{-0.003}(\text{theory})$. ATLAS-CONF-2013-041

Q11: How precise can we extract α_s at the LHC or elsewhere?

New Directions: Boosted Jets & Substructure

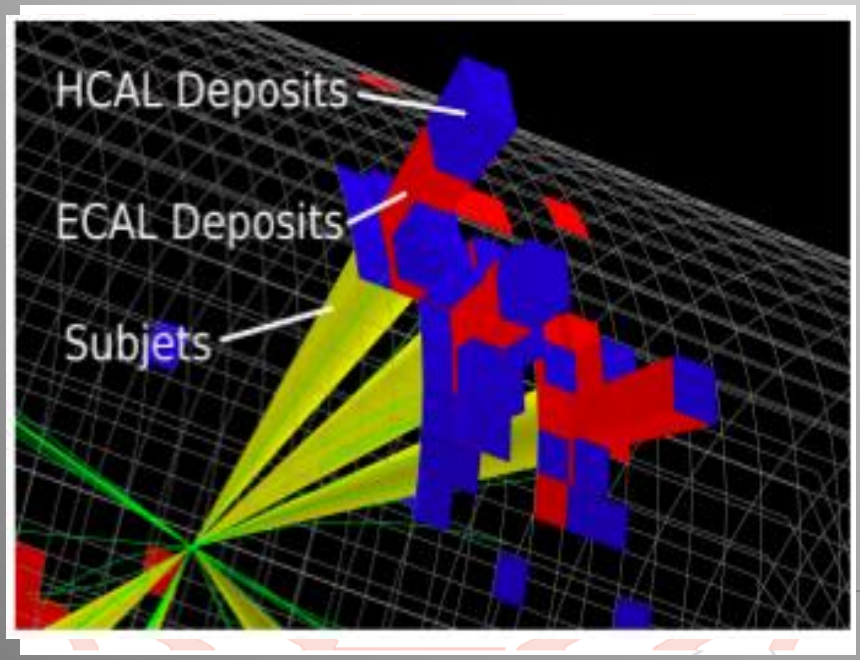
Analyse boosted/merged jets

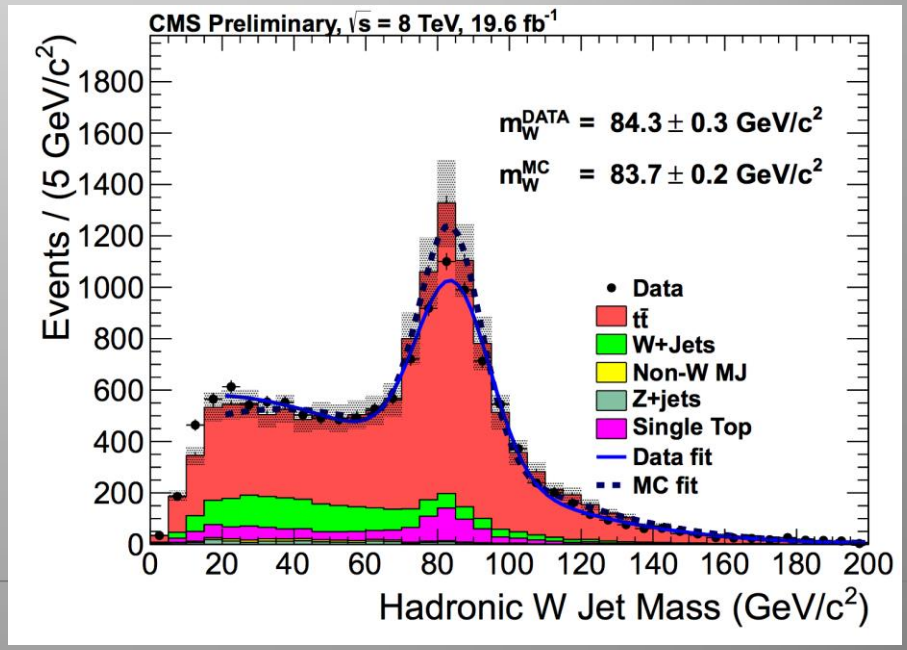
arXiv:0802.2470



- Start from Cambridge-Aachen FAT jets and apply jet "pruning" to find sub-jets
- Many methods being developed to analyse the jet substructure: grooming-> mass drop filtering, trimming, pruning…

Example: Boosted top events with b-jet and two merged jets from the W

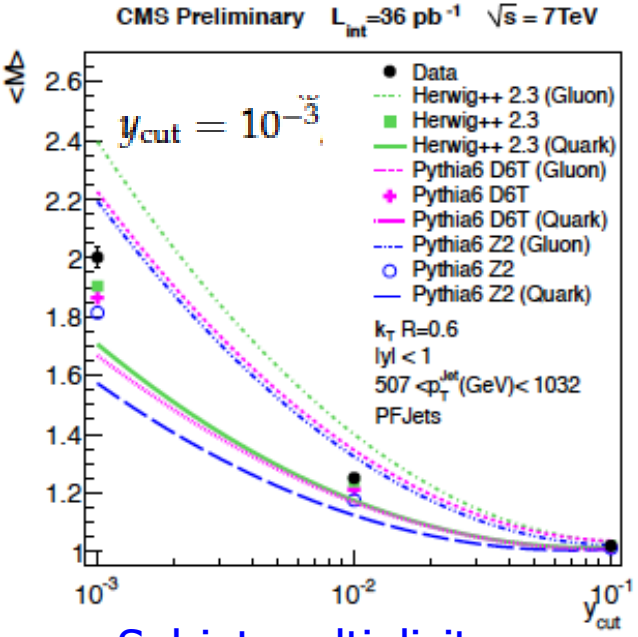




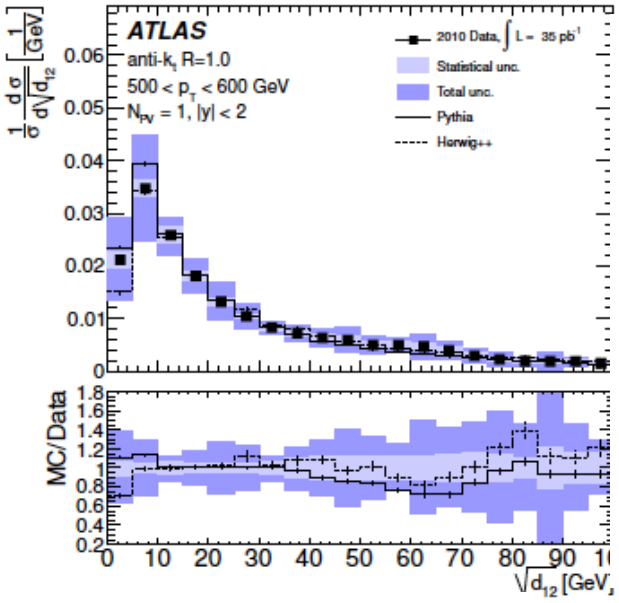
Detailed QCD Jet-structure Studies

- Detailed QCD jet studies such as substructure grooming are important to get:
  - Deeper insight into pQCD evolution in jets
  - To perform searches for New Physics in a new way

CMS-QCD-10-41

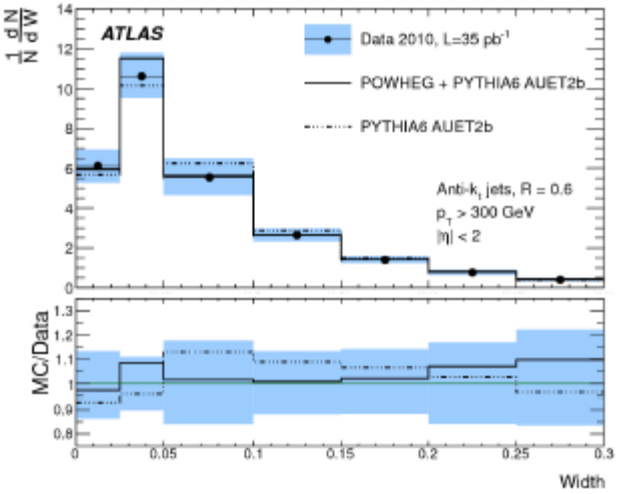


Subjet multiplicity



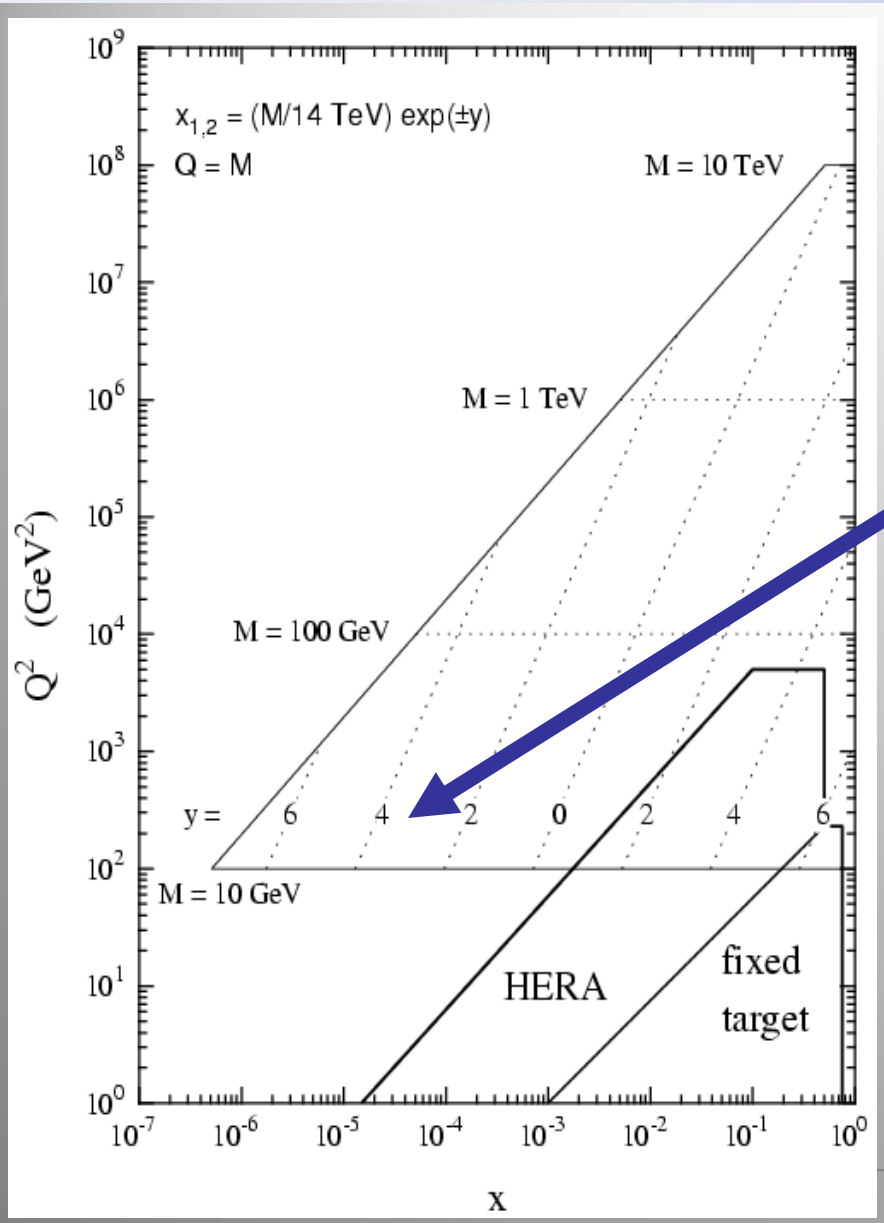
k_T splitting scale

arXiv:1203:4606



Jet width

Low-x Studies at the LHC



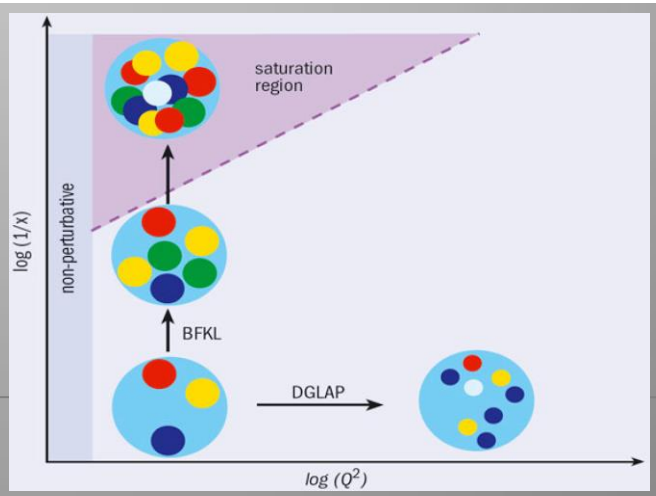
High energy of the LHC allows to access regions of low Bjorken-x Detector coverage to large |η| is important! Typical measurements:

- Low mass Drell-Yan, Jpsi…
- Prompt photon production
- Jet production with large rapidity

QCD Dynamics studies:

DGLAP: Dokshitzer, Gribov, Lipatov, Altarelli Parisi

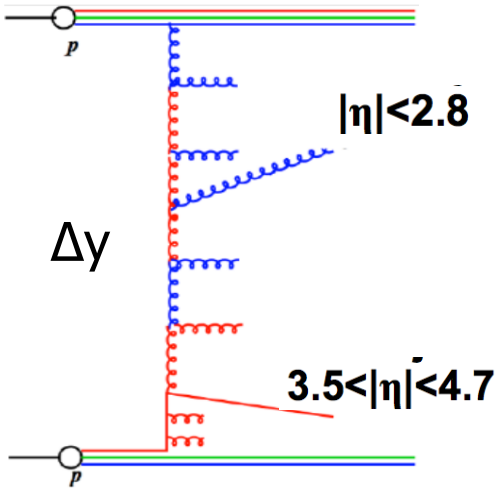
BFKL: Balitskii, Fadin, Kuraev, Lipatov



Low-x: Mueller-Navelet Jet Studies

- Look at correlations between jets -with p_T> 35 GeV- at large rapidity distance
- Proposed in the early '90's to as sensitivity test to BFKL and DGLAP evolution

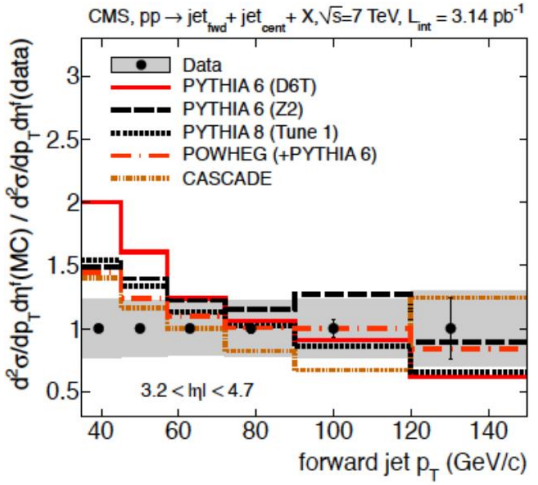
CMS-PAS-FSQ-12-002

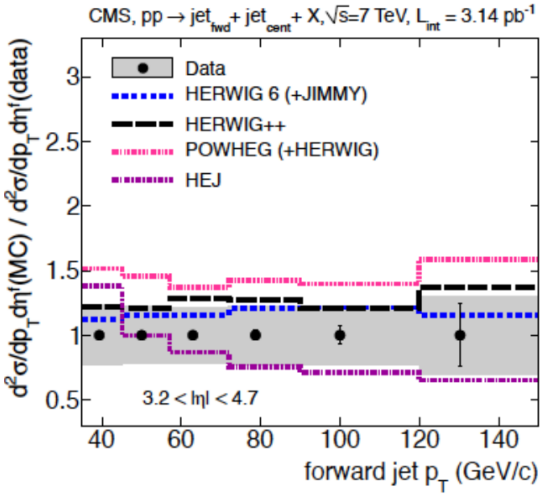


No model describes all these measurements very well

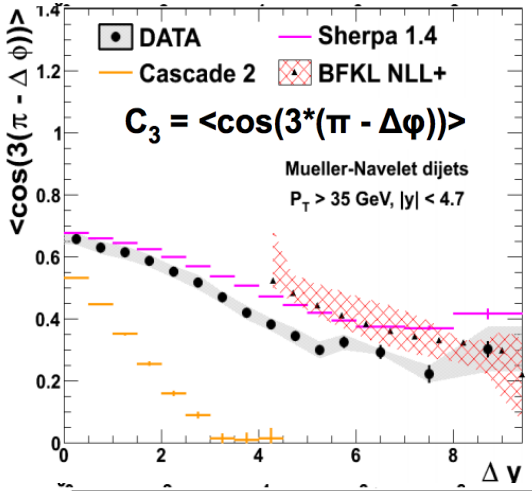
Q12: Do we need more dedicated measurements on low-x QCD effects

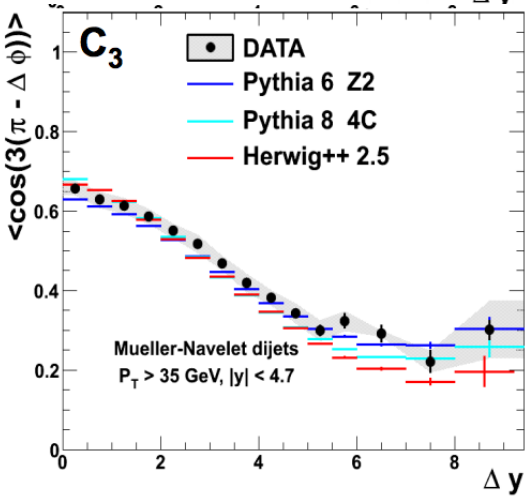
central + forward jet





azimuthal correlation vs Δy

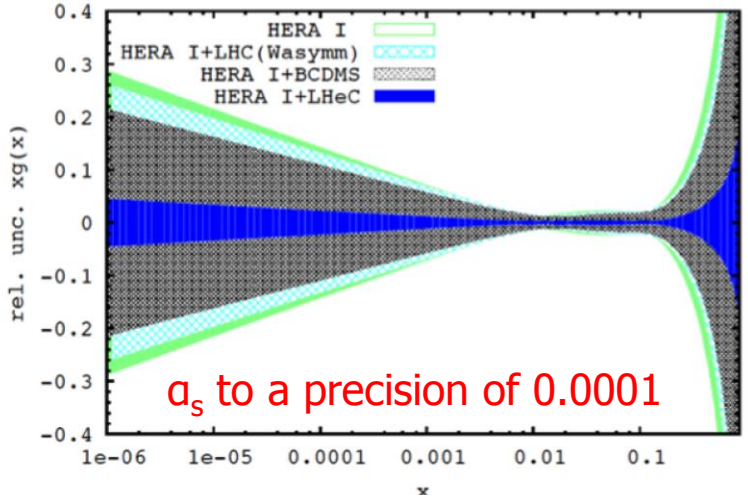


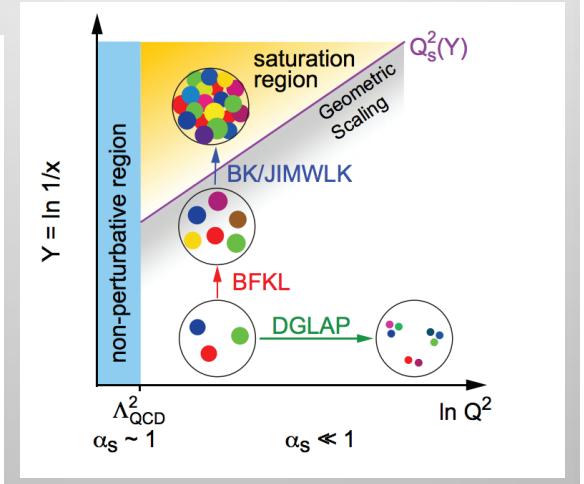


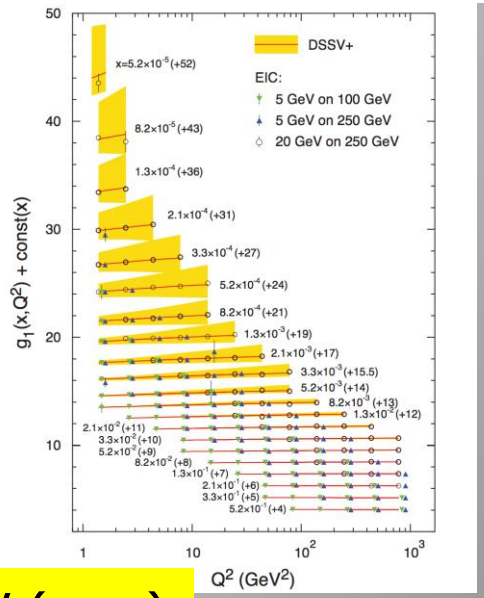
Future Facilities

- Future possible hadron and lepton colliders will be excellent QCD explorers
- High luminosity (10^{34}-10^{35}) and/or energy lepton-hadron colliders?
  ->Dedicated facilities include the LHeC (Europe) and EIC (US) projects

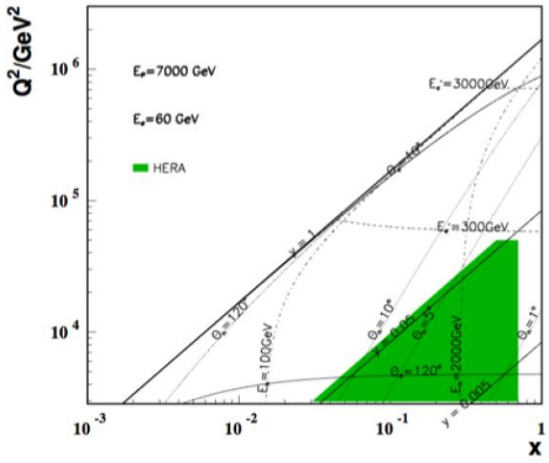
ep: 60 GeV x 7000 GeV



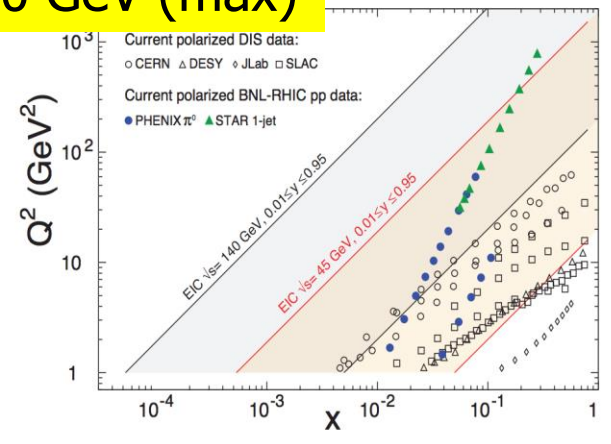




ep: 30 GeV x 250 GeV (max)



Q13: Do we need a new high intensity electron-proton machine in future?



Many Topics not Covered Today…

- Heavy flavor production
- Event shape events
- Hard diffraction
- Exclusive processes, particles with heavy flavors
- Many results on multi-particle production, cumulants, etc
- Correlations, such as Bose Einstein ones
- Hard scattering results produced photons
- Top mass precision issues
- Drell-Yan studies
- QCD coherence effects
- Jet shape and structure analyses
- Tools & calculations, higher orders,…

Conclusion

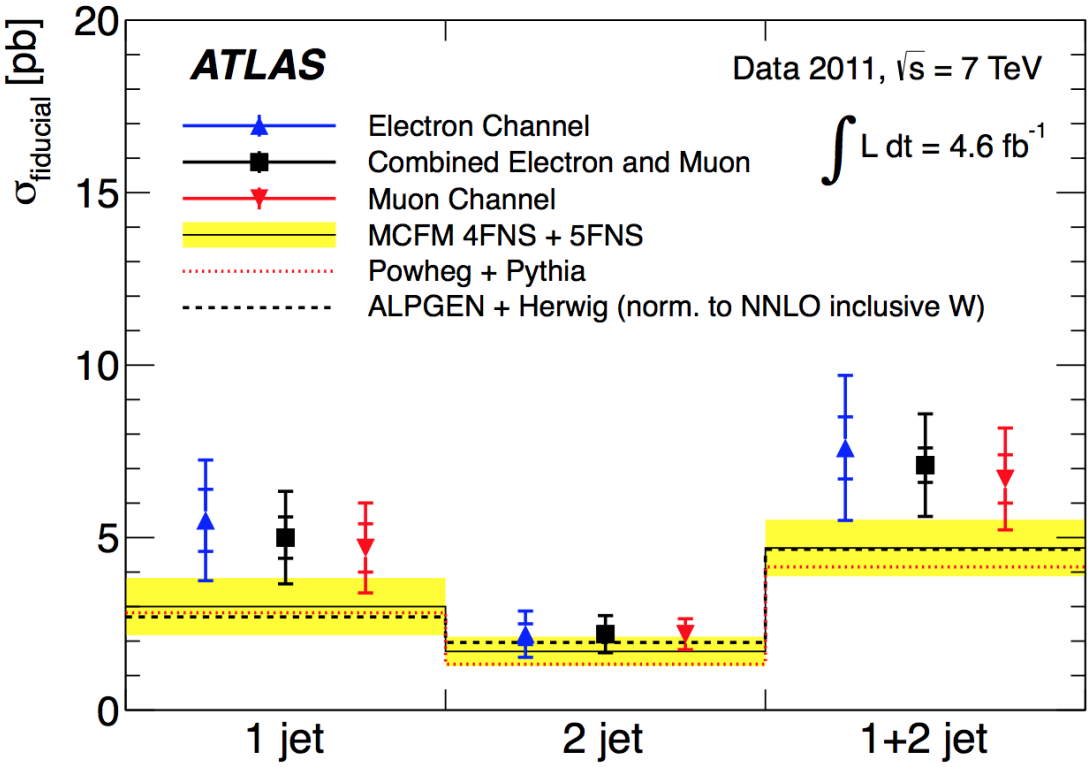
The LHC has provided a wealth of QCD results. QCD globally ok for the bulk of the LHC data. The statistics & high energy allow to explore more extreme phase space corners.

➡ Questions collected during this presentation:

- Understanding of the soft QCD dynamics -particle production, diffraction, correlations, DPS,...- useful for particle physics, cosmic rays... Are more dedicated LHC measurements needed? Boundary between pQCD and non-pQCD? More global MC tune effort needed?
- What dedicated pQCD measurements do we can we still make at the LHC to explore QCD further: Jet substructure, low-x region, very high p_T, very forward measurement? QCD scales?
- How precise can we/do we need extraction of the PDFs and α_s? What are the limitations? Can eg jet studies @ LHC add information? >NNLO?
- Do we control QCD radiation, especially ISR well enough to rely fully on that for analyses, eg trigger, to be used for searches & boosted objects?
- A future high luminosity/energy QCD ep machine??

Backup

W+b-jet Production



Excellent b-tagging in the experiments allows for further more sophisticated measurements such as associated b-jet production

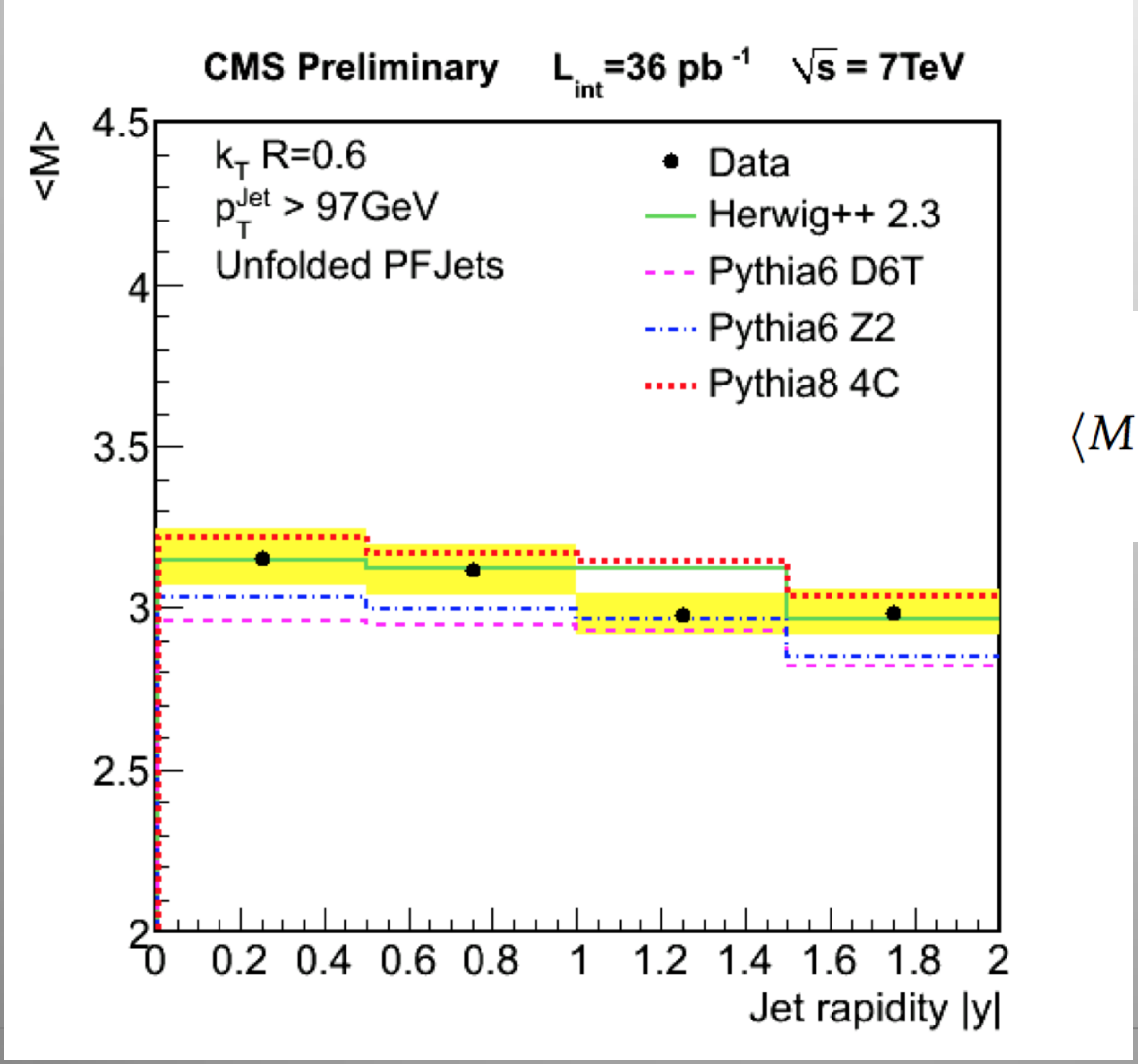
Also Z+b results

W+1 b-jet cross section on the high side
W+2 b-jets cross section agrees with prediction

Gluon splitting Issues?

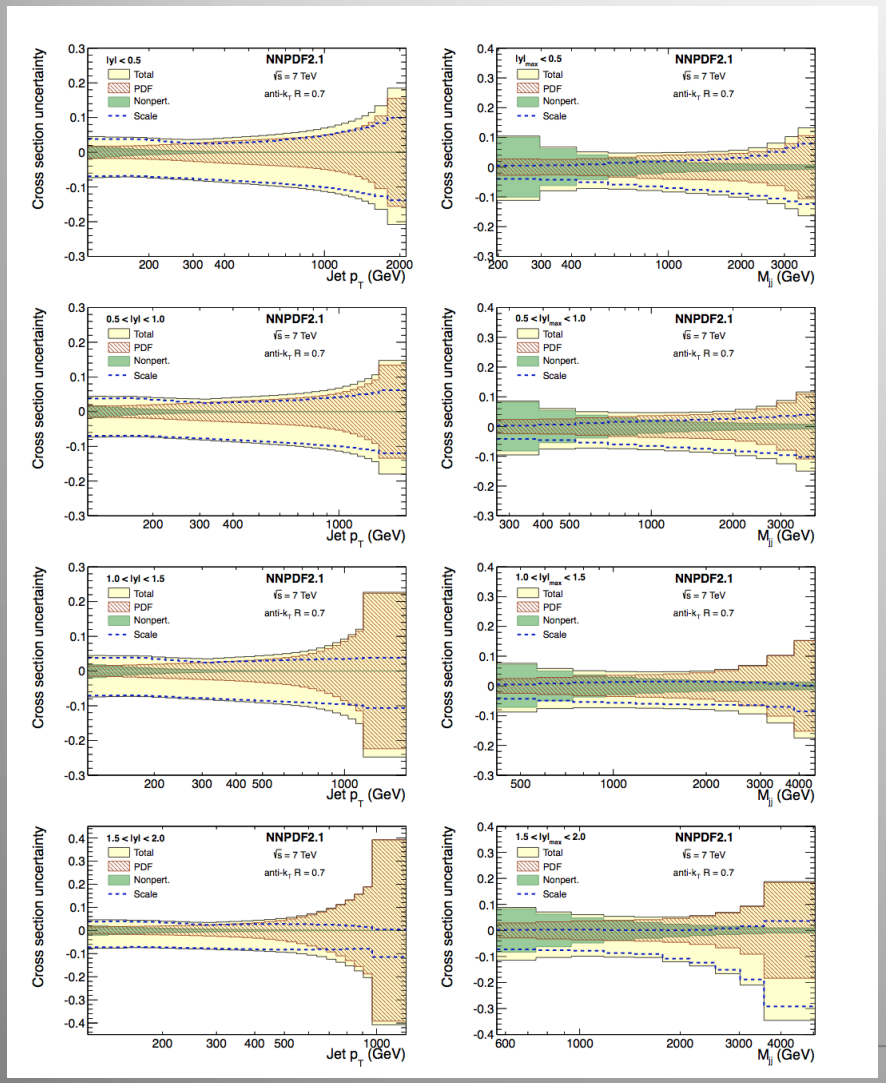
Q1: Understanding of the associated b-production -- just a MC issue?

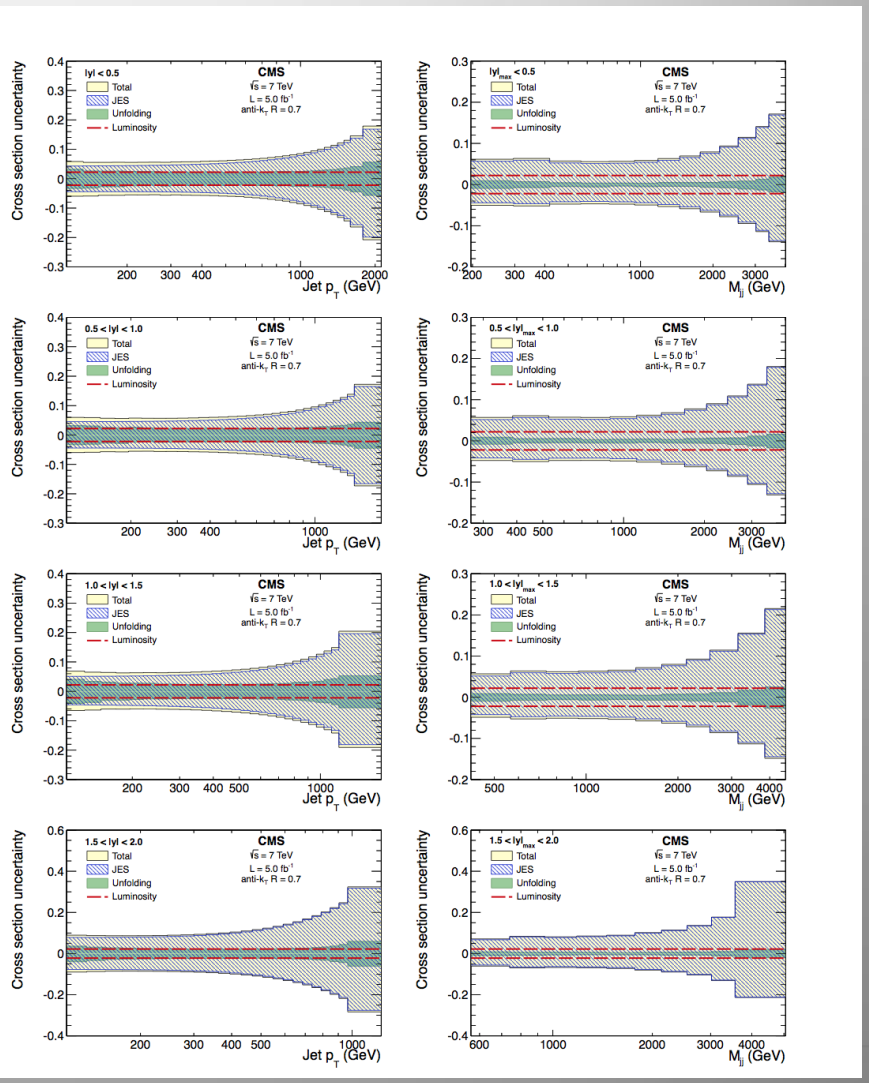
Jet Substructure



$$\langle M \rangle (y_{\text{cut}}) = \frac{1}{N_{\text{jet}}} \sum_{i=1}^{N_{\text{jet}}} M(y_{\text{cut}})$$

Jet systematic errors





Top Differential Cross Sections

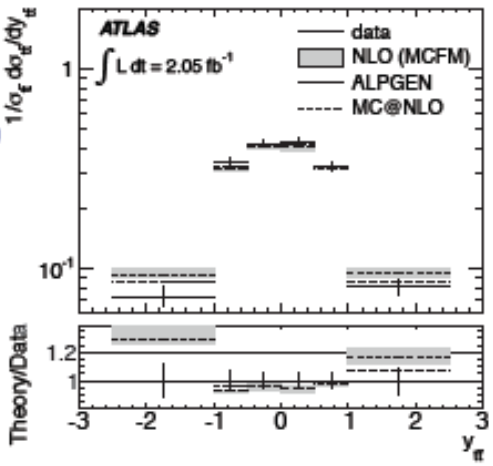
CMS: CMS PAS TOP-12-027 (l+jets)
CMS: CMS PAS TOP-12-028 (dilepton)

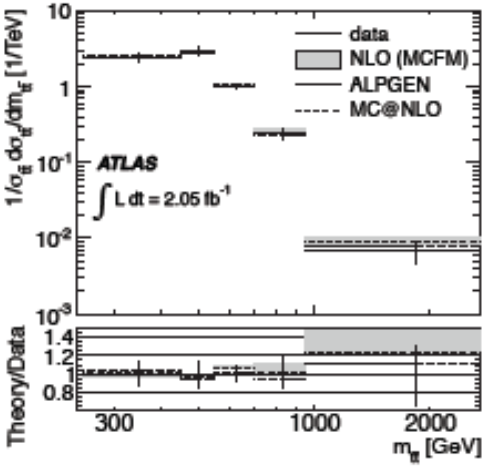
ATLAS: Eur. Pys. J. C (2013) (l+jets)

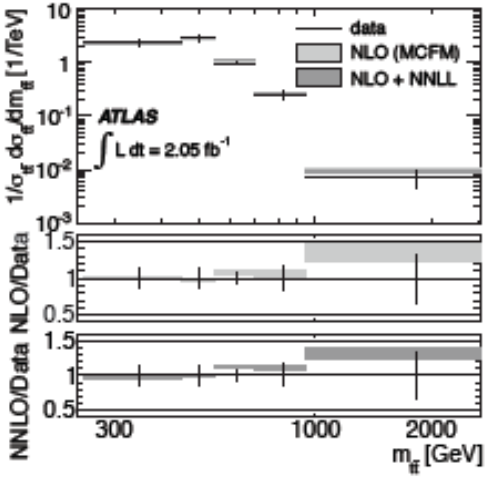
No significant deviation from SM observed

$$\frac{1}{\sigma}\frac{d\sigma(x_i)}{dx_i}$$

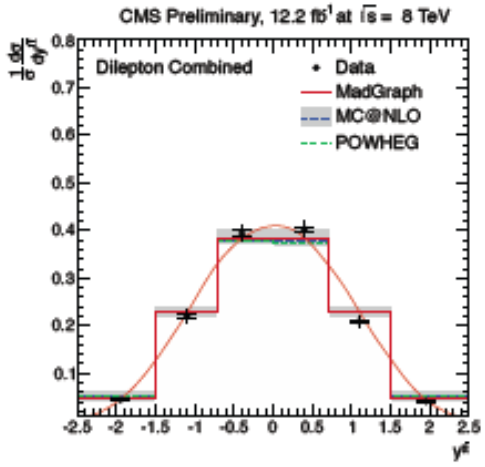
ATLAS

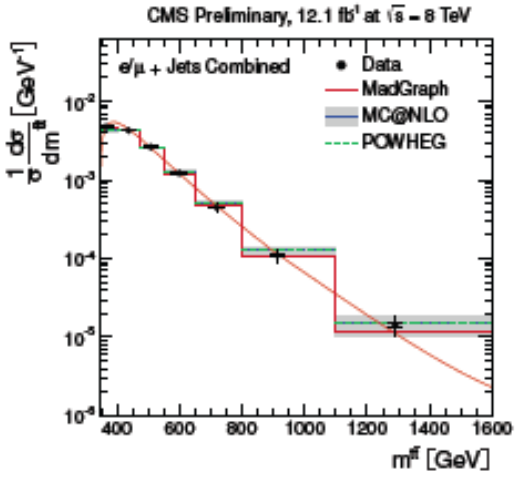


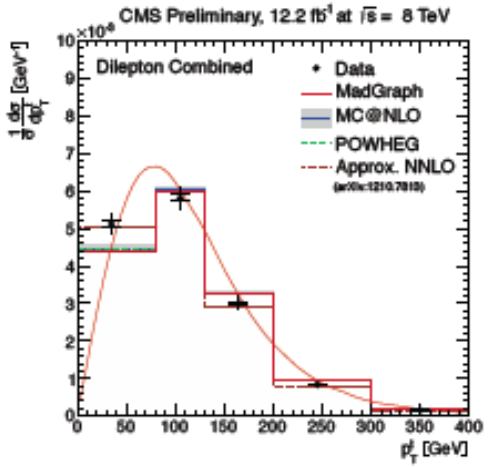




CMS New







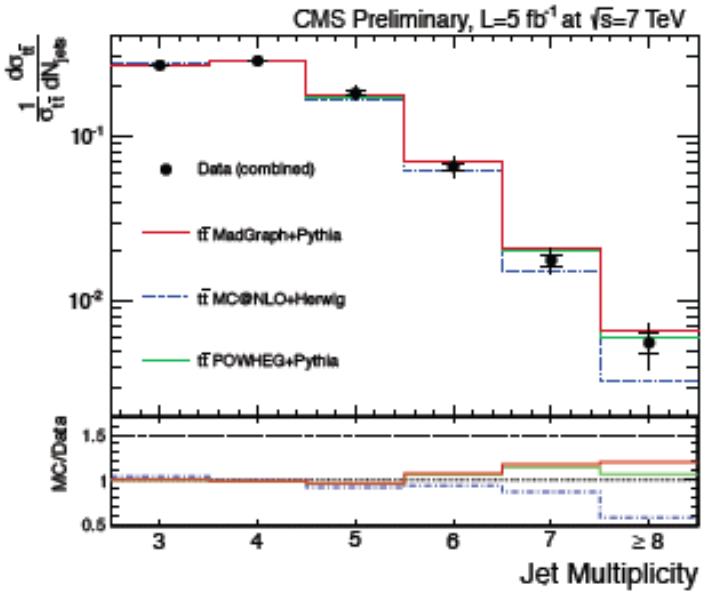
…thanks to the amount of top quarks produced at the LHC

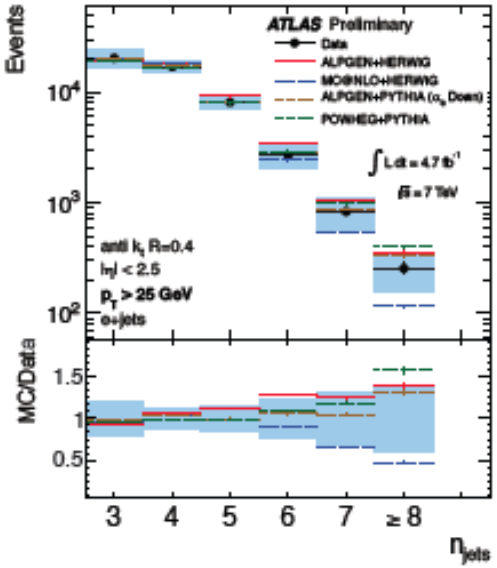
Top+ jet production

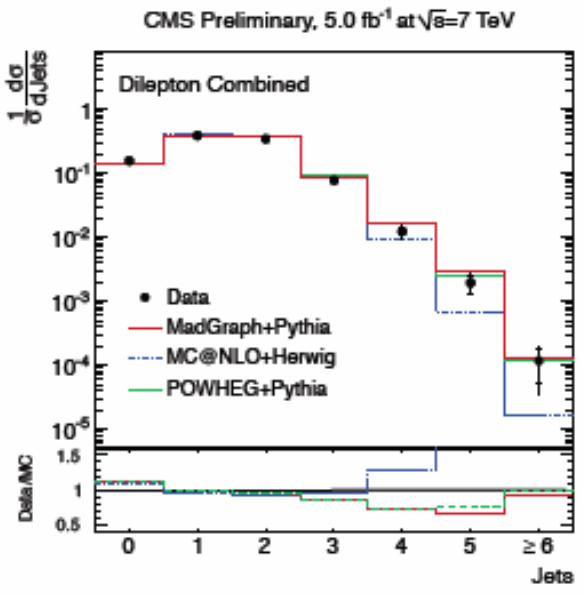
CMS PAS TOP-12-018 (l+jets)
ATLAS-CONF-2012-155 (l+jets)

$$\frac{1}{\sigma}\frac{d\sigma(N_{jets})}{dN_{jets}}$$

CMS PAS TOP-12-023
(dilepton)







Allows to probe correctness of simulation for high jet multiplicity QCD at the top scale and measure initial/final state radiation (ISR/FSR) contributions

- important for top, Higgs and many beyond SM studies
- meas. unfolded at MC level in visible experimental phase space

MC@NLO shows discrepancies in the # of high p_T jets