QCD Physics with CMS and ATLAS detectors

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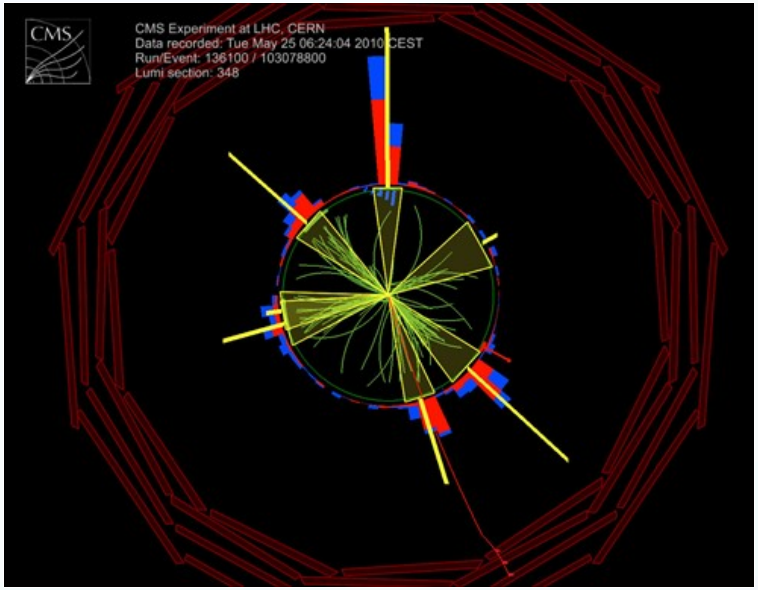
(on behalf of the CMS and ATLAS Collaborations)

Outline

- Motivation
- Soft physics
- Hard physics
- Summary

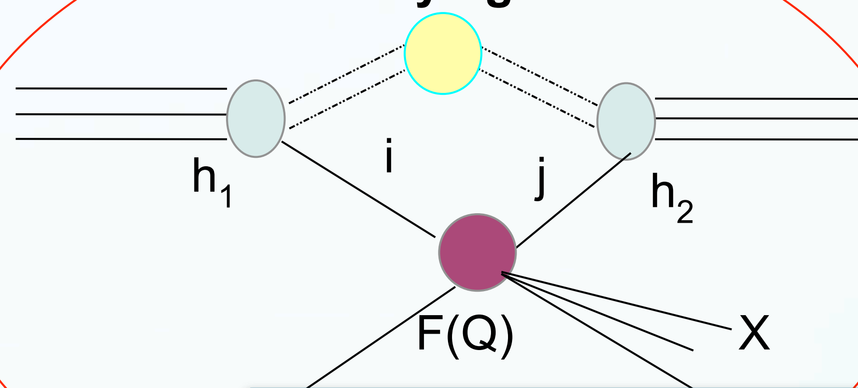


QCD is the theory that explains strong interactions as part of the Standard Model

QCD at hadron colliders

μ_F – **factorization scale separates long and short distance physics**
α_S (μ_R) – **running coupling constant**
μ_R – **renormalization scale**
$Q^2 = -q^2$ – **transferred momentum**

Soft underlying event



$p_1=x_1P_1$

$p_2=x_2P_2$

Factorization theorem

Hard interaction: production of the high-p_T objects

$$\sigma(P_{h_1},P_{h_2})=\sum_{i,j}\int dx_1 dx_2 f_{i/h_1}(x_1,\mu_F^2) f_{j/h_2}(x_2,\mu_F^2)\hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2;\mu_F^2,\mu_R^2)$$

Parton distribution function (PDF)

Partonic cross-section computed in pQCD

$$\hat{\sigma}_{ij}=\alpha_S^k\sum_n\left(\frac{\alpha_S}{\pi}\right)^n\sigma_{ij}^n$$

Fixed order pQCD

Soft interaction: production of the low-p_T hadrons

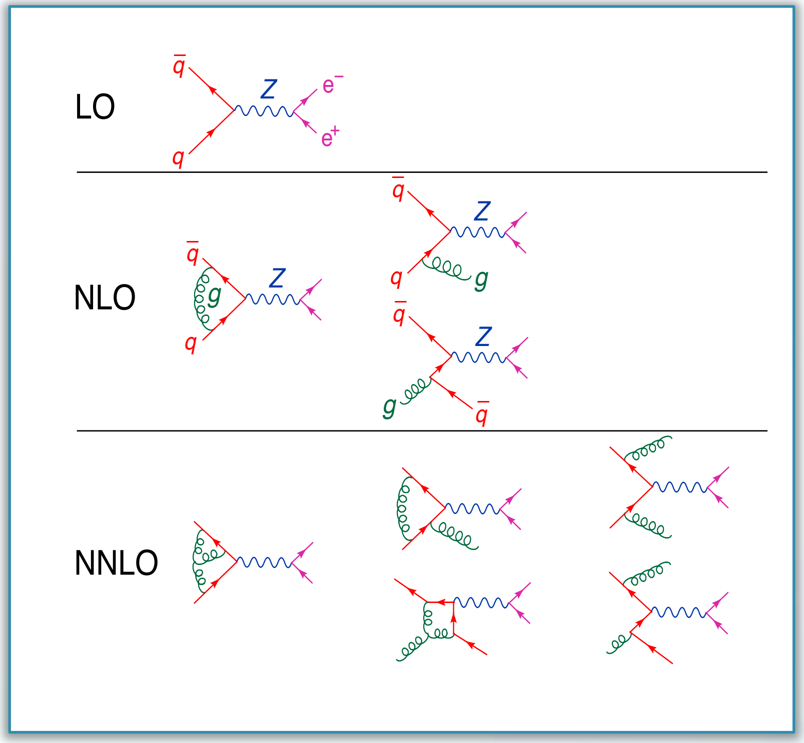
QCD at hadron colliders

pQCD prediction at fixed order calculation
Singularities (soft and collinear) are:

- ❑ **partially cancelled between real and virtual contributions,**
- ❑ **partially absorbed in PDFs and coupling renormalizations**

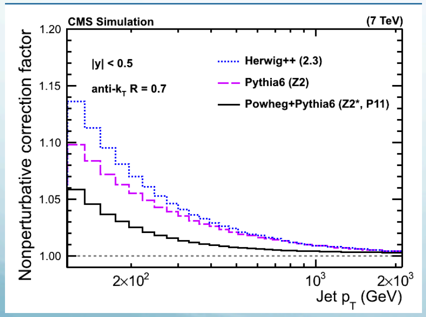
Finally, fixed order QCD calculations are matched with parton showers (PYTHIA or HERWIG) Monte-Carlo models which represent soft and collinear radiation patterns

OR in alternative approach non-perturbative and Electroweak corrections are applied as weights

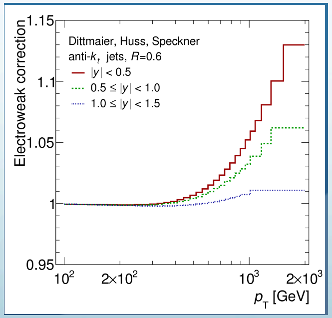


http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-13054.pdf

pQCD X



X



Where, why, what, how

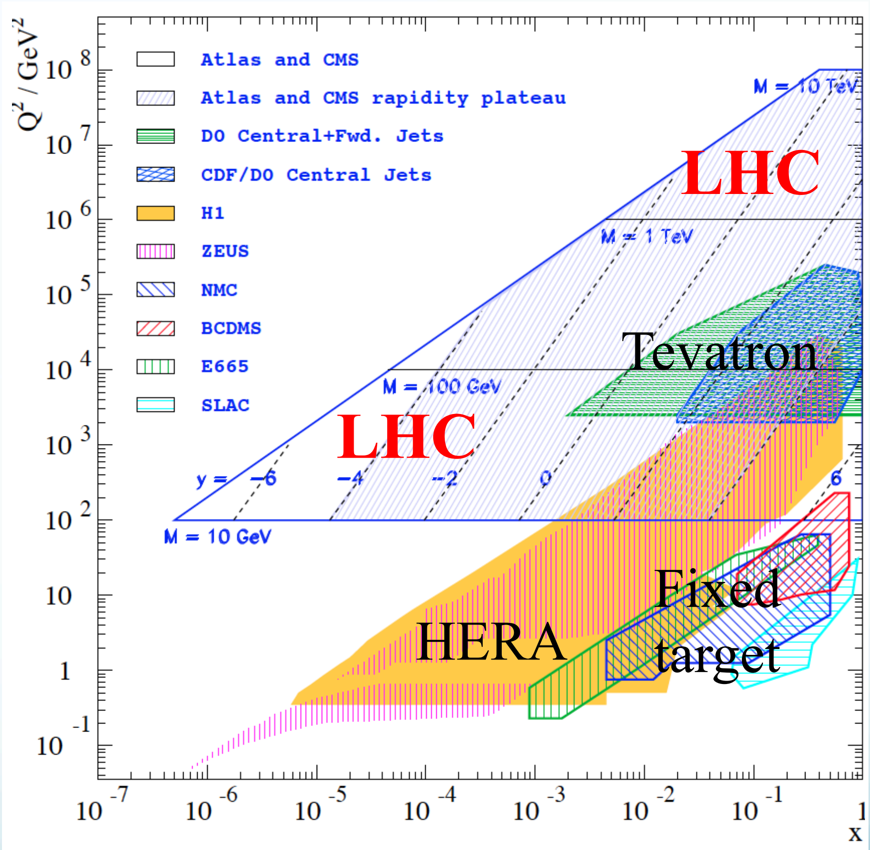
Why:
Important background for new physics searches

enormous cross section: QCD can hide many possible signals of new physics

QCD defines the hadronization process of partons whatever interaction mediator is in the hard production vertex

What:
Study the parton structure, constrain the strong coupling, …
all other pQCD theory components
Study non-perturbative effects
Tune Monte-Carlo generators

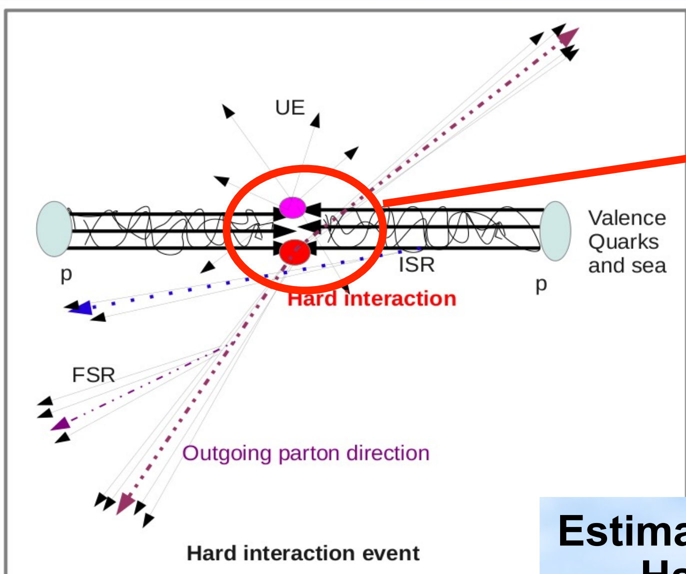
Where:

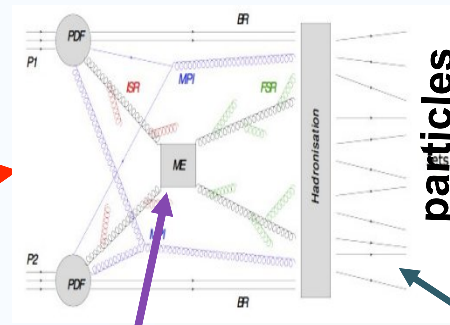


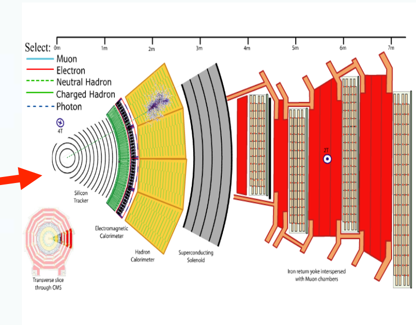
Probing the new territory (x,Q^2) range

How--→ next slide

How do we proceed







2 step unfolding
meet at particles level

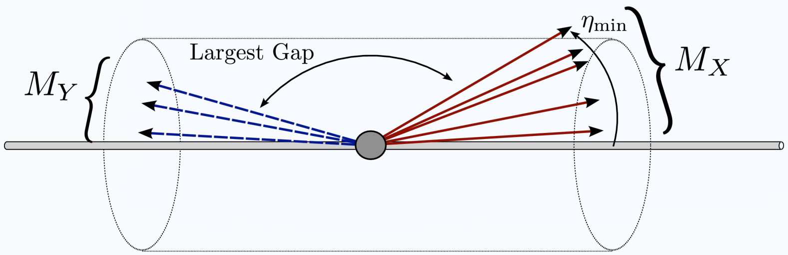
Reconstructed particles, reconstructed jets

Differential Cross-sections
Multiplicity
Rapidity
Momentum of Particles and Jets,
missing E_T

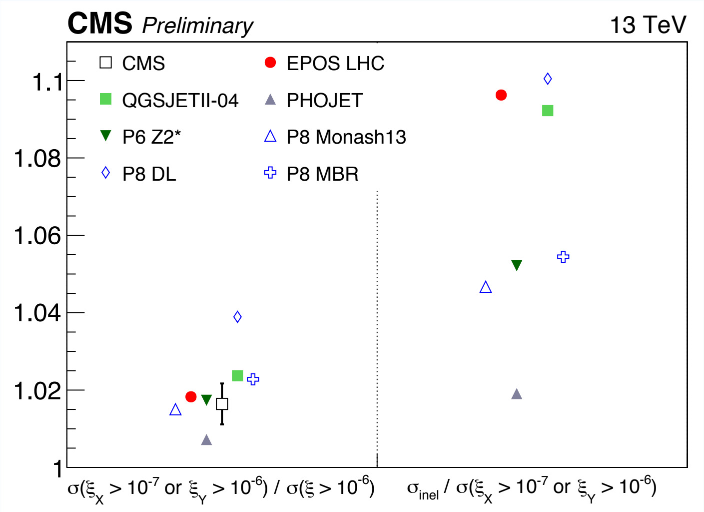
Estimate:
- **Hard interaction cross-section**
- **Parton Distribution Functions**
- **Parton showering details**

Theory approximations:
Perturbative QCD (pQCD):
LO, NLO, NNLO calculations: ME + parton showering (PS) , threshold resummation
non-pQCD: (Multi-parton interactions (MPI), String/Cluster fragmentation models)

Inelastic cross-section



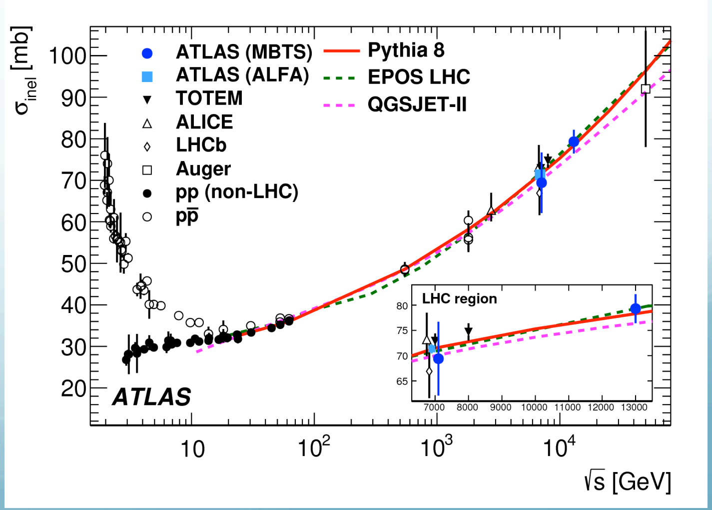
ATLAS: MBTS coverage 2.07<|η|<3.86
MX,MY>13 GeV
arXiv:1606.02625 (JHEP)



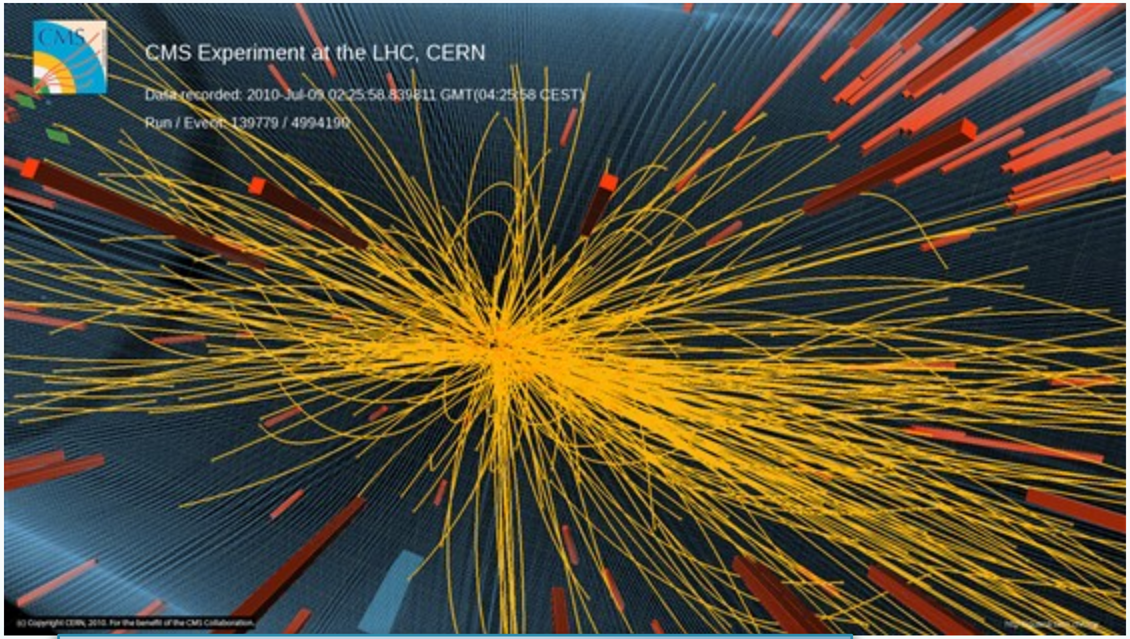
CMS: HF coverage 3.0<|η|<5.2
CASTOR -6.6<|η|<-5.2
MX>4.1 GeV MY>13 GeV
CMS-PAS-FSQ-15-005

ATLAS:
79.3±1.3(lum) ±+-2.5(ext) mb

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



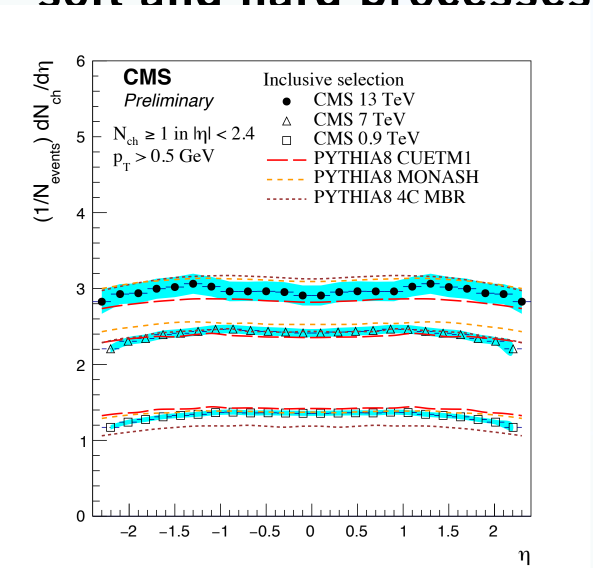
Soft particle production

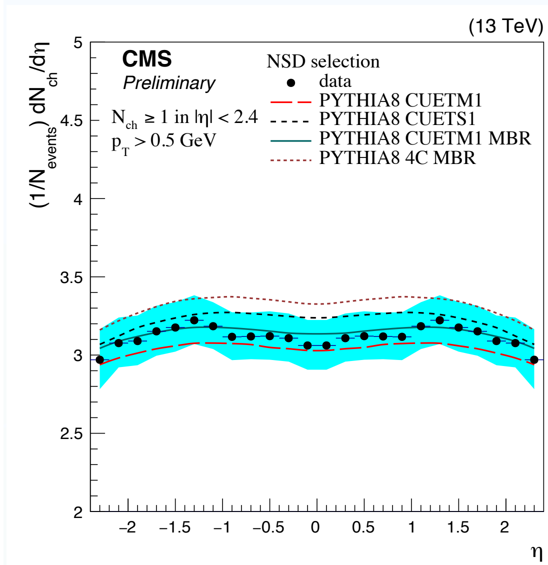


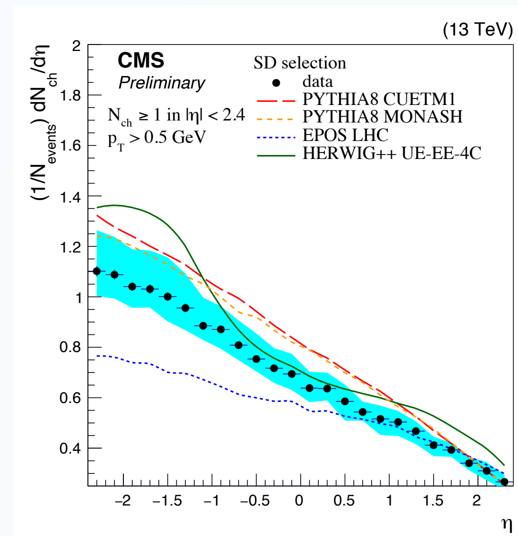
Charged particle multiplicity
Scaling, correlations
Underlying event

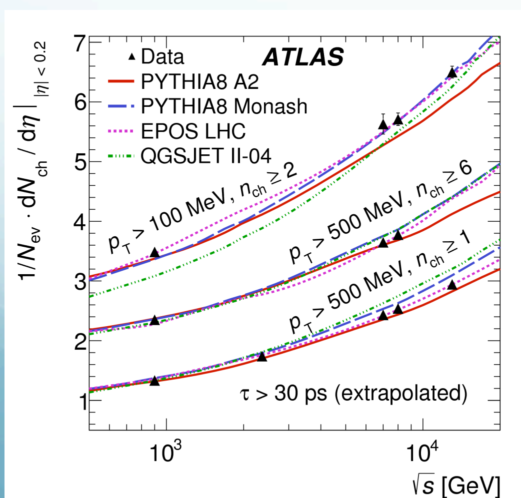
Charged particles density

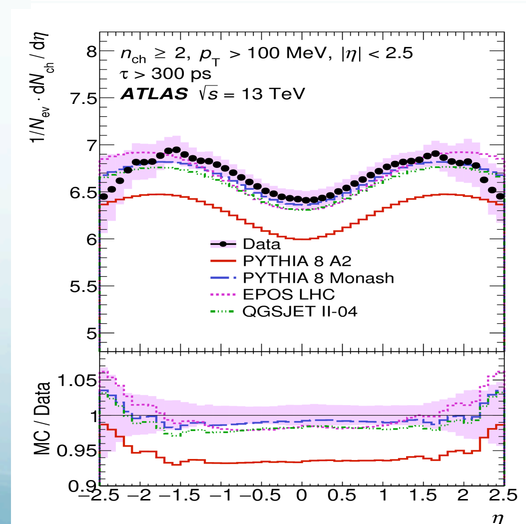
new input to the dynamics of soft hadronic interactions: interplay between soft and hard processes











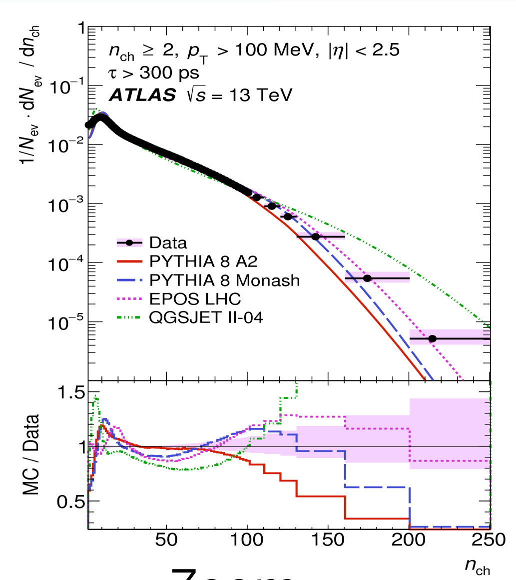
CMS and ATLAS give the consistent numbers for charged particles multiplicity

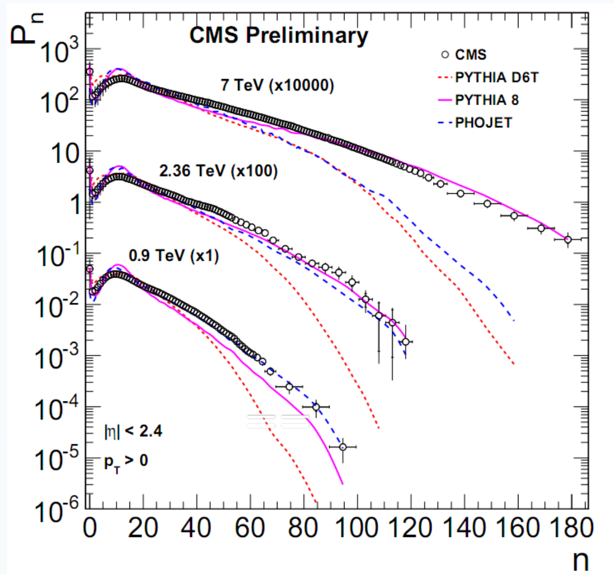
No-one MC can describe all data in all configurations

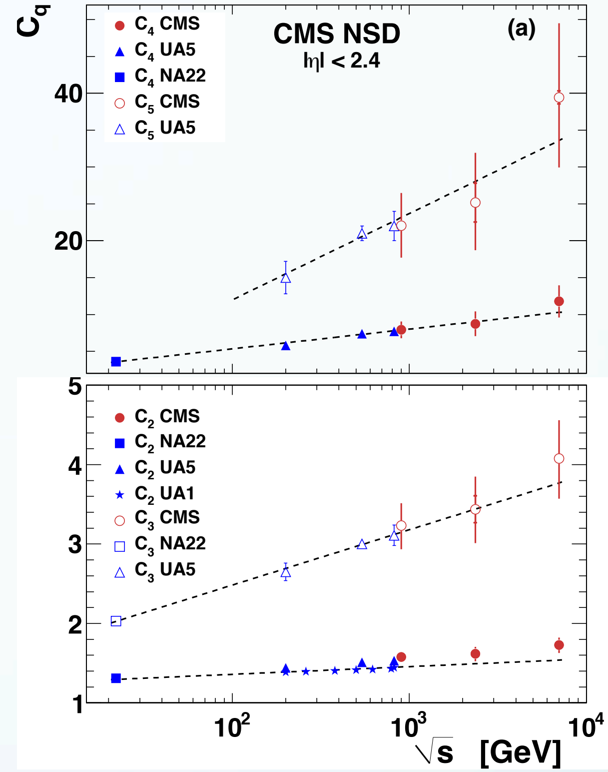
arXiv:1606.01133
CMS-PAS-FSQ-15-008

Charged particle multiplicity

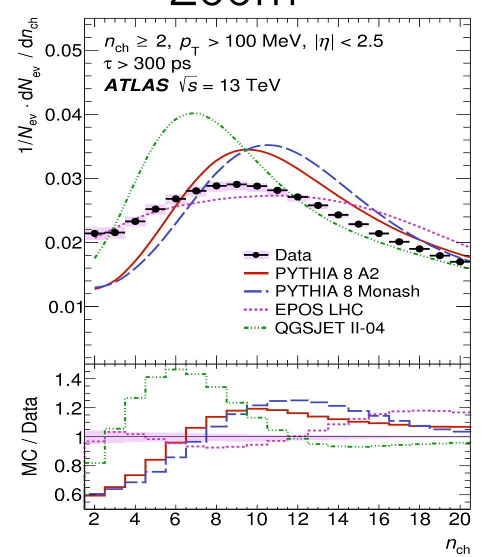
Evidence of the multi-component structure (change of the slope at n~20)

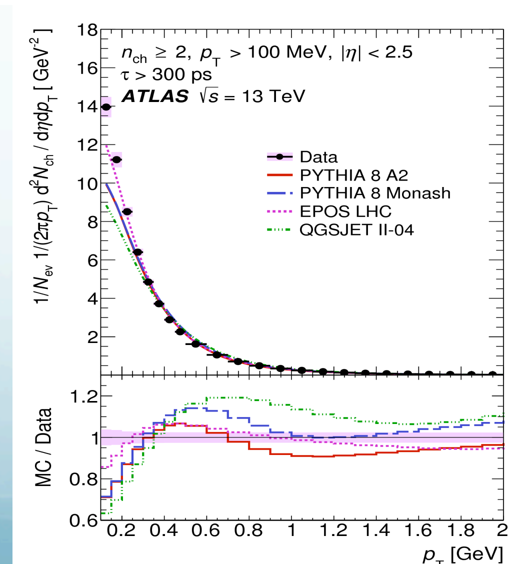






Zoom

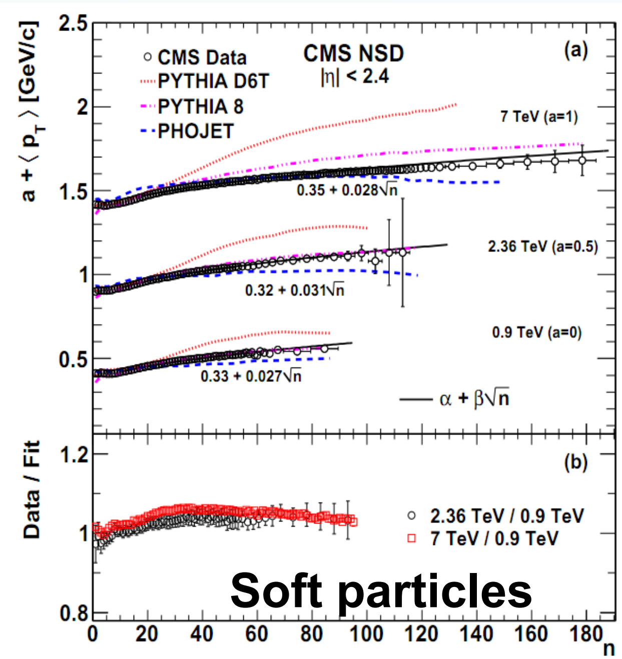


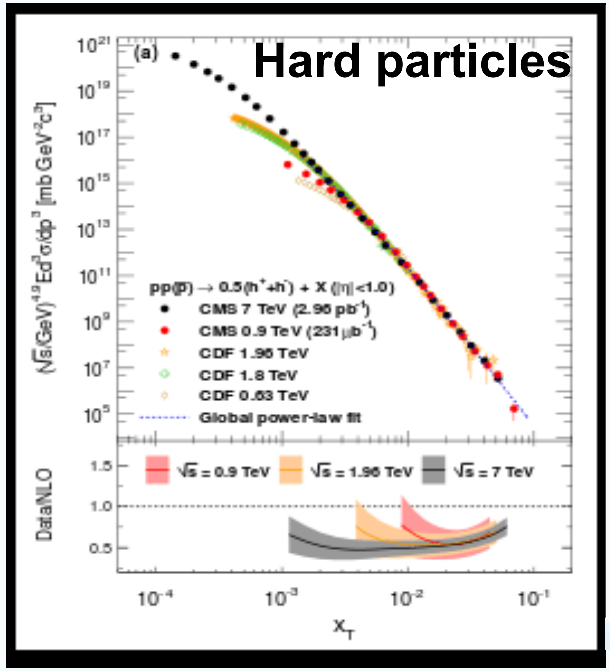


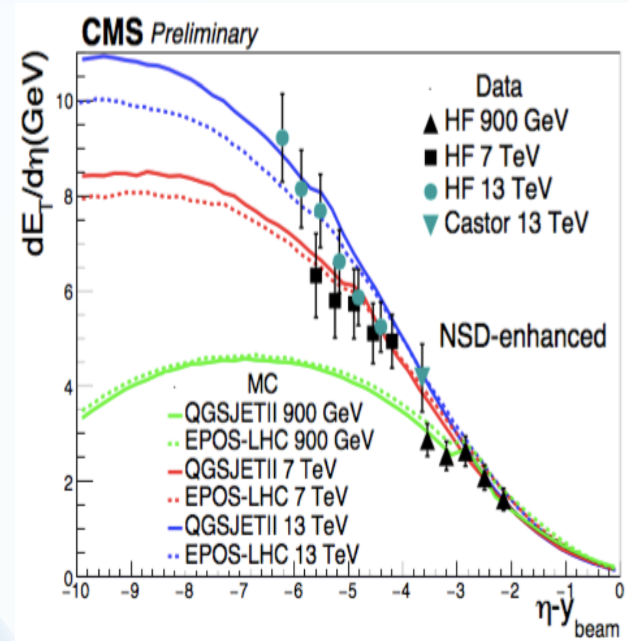
KNO scaling suppose the independence of C_q on the collision energy: violation in the Range |h|<2.4

JHEP01(2011)079
arXiv:1606.01133

p_T & x_T & limiting fragmentation







The rise of the <p_T> with Multiplicity Is energy independent

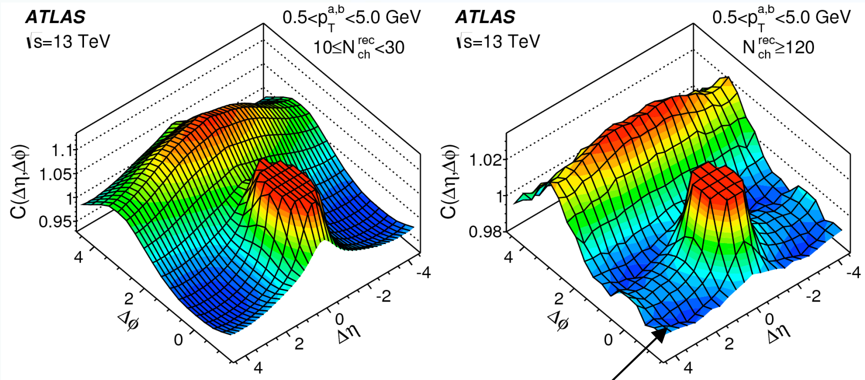
The CMS results are consistent with x_T=2p_T/√s scaling (pQCD prediction) with exponent N=4.9 +- 0.1

Consistent with the Hypothesis of limiting Fragmentation: Production of forward particles is independent On collision energy

Sensitive to the interplay between soft, semi-hard and hard particles production

JHEP 08 (2011) 086
JHEP 01 (2011) 079
CMS-PAS-FSQ-15-006

Long-range correlations



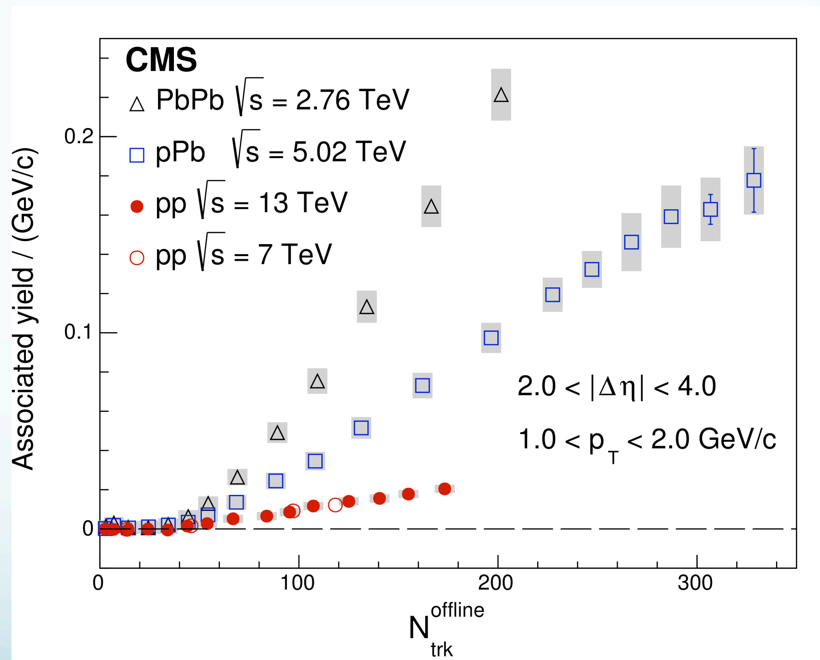
$$R(\Delta\eta,\Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

$$B_N(\Delta\eta,\Delta\phi) = \frac{1}{N^2}\frac{d^2N^{\text{mixed}}}{d\Delta\eta d\Delta\phi}$$

$$S_N(\Delta\eta,\Delta\phi) = \frac{1}{N(N-1)}\frac{d^2N^{\text{signal}}}{d\Delta\eta d\Delta\phi}$$

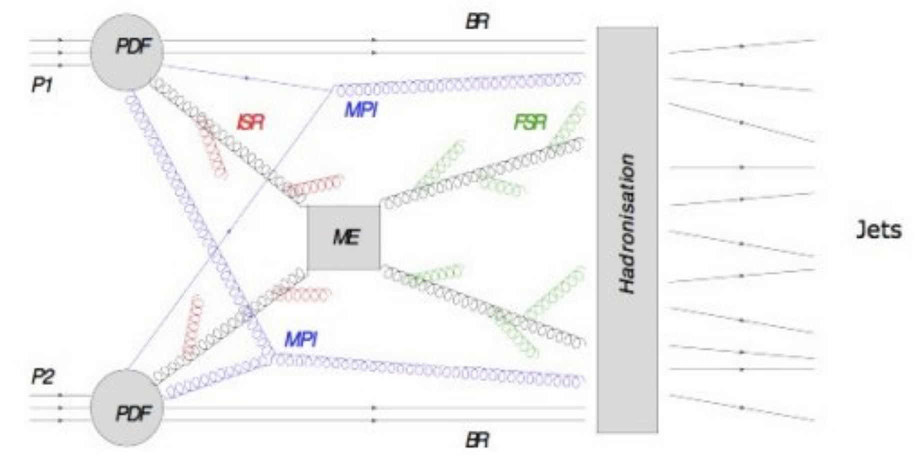
Ridge at Δφ~0 and large Δη at high multiplicity in pp events at intermediate p_T

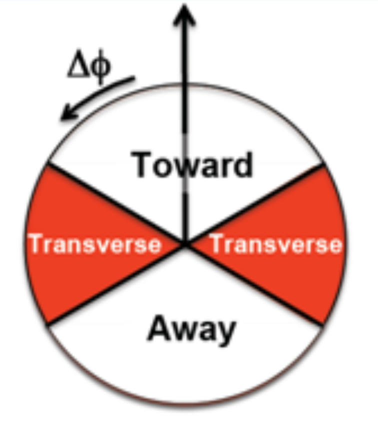
- ❑ **Effect has a maximum for particles with $2<p_T<3$ GeV/c and charged multiplicity>40**
- ❑ **Strong collision size dependence**
- ❑ **No energy dependence**



JHEP 1009:091,2010
Phys.Rev.Lett 116,172301(2016)
Phys.Rev.Lett 116,172302(2016)

Underlying events





Everything in event that is not hard interaction (ME): soft&semi-hard interactions which are not described with pQCD

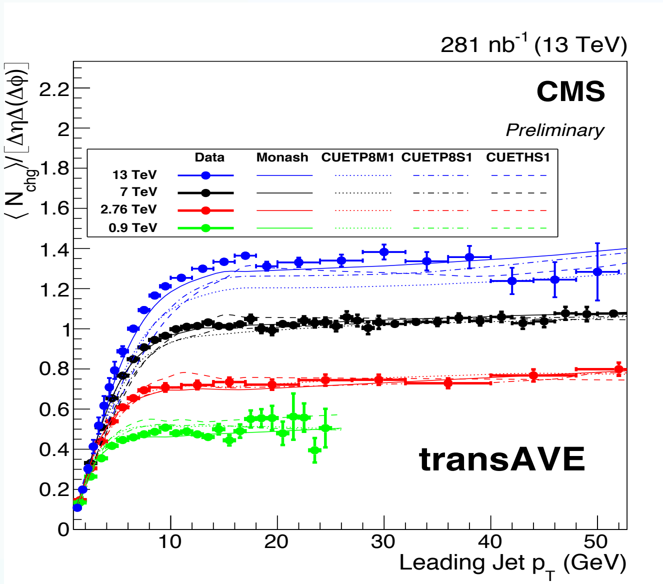
Beam remnants (BR): what remains after the interacting partons left the hadron

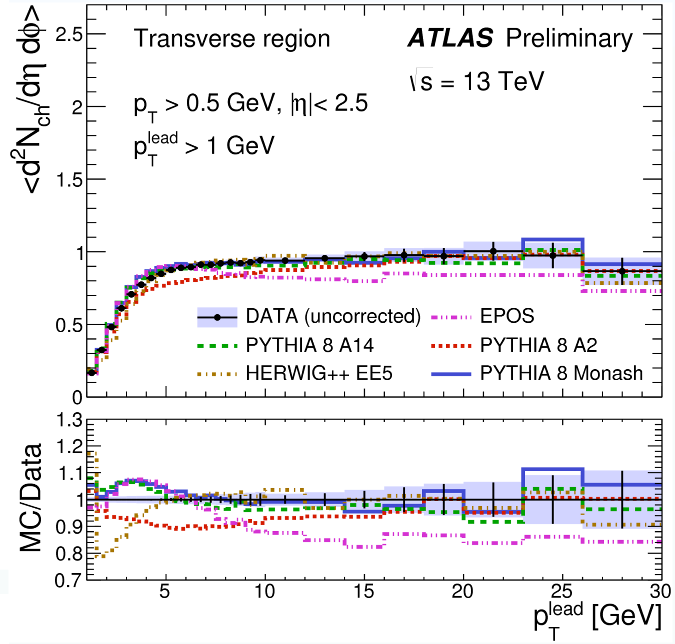
Initial (ISR) and final (FSR) state radiation

Multiple Parton Interactions (MPI). If higher pt interactions → Double Parton Scattering

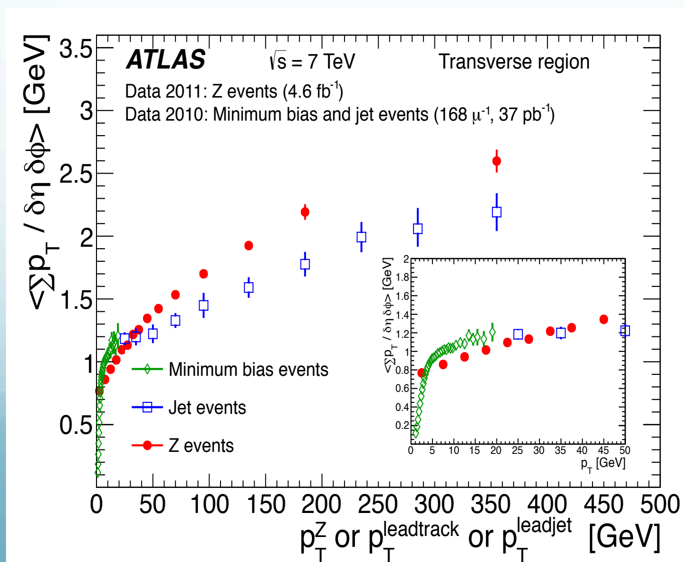
UE activity is typically studied in the transverse region in pp collisions as a function of the hard scale of the event, and at different centre-of-mass energies ($\sqrt{s}$):
Particle production in MinBias events or events with high energy track or jet (hadronic events)
Drell-Yan events

Underlying events





None of models Describe initial rise well



UE in hadronic events with leading track or track jet reflecting the direction of the parton. sensitive to ISR,FSR,MPI. Increase is due-to extra-jet activity from ISR/FSR/MPI contribution in the transverse region

CMS-PAS-FSQ-15-007
ATL-PHYS-PUB-2015-019

Double Parton scattering (DPS)

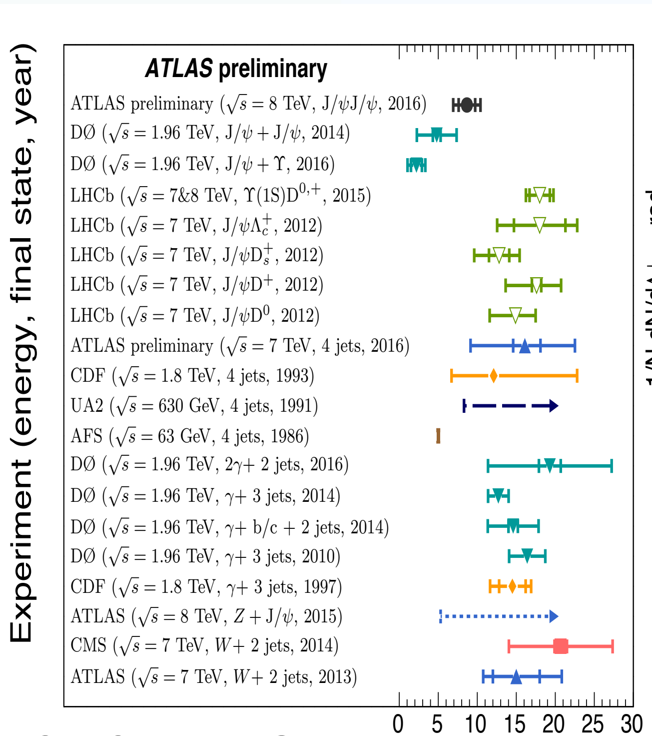
Two hard interactions within the same production vertex.

DPS is characterized by

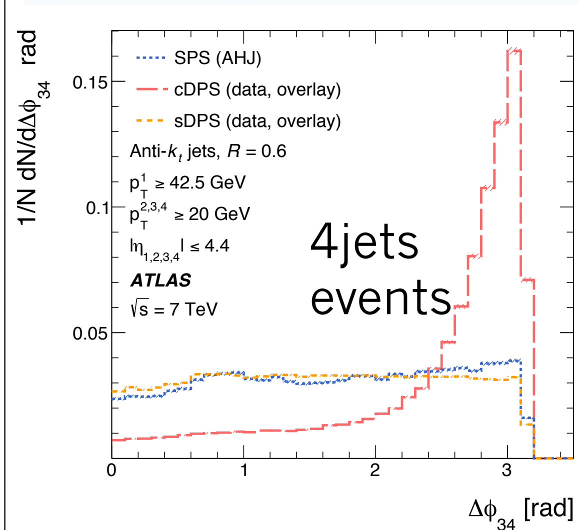
$$\sigma_{DPS}^{AB} = \frac{m}{2}\frac{\sigma_{SPS}^{A}\sigma_{SPS}^{B}}{\sigma_{eff}} \qquad \sigma_{eff} = \left[\int d^2b\,(T(\mathbf{b}))^2\right]^{-1}$$

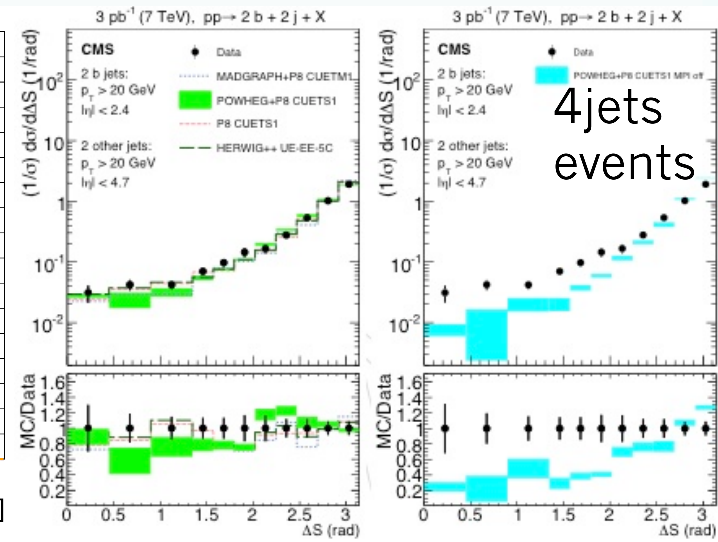
σ_{eff} differs from 10 to 20 mb

T(b) is the overlap function of two interacting hadrons



CMS:WW (8 TeV):
Lower limit 5.91 mb



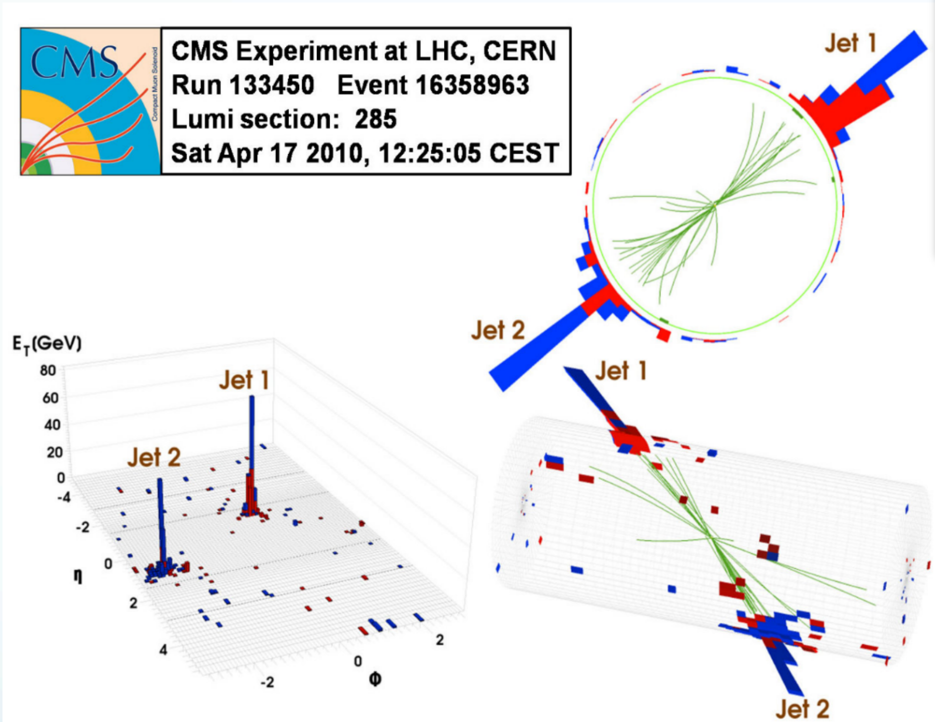


Δφij – azimuthal angle between two jets

ΔS – azimuthal Angle between Two dijet pairs

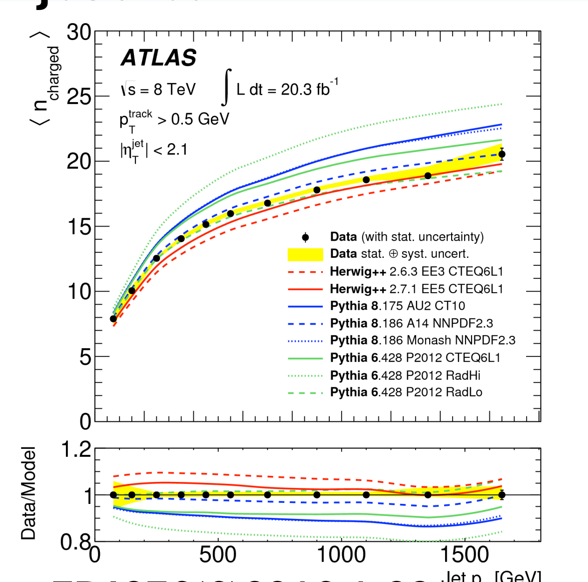
arXiv:1608.01857
ATLAS-CONF-2016-047
CMS-PAS-FSQ-13-001
CMS-PAS-FSQ-13-010 (subm to PRD)

Hard interactions



In this presentation:
PDFs and α_S measurement
Number of flavors

Number of charged hadrons in jet area



EPJC76(6)2016,1-23

Anti-k_T algorithm is used by ATLAS and CMS
CMS uses R=0.5,0.7 in Run1
R=0.4,0.6 in Run2
ATLAS uses R=0.4,0.6

PDFs and α_S

For the fixed pQCD order and definite PDF evolution (DGLAP, BFKL, CCFM,..):

A) Define PDFs at fixed α_S

B) Define α_S for the particular PDF set which gives the best approximation of the Data by Theory

C) Combined PDFs and α_S fit

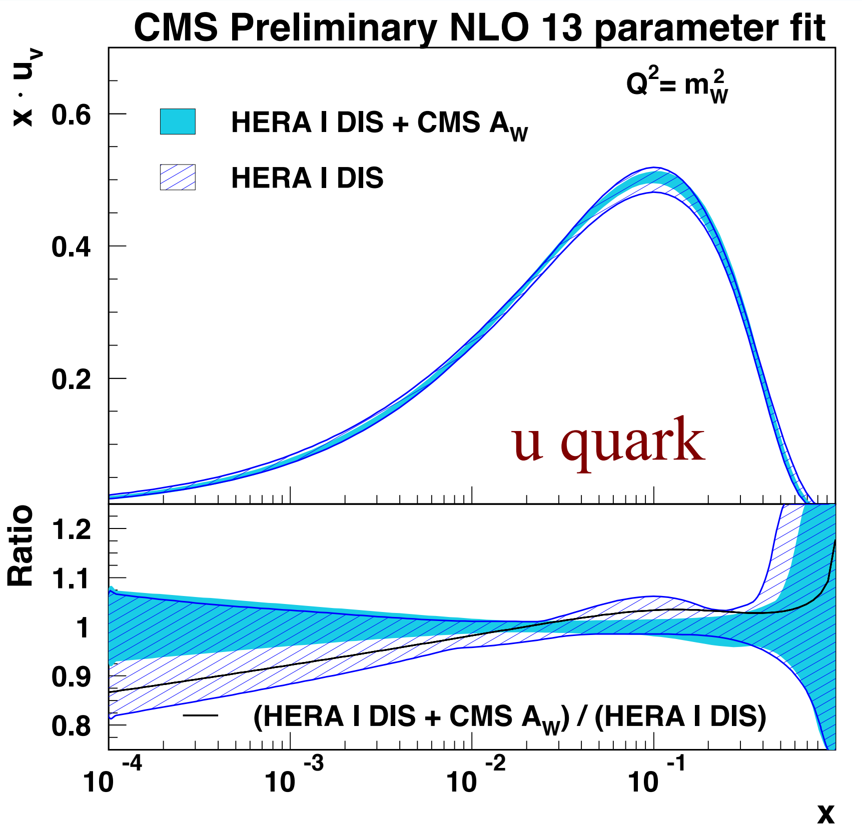
Using available sensitive processes:

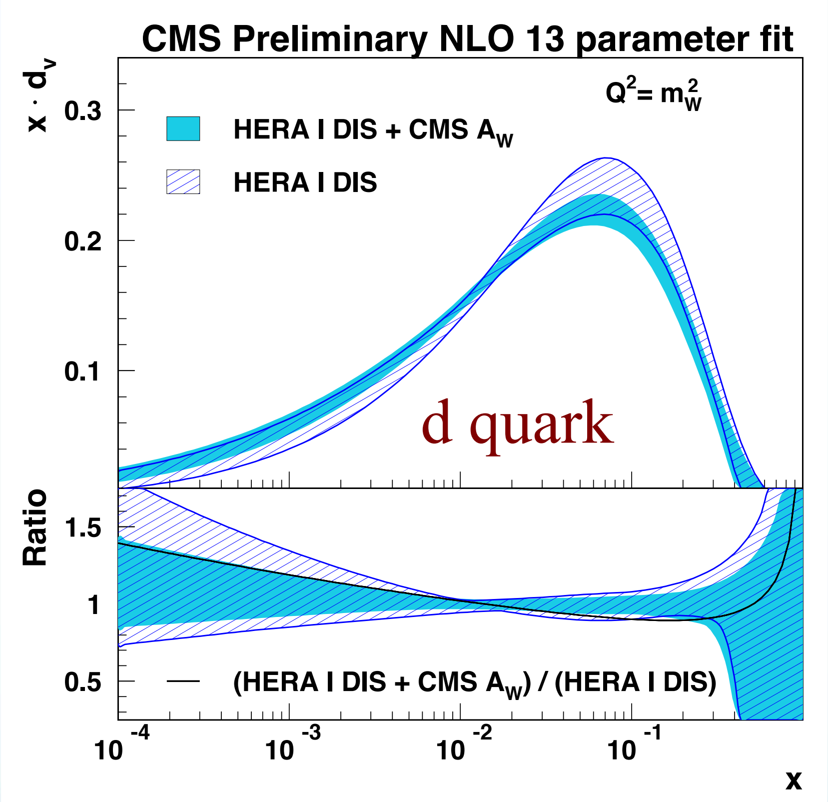
W,Z : light quarks at low and high x

Top: gluon at high x, u,d,b quarks

Jets: gluons at medium x

W charge asymmetry: u_v, d_v PDF



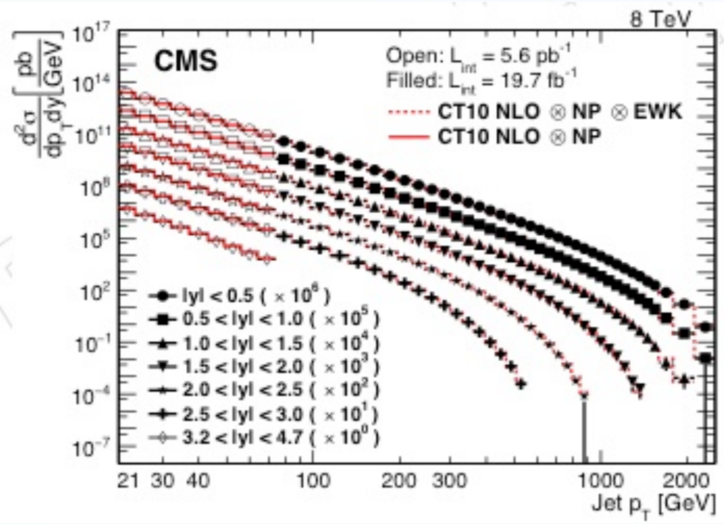


$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \mu^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \mu^-\bar{\nu})}$$

Reducing PDFs uncertainty up to 50%

CMS-PAS-SMP-14-022

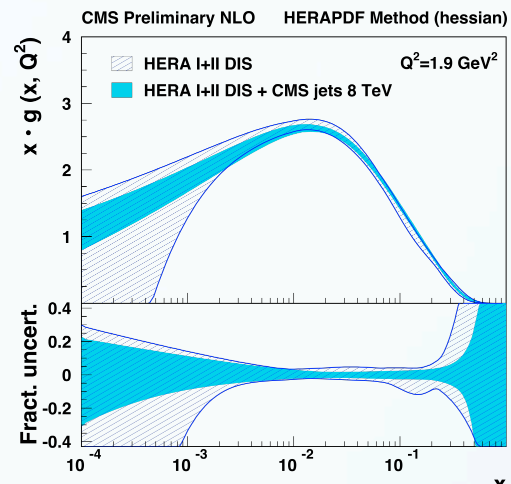
Inclusive jets: PDFs and α_S

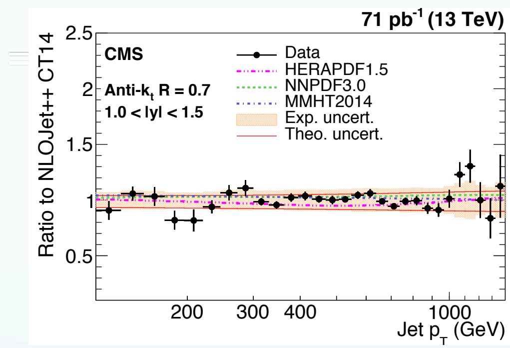


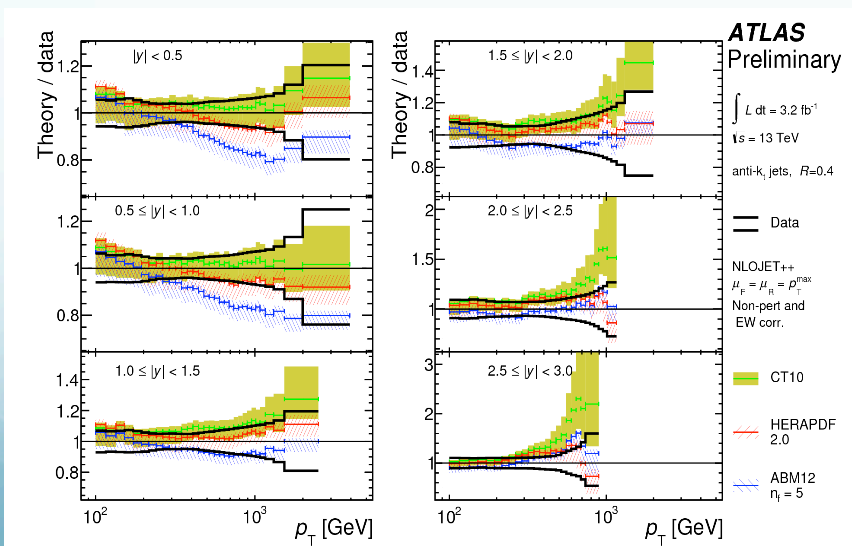
Cross-section is sensitive to α_S to g-pdf in the central region and to q-pdf In forward region.

$$\frac{d^2\sigma}{dp_t dy} \propto \alpha_S{}^2$$

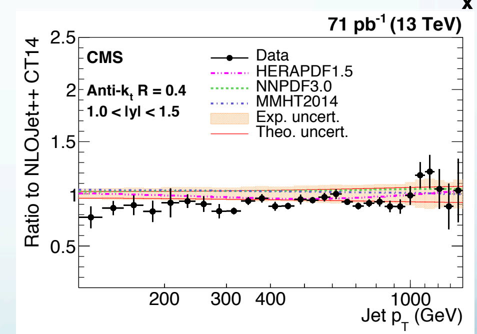
α_S=0.1164+0.0060-0.0043







Both ATLAS and CMS show rather good agreement between data and NLO+NP+EWK (except ABM11 PDF)

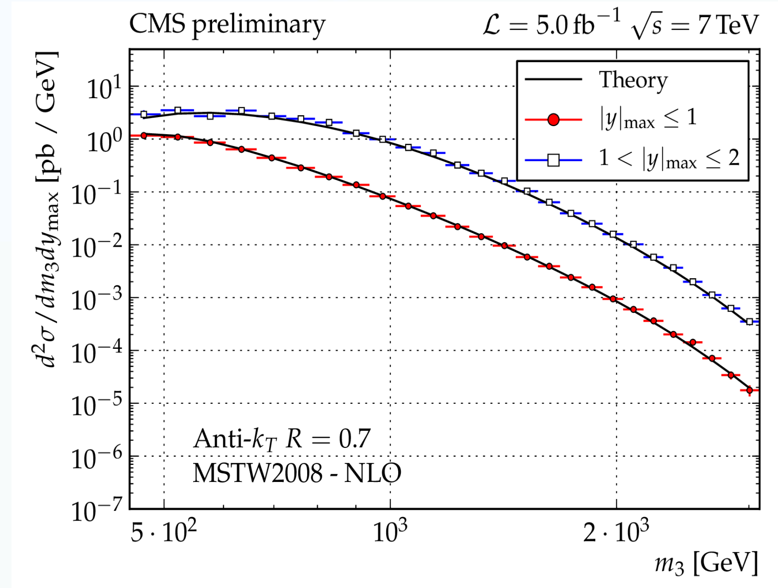


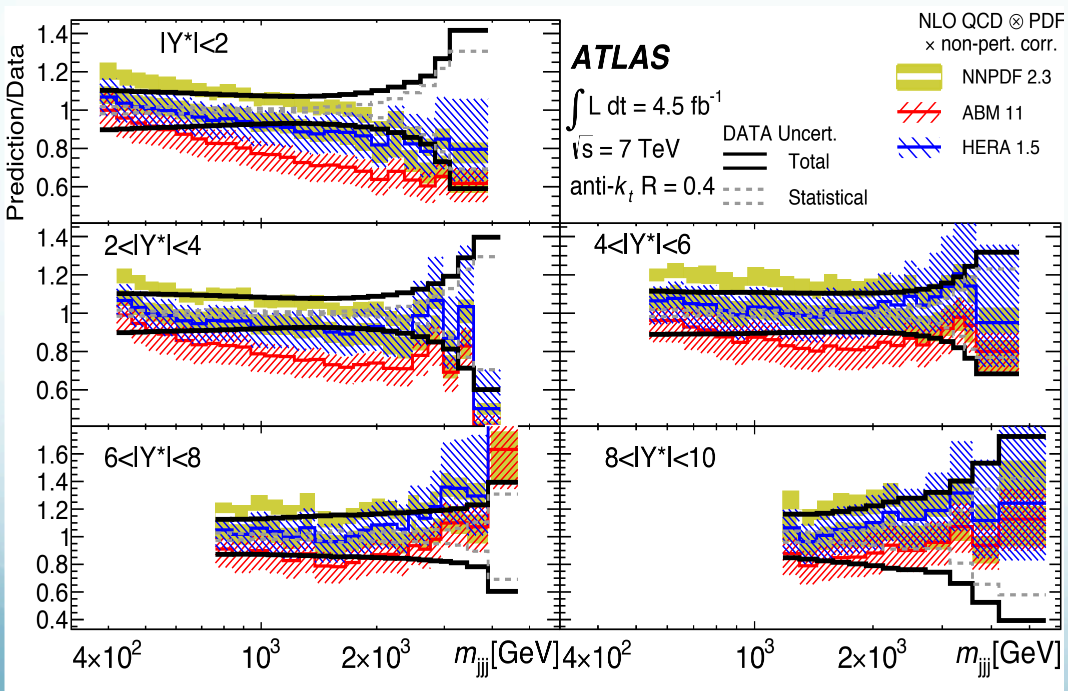
CMS-PAS-SMP-14-001
EPJC (2016) 76, 451
ATLAS-CONF-2016-002

Multijets (3 jets)

NLO with 3-4 partons (NLOJets++) sensitive to PDFs and α_s
$m_3^2 = (p1+p2+p3)^2$, $|y_{max}| = \max(|y_1|,|y_2|,|y_3|)$, $Q = m_3/2$

$$\frac{d^2\sigma}{dp_t dy} \propto \alpha_S{}^3$$



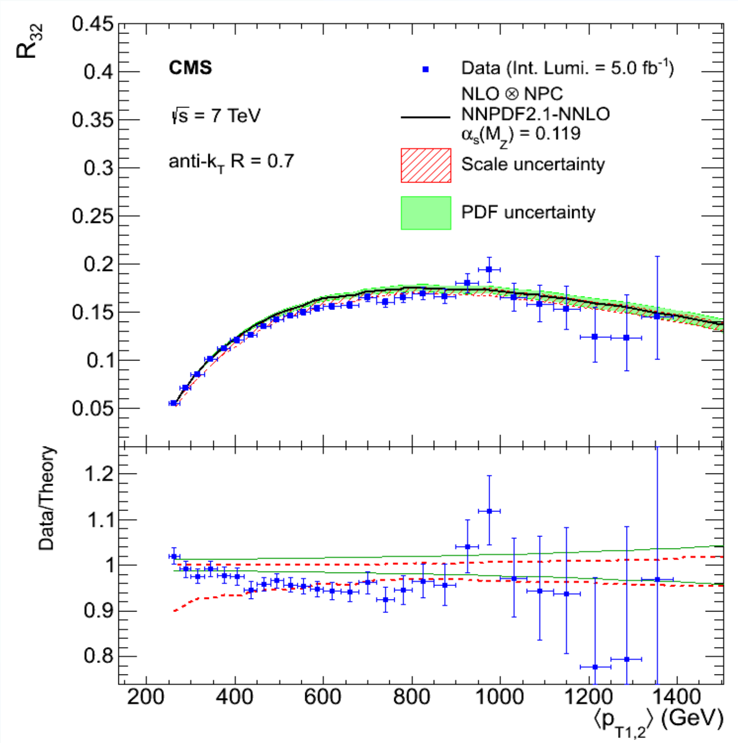


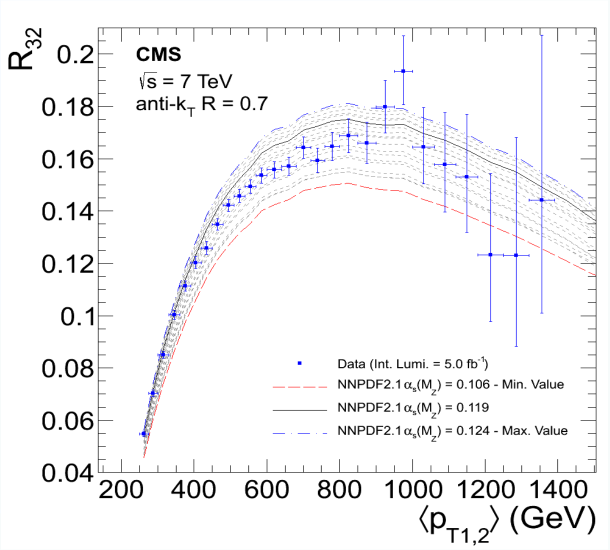
Agreement with pQCD @ NLO x NP
Most PDF sets compatible with data

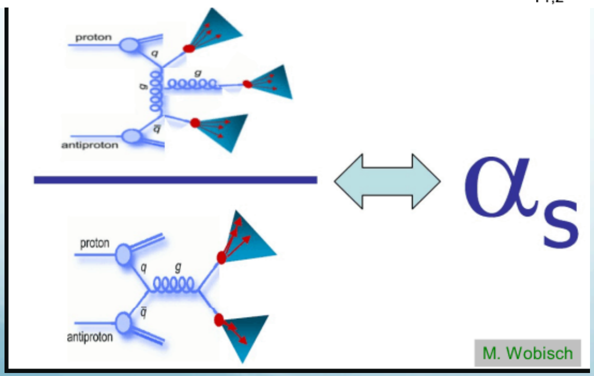
Deviations observed with NLO + ABM11 PDF

EPJC 73 (2013) 2604
CMS-PAS-SMP-12-027
Eur.Phys.J. C(2015) 75

3 over 2 jets ratio







Cross-section ratio R32:

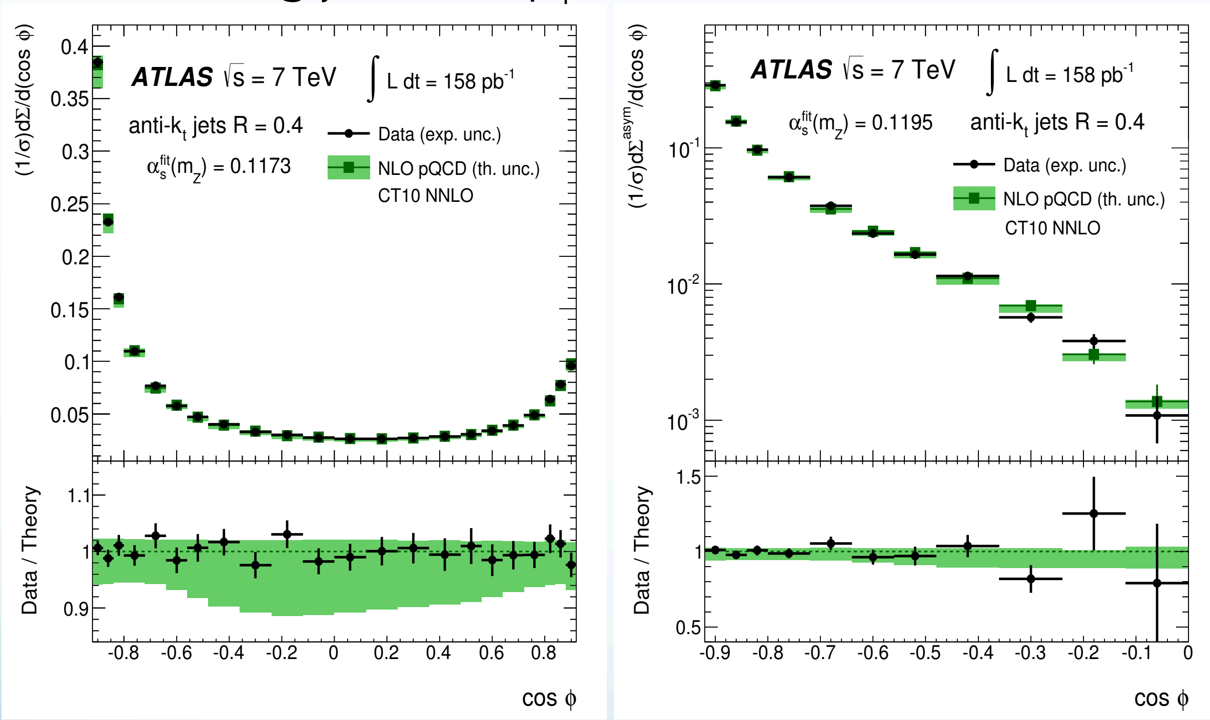
- ❖ **described by CT10 or MSTW2008 deviation observed with ABM11**
- ❖ **Multiple alternative phase-space options depending on the cut imposed on the 3rd jet p_T**

$\alpha_S = 0.1148 \pm 0.0014(exp) \pm 0.0018(PDF) \pm 0.005(theory)$

EPJC 73 (2013) 2604

Transverse energy-energy correlation and a_S measurement

Transverse energy-energy correlation and azimuthal asymetry of the transverse energy-energy correlations as QCD stress-test.
Two leading jets with p_T>250 GeV/c are selected.



$$\frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d(\cos\phi)} x_{Ti}x_{Tj}dx_{Ti}dx_{Tj}$$

$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d(\cos\phi)} \equiv \frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)}\bigg|_{\pi-\phi}$$

ϕ is the $d\phi_{ij}$
$x_{Ti} = E_{ti}/\mathrm{sum}(E_{Ti})$

Advantage: as 3j/2j Ratio TEEC and ATEEC Are less affected by Detector effects

α_S (MZ)= 0.1173±0.0010(exp) ±0.0017(PDF) ±0.0002(NPC) (based on TEE)
α_S (MZ)= 0.1195±0.0018(exp) ±0.0016(PDF) +0.0060-0.0015(scale) (based on ATEE)

Phys.Lett. B750(2015) 427-447

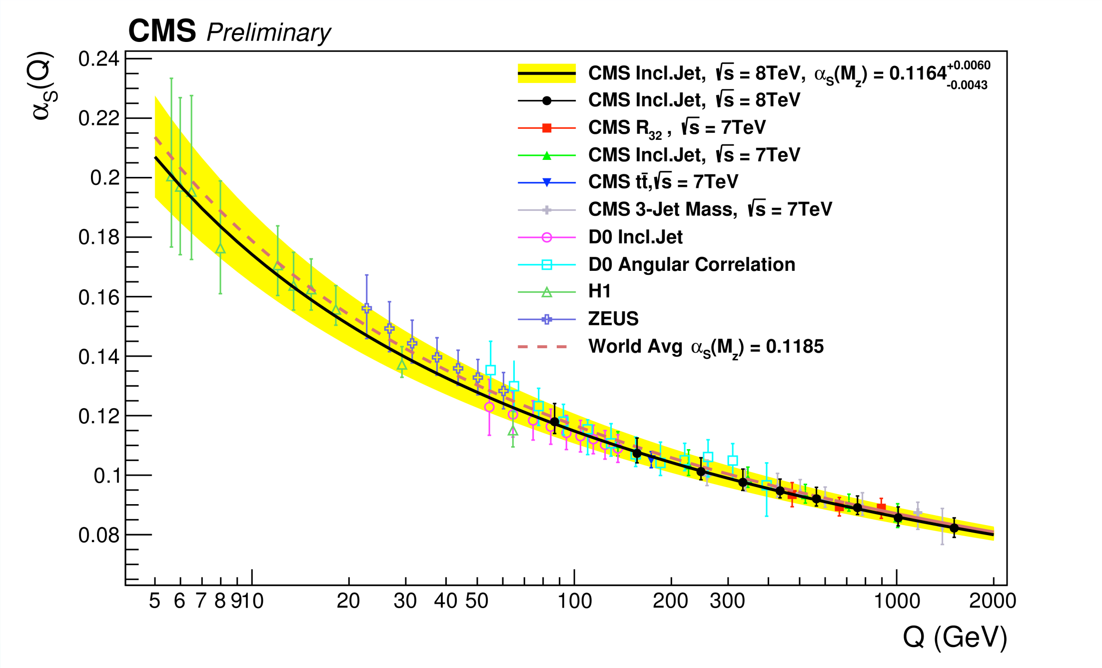
Summary of α_S extraction

LHC at 7 TeV and 8 TeV enables measurements up to 2 TeV

Theory at NLO and NNLO (tt cross-sections) plus the additional electroweak corrections

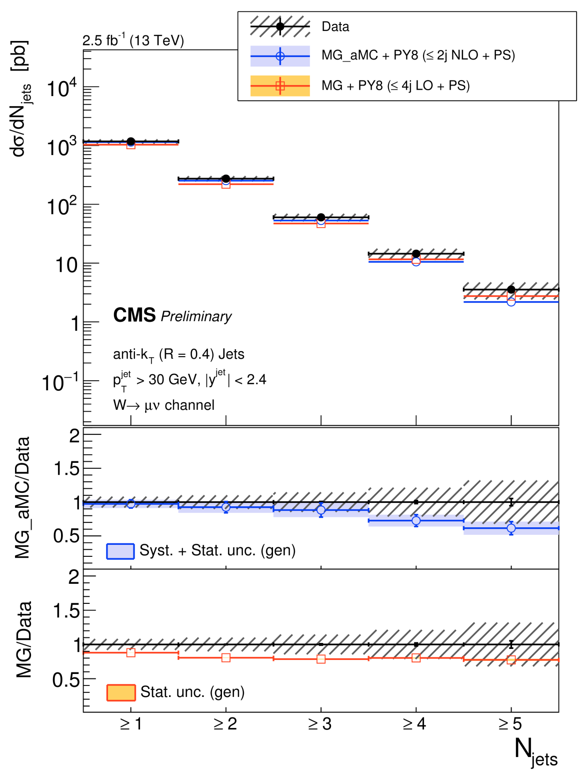
Typical uncertainty:

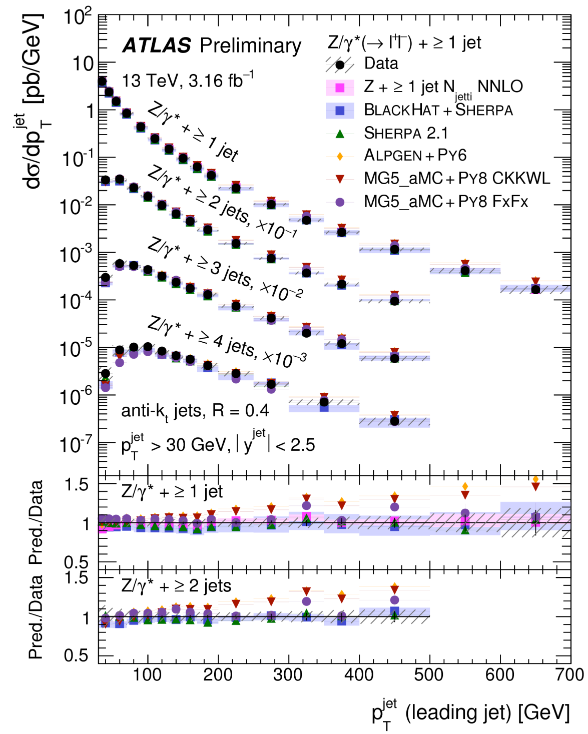
Experimental	**1-2%**
PDF	**1-2%**
Scale	**4-5%**
Non-perturbative effects	**<1%**
Other theory uncertainties	**?**

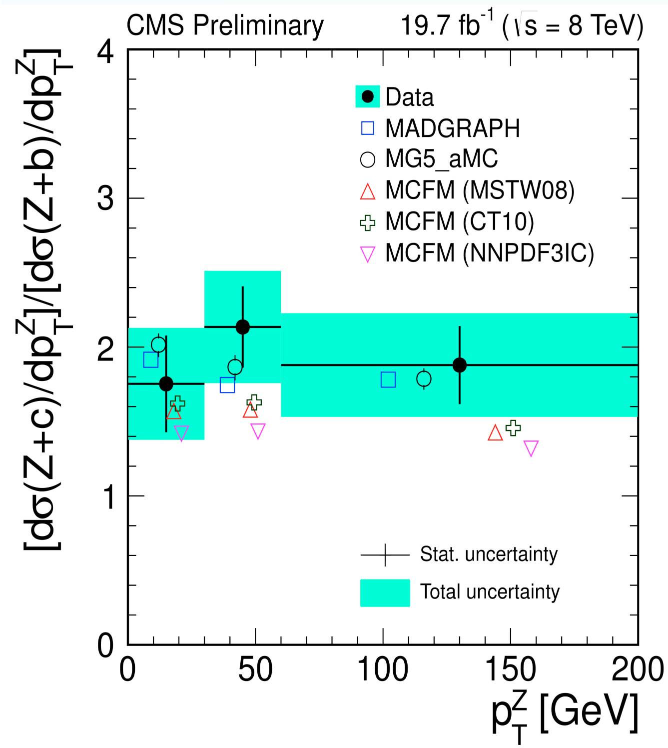


CMS-PAS-SMP-12-028
CMS-PAS-SMP-14-001

W/Z+jets





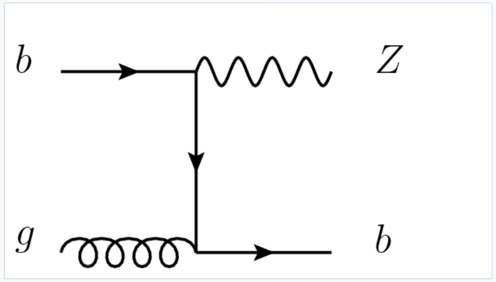


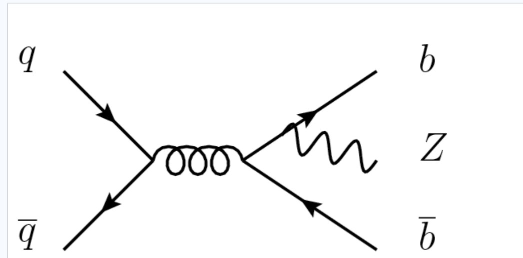
σ(pp->Z+c+X)=8.6±0.5(stat) ±0.7(syst)pb

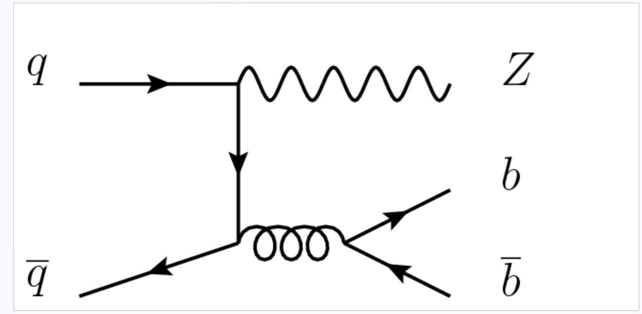
Test predictions of pQCD – give better understanding of strong interactions
And proton structure (intrinsic charm in proton)
Major background for the major of searches

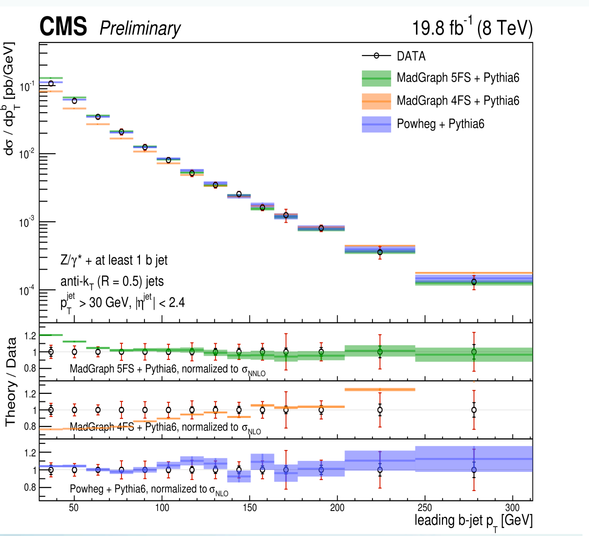
CMS-PAS-SMP-15-009
CMS-PAS-SMP-16-005
ATLAS-CONF-2016-046

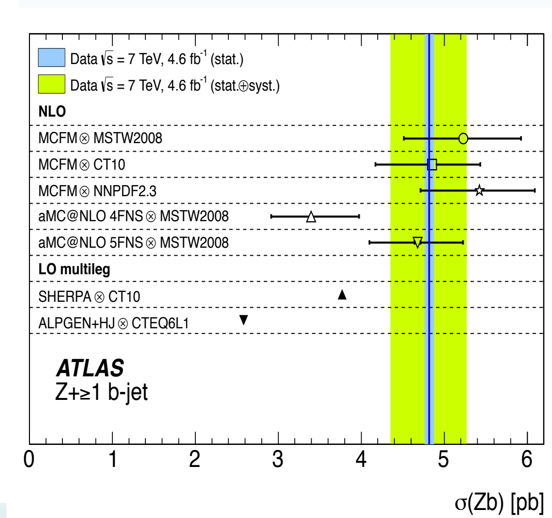
Zb(b) production at 7 and 8 TeV











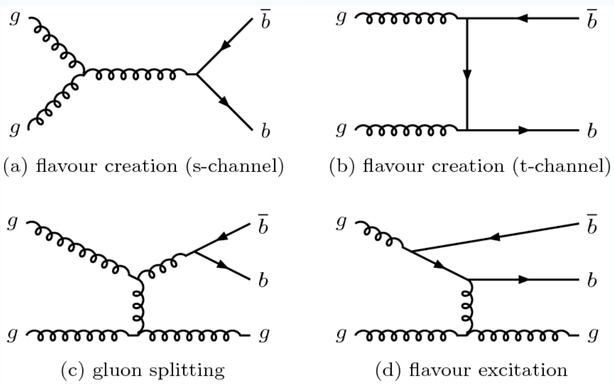
Test of 4 vs 5 QCD Flavors
Background to VH(->bb)

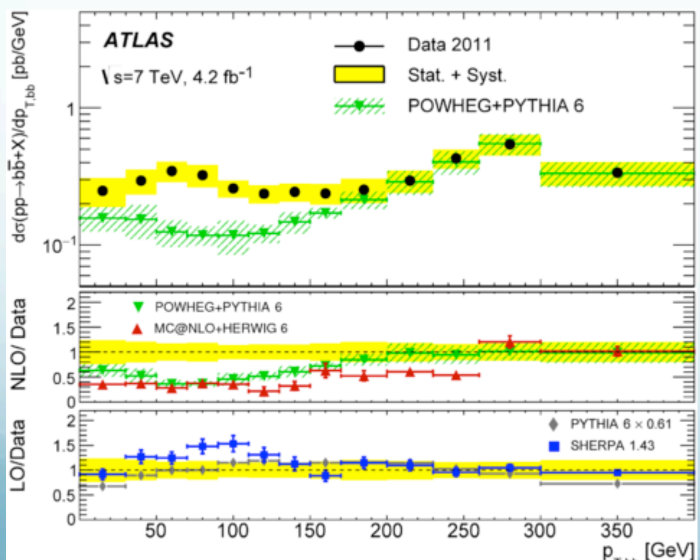
Unfolded spectra are compared with LO ME Madgraph + Pythia6
ALPGEN+HERWIG
NLO: Powheg+Pythia6
AMC@NLO
MCFM

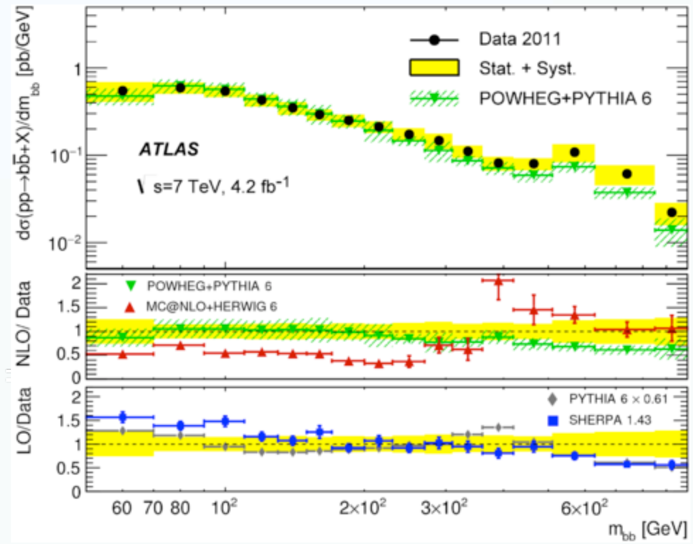
No clear preference to 4 or 5 QCD Flavors

JHEP 1406 (2014) 120
JHEP 10 (2014) 141

$b\bar{b}$ production







+ a set of other kinematical distributions available in this analysis.

Bottom line:
Current MC generators have significant difficulties in describing regions of phase space which are not dominated by two hard b-jets.

arXiv:1607.08430

Summary

- **ATLAS and CMS measure both hard and soft QCD processes in various phase space regions and compare them with a wide range of LO and NLO calculations**

- **ATLAS and CMS measurements are used for the combinations with other experiments in global fits and in Monte-Carlo Models tuning. Validation of the QCD predictions (scaling properties, particles spectra, strong coupling behaviour, PDFs, evolution, etc) allows to further constrain and tune existing models.**

More results can be found in ATLAS and CMS public web page:

http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

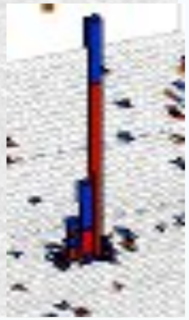
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ

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

Back-up

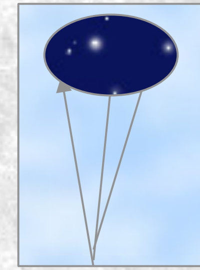
Jet reconstruction in detector

Calorimeter jets (CaloJets):
Jet clustered from Calorimeter Towers (CMS,ATLAS) Or TopoClusters (ATLAS)
CaloMET



Anti-Kt clustering algorithm is applied to the different objects

Tracker jets (TrackJets):
Jet clustered from Tracks

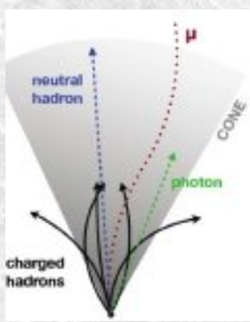


Subdetectors: Tracker

(ATLAS,CMS)

ParticleFlow jets (PFJets):
Jet clustered from Particle Flow objects (a la generator level particles) which are reconstructed based on cluster separation.
Subdetectors: ECAL,HCAL, Tracker, Muon

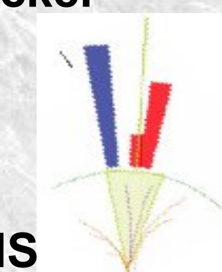
PFMET **CMS**



All subdetectors participate in reconstruction

The residual jet energy corrections is applied on top of all algorithms

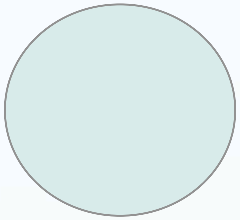
JetPlusTrack jets (JPTJets):
Starting from calorimeter jets tracking information is added via subtracting average response and replacing with tracker measurements.
Subdetectors: ECAL,HCAL, Tracker, Muon
TcMET **CMS**

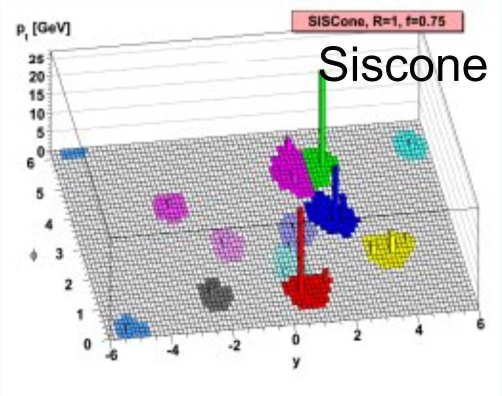


Jet clustering technique

Fixed cone algorithms:
- **Iterative Cone (CMS) / JetClu (ATLAS)**
- **Midpoint algorithm (CDF/D0)**
- **Seedless Infrared Safe Cone (SISCone)**

Iterative cone



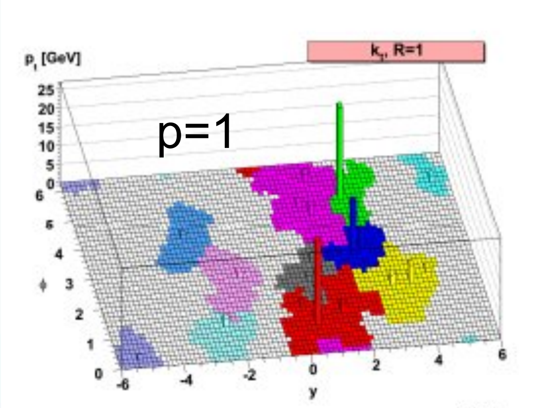


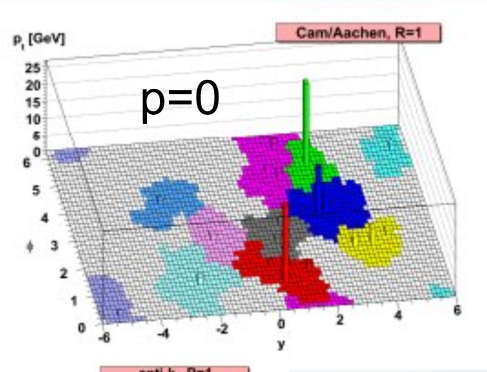
Successive recombination algorithms:

$$d_{ij} = min\left(k_{ti}^{2p}, k_{tj}^{2p}\right)\frac{\delta_{ij}^{2}}{R^{2}}$$

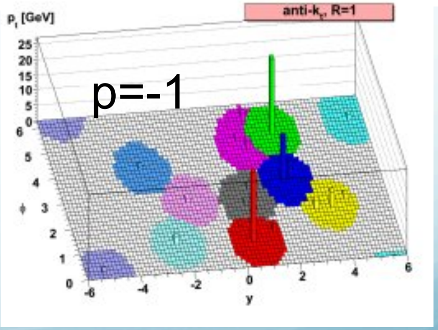
$$d_{iB} = k_{ti}^{2p}$$

if($d_{ij} < d_{iB}$) add i to j and recalculate p_j





p=1 ->k_T jet algorithm
p=0 ->CA jet algorithm
p=-1 ->"Anti-k_T" jet algorithm



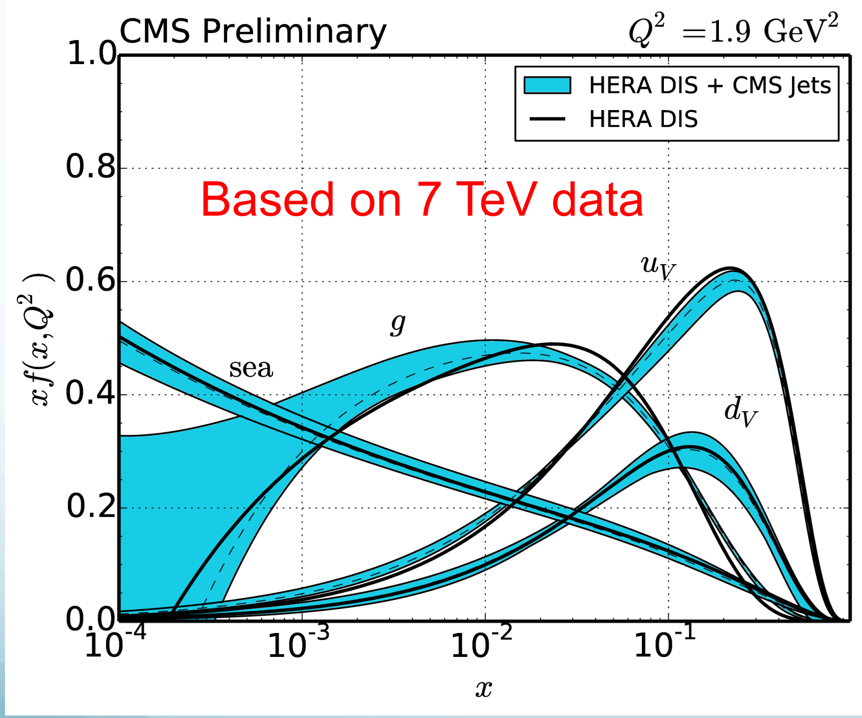
CMS uses R=0.5,0.7 in Run1
R=0.4,0.6 in Run2
ATLAS uses R=0.4,0.6

JHEP 1009 (2010) 091

Inclusive jets: PDFs and α_S

Combined fit of HERA DIS and CMS inclusive jets data is performed using DGLAP evolution at NLO with two options:

- **with fixed $\alpha_S(M_Z)=0.1176$**
- **simultaneous fit of PDFs and α_S**



Cross-section is sensitive to g-pdf in the central region and to q-pdf In forward region:

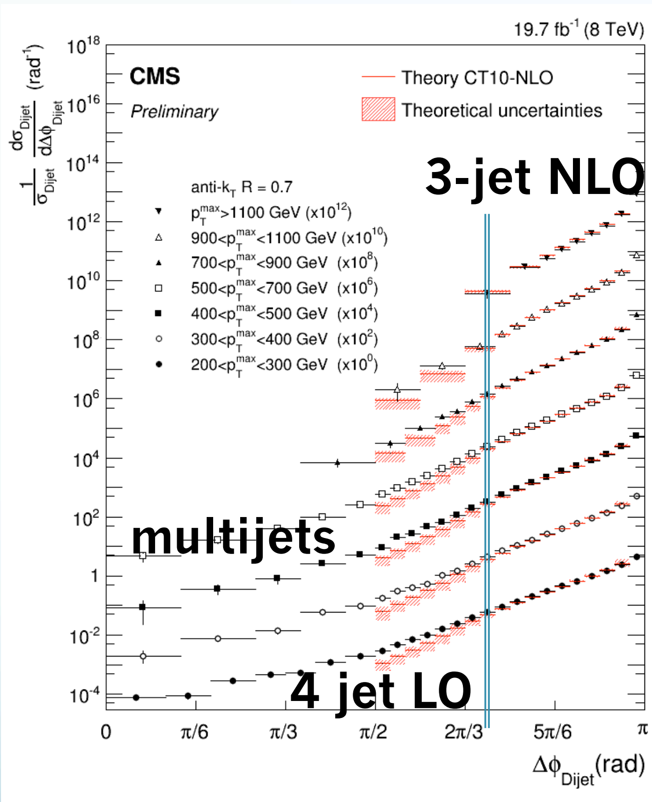
- **Change of gluon pdf at middle and high-x**
- **Slight change of d_{val} quark distribution**

$\alpha_s(M_Z)$ is extracted for each PDF set and from simultaneous fit of PDFs and α_S

CMS-PAS-SMP-12-028
see arXiv:1410.6765
JHEP1009 (2010)091

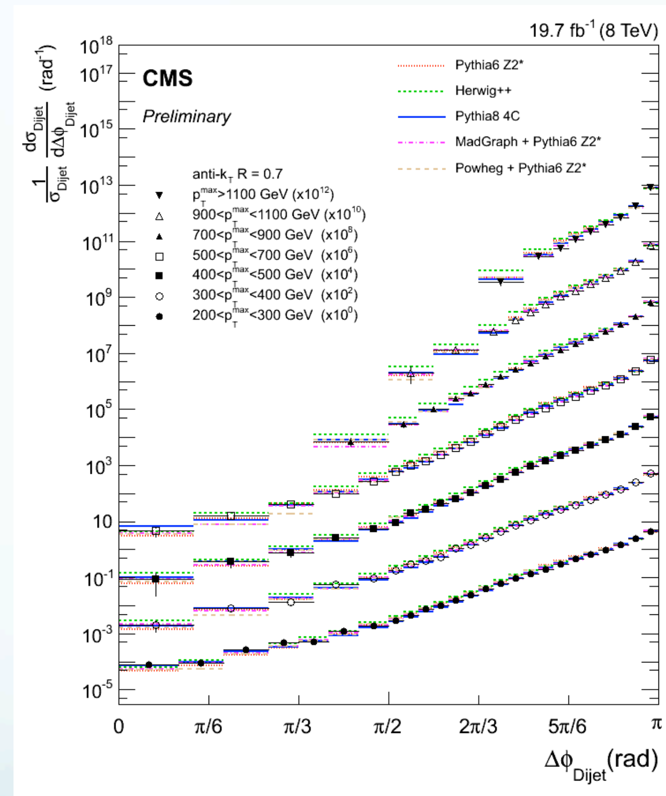
Azimuthal decorrelations at 8 TeV

$\Delta\phi_{jj}$ in bins of p_{T1} for p_T>100 GeV, p_{T1}>200GeV, $|y_1|$<2.5, $|y_2|$<2.5



Comparison is done with fixed-order pQCD (NLO)

And with LO ME+PS



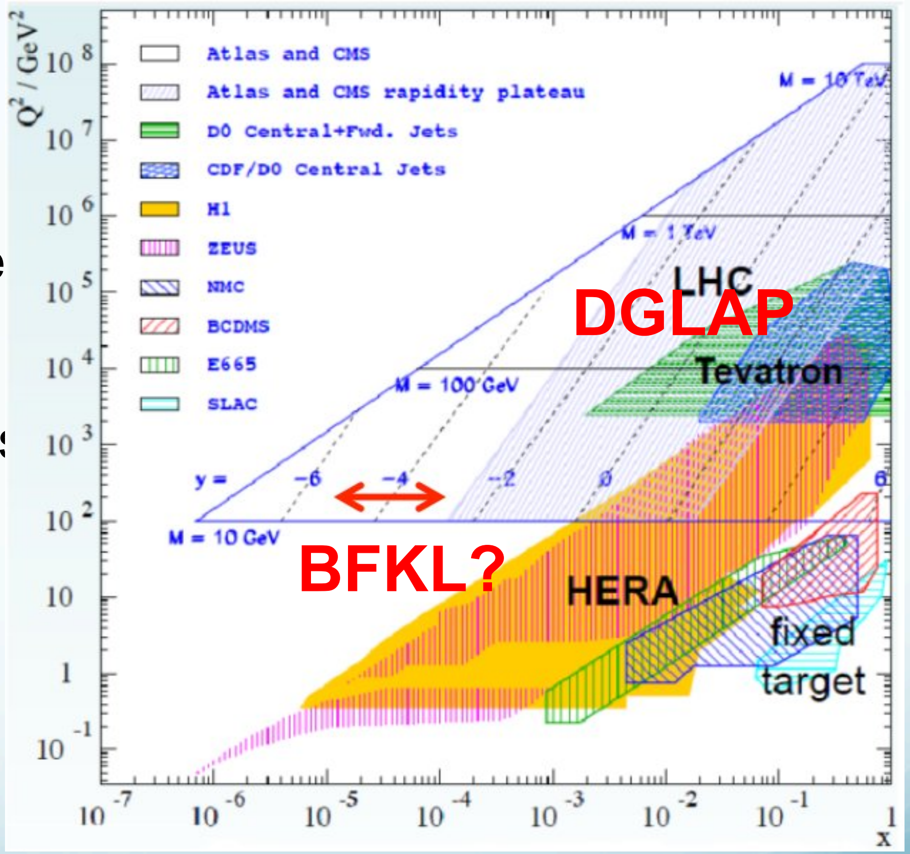
CMS-PAS-SMP-14-015

QCD Evolution equation

Connection between various scales in QCD (for instance, between PDF and the high-momentum scattering) is performed via evolution differential equations.

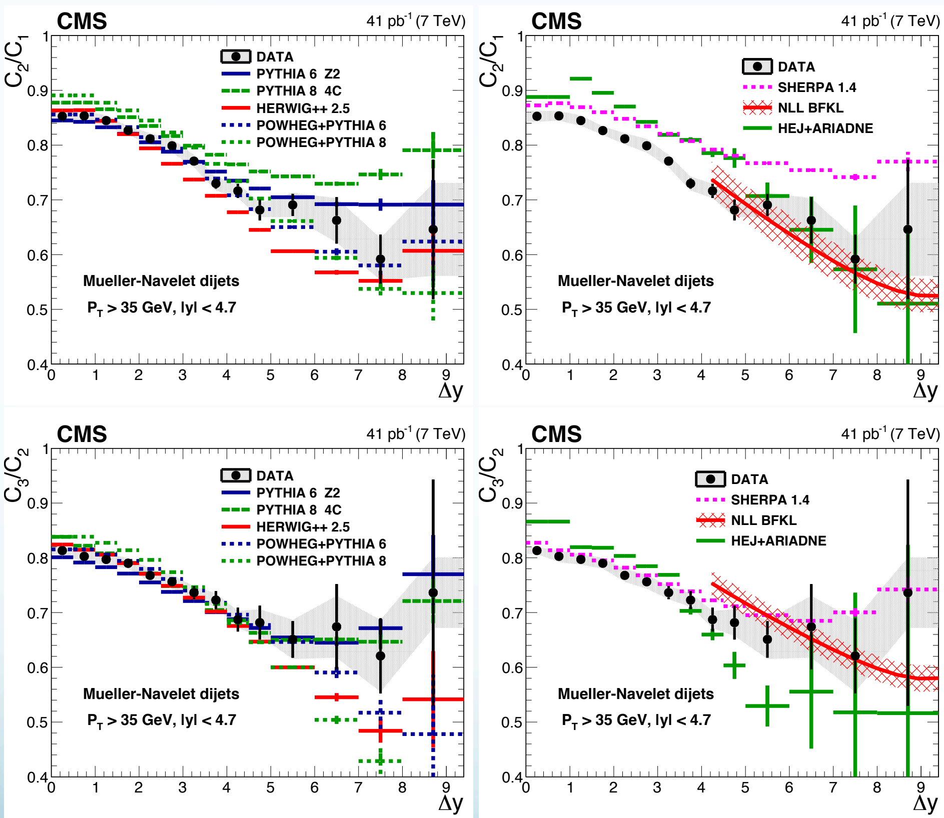
In small-x region standard approach to NLO QCD perturbative calculations.
DGLAP (expansion in terms of power of $a_S \ln(Q^2)$) is predicted to be not sufficient.

Need to develop alternative approaches
BFKL (expansion in terms of ln(1/x)).
CCFM angular and energy ordering
LDC (Linked dipole chain)
…
Non perturbative effects, Multi Parton Interaction (MPI) etc. models have to be tuned to data.



Angular correlations of jets

- Events with at least two jets passing cuts: p_T>35 GeV in |η|<4.4
- For a pair of jets with the largest Δη (CMS) the angular distance is calculated: Δφ = φ1 – φ2



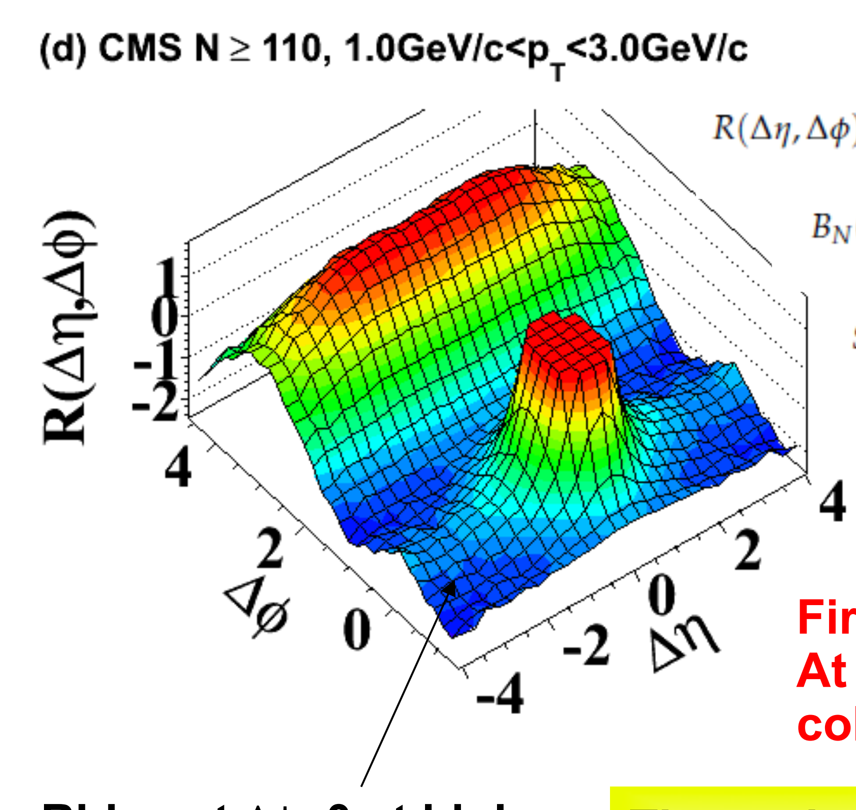
$C_n(\Delta y, p_{Tmin}) = \langle \cos(n(\pi - \Delta\phi)) \rangle$

DGLAP generators starts to be worse in high Δy description

An analytical BFKL Calculations at NLL Accuracy with an optimized renormalization schema Provide reasonable description of Data for the measured jet Variables at Dy>4

JHEP08(2016)139

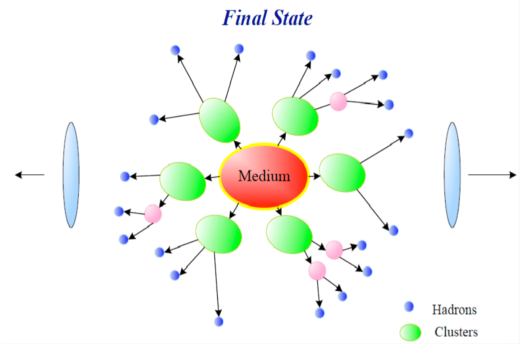
Long-range correlations

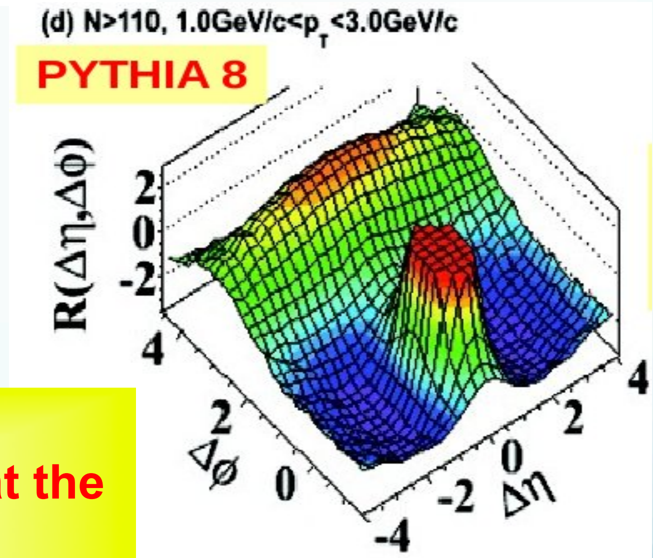


$$R(\Delta\eta,\Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

$$B_N(\Delta\eta,\Delta\phi) = \frac{1}{N^2}\frac{d^2N^{\text{mixed}}}{d\Delta\eta d\Delta\phi}$$

$$S_N(\Delta\eta,\Delta\phi) = \frac{1}{N(N-1)}\frac{d^2N^{\text{signal}}}{d\Delta\eta d\Delta\phi}$$





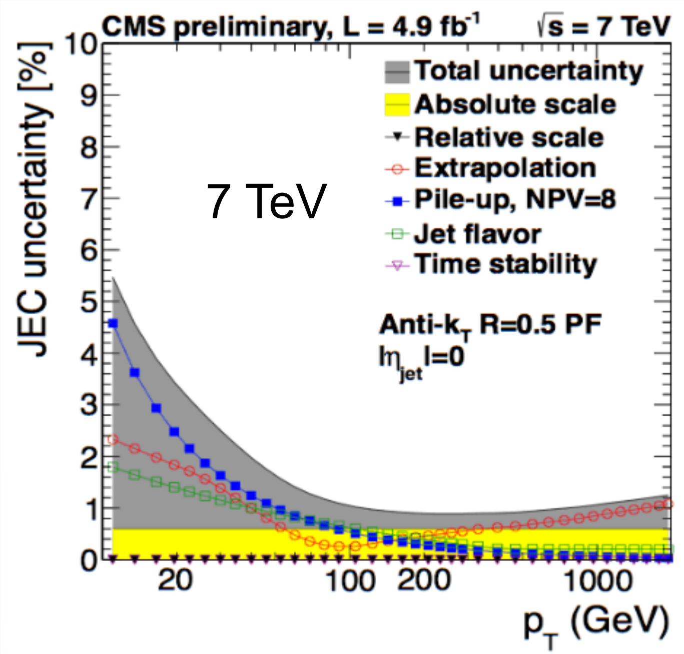
Firstly observed At RHIC in Au-Au collisions

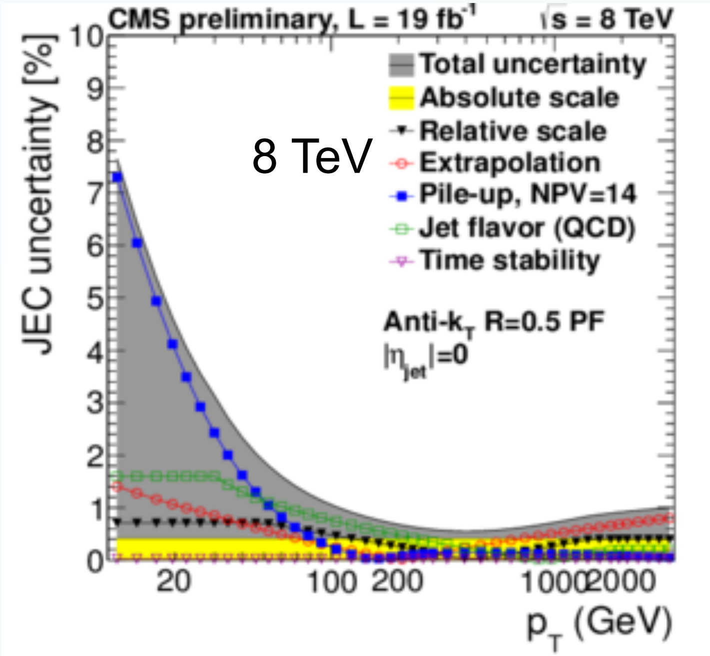
Ridge at Δϕ~0 at high multiplicity in pp events at intermediate pT

Theoretical hypothesis:
- collective parton flow at the initial or final state
EPOS and some other models can describe the effect

JHEP 1009:091,2010

Jet energy scale uncertainties





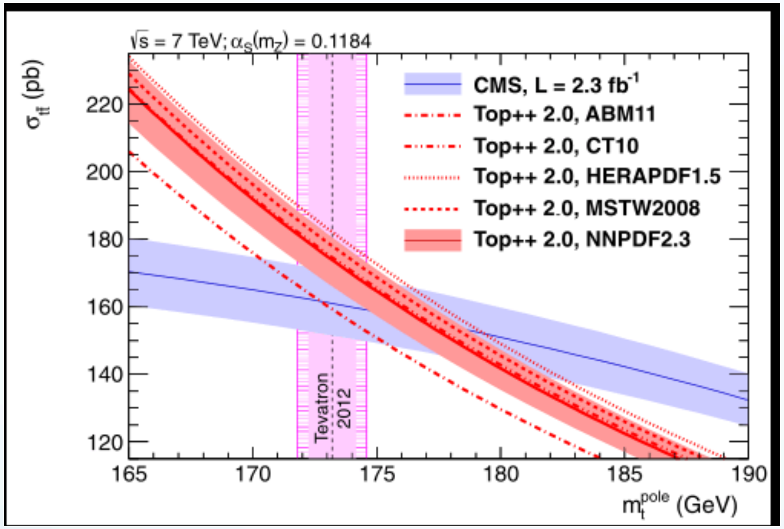
Sources of the jet energy scale distortion

- ❖ **Calorimeter response**
- ❖ **Magnetic field**
- ❖ **Electronic noise**
- ❖ **calorimeter thresholds**
- ❖ **Dead materials and cracks**
- ❖ **Longitudinal leakage**
- ❖ **Shower size, out of cone loss**
- ❖ **pileup contribution**

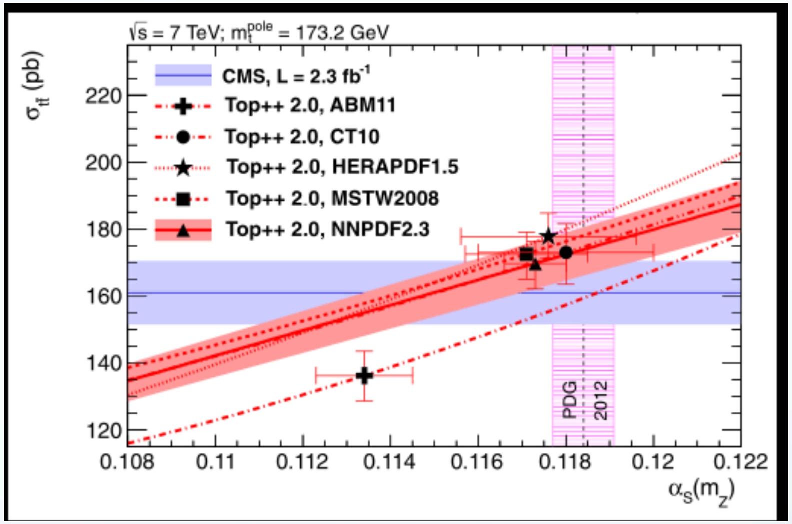
JINST 6 P11002 (2011)
CMS DP-2012-006
CMS-DP-2013-033

α_S fit with top production

Top pairs production is sensitive to m_t^{pole}, $g(x,\mu^2_F)$, α_S. The main production process is from gg.
Cross-section measurement (dilepton channel). Combined fit is not possible.
Fit is performed fixing one of the 5 PDF sets within NNLO+NNLL approximation.



Fix α_S -> constrain m_t^{pole}



Fix m_t^{pole} -> constrain α_S

$$\alpha_S = 0.1151 \pm 0.0025(\text{exp})^{+0.0013}_{-0.0011}(\text{PDF}) \pm 0.0013(m_t^{pole}) \pm 0.0008(E_{LHC})$$

CMS, PLB 728, 496 (2013)
JHEP 11, 067 (2012)