Soft and Hard QCD Processes in CMS

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On behalf of the CMS Collaboration
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WE-Heraeus Physics School

QCD – Old Challenges and New Opportunities

Bad Honnef, Sept 24–30, 2017

Thanks to WE-Heraus Foundation and School organizers: R. Schicker and A. Szczurek

Outline

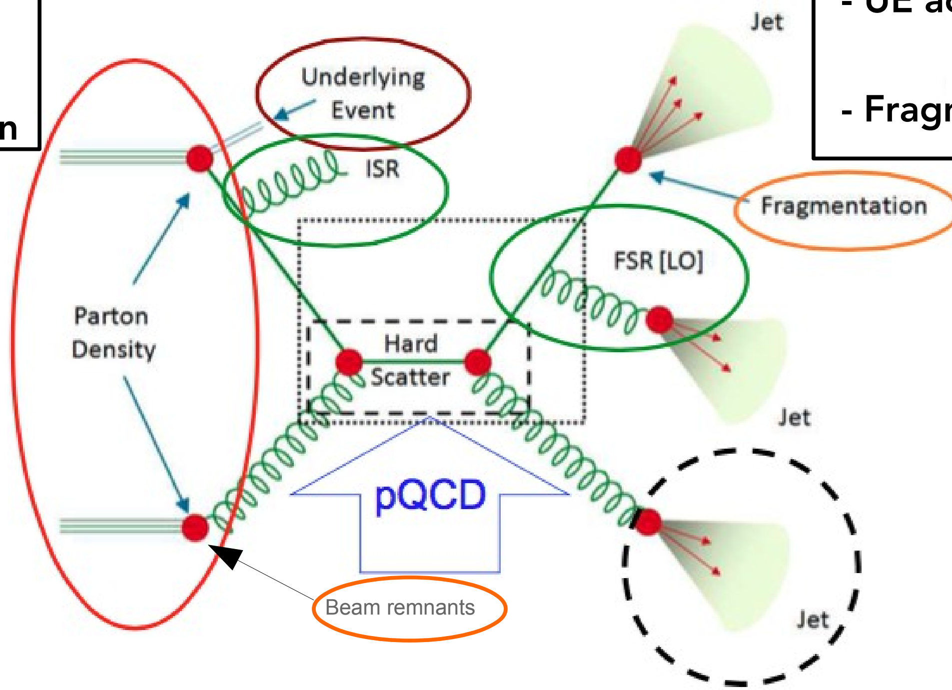
- Introduction
  - QCD at LHC
- CMS Detector
- QCD measurements on the LHC data (Run I and Run 2)
  - Soft QCD
  - Hard QCD
- Summary

QCD at the LHC

- The main goal of QCD studies is to improve our detailed description of the SM physics.
- QCD is the theory of strong interaction describing the interactions between quarks & gluons

Hard QCD
- Perturbation theory pQCD
- PDFs
- Initial & final state radiation (ISR, FSR)
- Parton shower & hadronization

Theoretically



Soft QCD
- Multiparton scattering
- UE activity
- Fragmentation

QCD at the LHC

- The main goal of QCD studies is to improve our detailed description of the SM physics.
- QCD is the theory of strong interaction describing the interactions between quarks & gluons

Hard QCD
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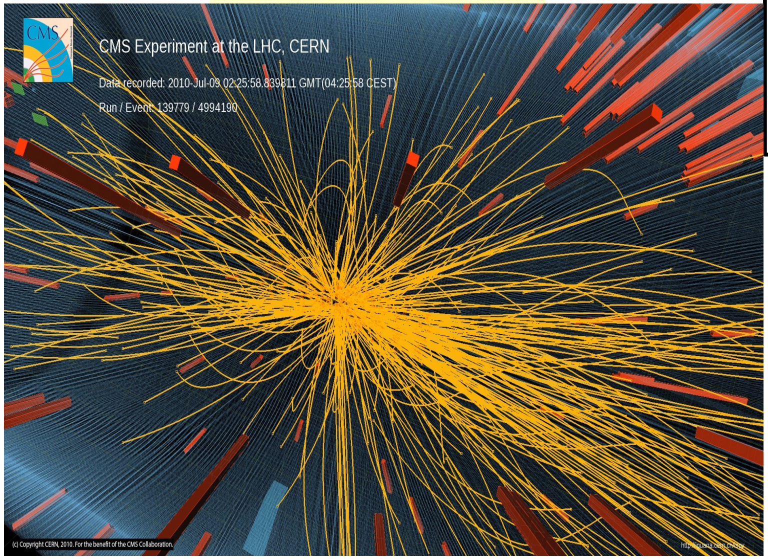
Experimentally

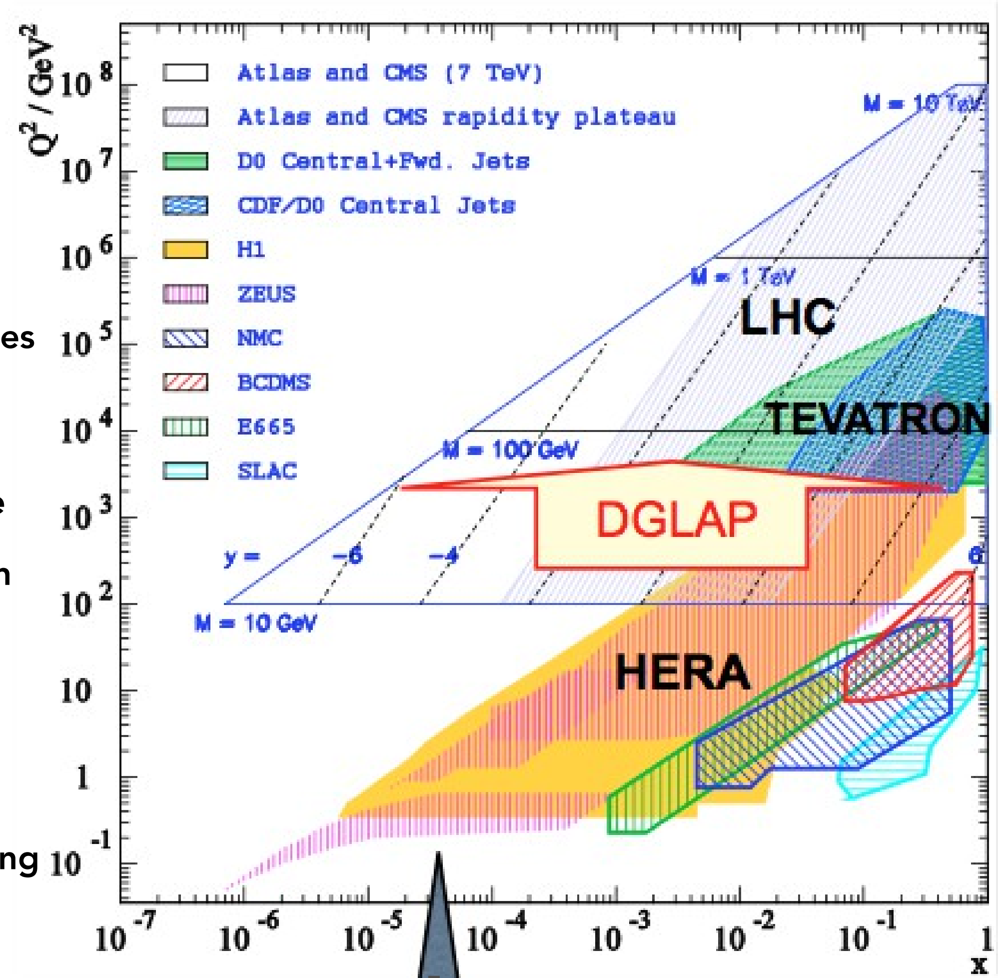


Soft QCD
- Multiparton scattering
- UE activity
- Fragmentation

- QCD events are immensely complicated
  - theoretical predictions very hard
  - Experimental challenges
- Studies of QCD are key to understand production of all (B)SM signals & backgrounds at the LHC.

Why care about the QCD?

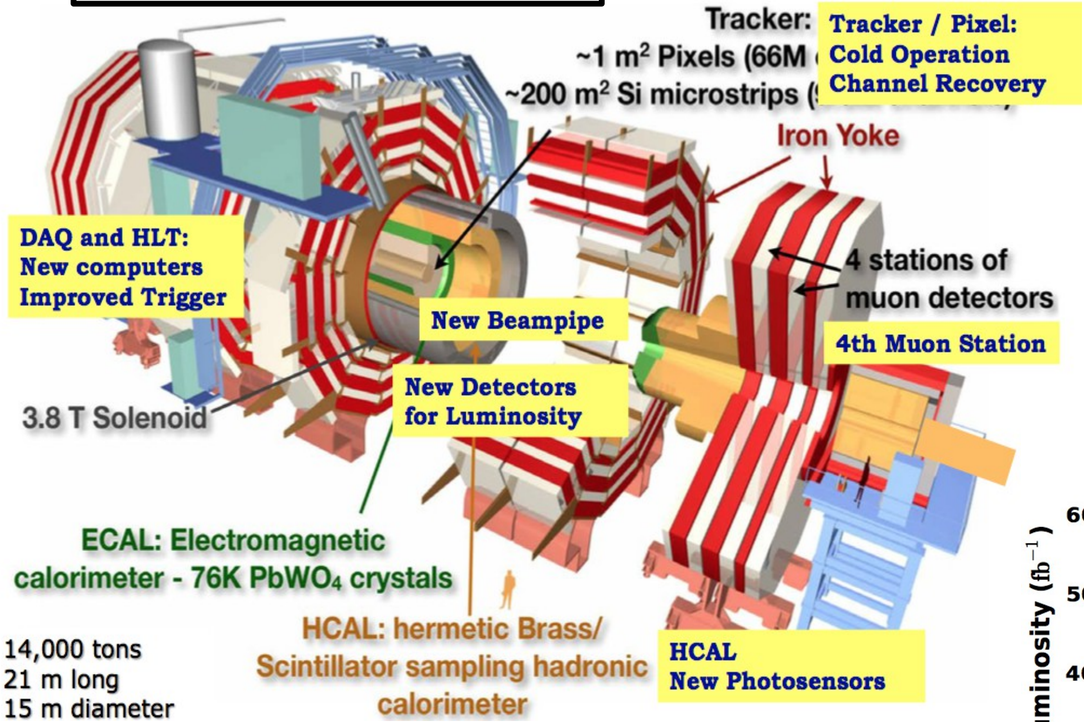
- Very rich and interesting theory:
  - needs to be better understood
  - deserves exploration
- QCD measurements are important for
  - data interpretation
  - precise studies
  - sizable background for new physics searches
- LHC provides
  - unexplored & accessible large phase space
  - many various final states to study with high accuracy
  - tests pQCD in a new energy regime (totally unexplored kinematic region).
  - provide constraints on PDFs, measure strong coupling constant,
  - study initial and final state radiation
  - fragmentation and parton showering effects.
  - tune MC generators to better describe the data



Experimental access to large phase space

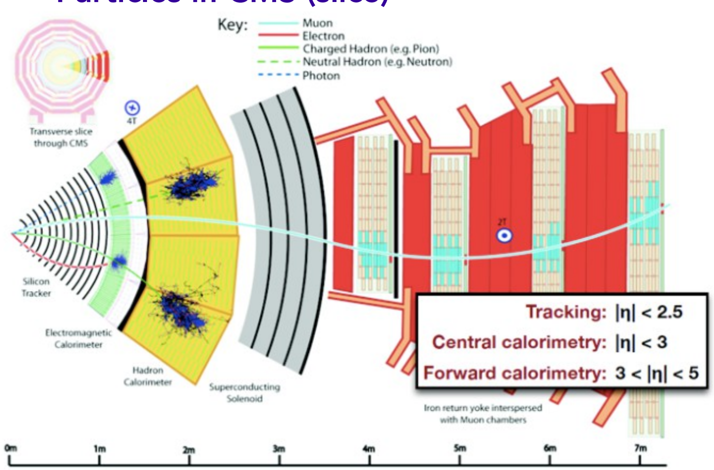
CMS Detector

CMS after Long Shutdown 1

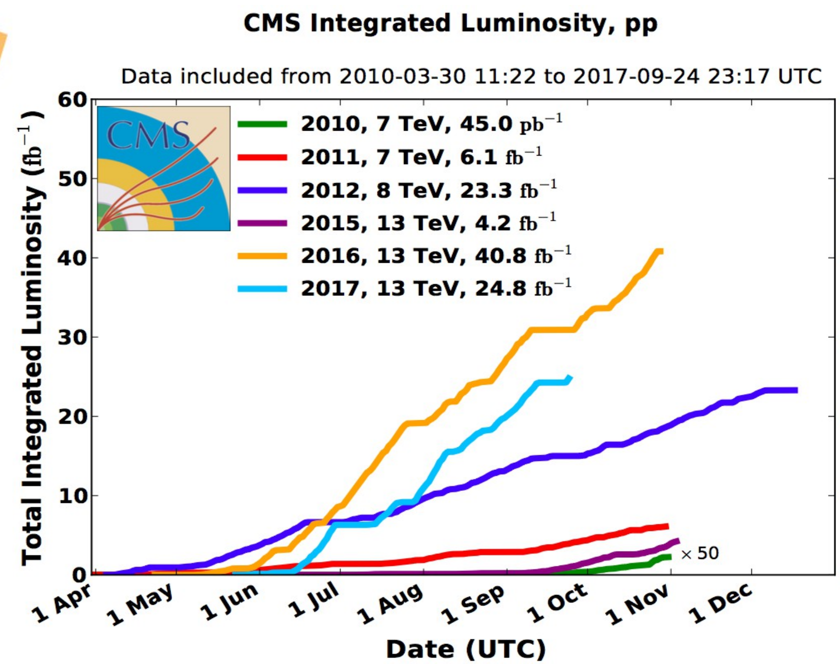


3rd of June 2015: LHC back in business with record pp collision energy of 13 TeV

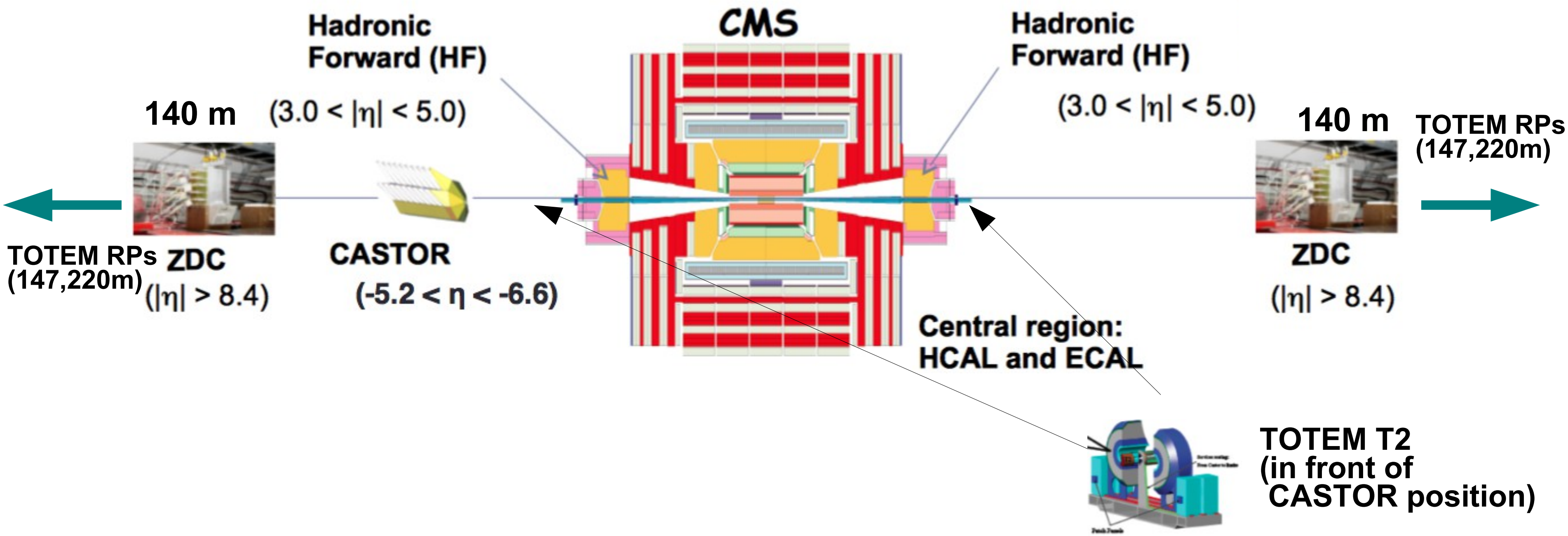
Particles in CMS (slice)



Run I and II pp collisions



Forward Detectors at CMS

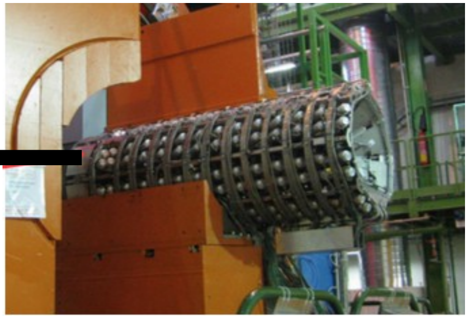


HF Detector

- @11.2 m from interaction point
- Rapidity coverage: **3 < |η| < 5**
- Steel absorbers/quartz fibers (Long+short fibers)
- 0.175x0.175 η/φ segmentation

- Tungsten-Quartz-Cherenkov sampling calorimeter
- Octagonal cylindrical shape
- Segmented in 16 sectors in φ and 14 modules in z
- Separated electromagnetic and hadronic sections
- Located at 14.4 m from IP in CMS

CASTOR

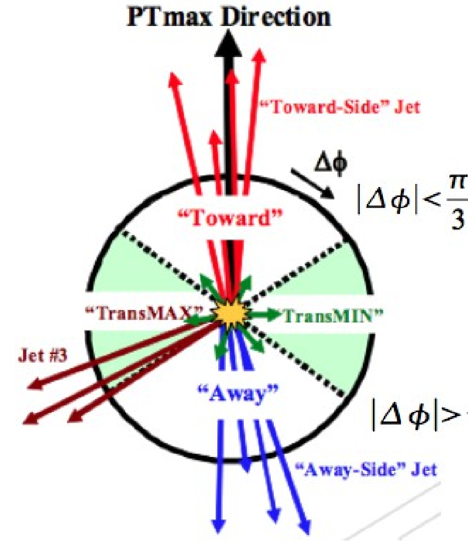


Soft QCD & radiation effects

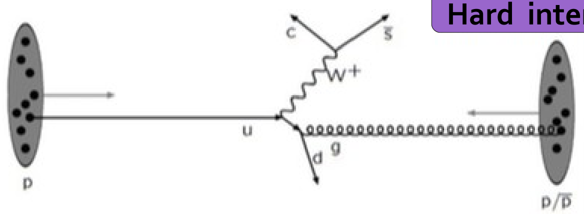
Underlying Event

- A hard p-p collision at LHC can be interpreted as a hard scattering between partons accompained by Underlying Event (UE) consisting of:
  - Initial and final state radiation (ISR & FSR)
  - Beam - Beam remnants (BBR)
  - Multiple (soft) Parton Interactions (MPI)

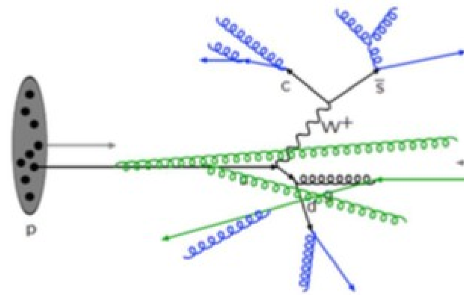
  } cannot be separated experimentally
- Non-pertubative QCD – only models
  - measurements important for tuning
- Many measurements: require hard object, split event into three regions
  - Toward : close to leading object
  - Away : recoil of leading object
  - Transverse: sensitive to UE



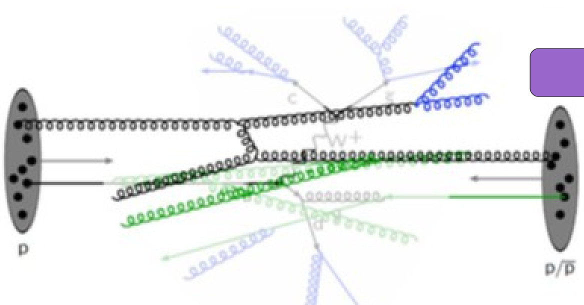
Hard interaction



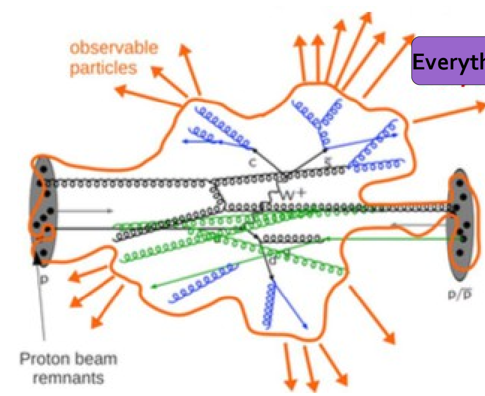
ISR/FSR



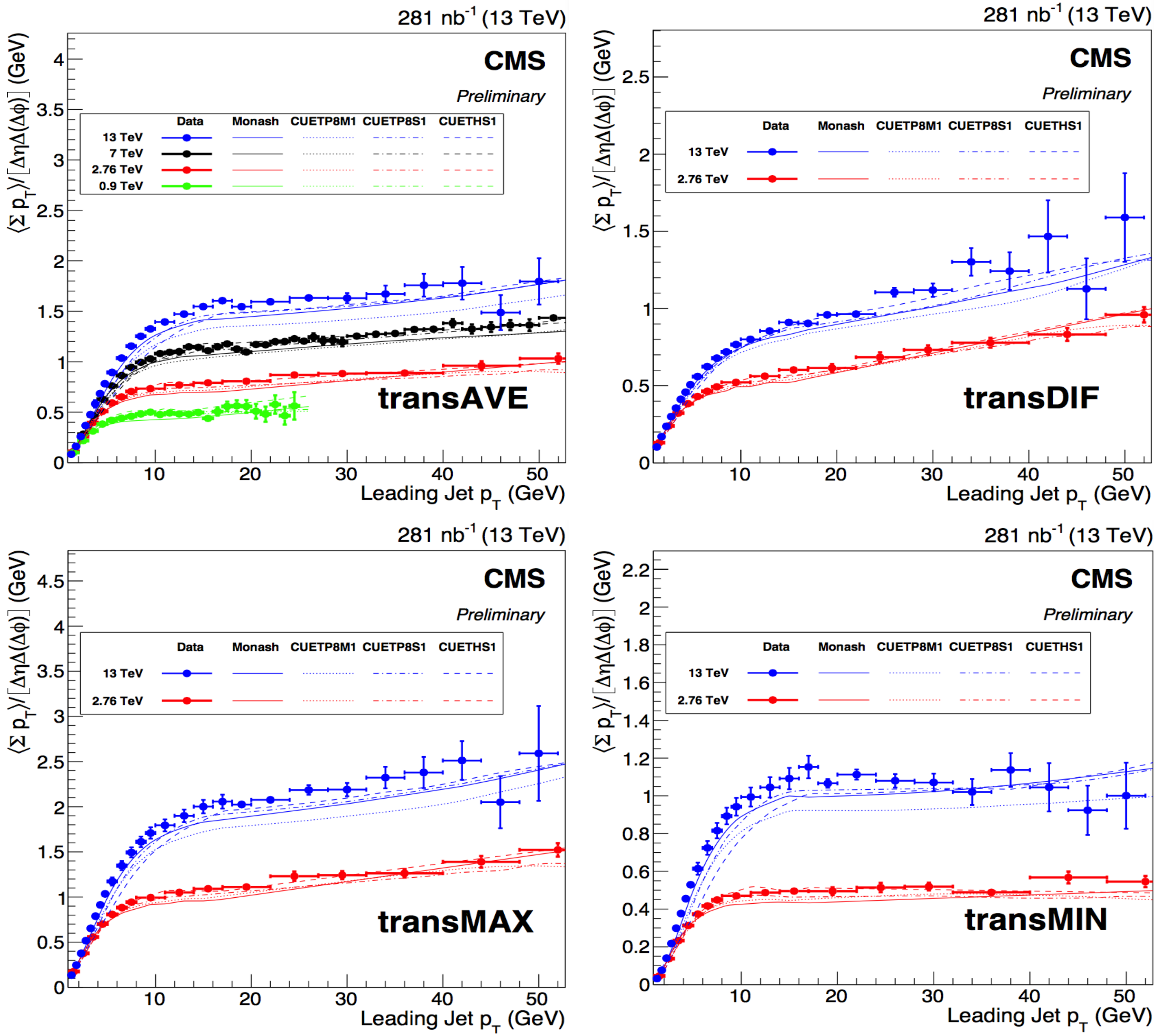
MPI



Everything+hadronistaion



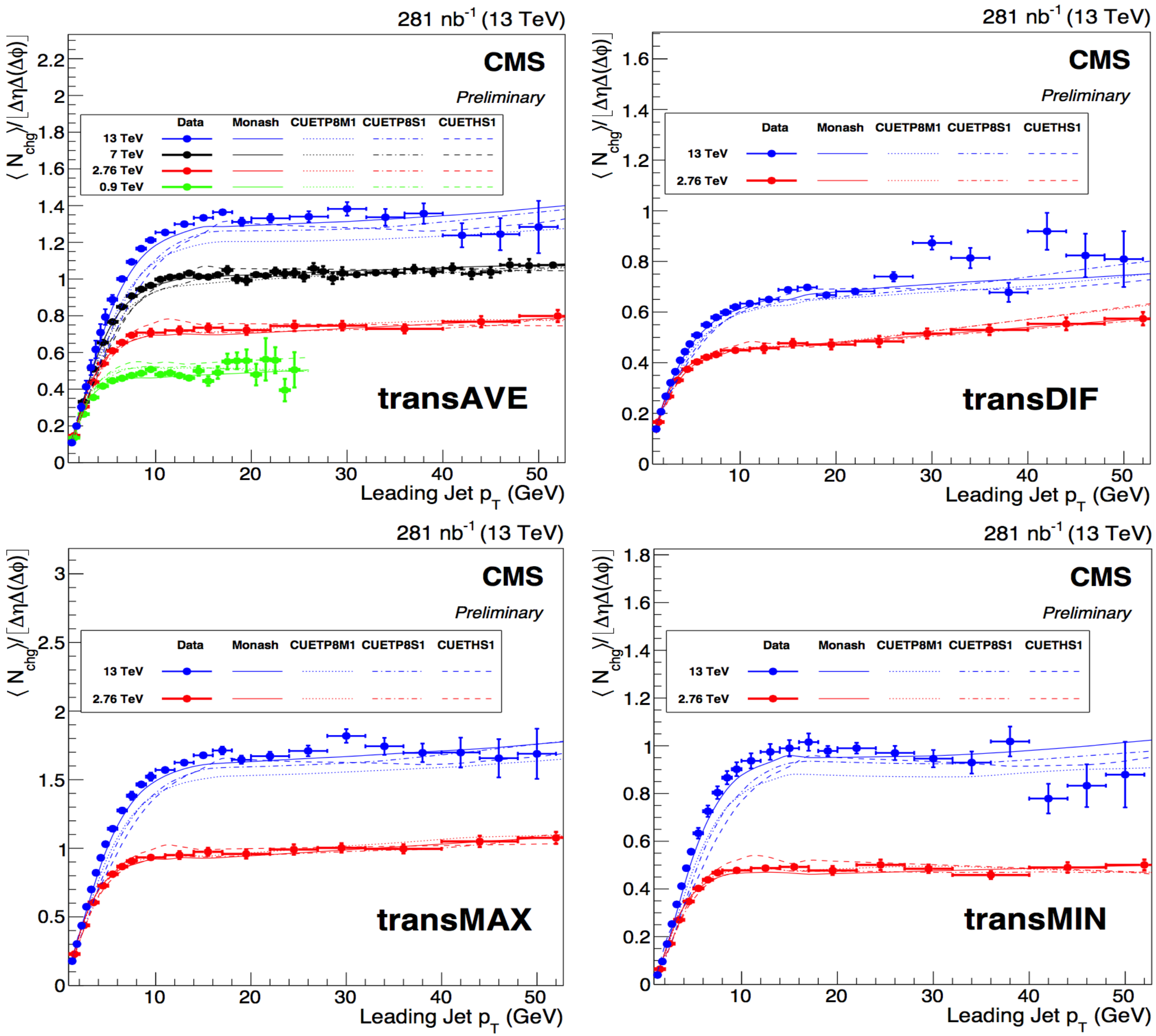
UE activity @13 TeV (II)



CMS-PAS-FSQ-15-007

- **Average transverse momentum density – energy dependence**
- Strong rise in the UE activity as a function of the centre-of-mass energy as predicted by the MC tunes.
- The level of agreement between simulations and the measurements fall within 10–20% in the plateau region but differ in the low p_T region.
- The sharp rise with p_T is interpreted in the MC models as due to an increase in the MPI contribution which reaches a plateau at high p_T.
- transMIN rise faster than transDIF ;
  - MPI activity rises faster than ISR/FSR activity

UE activity @13 TeV (III)



CMS-PAS-FSQ-15-007

- **Average charged particle multiplicity density – energy dependence**

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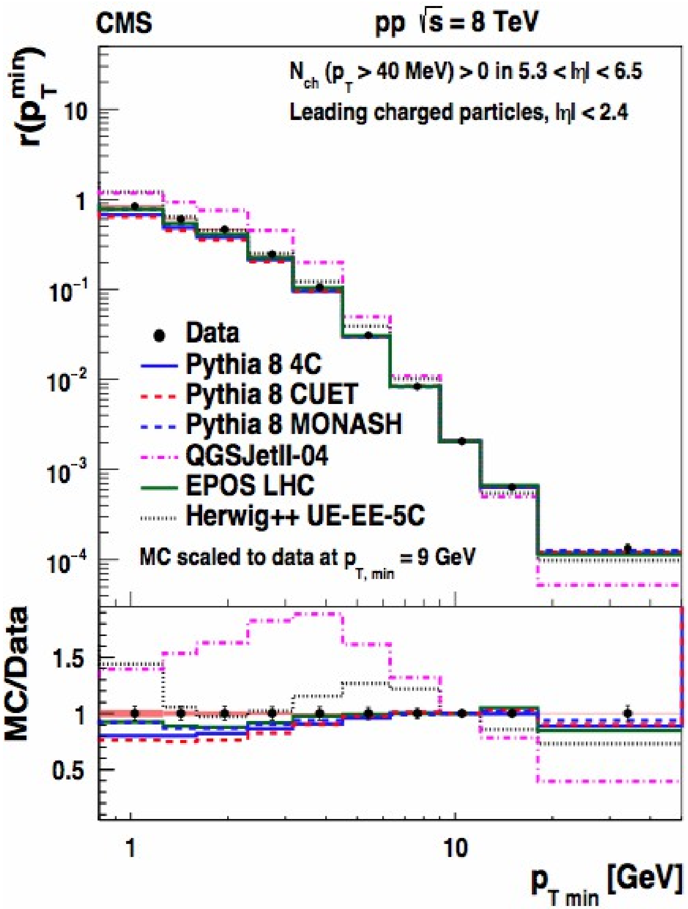
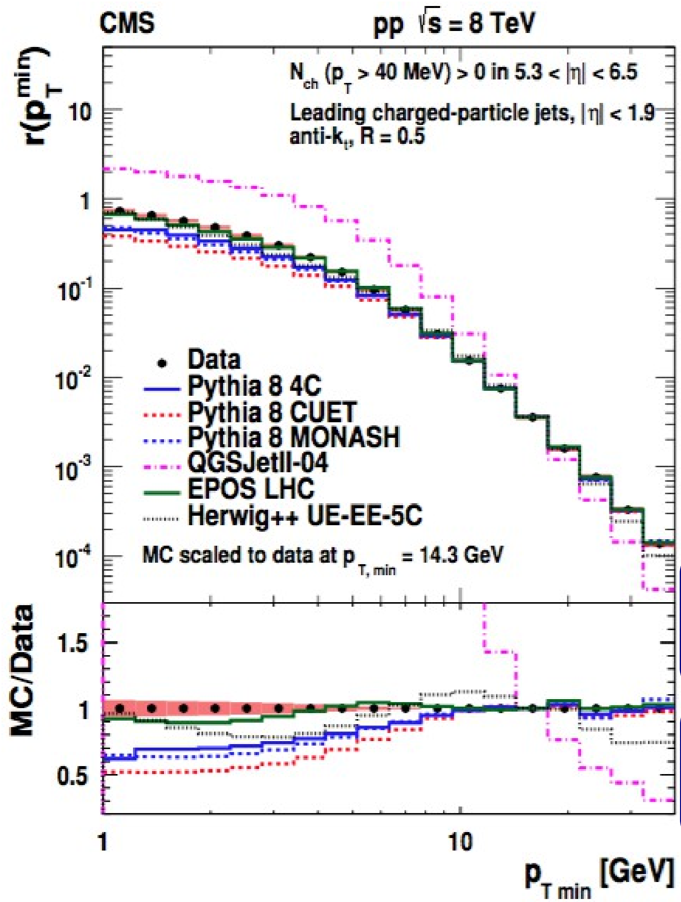
- transMIN rise faster than transDIF ;
  - MPI activity rises faster than ISR/FSR activity

Leading charged particles and charged particle jet

PRD 92 112001 (2015)





- Sensitivity seen for data to momentum scale at which parton densities saturate, MPI, soft-hard QCD transition

- Fixed order partonic cross section diverges at low p_T

- PYTHIA the rise of σ_{int} is tamed by:

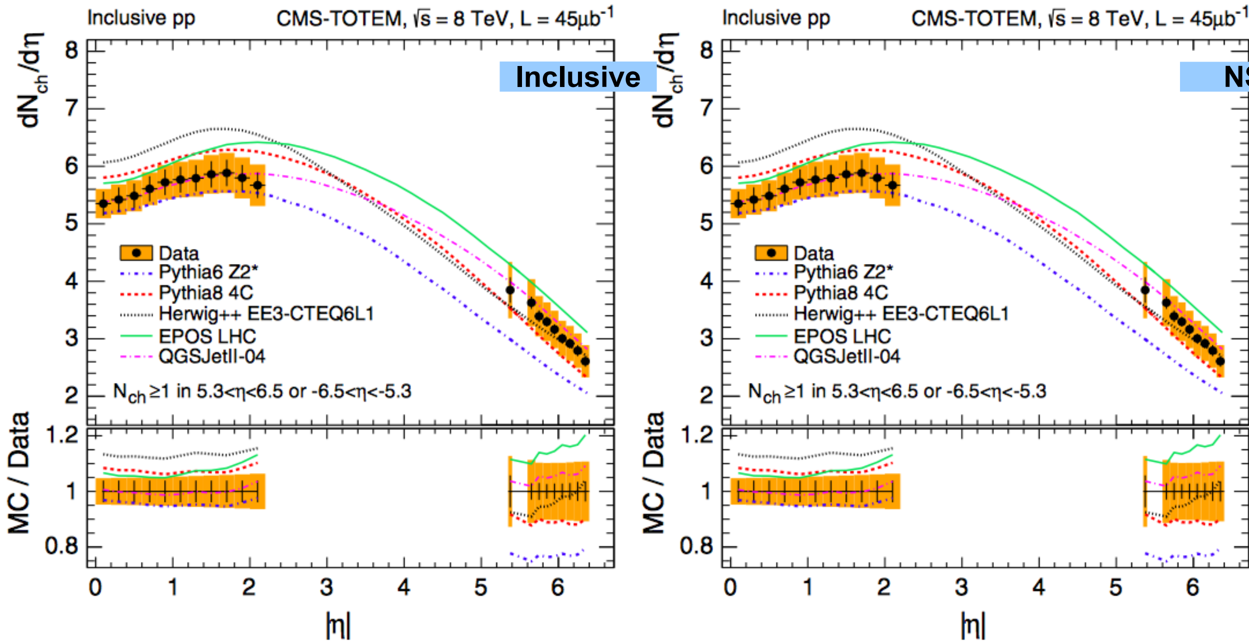
$$\sigma \rightarrow \sigma \times \frac{\alpha_s^2(p_{T0}^2+p_T^2)}{\alpha_s^2(p_T^2)} \frac{p_T^4}{(p_{T0}^2+p_T^2)^2}$$

$$r(p_{\mathrm{T}}^{\mathrm{min}}) = \frac{1}{N_{\mathrm{evt}}} \sum_{p_{\mathrm{T}}^{\mathrm{lead}} > p_{\mathrm{T}}^{\mathrm{min}}} \Delta p_{\mathrm{T}}^{\mathrm{lead}} \left(\frac{\Delta N}{\Delta p_{\mathrm{T}}^{\mathrm{lead}}} \right)$$

- Normalized integrated charged-particle or charged particle jet event cross-section as a function of $p_{T,min}$ for events with a leading charged particle (jet) with $p_T > p_{T,min}$
  - No sensitivity to particle multiplicities in events.
  - Distribution converges to one by construction
  - Predictions scaled to data @ $p_{T,min}$ = 9 and 14 GeV
  - EPOS provides the best description of data

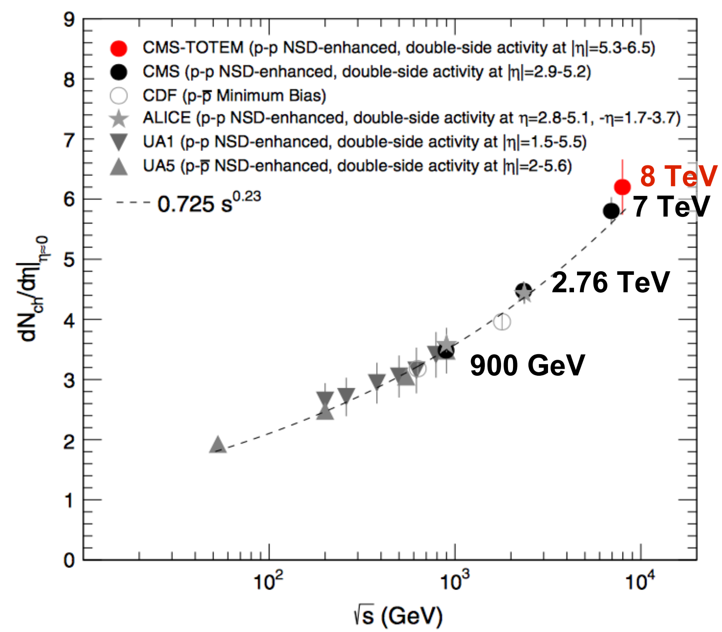
Hadron production in pp @ 8 TeV

EPJ C 74 (2014) 3053



- Most of the particles produced in pp collisions arise from semi-hard (multi)parton scatterings which are modeled phenomenologically.
- Experimental results provide important input for tuning various MC models and event generators.

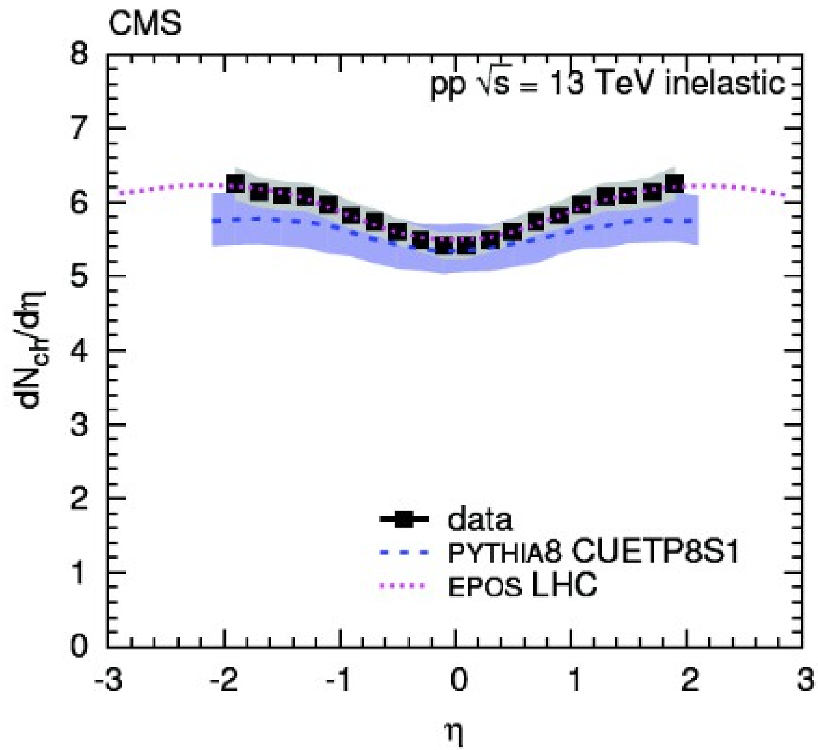
- η distributions are measured for different event topologies: either inclusive or dominated by non-single diffractive dissociation (NSD), for charged particles with $p_T > 0.1$ GeV and $p_T > 1$ GeV
- Results: based on different requirements,
  - dominated by different types of collisions
  - focus on the primary charged-particle multiplicity density ($dN_{ch}/d\eta$) and the highest-p_T leading track in $|\eta| < 2.4$.
- Inclusive setup: poor description by Pythia6 (>30% off @ $|\eta| > 5.2$)
- NSD setup:
  - the power-like centre-of-mass energy dependence indicated by previous NSD measurements at different energies
  - generators do not describe the data

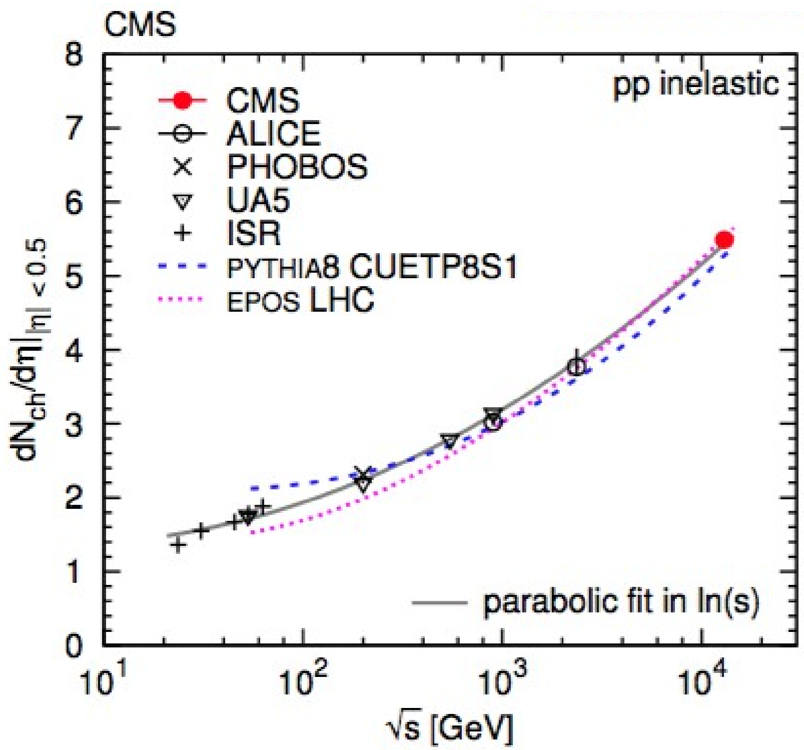


Charged hadrons @ 13 TeV

Phys.Lett. B751 (2015) 143-163

- First LHC paper at 13 TeV
- Datasets:
  - data taken June 7, 2015
  - number of collisions per bunch crossing: ~0.05
  - CMS tracker and pixel detectors ON
  - CMS magnet off, B=0 (straight tracks)



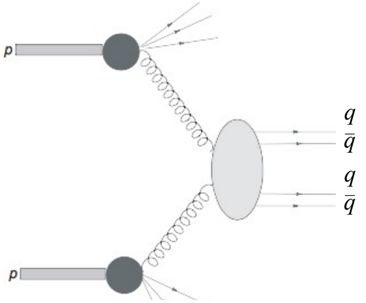


- Pseudorapidity density distributions of charged hadrons in the region $|\eta| < 2$ for inelastic pp collisions
- Charged hadron multiplicity at midrapidity:
  5.49 ± 0.01 (stat.) ± 0.17 (syst.)

- Center-of-mass energy dependence
- PYTHIA8 and EPOS globally reproduce collision-energy dependence of hadron production in inelastic pp collisions. However,
  - EPOS is better than PYTHIA8

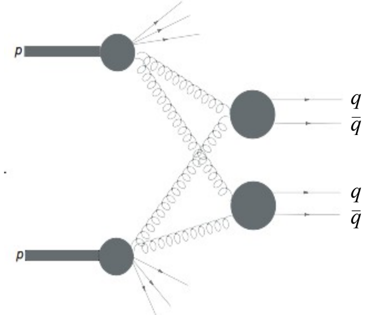
Double Parton Scattering

- **Single Parton Scattering (SPS)**
  - one hard parton-parton scatter
  - probe higher-order diagrams
  - disentangle backgrounds at higher $\sqrt{s}$



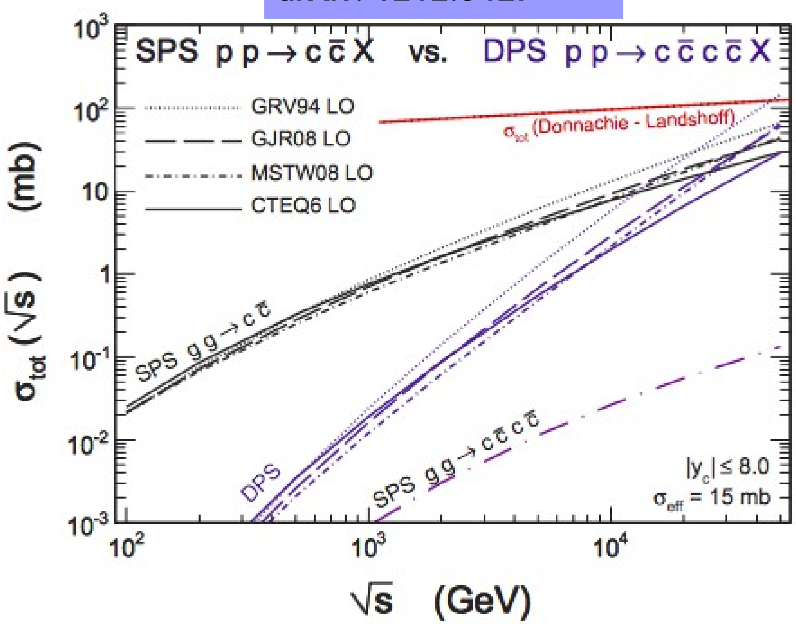
- NLO SPS
  $\sigma_{SPS} \sim$ (parton density)^2

- **Double Parton Scattering (DPS)**
  - two hard scatters within same protons
  - increasingly important at higher s
  - probe transverse profile of proton PDF
  - partonic correlations ?
  - color, flavor interference, spin effects ?



- LO DPS
  $\sigma_{DPS} \sim$ (parton density)^4

Szczurek and Maciuáa
arXiv: 1212.5427



- The cross-section for a generic process that involves DPS:

$$\sigma^{DPS}_{(hh'\to ab)} = \left(\frac{m}{2}\right)\frac{\sigma^{SPS}_{(hh'\to a)}\cdot\sigma^{SPS}_{(hh'\to b)}}{\sigma_{\rm eff}}$$

  - m is number of "distinguishable partonic subprocesses"
    - m = 1 when a = b, m = 2 when a ≠ b
  - Effective cross section, σ_{eff}, regarded as an important link to the theories.

$$\sigma_{\rm eff} = \left(\frac{m}{2}\right)\frac{\sigma^{SPS}_{(hh'\to a)}\cdot\sigma^{SPS}_{(hh'\to b)}}{\sigma^{DPS}_{(hh'\to ab)}}$$

Results: DPS using 2b + 2-jet events @ 7 TeV

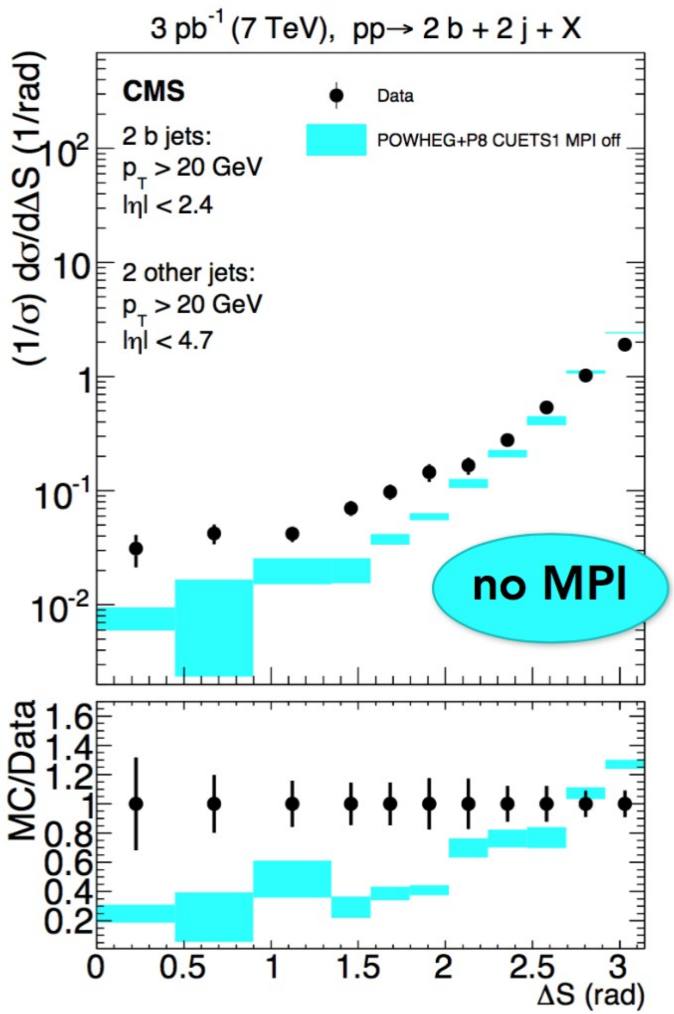
PRD 94 112005 (2016)

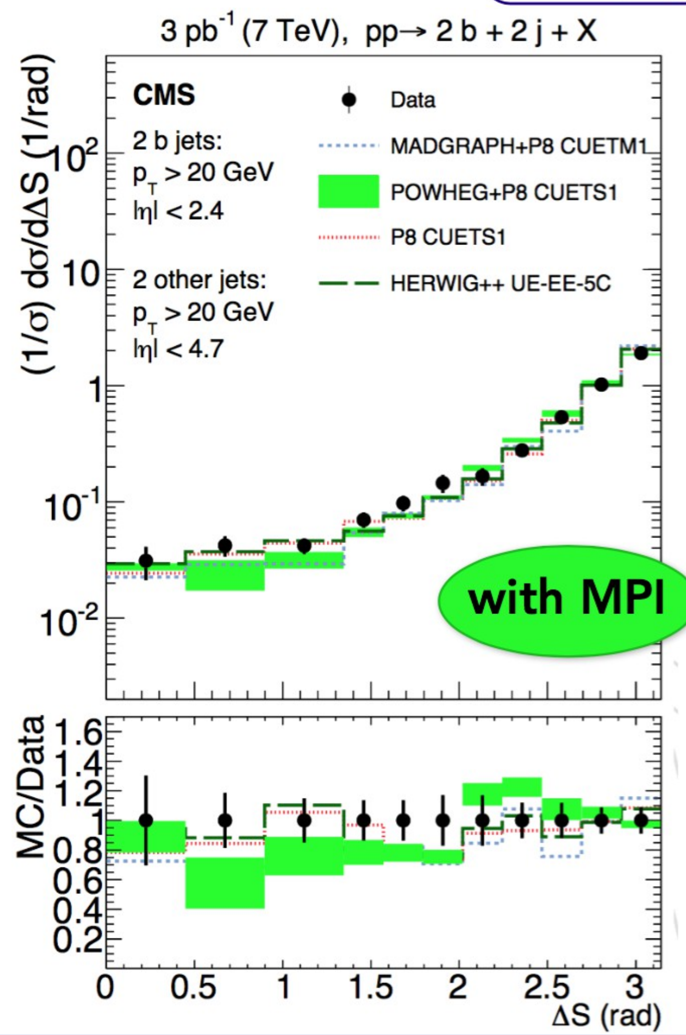
- Comparison with different MC models and test of their performance
- Study and separate the different topologies for events coming from single chain and double chain processes
- Key observable: azimuthal angle between b-jets and light jets ΔS
  - MC cannot reproduce data (~60% low) when MPI off
  - MC agrees with data with MPI

$$\Delta\phi(j_i^l, j_k^l) = |\phi_i - \phi_k|$$

$$\Delta S = arccos\left(\frac{\vec{p}_T^{\,b} \cdot \vec{p}_T^{\,l}}{|\vec{p}_T^{\,b}| \cdot |\vec{p}_T^{\,l}|}\right)$$

$$\Delta^{rel}_{pair} p_T = \frac{|p_T(j_i^l, j_k^l)|}{|p_T(j_i^l)| + |p_T(j_k^l)|}$$

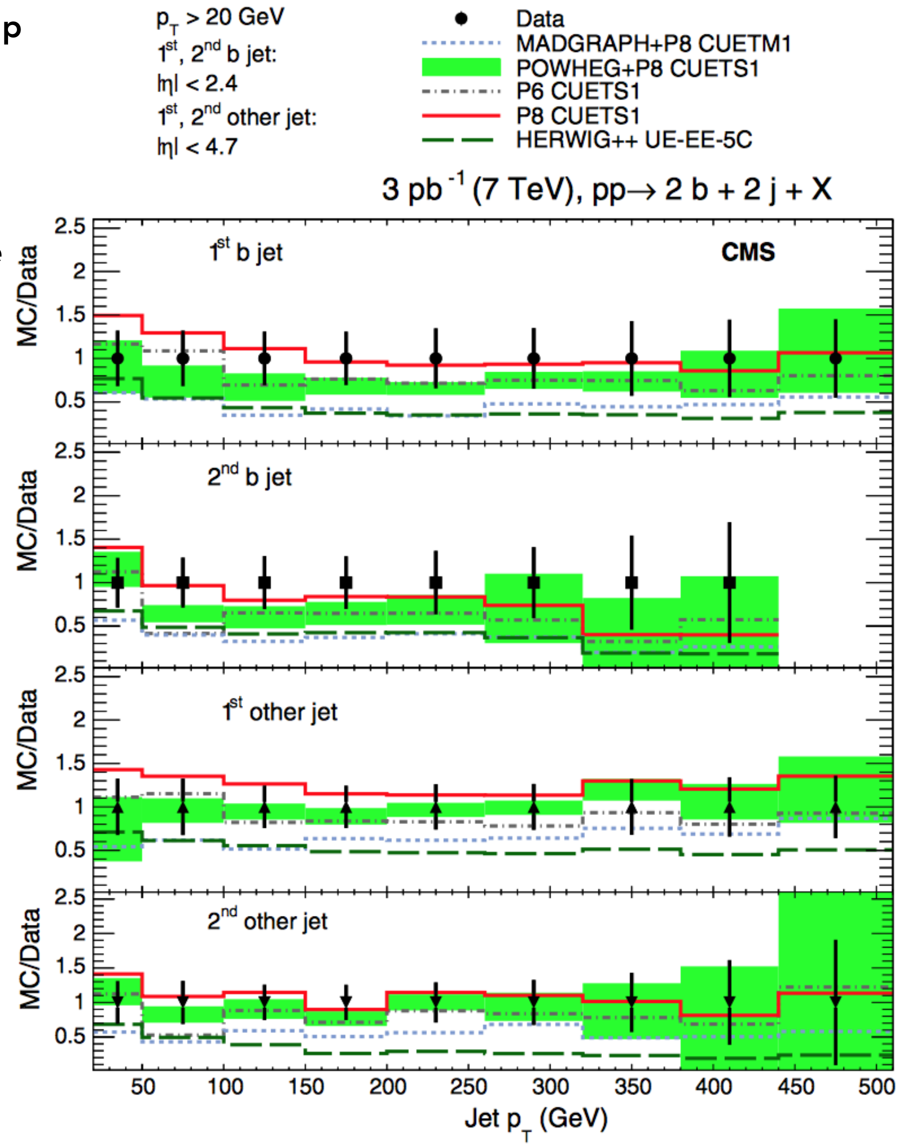




Results: DPS using 2b + 2-jet events @ 7 TeV

PRD 94 112005 (2016)

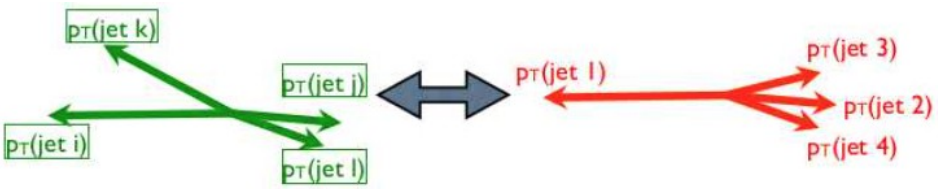
- Jets need to be associated in pairs: different flavour can help
- Equal scale of the 2 jet pairs should suppress the SPS contribution (at least 4 jets with p_T > 20 GeV)
- MADGRAPH, PYTHIA6 and POWHEG are able to reproduce quite well jet p_T spectra
- HERWIG++ tends to underestimate data at low p_T region



DPS using 4-jet events @ 7 TeV

PRD 89 092010 (2014)

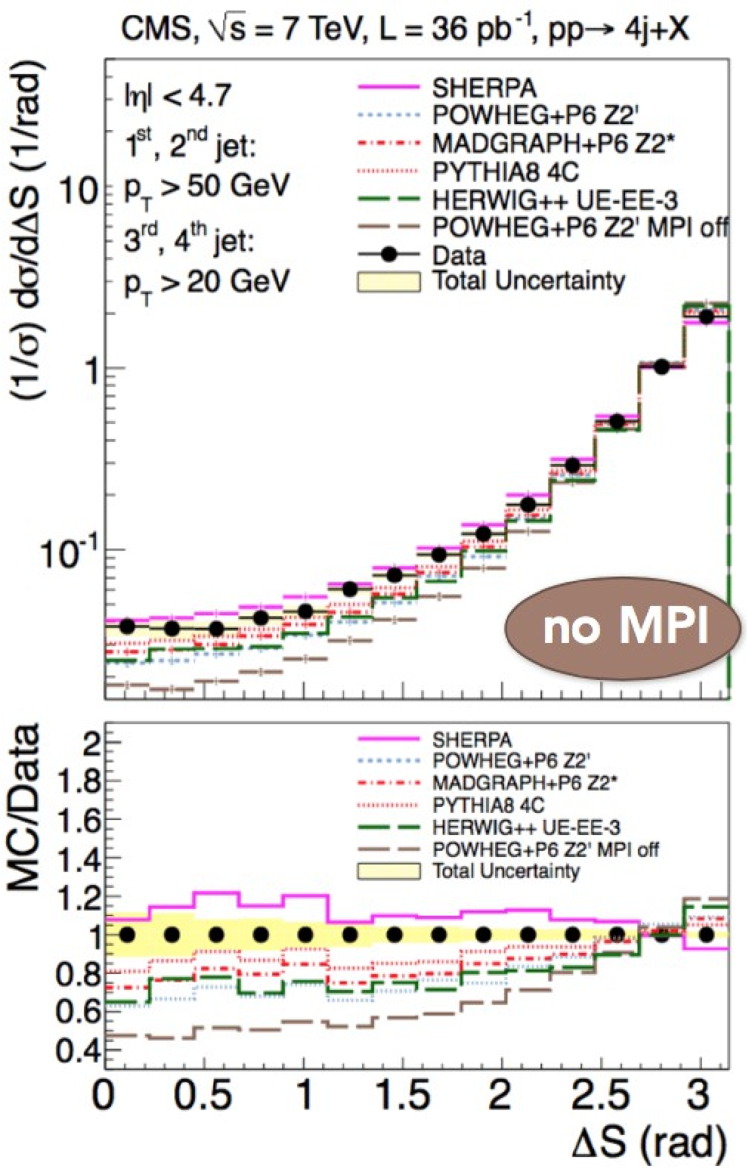
- 4-jet final state may arise from either parton shower or second hard scattering.
- 4 jets measurements are sensitive to hard matrix element and underlying events:



- azimuthal angle between hard- and light-jet pairs

$$\Delta S \equiv \Delta\phi\left(\vec{q}_{\mathrm{T}}^{\,1},\ \vec{q}_{\mathrm{T}}^{\,2}\right)$$

- MC cannot reproduce data (~50% low) when MPI is off
  - with MPI, MC still ~20% low (except Sherpa)



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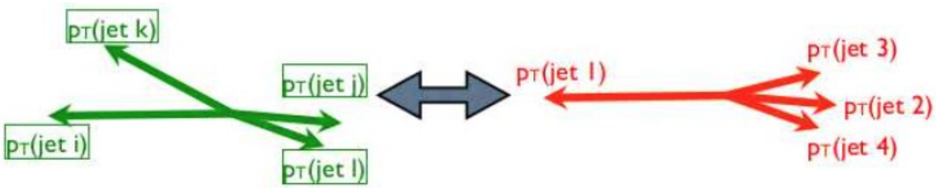


- azimuthal angle between hard- and light-jet pairs

$$\Delta S \equiv \Delta\phi\left(\vec{q}_T^{\,1},\ \vec{q}_T^{\,2}\right)$$

- MC cannot reproduce data (~50% low) when MPI is off
  - with MPI, MC still ~20% low (except Sherpa)

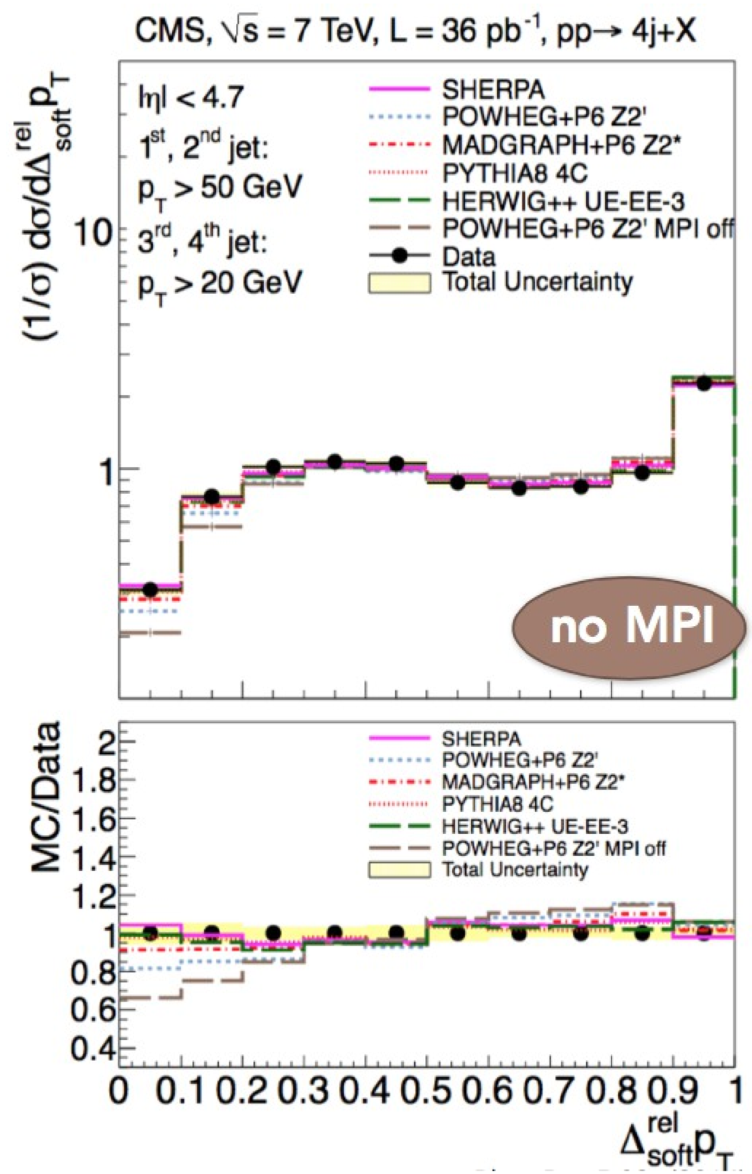
- some sensitivity via relative p_T balance between 2 softer

jets

$$\Delta^{\rm rel}_{\rm soft}p_T = \frac{|\vec{p}_T(j^{\rm soft_1}) + \vec{p}_T(j^{\rm soft_2})|}{|\vec{p}_T(j^{\rm soft_1})| + |\vec{p}_T(j^{\rm soft_2})|}$$

- POWHEG + PYTHIA with MPI off underestimates the data

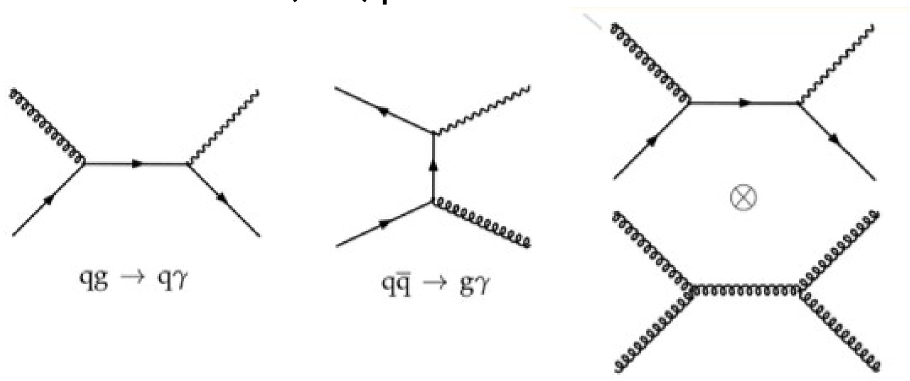
- 4 jets less sensitive to DPS than 2 b-jets + 2 jets
- needs more kinematic study of MPI with UE data
  - no σ_{eff} estimation

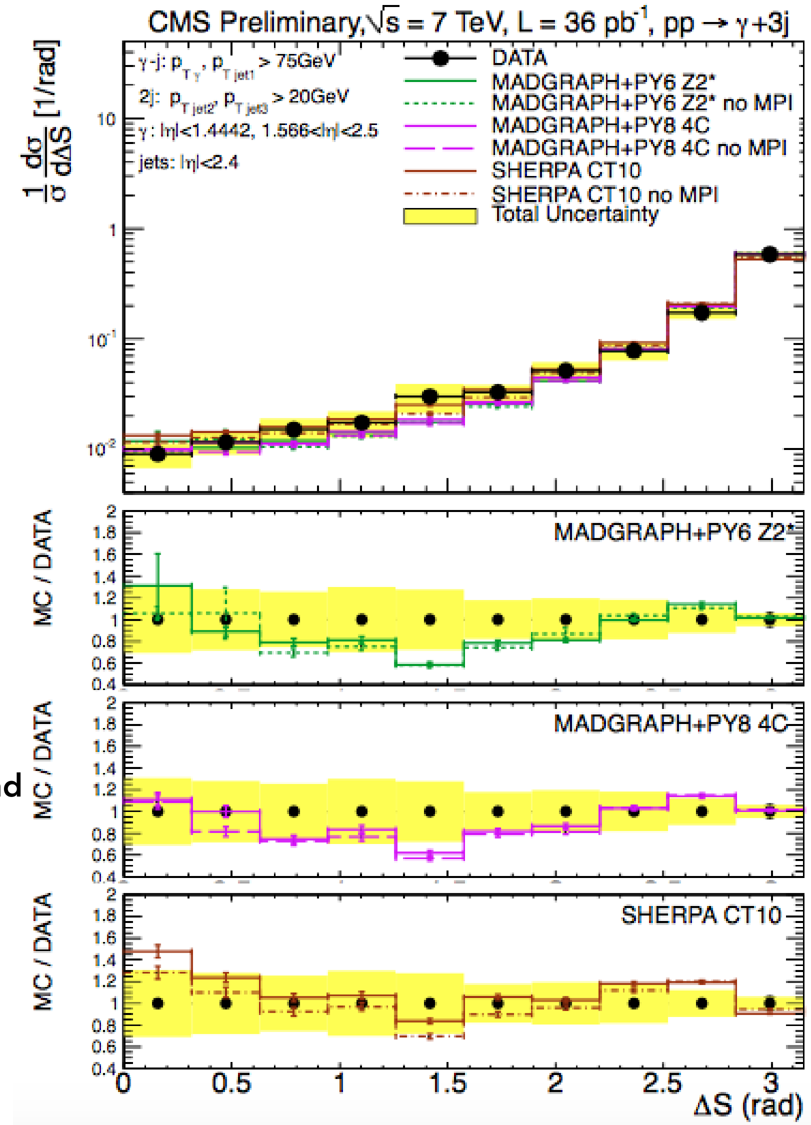


DPS with photon + 3 jets

CMS PAS-FSQ-12-017

- Three kinds of contributions : 3 jets +
  - direct photon
  - fragmentation photon
  - misidentified (fake) photon



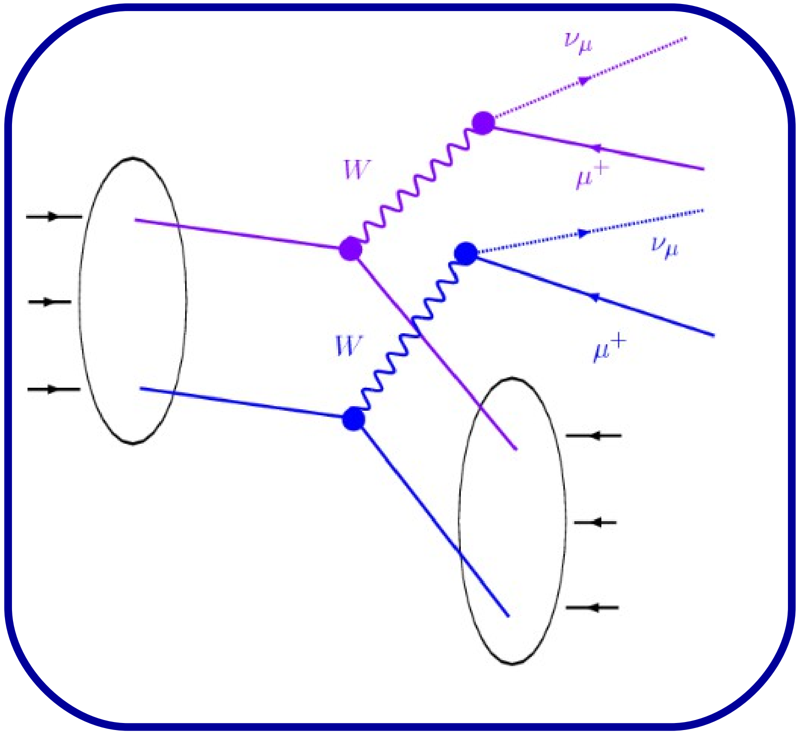


- Event selection:
  - gamma and one jet in the central region with p_T > 75 GeV
  - two jets with p_T > 20 GeV and |η| < 2.4
- Data:
  - well described by all MC
  - measurement not very sensitive to MPI
- Azimuthal angle between the p_T vectors of the photon-jet pair and the di-jet pair ΔS

CMS PAS-FSQ-13-001

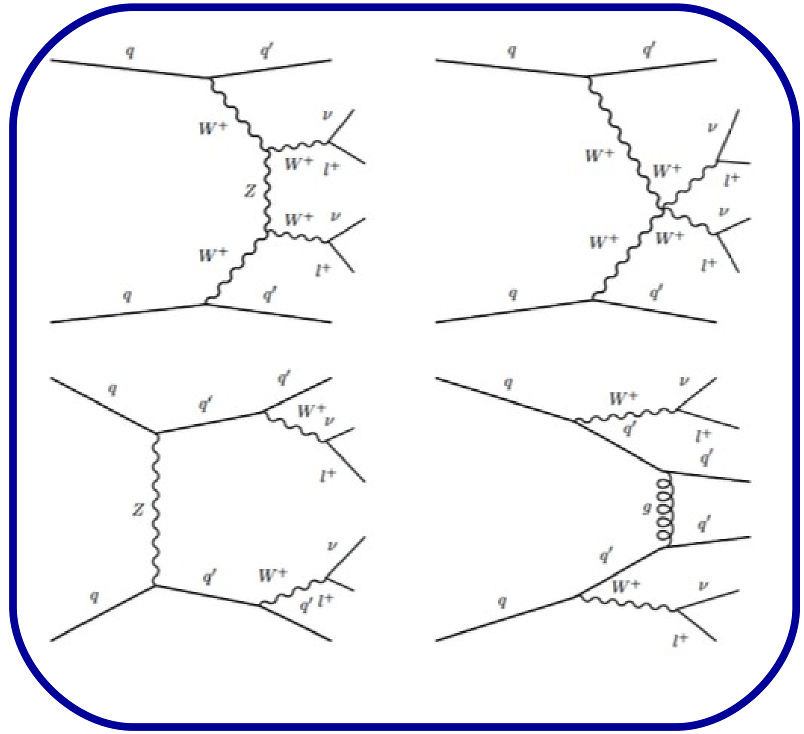
- W Boson Production: a benchmark process at LHC
- Same-sign WW DPS to leptons is very promising theoretically
  - Opposite-sign WW production cross-section via DPS is smaller than that of via SPS.
    - production cross-section via DPS is comparable to the same via SPS
  - very clean final state: two leptons with some missing E_T
  - good process to track down correlations in proton's pdf structure!

DPS



$$
\begin{aligned}
pp &\rightarrow W^{\pm}W^{\pm} + X \\
q\bar{q} &\rightarrow W^{\pm} \rightarrow l_1 + \nu_1 \\
q\bar{q} &\rightarrow W^{\pm} \rightarrow l_2 + \nu_2
\end{aligned}
$$

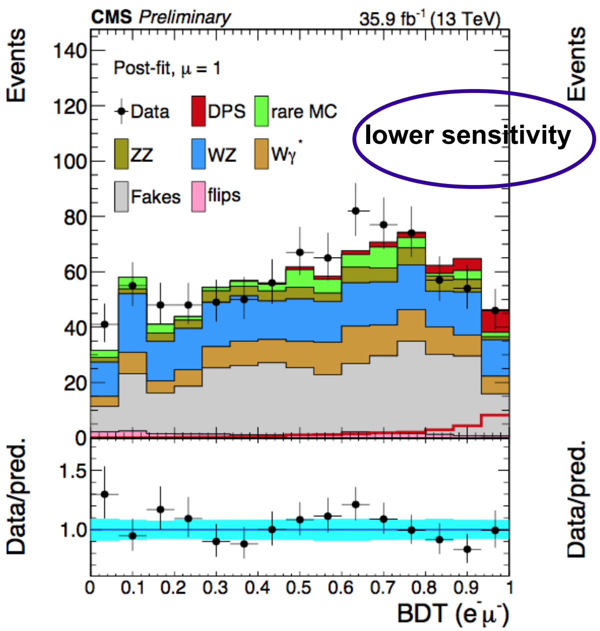
SPS

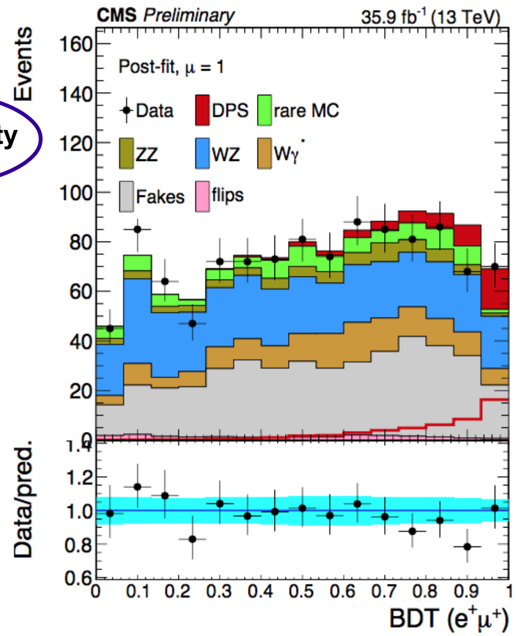


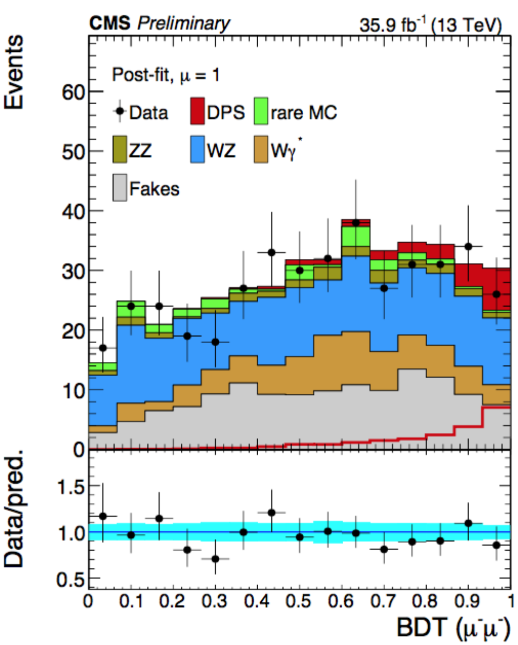
$$
\begin{aligned}
pp &\rightarrow W^{\pm}W^{\pm}jj + X \\
q\bar{q} &\rightarrow W^{\pm}W^{\pm}jj \rightarrow l_1 + l_2 + \nu_1 + \nu_2
\end{aligned}
$$

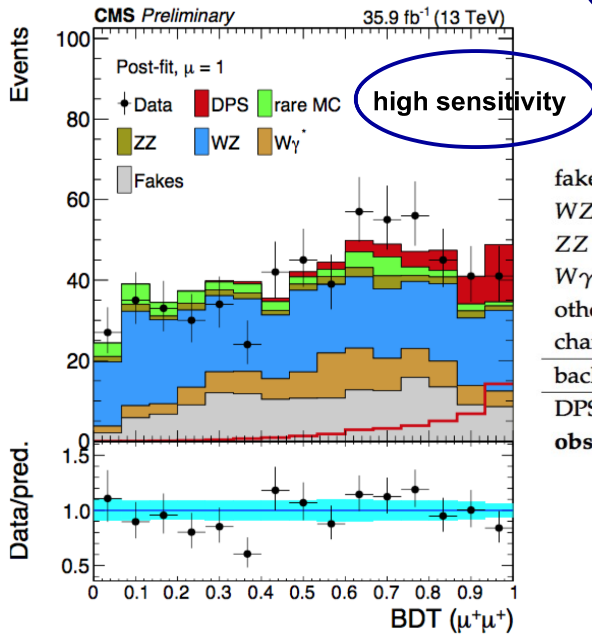
Results: DPS WW @ 13 TeV

CMS PAS-FSQ-16-009









- Final BDT classifier output with all background estimations
- Overall good agreement between the background predictions is observed in the low-BDT classifier region.
- A slight over-prediction of the background plus signal is seen in the high-BDT classifier region.

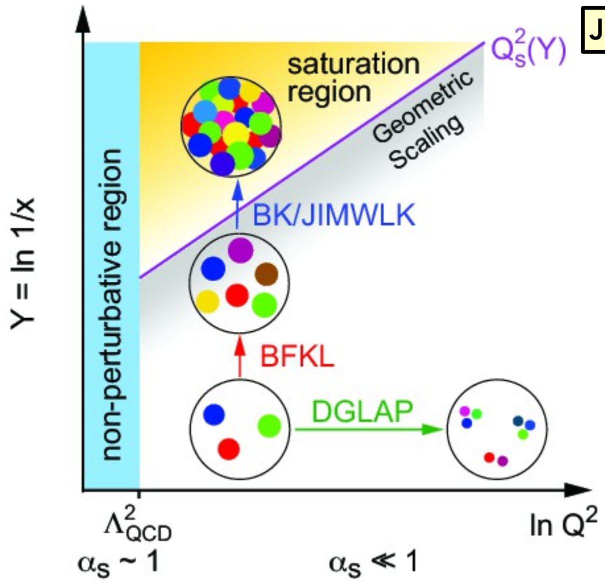
Expected background and signal yields

	$\mu^+\mu^+$	$\mu^-\mu^-$	$e^+\mu^+$	$e^-\mu^-$
fakes	151.1 ± 26.6	132.7 ± 23.4	412.7 ± 47.2	341.4 ± 39.0
WZ	277.2 ± 28.1	164.5 ± 16.7	355.9 ± 36.1	228.1 ± 23.2
ZZ	24.8 ± 7.0	18.7 ± 5.3	57.8 ± 16.4	55.8 ± 15.8
$W\gamma*$	85.9 ± 27.5	73.1 ± 23.4	142.8 ± 45.7	127.7 ± 40.9
other rare	39.7 ± 15.0	20.2 ± 7.7	83.7 ± 31.7	49.4 ± 18.8
charge flips	—	—	20.4 ± 0.0	21.5 ± 0.0
background	578.6 ± 50.3	409.2 ± 38.2	1073.3 ± 83.0	824.0 ± 65.8
DPS WW	41.1 ± 1.0	20.6 ± 0.5	48.7 ± 1.2	24.1 ± 0.6
observed	604	411	1091	869

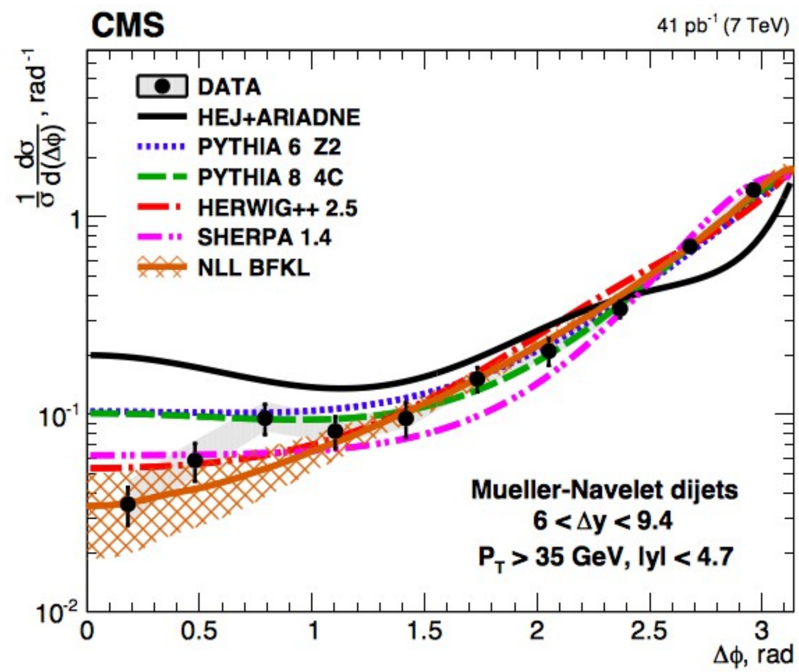
Decorrelation of forward jets at 7 TeV

JHEP 08 (2016) 139

- Approaches to higher-order calculations:
  - DGLAP approach: resummation in terms of $\ln(Q^2)$
  - BFKL approach: resummation in terms of $\ln(1/x)$

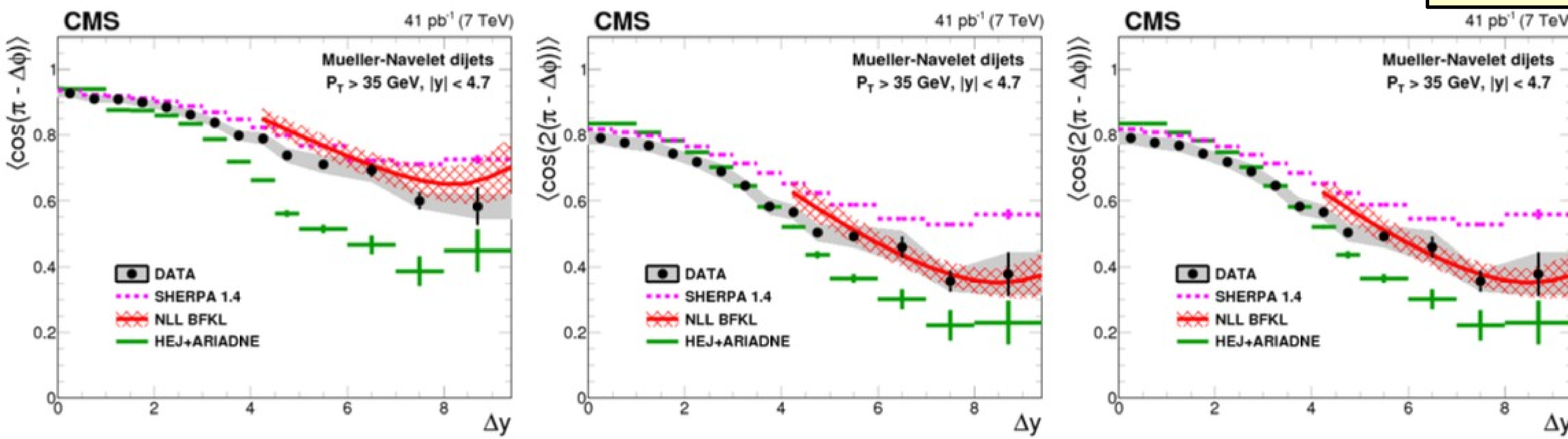


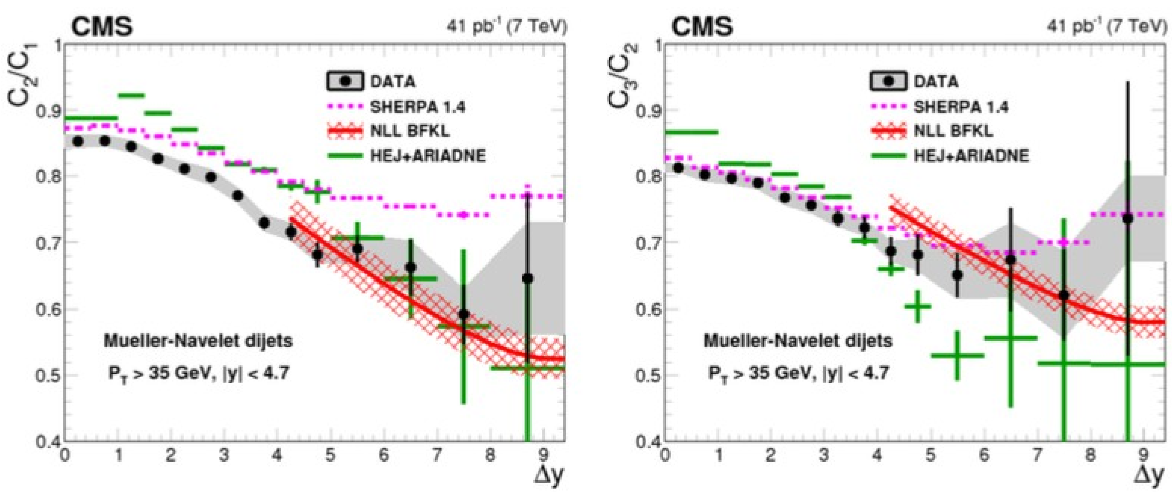
- Most forward and most backward jets with p_T > 35 GeV
- Results given for up to $|\Delta y|$ = 9.4
- Compared to predictions
  - DGLAP-based LO MCs
  - HEJ: LL BFKL-based MC
  - NLL BFKL prediction
- Angular variables also studied as a function of Δy



Mueller-Navelet dijet azimuthal decorrelations

JHEP 08 (2016) 139





- Mueller-Navelet dijets: pair of jets with the largest rapidity interval
- Decorrelation of Δφ MN pair: sensitive to QCD dynamics
- Cross section vs. Δφ expanded in terms of cos[n(π-Δφ)]
  - expansion coefficients and their ratio depend on Δy
  - region of large Δy probes the BFKL evolution

- Good data-theory agreement: NLL BFKL analytical calculations at large Δy
- BFKL NLL calculations, parton level (small effects from hadronization) (JHEP 1305(2013) 096) sensitivity to MPI and angular ordering

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

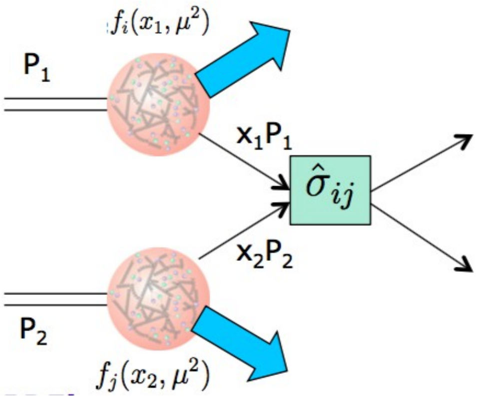
Hard QCD measurements:

- *PDFs & perturbative QCD with jets*
- *measurements of α_S*
- *measurements with photons*
- *measurements with vector bosons + jets*

Hard QCD cross sections

- Parton density functions (PDFs)
  - evolution with DGLAP equations (Q^2 ordered)

- Hard scattering cross section
  - depend on process
  - valid in short distance
  - small coupling constant
  - calculable with pQCD



$$\sigma(P_1,P_2)=\sum_{i,j}\int dx_1 dx_2 f_i(x_1,\mu^2) f_j(x_2,\mu^2)\,\hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu^2),Q^2/\mu^2)$$

+ parton fragmentation

- Final-state hadronization (q,g,Q→π,k,p,D,B)

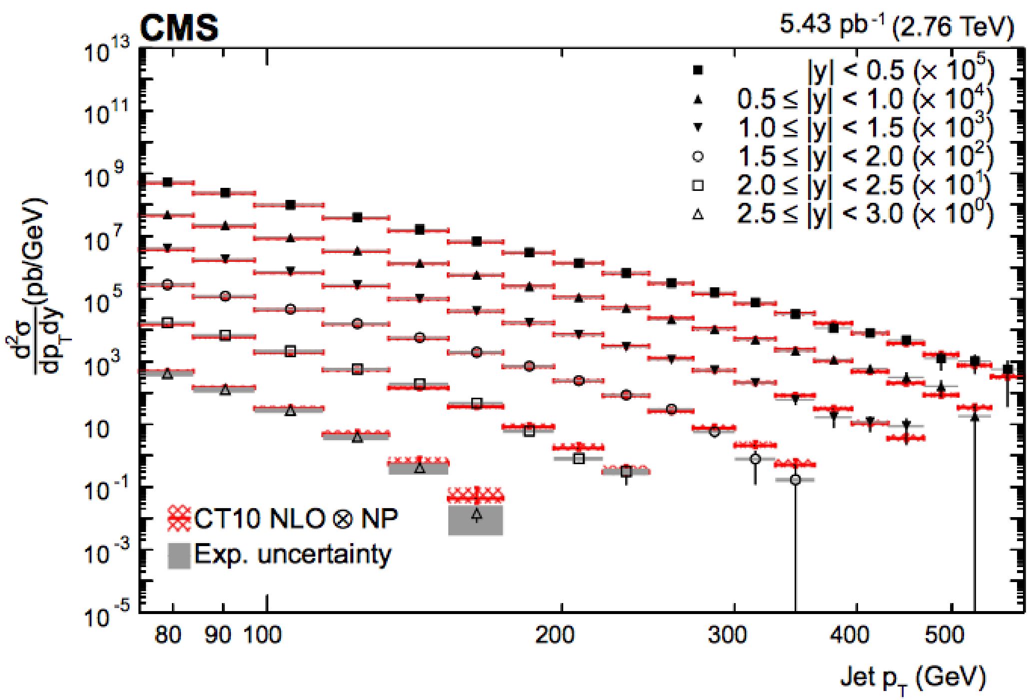
  or bound-state formation (ccbar,bbar):

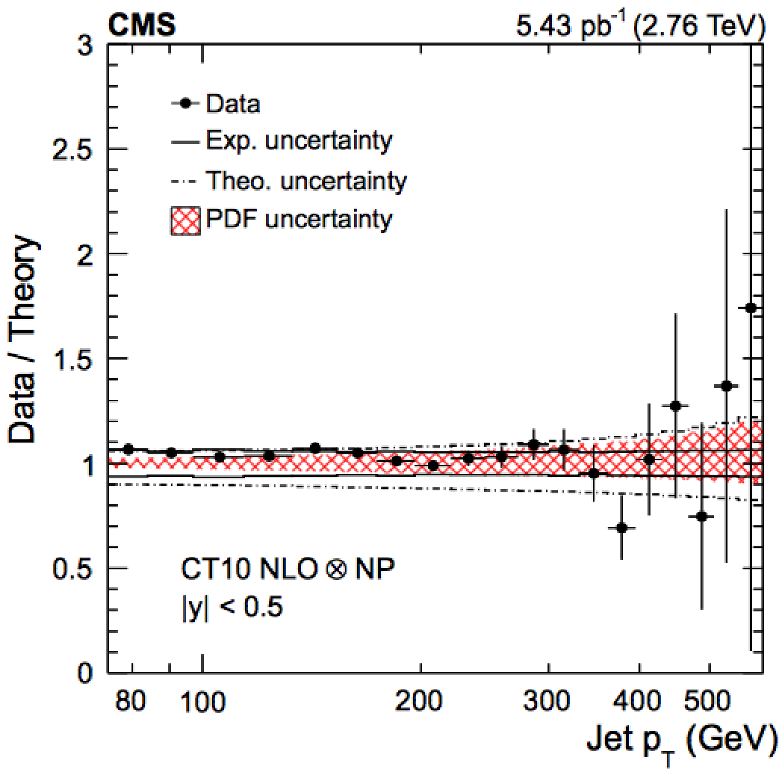
  Universal FFs fitted from data + DGLAP evolution

Inclusive Jet Cross Sections @ 2.76 TeV

EPJC 76 (2016) 265

- Data taken right after 8 TeV (Feb 2013, last Run I data) ensuring consistency with 8 TeV
  - Fills in the region between Tevatron's 1.96 TeV and LHC's 7 and 8 TeV (and 13 TeV)
- Jet p_T range measured: [74 , 592] GeV
- Fixed-order NLO calculations corrected for NP effects describe the measurement very well over the whole p_T & y range
- To enhance the impact of jet data, it's smart to consider ratios:
  - the major experimental systematic - the Jet Energy Scale - cancels out, i.e. 2.76 vs 8 TeV



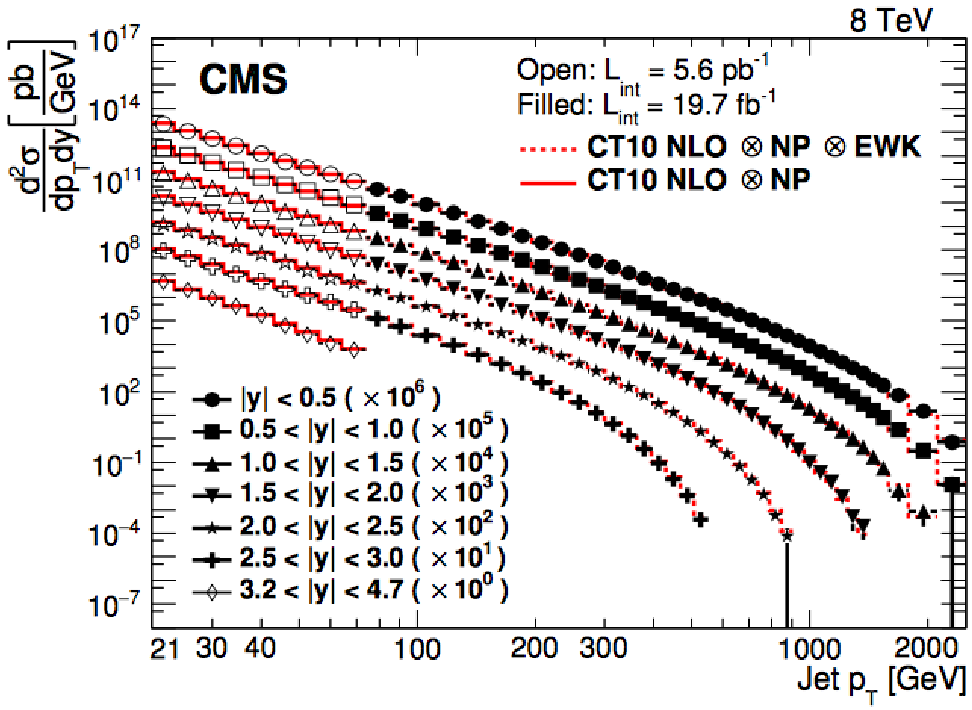


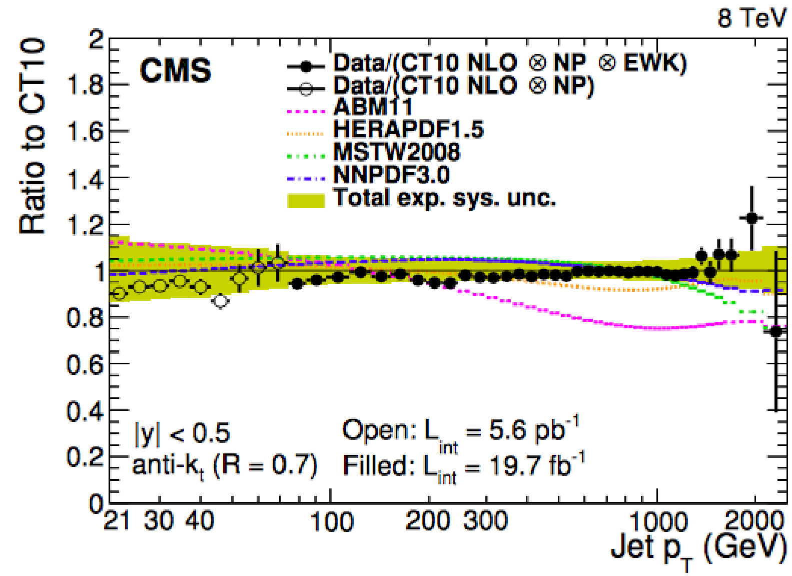
Inclusive Jet Cross Sections @ 8 TeV

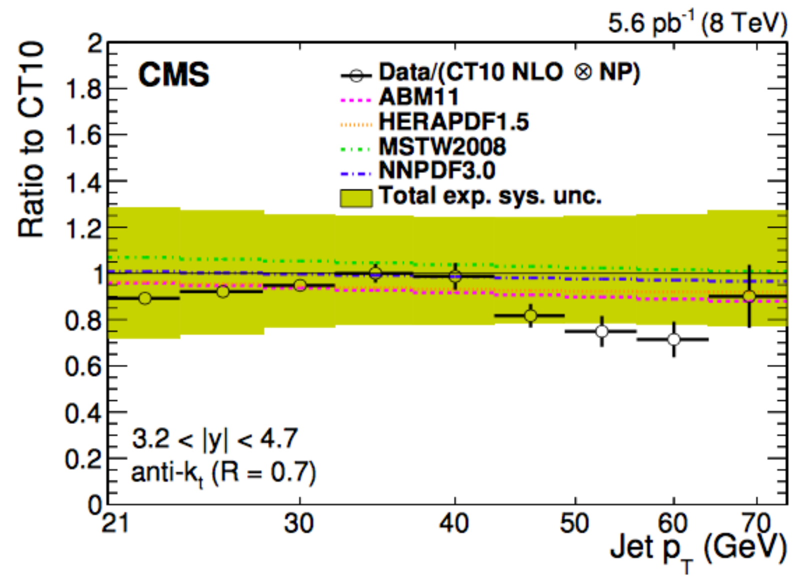
NEW!

JHEP 03 (2017) 156

- Jet p_T range measured: [74 , 2500] GeV for |y| < 3 and [21, 74] GeV for 3.2 < |y| < 4.7
- Good agreement over the whole p_T and y range for fixed-order calculations corrected for NP and EW effects
- Comparison with NLO QCD using several PDFs (two representative rapidity bins shown)







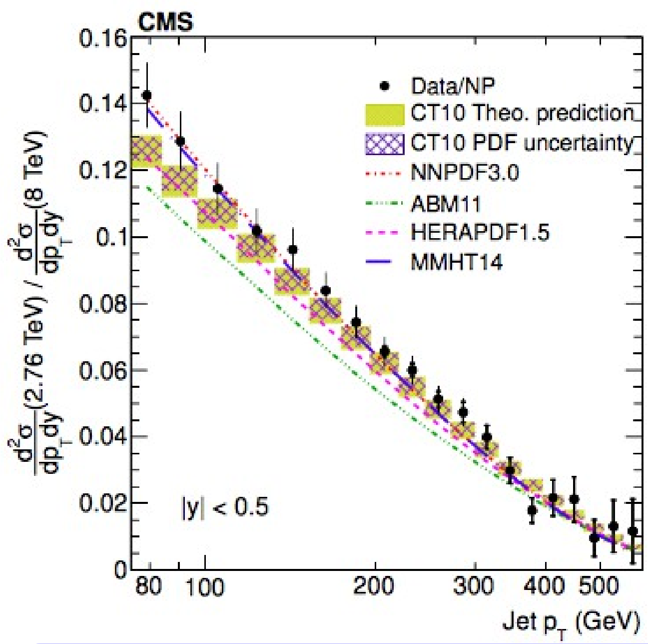
Double differential inclusive jet cross section

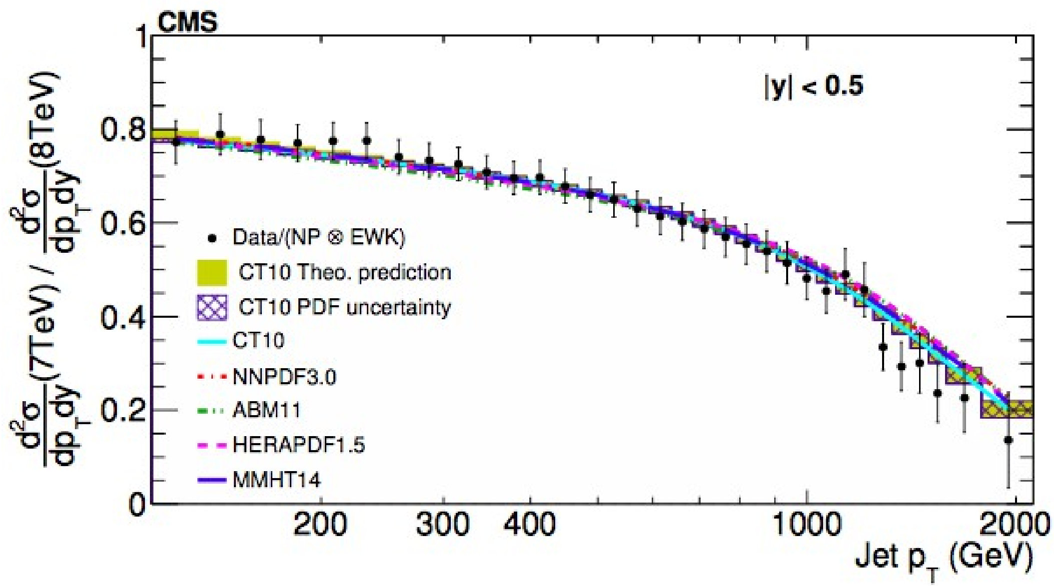
$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon \mathcal{L}_{int,eff}} \frac{N_{jets}}{\Delta p_T \, (2\Delta|y|)}$$

Ratios

JHEP 03 (2017) 156

- Careful study of uncertainty correlations between 2.76, 7 and 8 TeV measurements
- Partial cancellation of experimental and theory systematics
- General agreement between data and theoretical predictions
- Useful for future PDF constraints





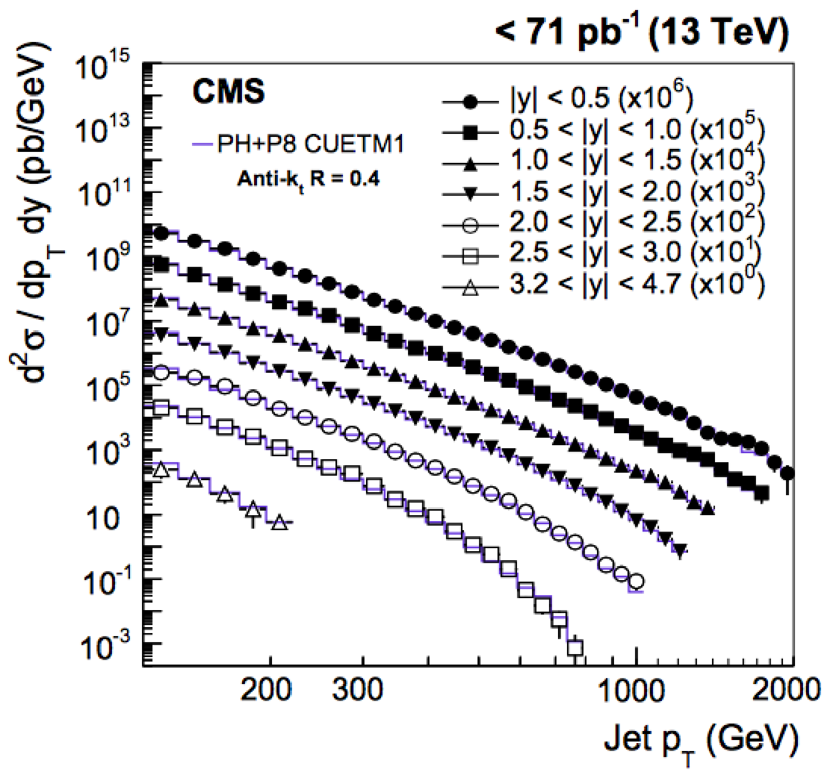
- The central value of the theoretical prediction and its uncertainty dominated by the choice of PDFs
- strong sensitivity of the 2.76 to 8 TeV cross section ratio to the description of the proton structure.

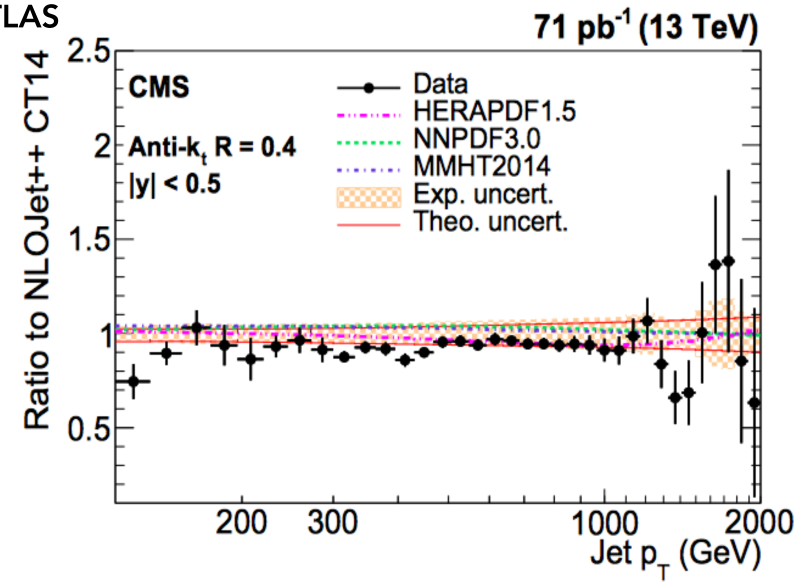
- Some discrepancies are visible at high p_T
- central values of predictions not strongly influenced by the choice of PDFs.
- uncertainty is mostly dominated by PDF unc.

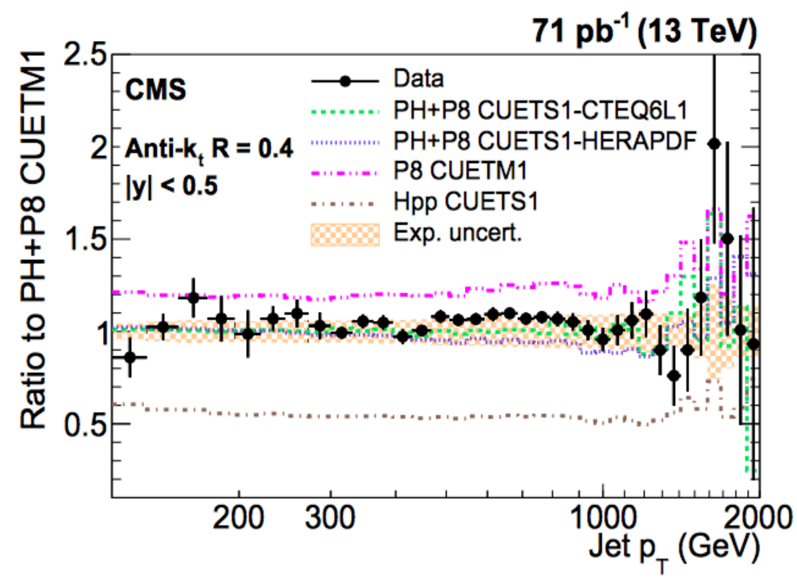
Inclusive Jet Cross Sections @ 13 TeV

EPJ C 76 (2016) 451

- Jet p_T range measured: [74 , 2500] GeV for |y| < 4.7
- Results for ΔR = 0.7 and 0.4 up to |y| = 4.7
  - Smaller cone size, R=0.4, enables direct comparisons to ATLAS
- Excellent agreement with Powheg+Pythia8
  - p_T shape OK in Herwig++
  - Softer p_T in Pythia8 for larger |y|
  - Same results for both ΔR

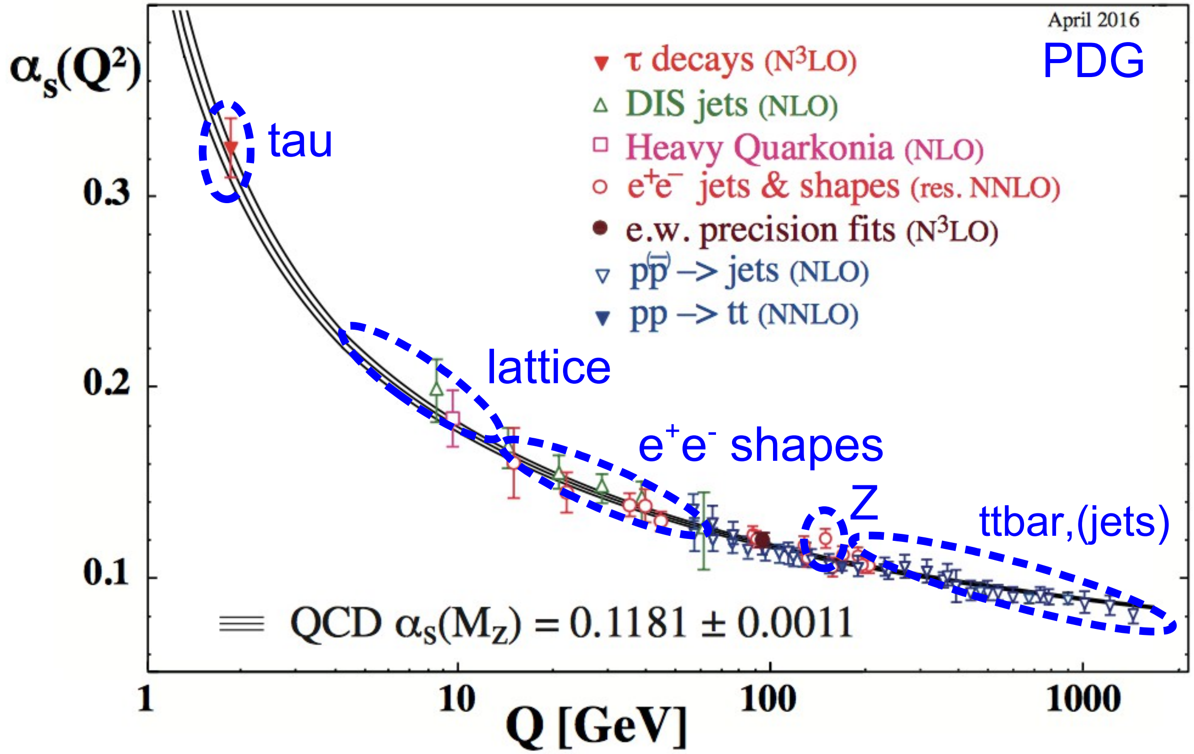






Determination of the strong coupling constant α_s

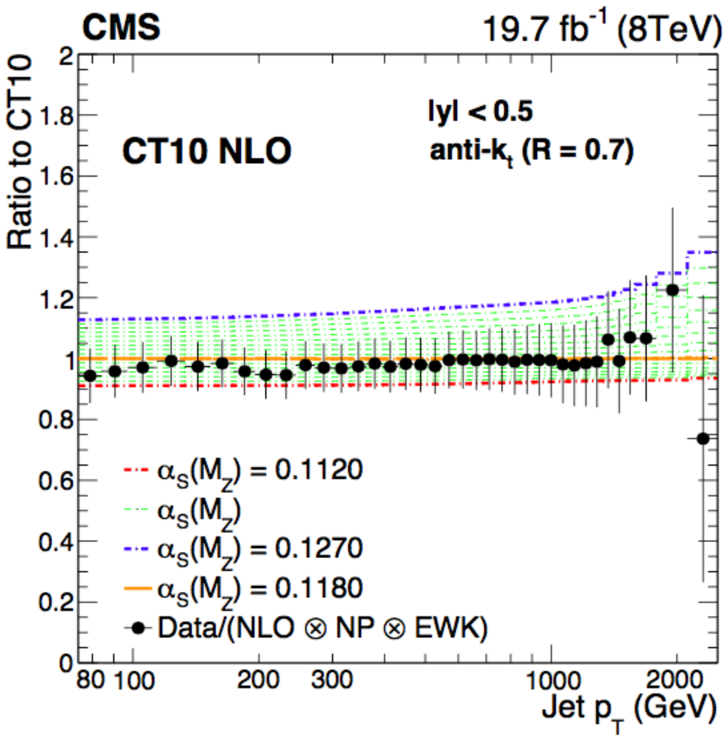
- α_s : Single free parameter in QCD (in the $m_q \to 0$ limit).
  - Determined at a given reference scale (usually m_Z).
  - Decreases as $\sim 1/\ln(Q^2/\Lambda^2)$, with $\Lambda \sim 0.25$ GeV
- Determined through comparison of various experimental (ee, ep, pp) observables to associated pQCD predictions at NNLO accuracy.
- Least precisely known of all couplings: $\delta\alpha_s \sim 1\%$(!), $\delta\alpha \sim 3\cdot 10^{-10}$, $\delta G_F \sim 5\cdot 10^{-8}$, $\delta G \sim 10^{-5}$
- Impacts all LHC cross-sections.
- Key for precise SM studies. Uncertainties: ±4% σ(ggH), ±7% H→cc, ±4% H→gg
- BSM physics (e.g. new coloured sectors).

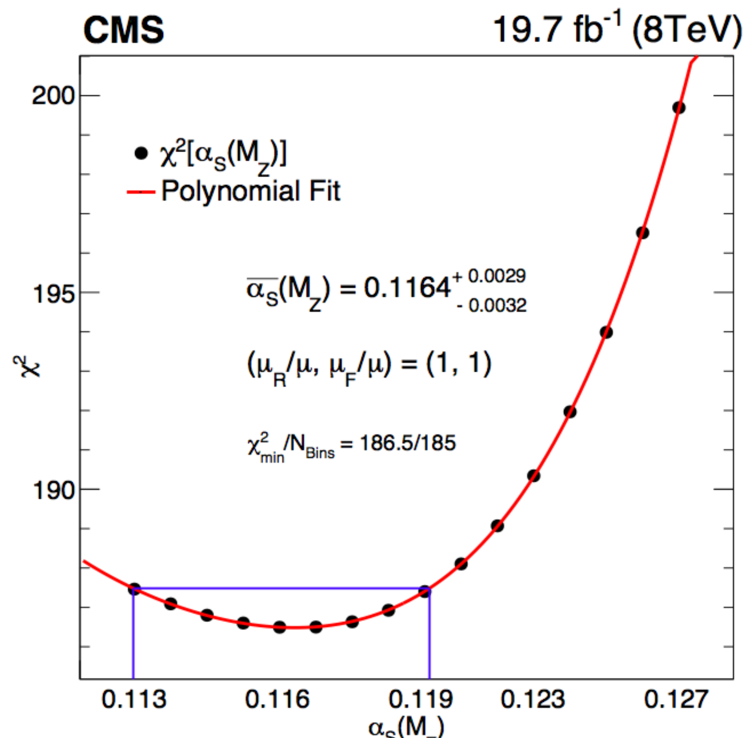


α_s from jet observables

JHEP 03 (2017) 156

- CMS jet cross section measurement compared to NLO QCD ⊗ PDFs in each bin of p_T and y
- Different sets of PDFs used, each set has its α_s - dependence
- In each y bin, for each PDF, α_s is determined by minimizing χ^2 between data and NLO prediction (corrected for NP and EW effects)





- CT10 NLO PDF set provides variants corresponding to 16 different $\alpha_s(M_Z)$ values in the range 0.112–0.127 in steps of 0.001.
- The sensitivity of the theory prediction to the α_s choice in the PDF
- The variation of χ^2 with α_s is fitted with a fourth-order polynomial, and the minimum (χ^2_{min}) corresponds to the best $\alpha_s(M_Z)$ value.

The strong coupling constant α_s

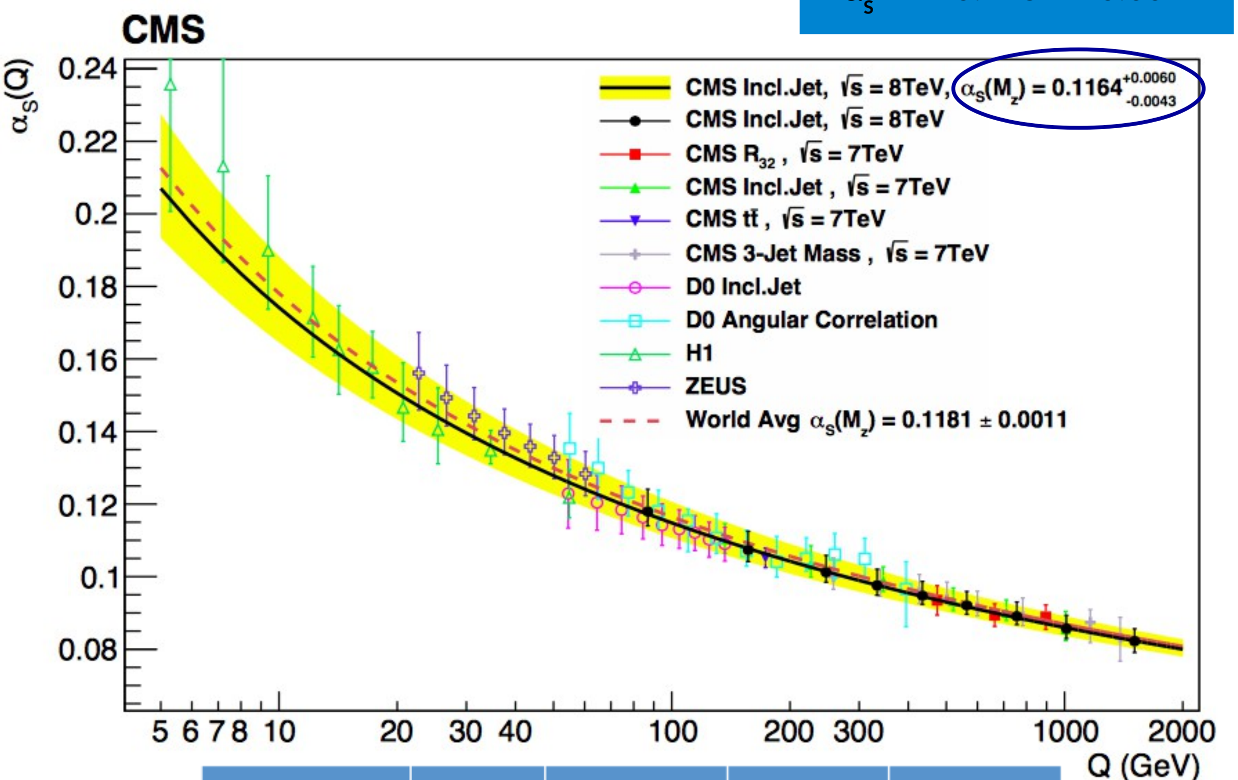
NEW!

Diifferent approaches

JHEP 03 (2017) 156

- Inclusive jets: least square minimization on $p_T(y)$ spectrum using NLO parton level predictions.
- Multijet: 3-jet to 2-jet cross section ratio R_{32}, insensitive to many theor. and exp. systematics.
- Triple differential cross section together with PDF fit.

$\alpha_s^{PDG} = 0.1181 \pm 0.0011$



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CMS PAS-SMP-16-008

CMS PAS-SMP-16-011

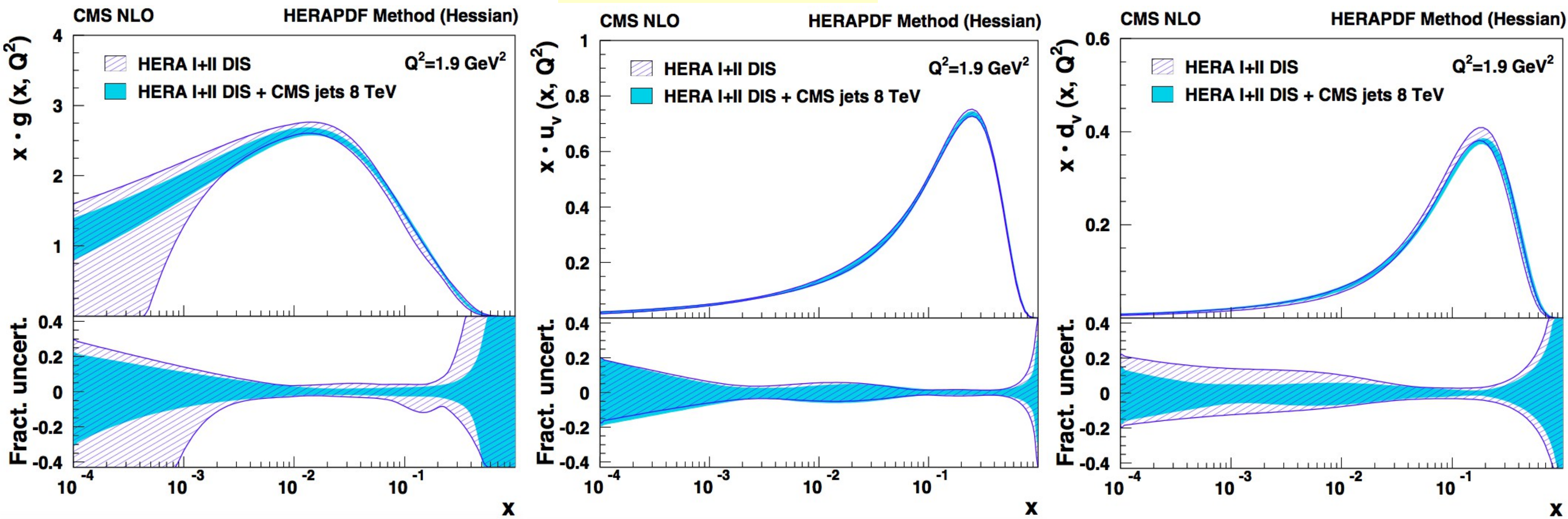
method	$\alpha_s(m_Z)$	scale unc.	exp. unc.	PDF unc.
Inclusive jet	0.1164	+0.0053 -0.0028	+0.0015 -0.0016	+0.0025 -0.0029
multijet	0.1150	+0.0050 -0.0000	±0.0025	±0.0013
Triple diff. Xsection	0.1199	+0.0031 -0.0020	+0.0015 -0.0015	+0.0004 -0.0006

PDF determination

JHEP 03 (2017) 156

- Together with HERA DIS cross section data, the inc. jet measurements provide important constraints on the gluon and valence-quark distributions in the kinematic range studied.
- The parametrization uncertainty is significantly reduced once the CMS jet measurements are included.

$Q^2 = 1.9$ GeV^2

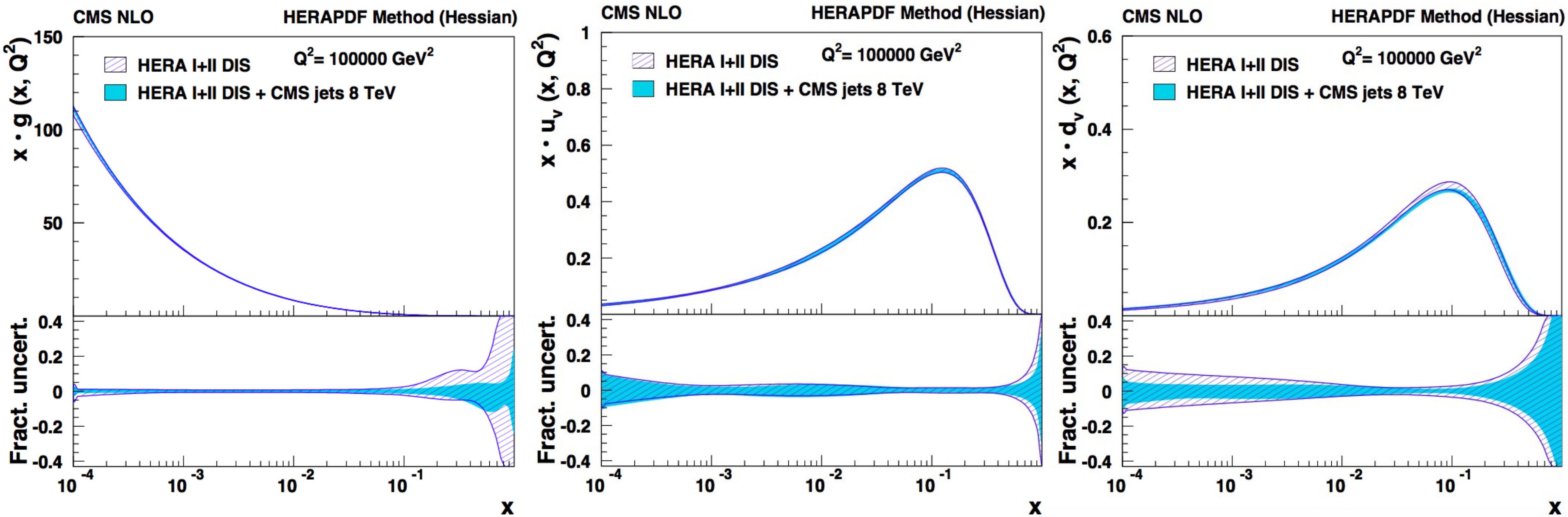


- No deviation from the QCD predictions is observed.
- Improvement in the uncertainty of the gluon distributions at high-x
  - Data: HERA I+II DIS [EPJ C 75 (2015) 2604] + CMS inc.jet at 8 TeV, 19.7 fb^{-1}
  - Theory for jet production in *pp:* NLOJET++ version 4.1.3, interfaced via fastNLO QCD scales: $\mu_r = \mu_f = p_{T,\,jet}$, $\alpha_S(M_Z) = 0.1180$

JHEP 03 (2017) 156

- Together with HERA DIS cross section data, the inc. jet measurements provide important constraints on the gluon and valence-quark distributions in the kinematic range studied.
- The parametrization uncertainty is significantly reduced once the CMS jet measurements are included.

$Q^2 = 10^5$ GeV^2



- No deviation from the QCD predictions is observed.
- Improvement in the uncertainty of the gluon distributions at high-x

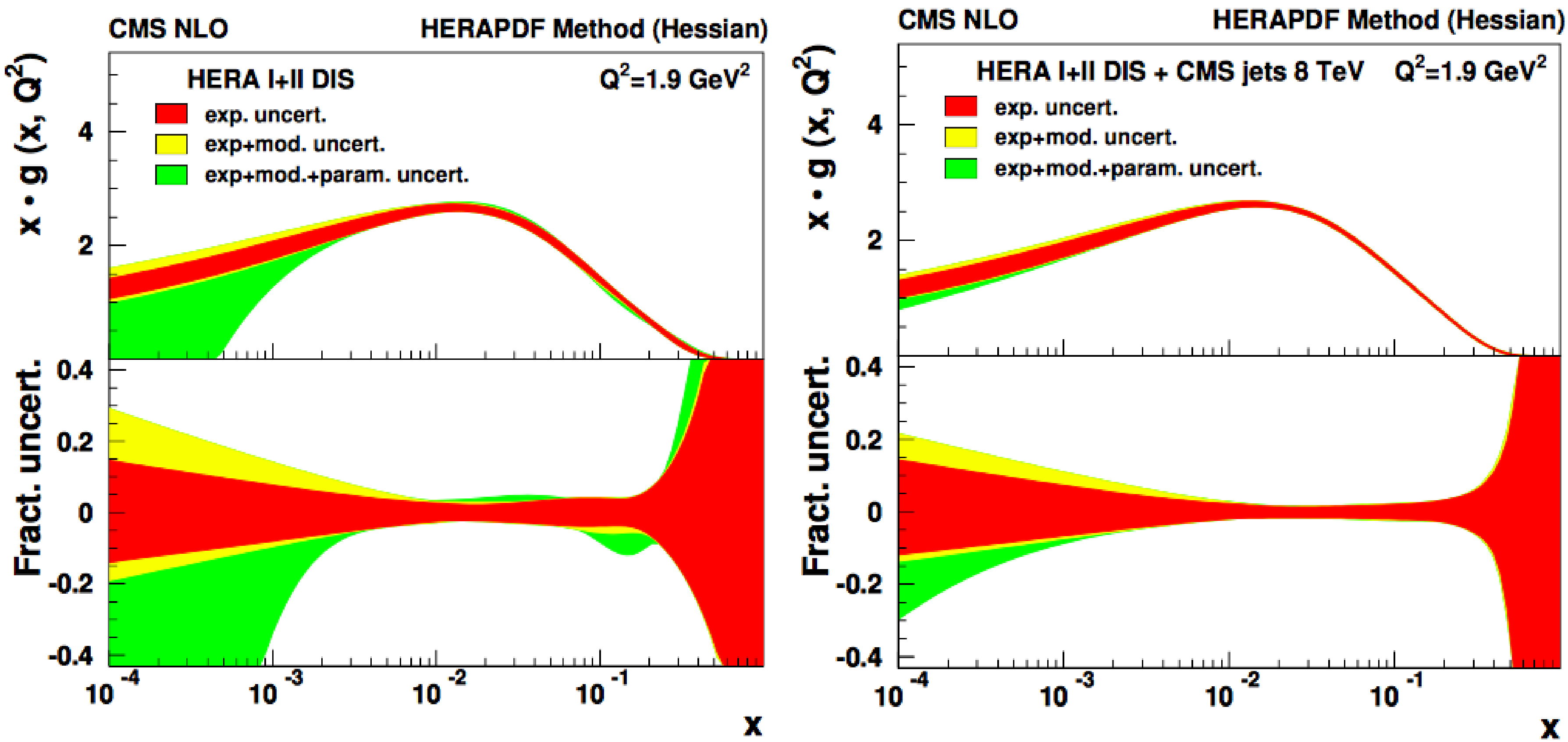
- Data: HERA I+II DIS [EPJ C 75 (2015) 2604] + CMS inc.jet at 8 TeV, 19.7 fb^{-1}

- Theory for jet production in *pp:* NLOJET++ version 4.1.3, interfaced via fastNLO

QCD scales: $\mu_r = \mu_f = p_{T,\,jet}$, $\alpha_s(M_Z) = 0.1180$

Impact of CMS jet measurements on PDFs

JHEP 03 (2017) 156



- The uncertainties for the gluon distribution, as estimated by using the HERAPDF method for HERA-only and HERA+CMS jet analyses

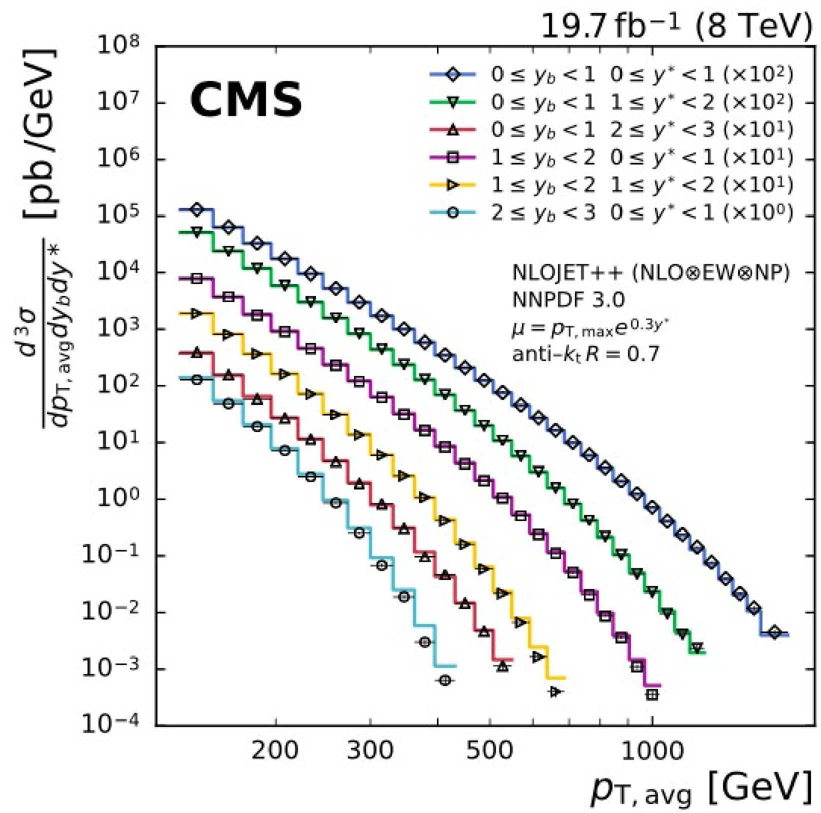
- The parameterization uncertainty is significantly reduced once the CMS jet measurements are included!

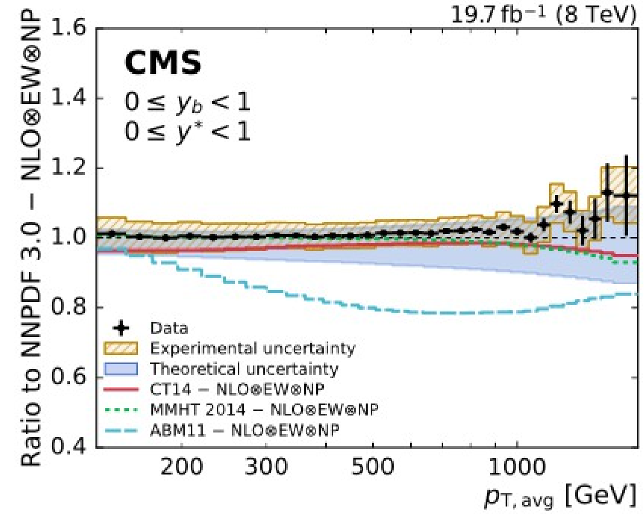
Triple-differential dijet cross section

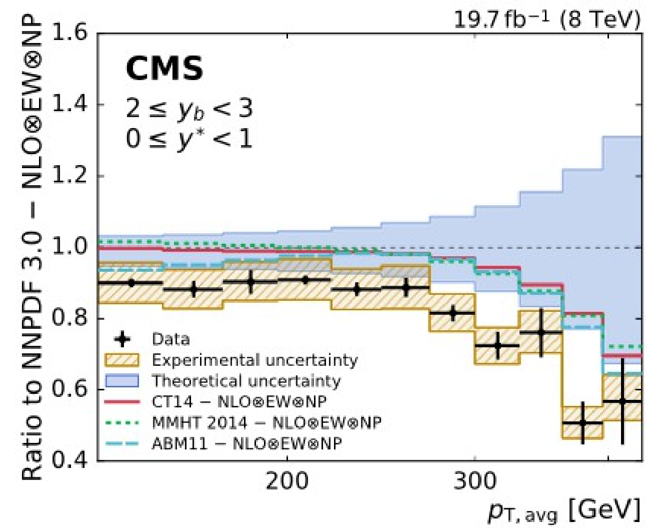
NEW!

arXiv:1705.02628
Submitted to EPJ C

- Cross sections measured as a function of: <p_T>, half the rapidity separation: $y^*=1/2|y_1 y_2|$ and boost of the two leading jets $y_b=1/2|y_1+y_2|$
- Apart from the boosted region, the data are well described by the predictions at NLO accuracy over many orders of magnitude.







Triple differential dijet cross section

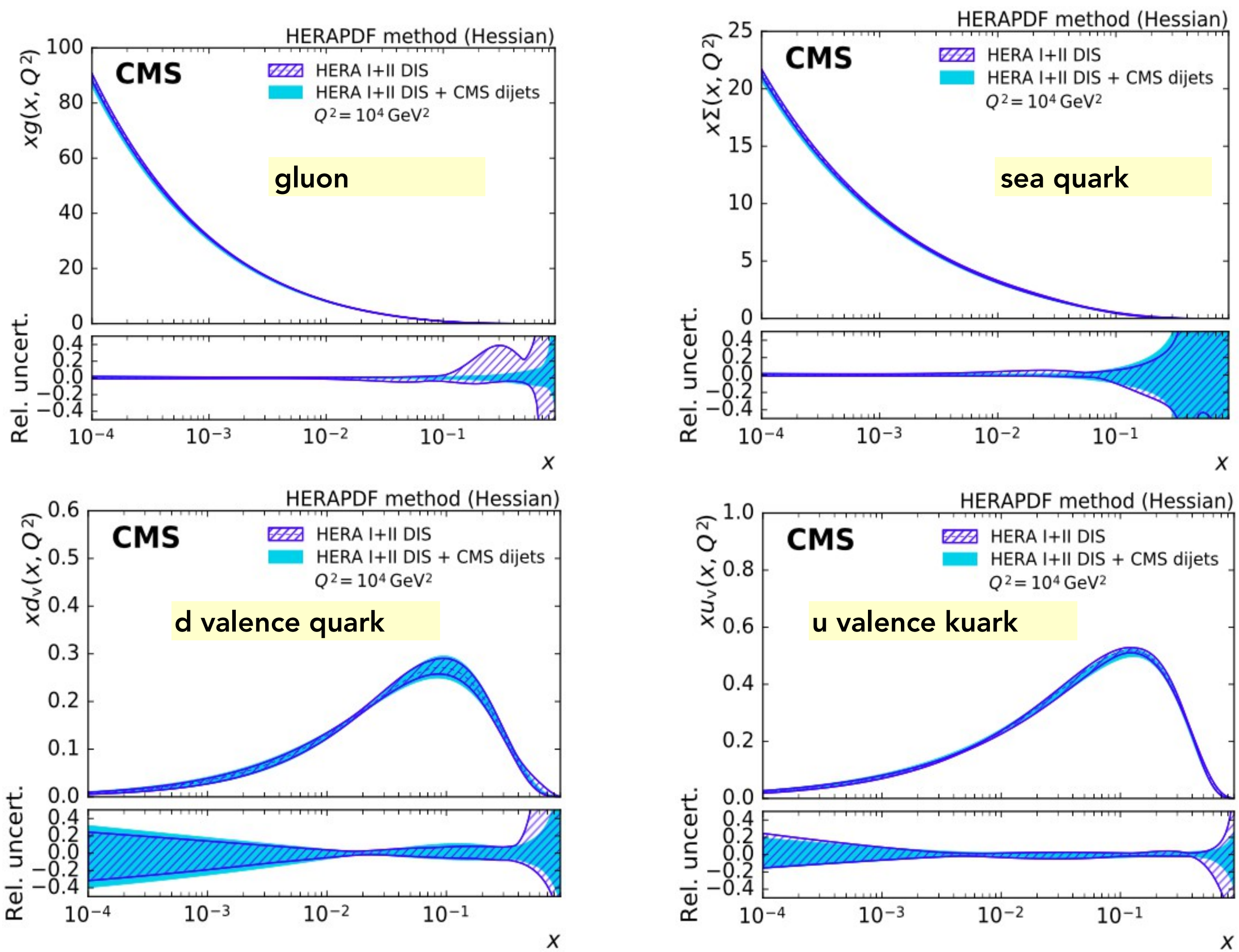
$$\frac{d^3\sigma}{dp_{T,avg}dy^*dy_b} = \frac{1}{\epsilon \mathcal{L}_{int}^{eff}} \frac{N}{\Delta p_{T,avg} \Delta y^* \Delta y_b}$$

Triple-differential dijet cross section (II)

NEW!

arXiv:1705.02628
Submitted to EPJ C

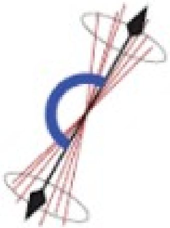
- This measurement is very well suited to extract PDFs and α_s:
  - central region most suited for α_s extraction at high energy scales
  - boosted region high-x region of PDFs can be better constrained
  - large rapidity separation PDF and detector effects can be better disentangled
- Fit combines HERA and CMS data



Dijet azimuthal decorrelation at 8 TeV

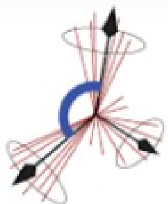
EPJ C 76 (2016)536

- At LO in pQCD the two final-state partons are produced back-to-back in transverse plane.



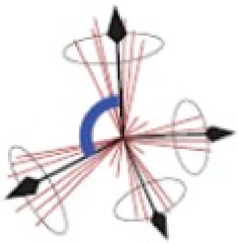
$$\Delta\varphi_{\mathbf{dijet}} = \pi$$

- The production of a third jet leads to a decorrelation in azimuthal angle.



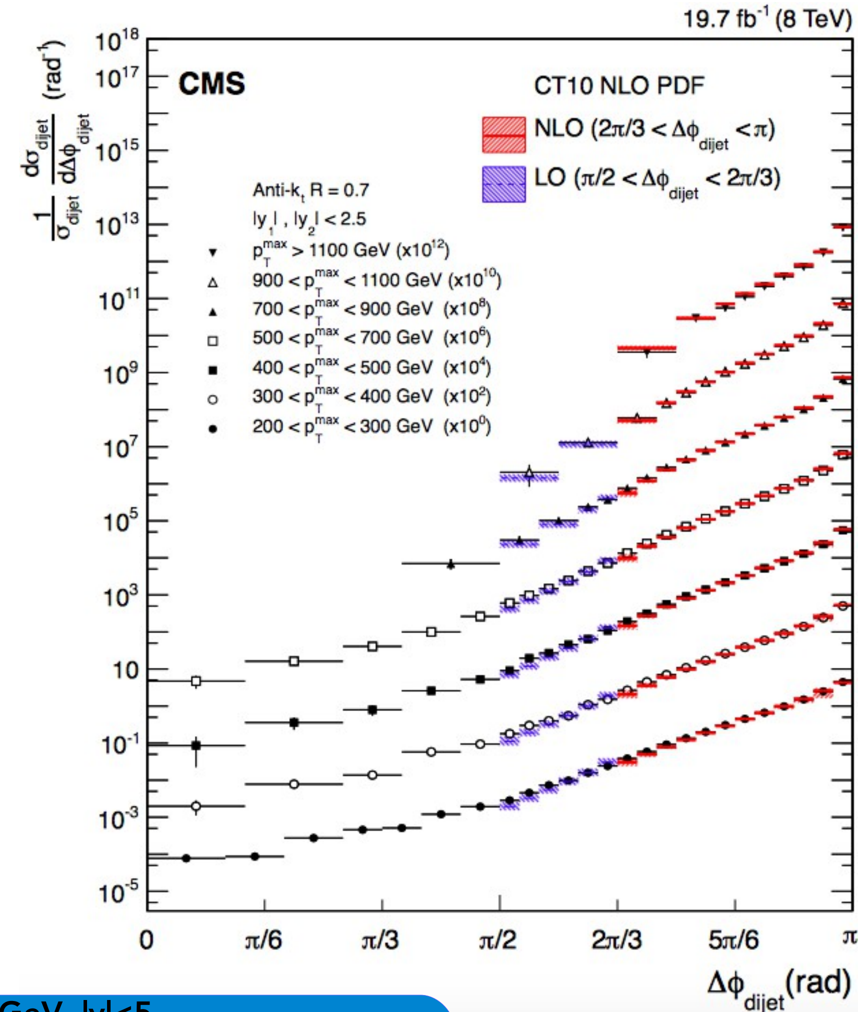
$$2\pi/3 \leq \Delta\varphi_{\mathbf{dijet}} < \pi$$

- If more than three jets are produced, the azimuthal angle between the two leading jets can approach zero.



$$0 < \Delta\varphi_{\mathbf{dijet}} \ll \pi$$

- The dijet azimuthal angular decorrelation probes the multijet production processes without measuring jets beyond the leading two.



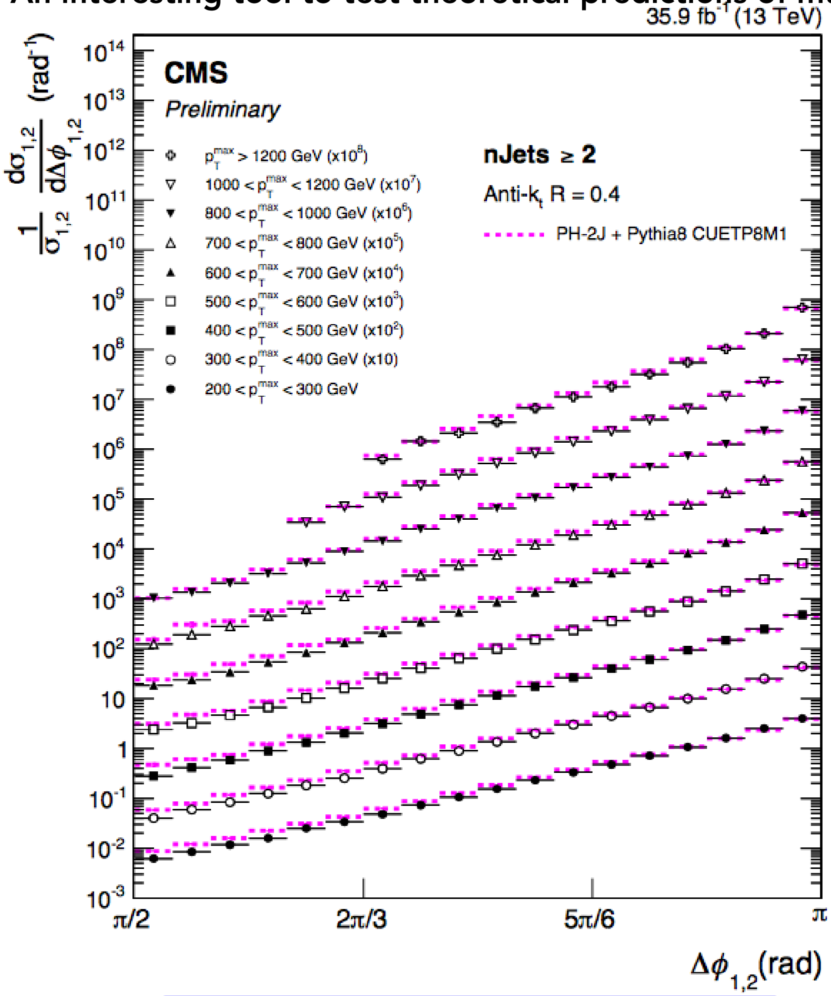
- Two leading among jets with p_T>100 GeV, |y|<5
- Compared to 3-jet production at NLO from NLOJet++
- No fix order predictions below $\pi/2$
- The $\Delta\varphi_{dijet}$ distributions are strongly peaked at π and become steeper with increasing p_T^{max}.

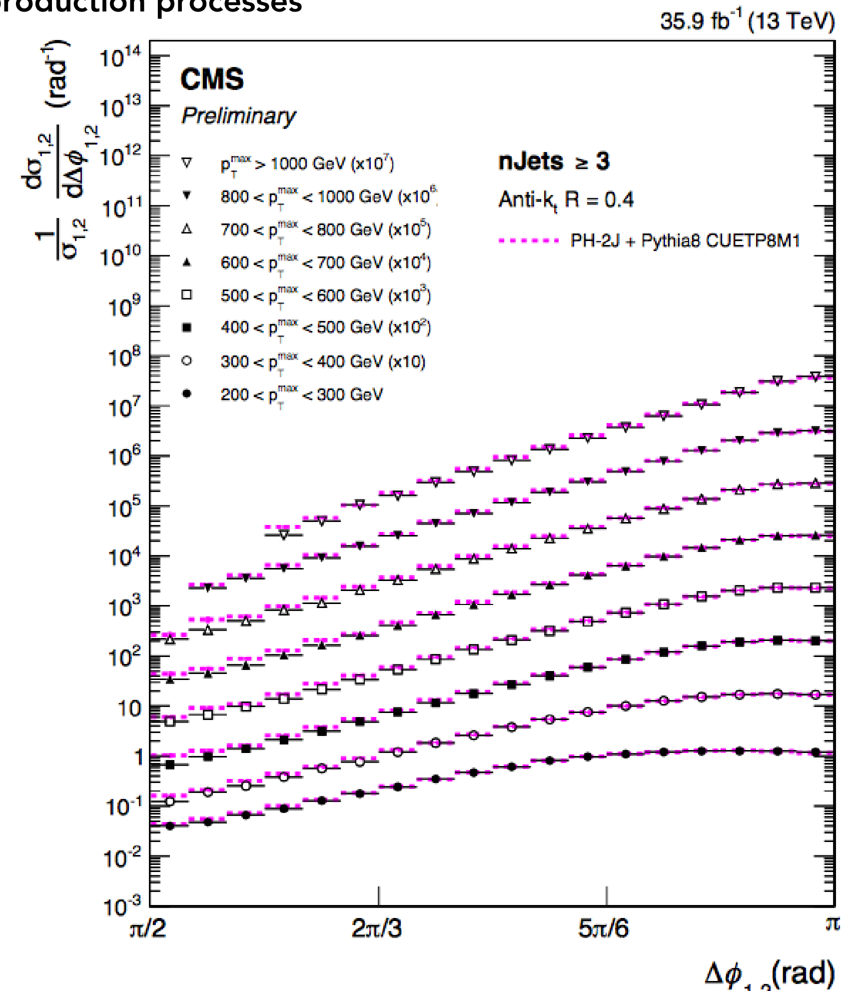
Multijet azimuthal decorrelation at 13 TeV

NEW!

CMS PAS-SMP-16-014

- Normalized inclusive 2-jet, 3-jet, and 4-jet cross sections as a function of the azimuthal angular separation between the two highest p_T (leading) jets $\frac{1}{\sigma_{1,2}}\frac{d\sigma_{1,2}}{d\Delta\phi_{1,2}}$,
- An interesting tool to test theoretical predictions of multijet production processes



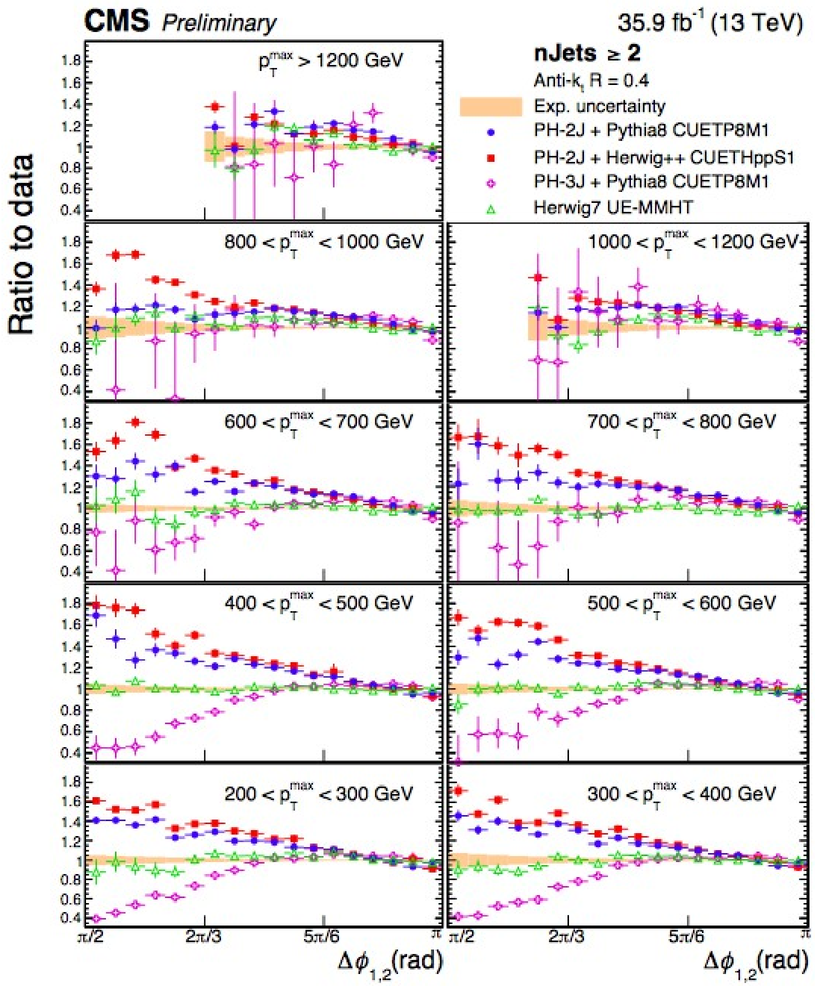


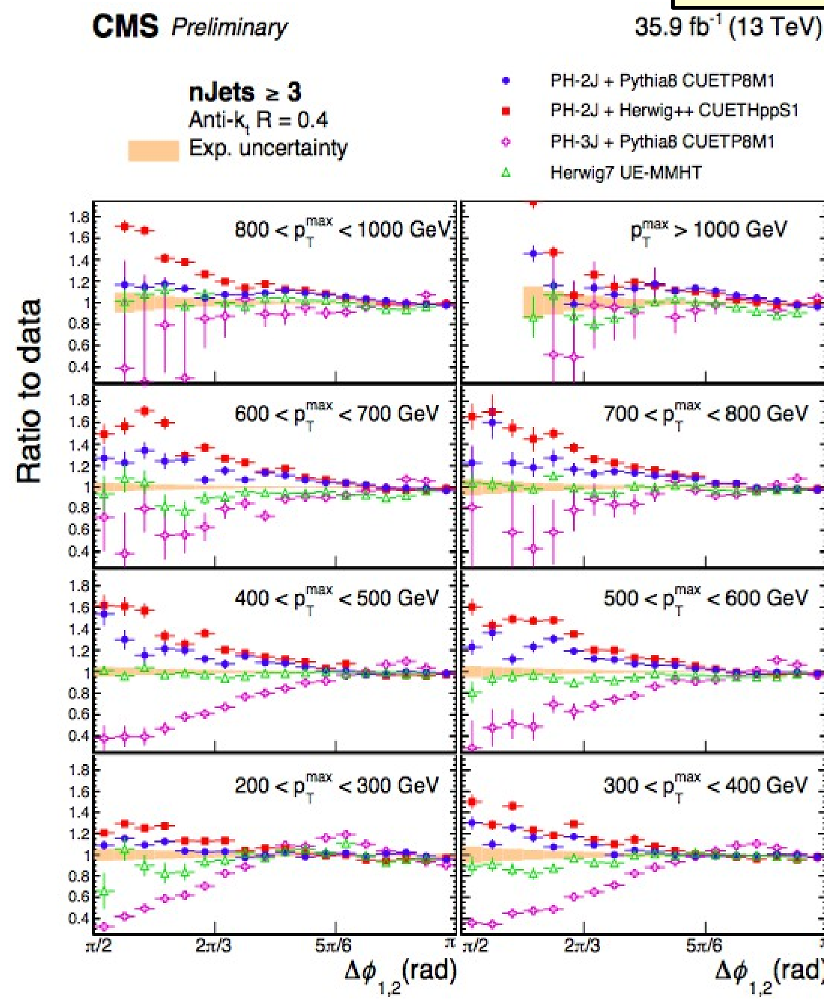
- Higher order predictions describe the measurements very well

- Spectrum gets flatter, as dijet events are no more included
- The production of a 3rd jet leads to a decorrelation in azimuthal angle.

Multijet azimuthal decorrelation at 13 TeV (II)

CMS PAS-SMP-16-014



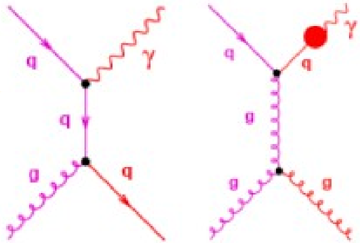


- PH-2J (NLO dijet calculation) gives better results when matched with P8 than Herwig++
- PH-3J+P8 is generally lower than PH2J+P8.
- Predictions of PH-2J or PH-3J exhibit large deviations from the measurements

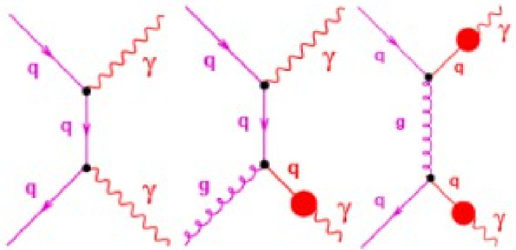
Photon Measurements

- Measurement of the production of pairs of photons in hadron colliders help also to understand the QCD background to Higgs production and BSM searches.
- Prompt photons are produced at the LHC in the hard process pp $\rightarrow \gamma$ + X.
  - provides a clean probe of pQCD
  - can be used to study the gluon PDF of the proton through LO process qg $\rightarrow$ q γ.

Direct photon production
pp $\rightarrow \gamma$ + X



Diphoton production
pp $\rightarrow \gamma\gamma$ + X

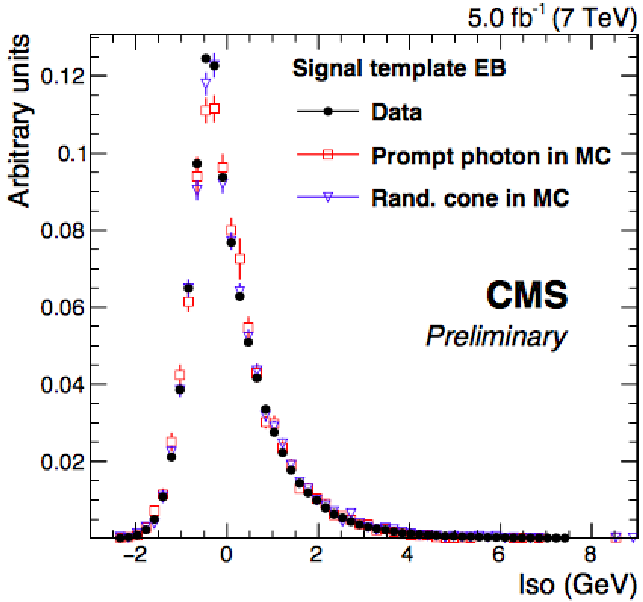


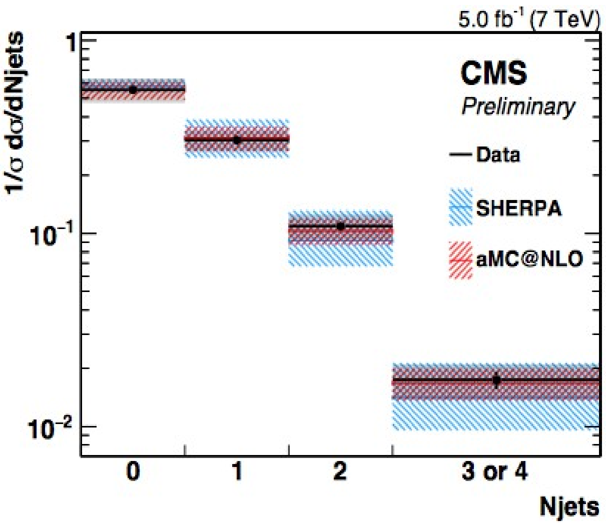
- Photon identification in CMS:
  - 2-dimensional clusters of different size in the barrel and in the endcap electrons from converted photons also reconstructed in the tracker
  - Main background from light neutral mesons (i.e pi, eta) decays (10^5 jets / photon)
    - removed with shower shape id + isolation

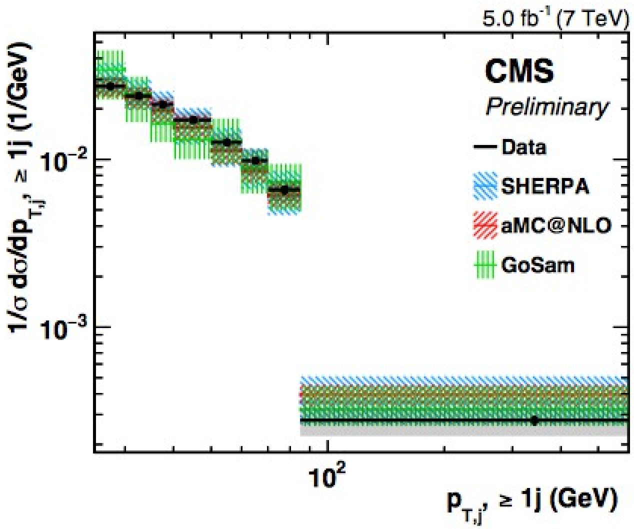
Diphoton + jets at 7 TeV

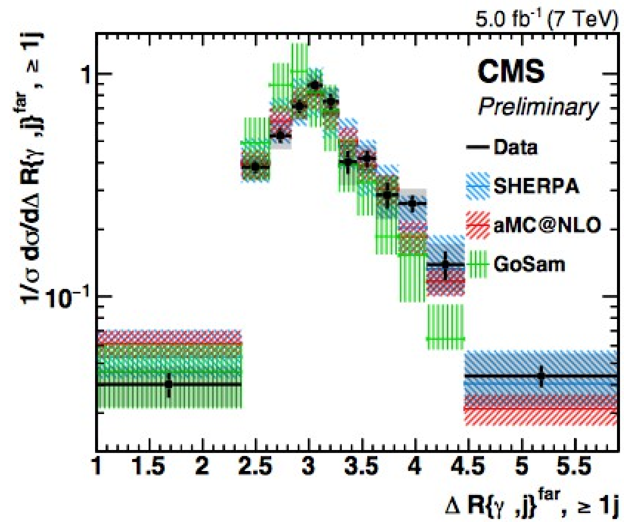
CMS PAS-SMP-14-021

- Background for Higgs produced in VBF
- Isolation template from random cones for signal and sideband for background
- Differential xsec of jet multiplicity, p_T, angular correlations
- aMC@NLO and Sherpa agree well with data
- GoSam (corrected for PS and UE) shows some discrepancies for angular distributions





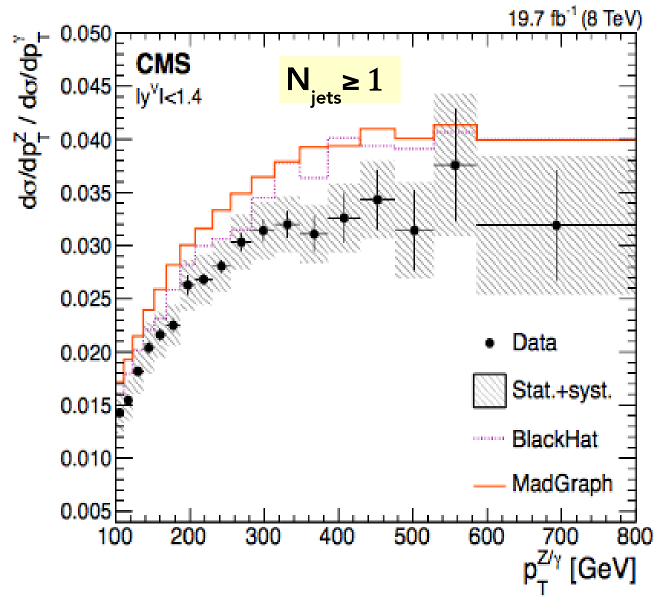




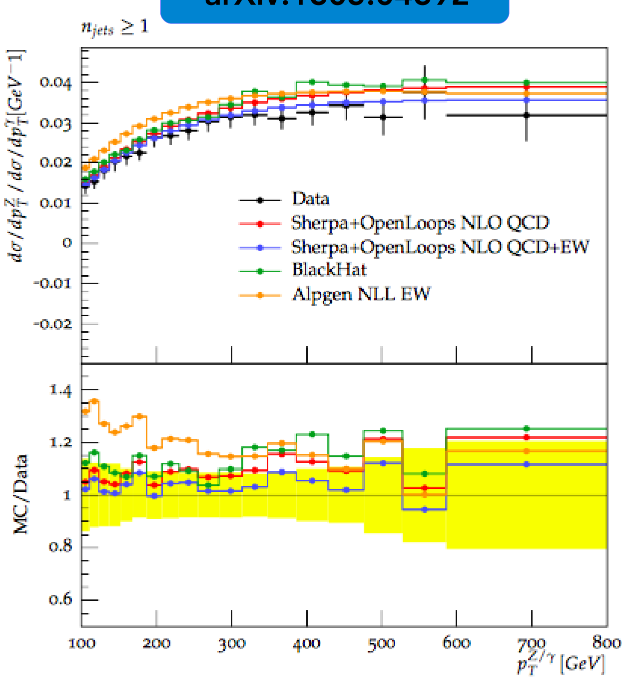
Z/γ* + jets to γ + jets @ 8 TeV

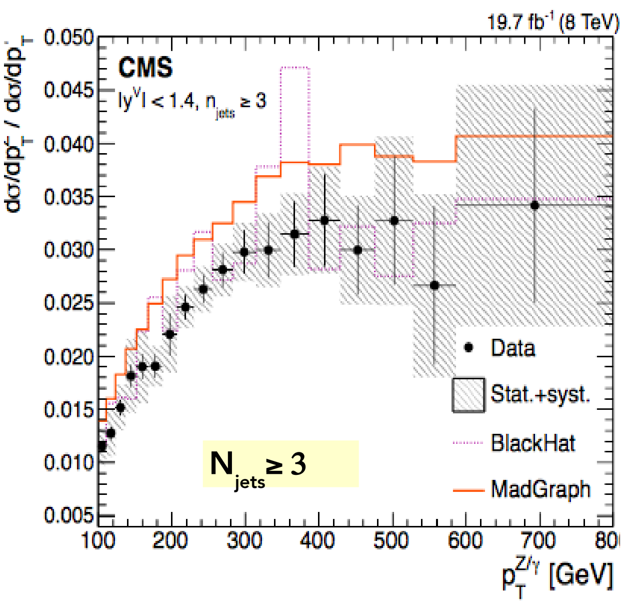
JHEP 10 (2015) 128

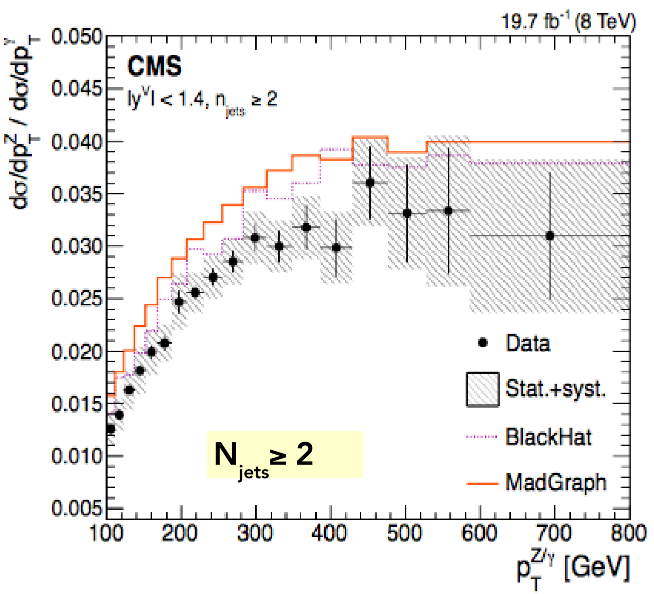
- Compare the cross sections for Z + jets and γ + jets as a function of p_T is measured in the phase space regions: njets ≥ 1, 2, 3
- BLACKHAT reproduces shape of the data in n_{jets} ≥ 2 and n_{jets} ≥ 1 in γ +jets case
- 15-20% discrepancies to both LO and NLO predictions
- Possible indication of EWK corrections from recent theoretical results



arXiv:1605.04692



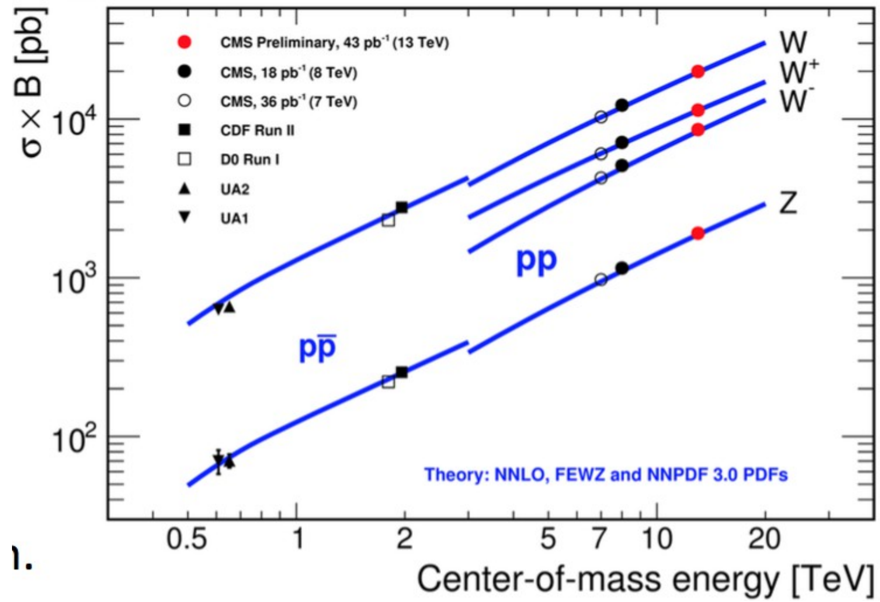




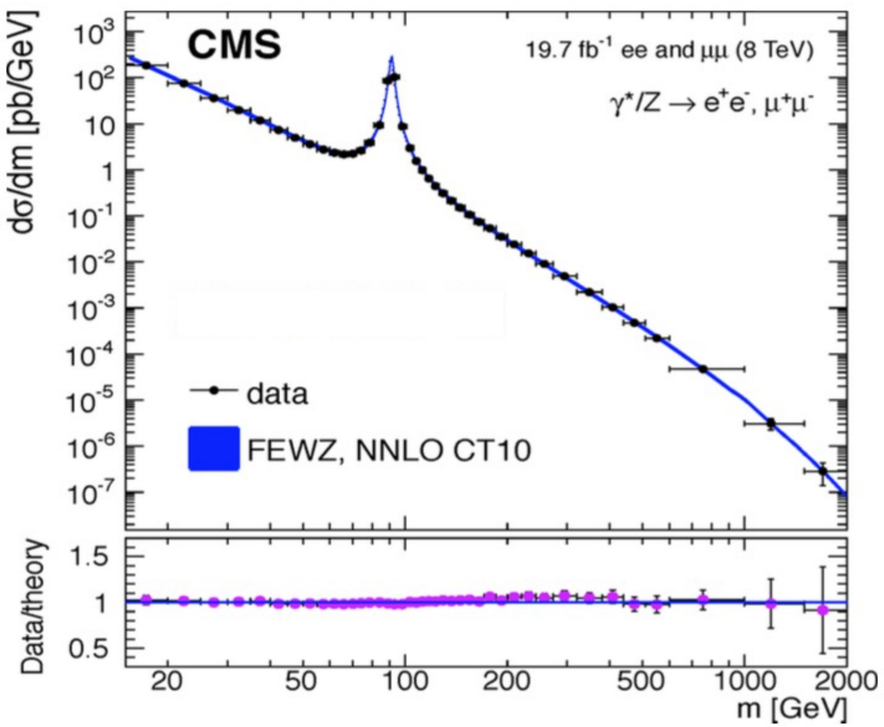
W/Z production

- Standard physics objects ("candles") at colliders
- √s dependence is well described by NNLO predictions.
- Sensitive to PDFs

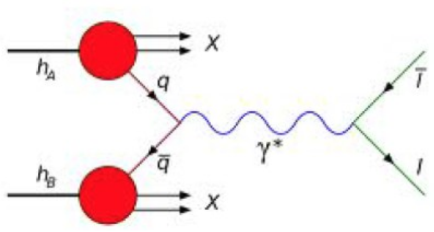
CMS-PAS-SMP-15-004



EPJC 75 (2015) 147



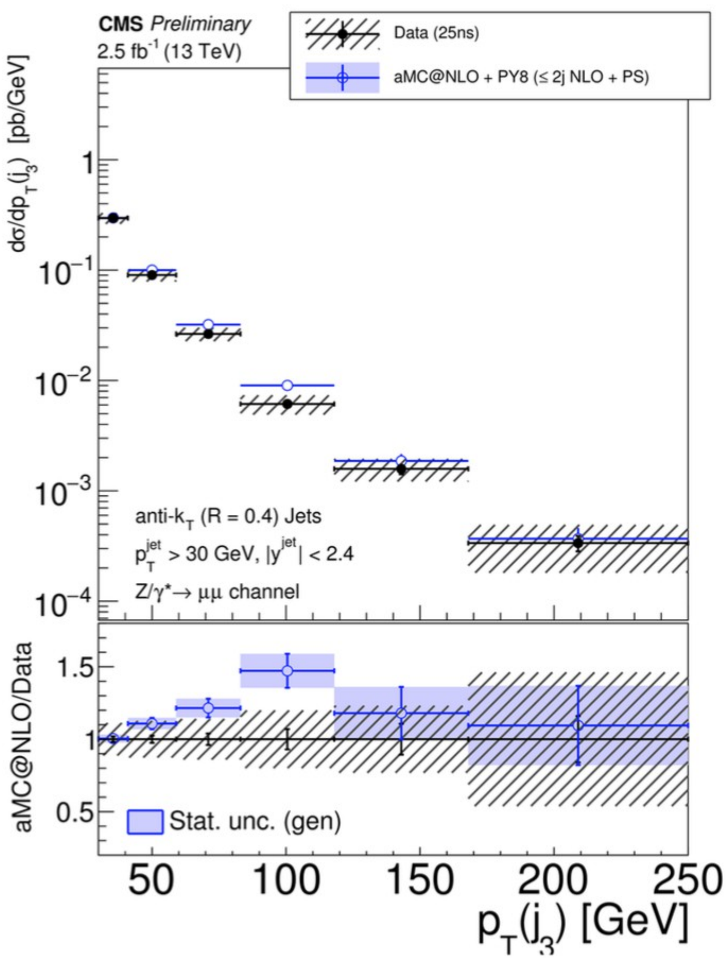
- Sensitive to quark and photon distributions.
- Differential Drell-Yan+Z cross-section in accord with NNLO over 9 orders-of-magnitude & forward:



W/Z + jet production

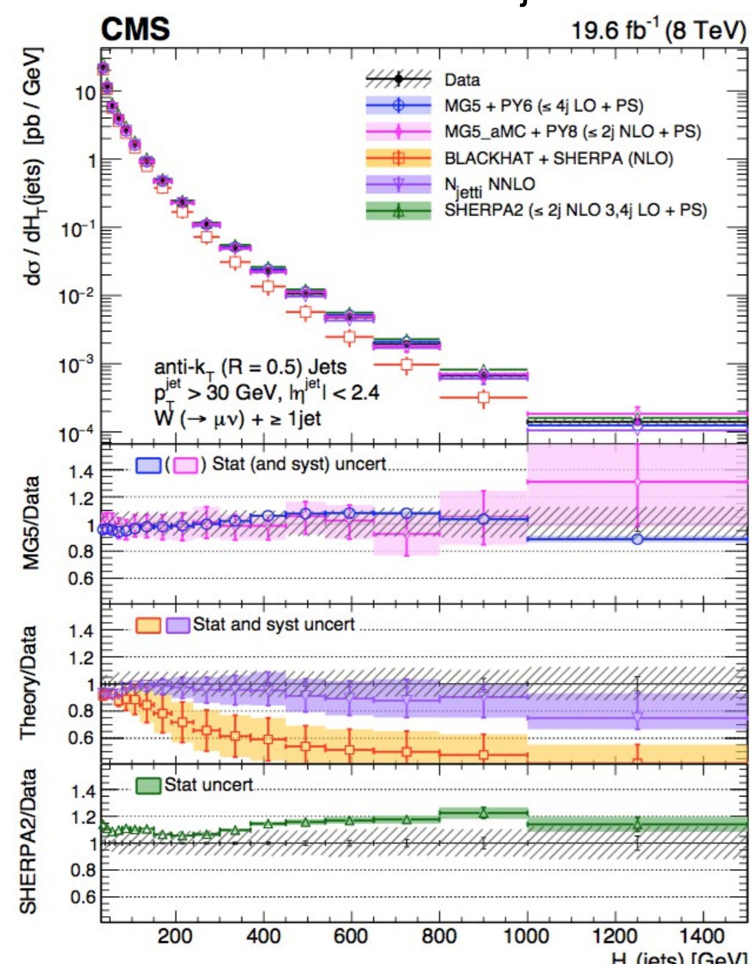
- Fundamental test of description of QCD radiations
- Prediction: NLO up to 2 jets, with parton-shower jets
- 3rd jet p_T is difficult to be described.

CMS-PAS-SMP-15-010



- Kinematic distributions are difficult to be fully described.
- Compared to:
  - multileg MCs NLO MCs
  - NLO upto 2jet
  - NLO for 4 jet
  - NNLO calculation for W+1jet

CMS-PAS-SMP-14-023
Accepted by Phys. Rev. D



Summary

- Significant ongoing effort to improve our understanding of QCD
  - both experimental and theoretical
  - LHC has provided access to a large phase space for understanding of various aspects of QCD
- CMS has a rich physics program which is the perfect testing ground for QCD models and theory
  - results provide new constraints for non-perturbative and semi-hard QCD dynamics on MC
- Ranging from low p_T to high p_T and from inclusive to exclusive observables a large amount of QCD precision measurements
  - measurements of α_s at the TeV scale for the first time, with no deviation from the QCD predictions
- Still more measurements and efforts on-going stay tuned!

Thank you for your attention!

BACKUP

Identified Charged Hadrons @ 0.9, 2.76 and 7

Hadron spectra

– Long history in high energy particle, nuclear and cosmic ray physics

– One of the simplest and most relevant physics quantities

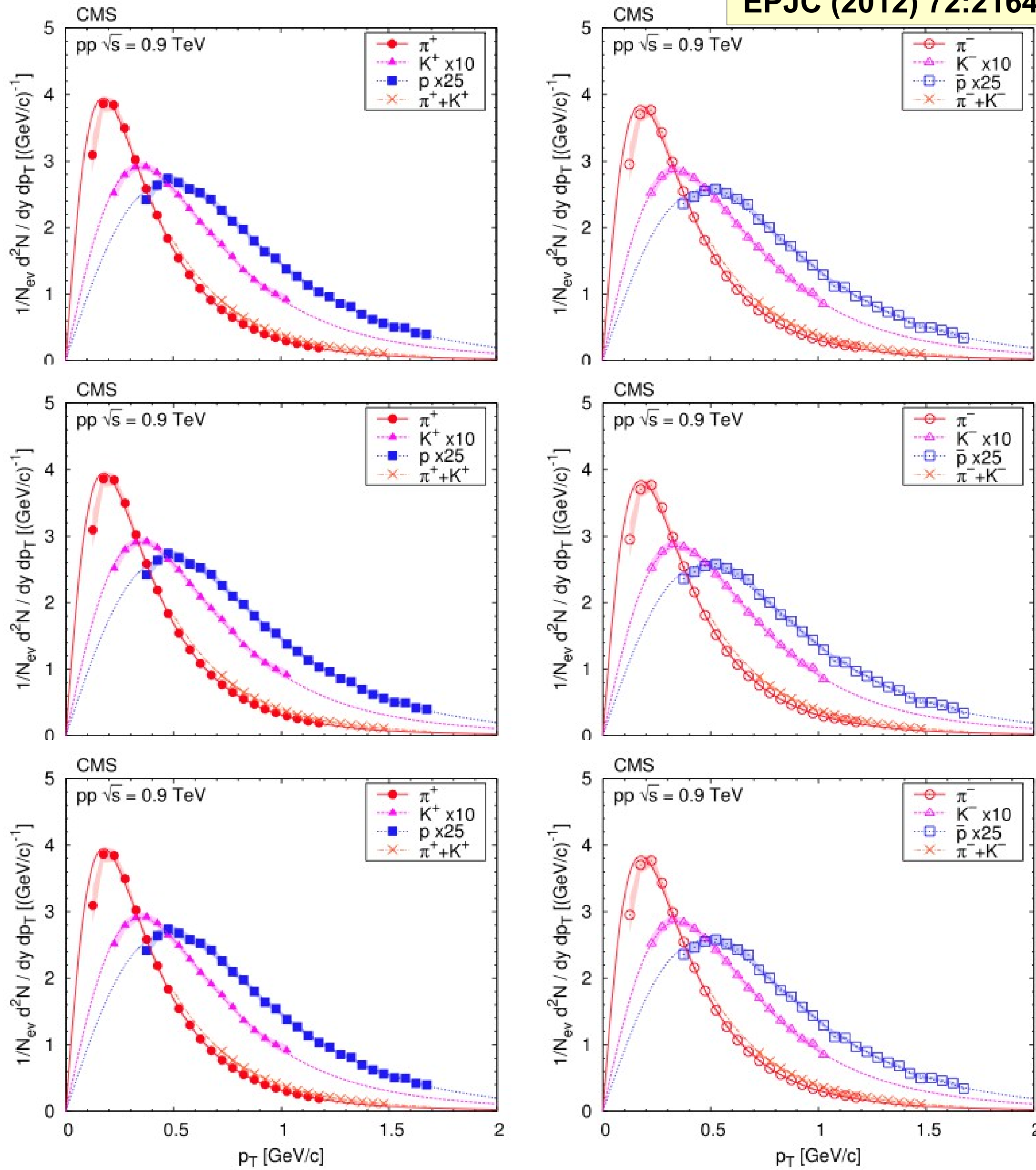
– Scaling properties of particle production; predictions of models and generators

– Particle production at LHC energies is strongly correlated with event multiplicity rather than with the center-of-mass energy of the collision

– Common underlying physics mechanism:

– At TeV energies, the characteristics of particle production are constrained by the amount of initial parton energy that is available in any given collision

EPJC (2012) 72:2164



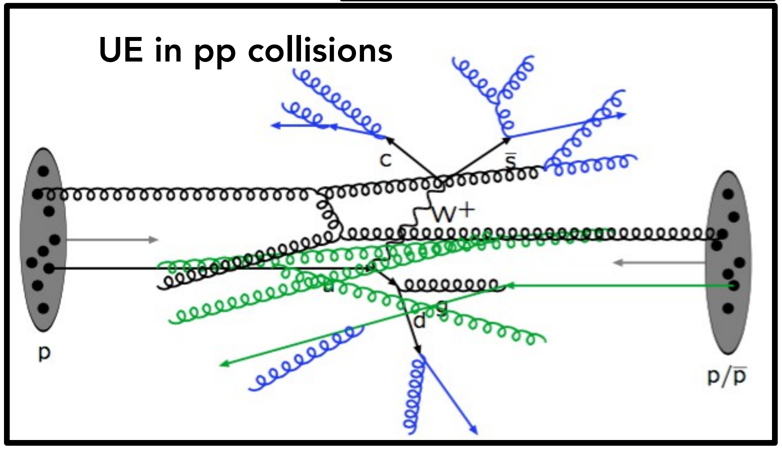
UE activity @13 TeV

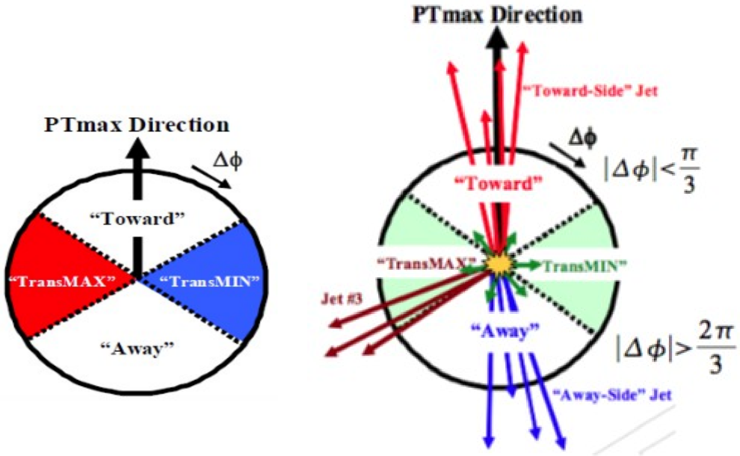
CMS-PAS-FSQ-15-007

- Improve the differential power in the quantification of the activity coming from MPI which allows for the better tuning of the model parameters describing the MPI.

Transverse region divided:

- **TransMIN** – lower activity, sensitive to MPI + BBR
- **TransMAX** – higher activity, sensitive to MPI + BBR + initial and final radiation
- **TransDIF** = TransMAX – TransMIN, sensitive to initial and final radiation
- **TransAVE** = (TransMIN+TransMAX) / 2





Leading jet : p_T > 1 GeV, $|\eta|$< 2

Leading track : p_T> 0.5 GeV, $|\eta|$<2

Observables:

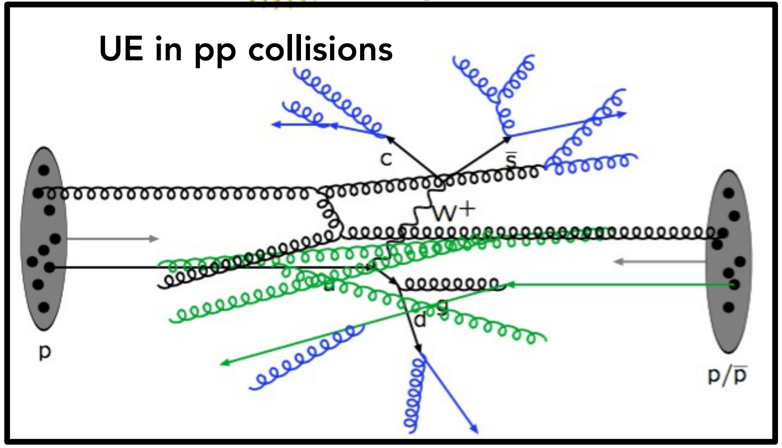
- **The charge density: N_{ch}**
- **The transverse momentum density: $\sum p_T$**

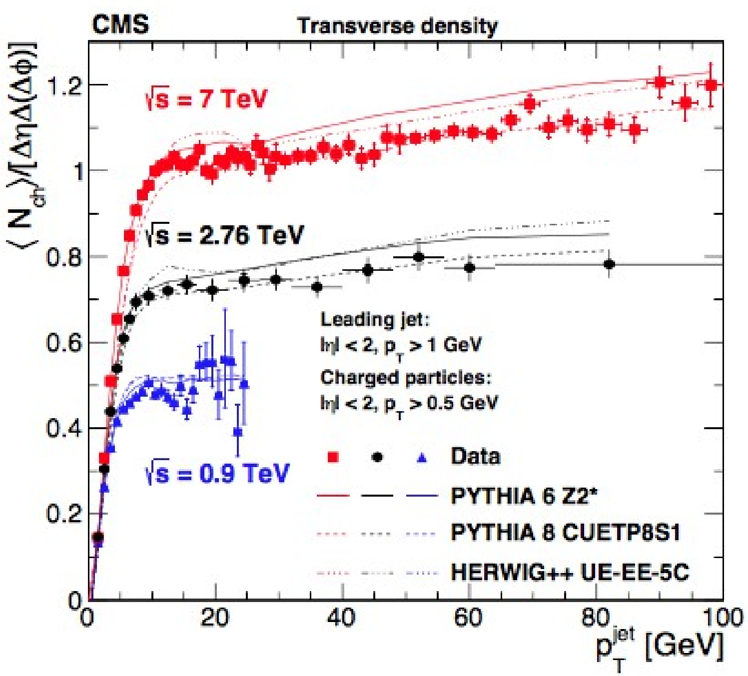
Underlying event (UE) activity @ 2.76 TeV

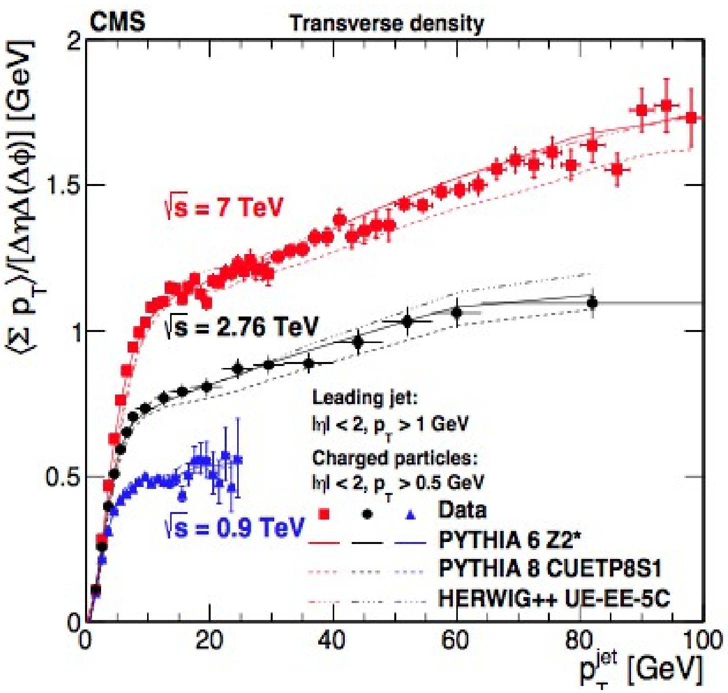
NEW!

arXiv:1507.0722
9

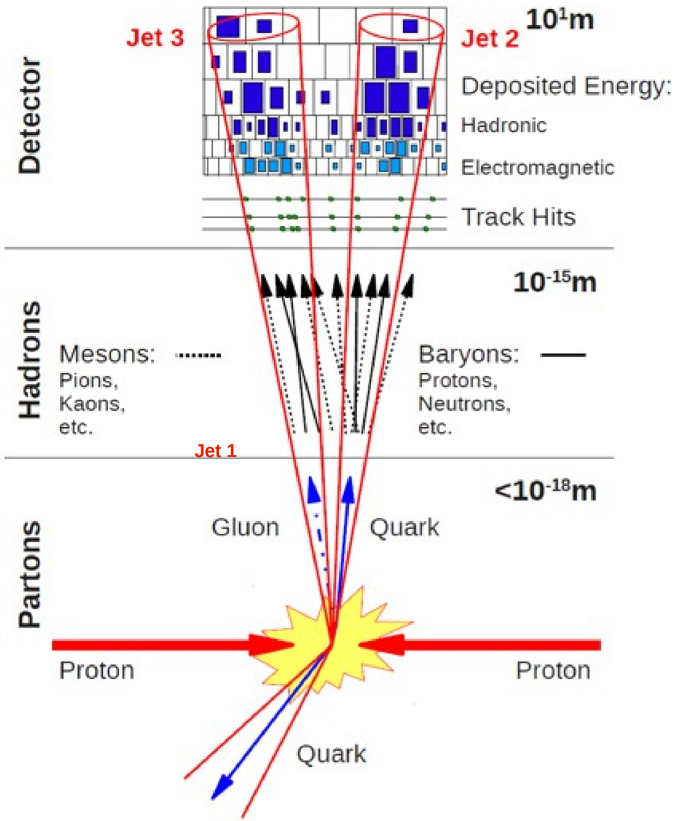
- UE activity:
  - using events with a leading charged particle jet
  - produced at central region (|η jet| < 2) & 1 < p_T < 100 GeV.
- Charged particle and p_T sum density in transverse region to highest p_T jet well described by PYTHIA and HERWIG
- Good description of energy dependence.



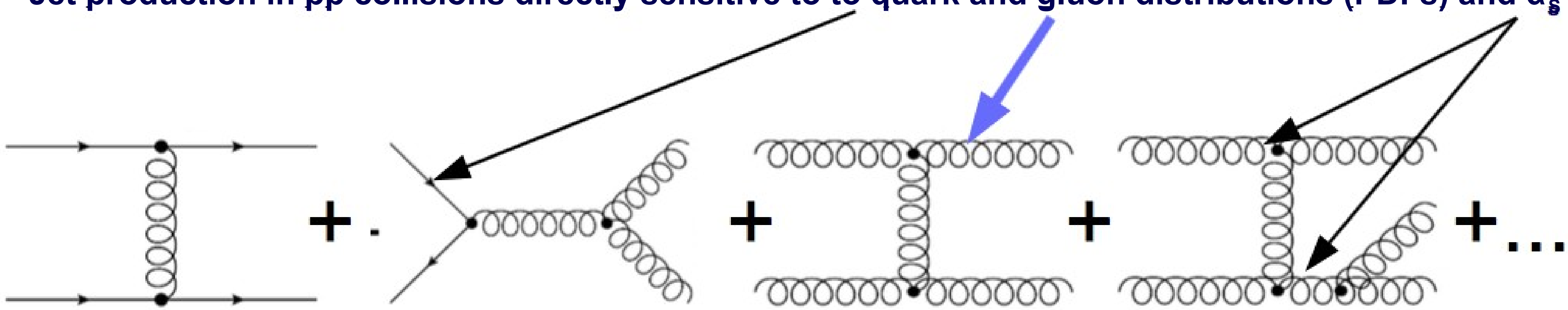




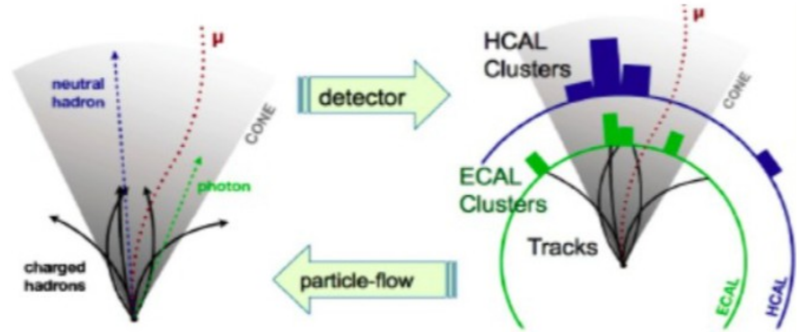
- Jets
  - Collimated spray of particles
  - The experimental signatures of quarks and gluons.
  - Invaluable objects to probe QCD
  - Abundantly produced at hadron colliders ("jet laboratories")
  - Important signature for many physics processes (Higgs, top, SUSY, ...)
  - Important for almost all LHC physics analyses!



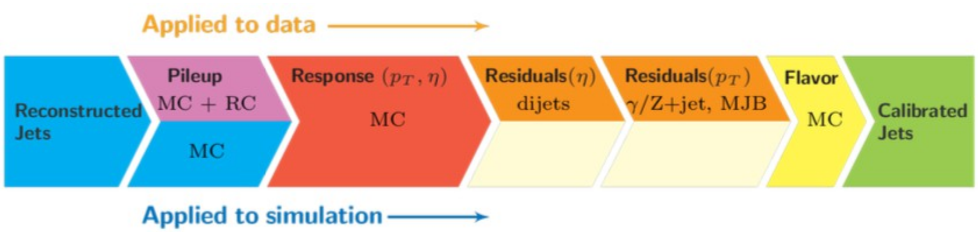
- **Jet production in pp collisions directly sensitive to to quark and gluon distributions (PDFs) and α_s**



- A jet in CMS is seen as a bunch of particles in the detector
- Jet reconstruction procedure: input objects (e.g. particles)Δ apply jet finding algorithm Δ jet reconstruction
- Anti-k_t algorithm (infrared and collinear safe) is used
- Particle Flow (PF) Jets: Clustering of Particle Flow candidates constructed by combining information from all sub-detector systems.

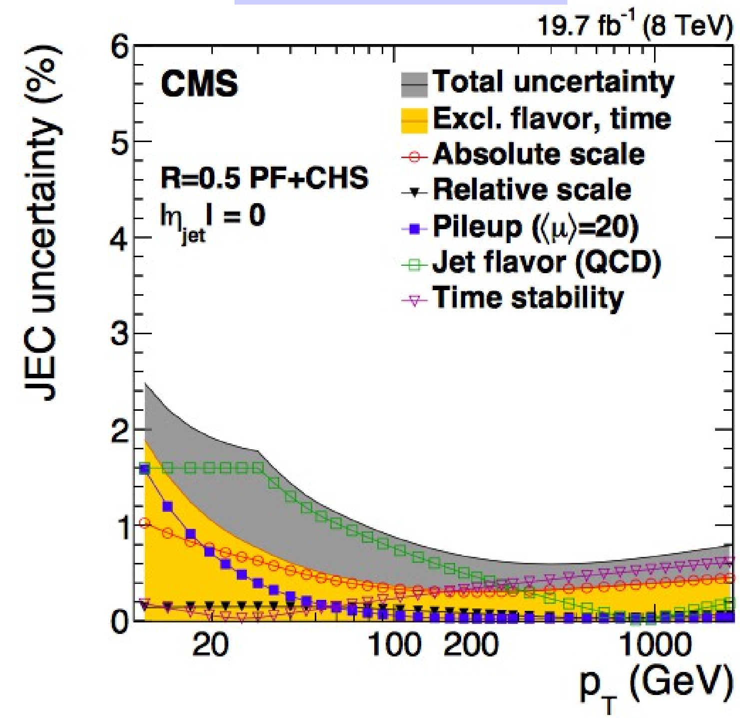


- Factorized Jet Energy Correction approach in CMS:

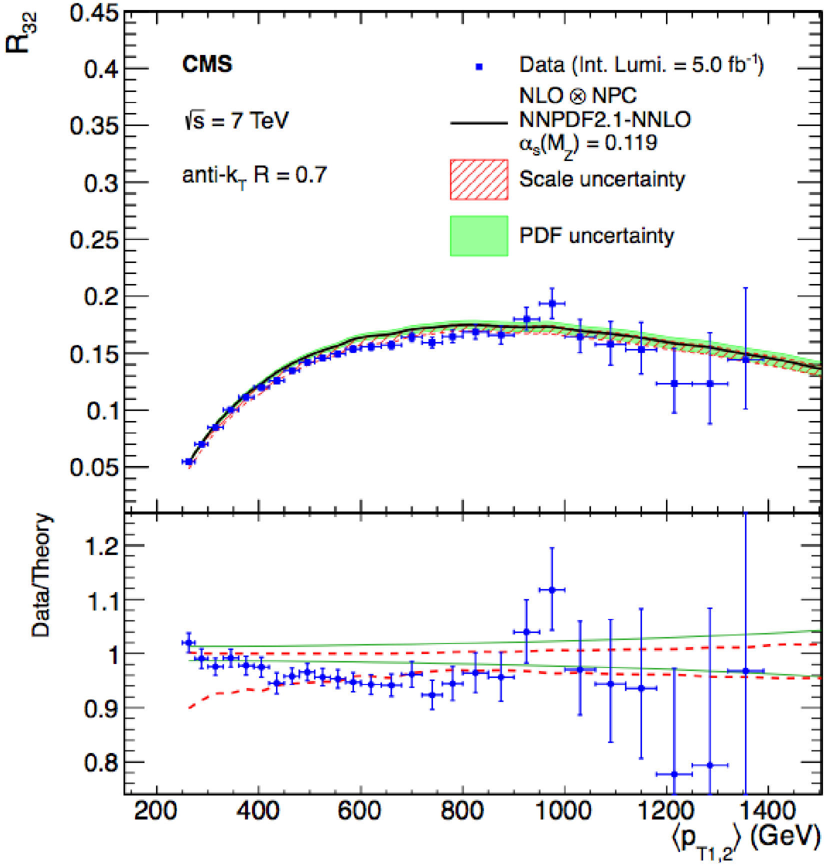


- Pileup → corrects for "offset" energy
- Response → Make jet response flat on η and p_T
- Data/MC residuals → residual differences between data & MC
- Flavor (optional) → corrects dependence on jet flavor

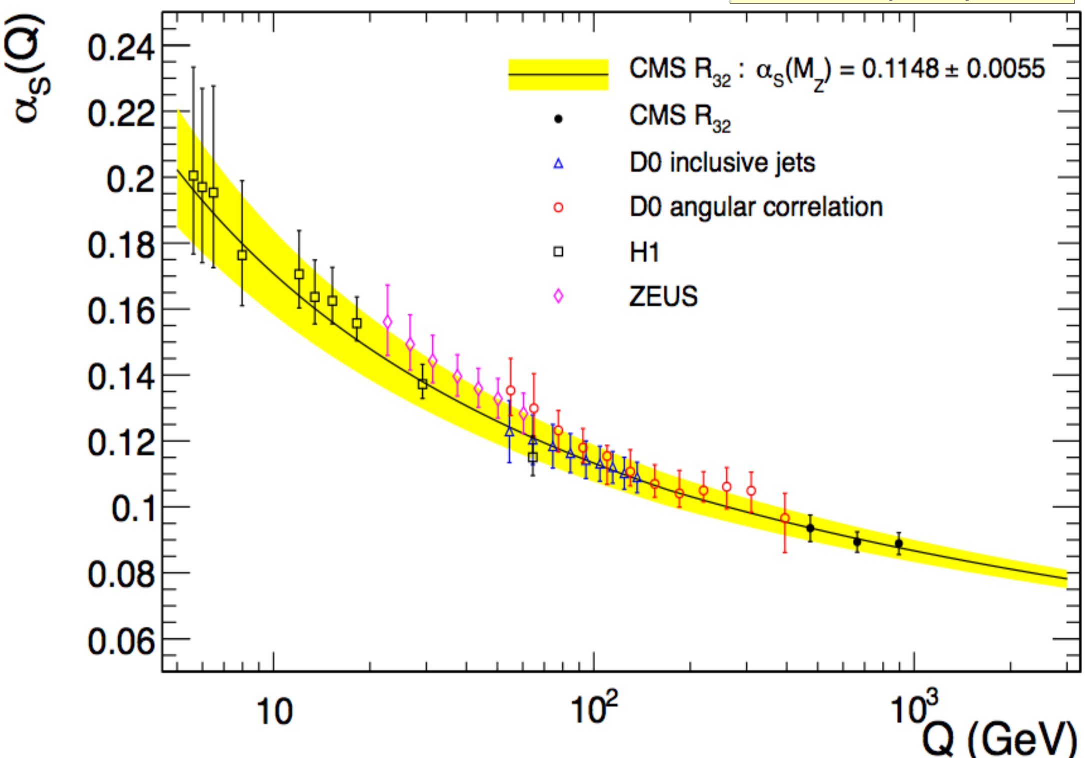
JINST 12 (2017) P02014



3 to 2 Jet Ratio and α_s @ 7 TeV



EPJ C73 (2013) 2604



$$\alpha_s(M_Z) = 0.1148 \pm 0.0014(exp.) \pm 0.0018(PDF) \pm 0.0050(theo.)$$

$$R_{32}(< p_{T1,2} >) = \frac{\sigma_3}{\sigma_2} = \frac{\sigma(pp \to njets + X; n \geq 3)}{\sigma(pp \to njets + X; n \geq 2)}$$

- Ratio R_{32}: probability to find a third jet in an inclusive dijet event
  - Sensitive to high order radiation and $\alpha_S(Q)$
  - Q is the average transverse momentum of the two jets leading in p_T ($Q = p_{T1} + p_{T2} / 2$)
  - Measurements of the running of $\alpha_S(Q)$ provide a stringent test of QCD.
  - Almost independent of PDFs
- Many experimental uncertainties (eg. JES) cancel out in the ratio
- One of the first and very precise measurement at the TeV scale.
- The extracted constant is compatible with the world average and the running of α_S is also predicted accurately

Inelastic pp cross section @ 13 TeV

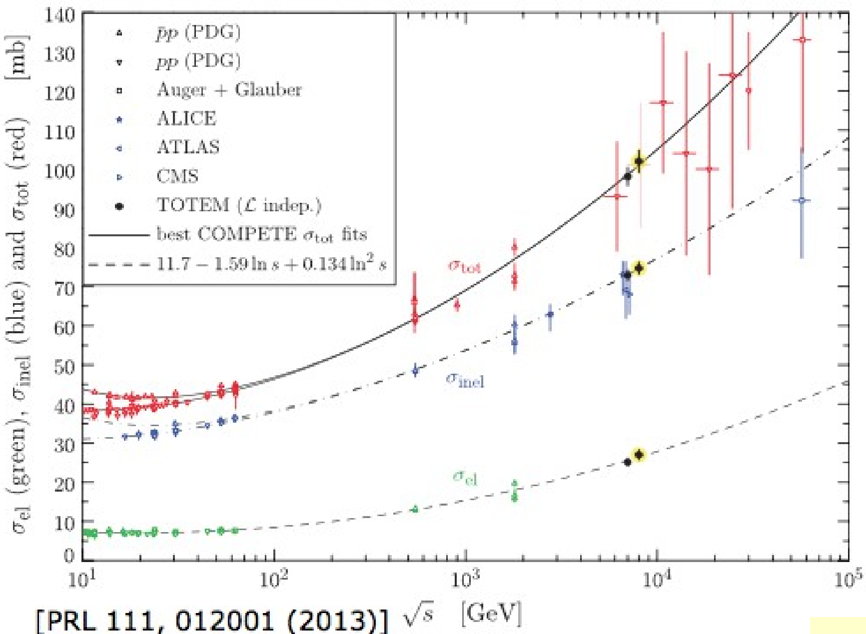
CMS PAS FSQ-15-005

- Motivation:
  - measure the inelastic pp cross section at 13 TeV in the largest possible phase space that is experimentally accessible
  - extrapolate to the total inelastic phase space domain

$$\sigma_{tot}(s) = \sigma_{el}(s) + \sigma_{inel}(s)$$

$$\sigma_{inel}(s) = \sigma_{sd}(s) + \sigma_{dd}(s) + \sigma_{cd}(s) + \sigma_{nd}(s).$$

  - go more forward and gain information on relative increase
  - reduce extrapolation uncertainty



[PRL 111, 012001 (2013)]

- Results from CMS, ATLAS, ALICE, LHCB @ 7 TeV : σ_{inel} 66.9-72.7 mb
- Measurements from TOTEM (with optical theorem)
  - 7 TeV: σ_{inel} = 73.5 ± 1.9 mb
  - 8 TeV: σ_{inel} = 74.7 ± 1.7 mb

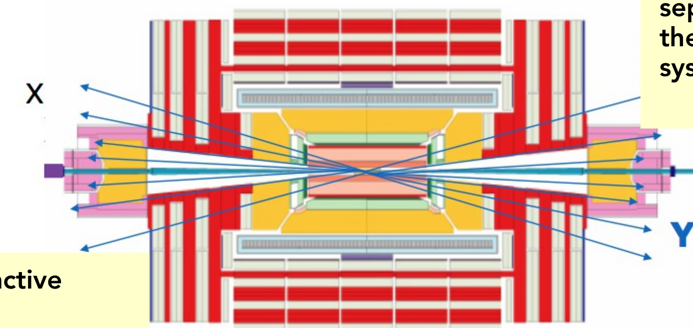
- Analysis strategy:
  - Use low pile-up runs from 2015 with B = 0 T and 3.8 T
  - Trigger: both beams present @ IP
  - Count events with an energy deposit above threshold

HF OR	HF/CASTOR OR
@ least one HF tower above 5 GeV $\xi_X > 10^{-6}$ and $\xi_Y > 10^{-6}$	@ least one HF or CASTOR tower above 5 GeV $\xi_X > 10^{-6}$ and $\xi_Y > 10^{-7}$

$$\xi_X = \frac{M_X^2}{s} \qquad \xi_Y = \frac{M_Y^2}{s} \qquad \xi = \max(\xi_X, \xi_Y)$$

  - Correction for noise from no-beam events
  - Data driven correction for pile-up events
  - Correction to the particle level–different MC models: PYTHIA8 (D-L and MBR for diffraction), PYTHIA6, EPOS, QGSJET-II, PHOJET

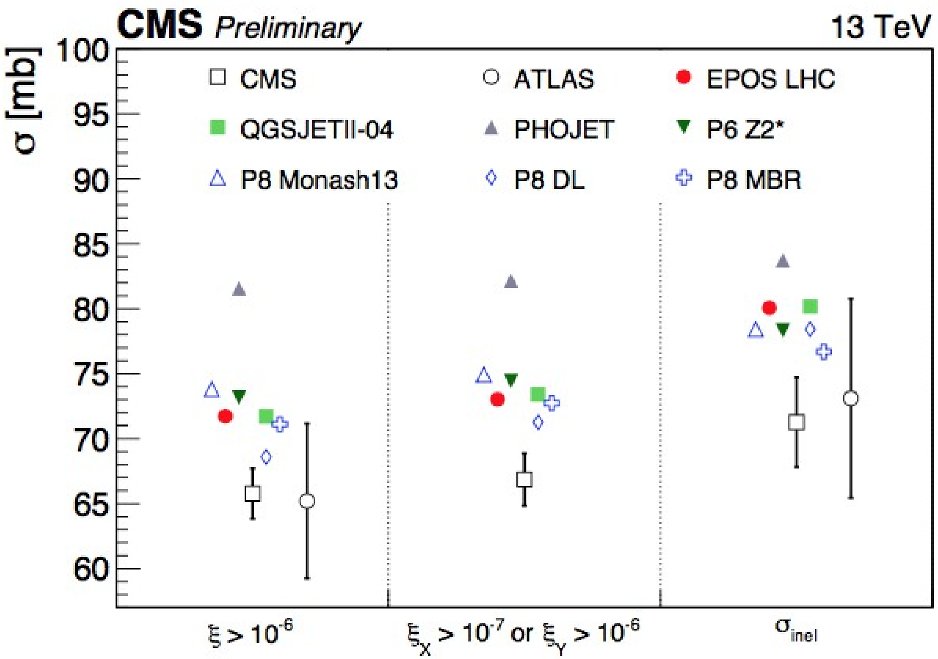
Diffractive events:
- largest gap separates the dissociation systems



Non-Diffractive events:
- Small largest gap
- randomly located

Inelastic pp cross section @ 13 TeV (cont'd)

CMS PAS FSQ-15-005



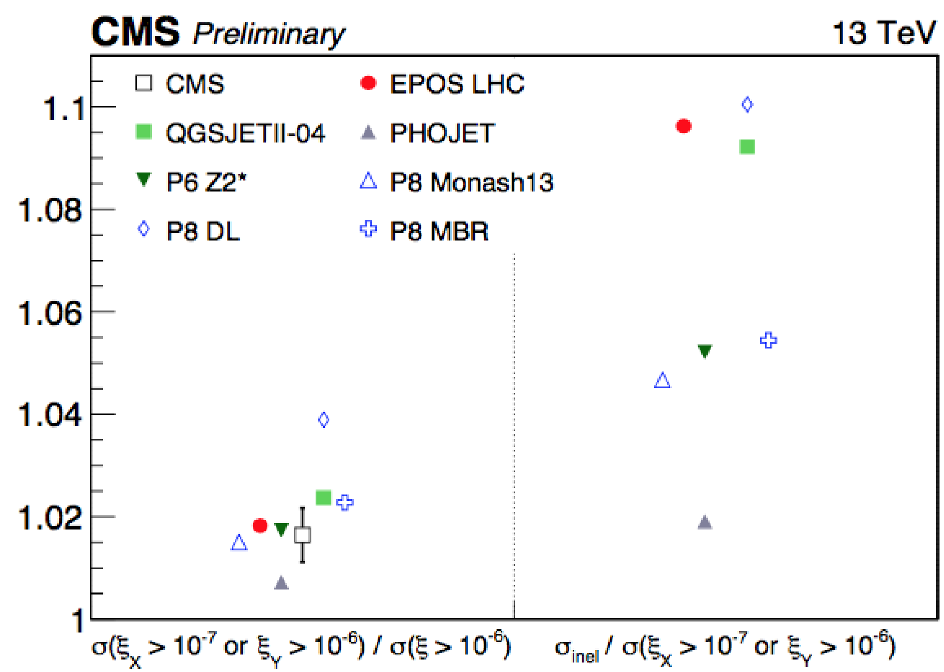
- Most models describe the relative acceptance increase from (ξ_X>10-6, ξ_Y>10^{-6}) to (ξ_X> 10^{-7}, ξ_Y > 10^{-6}) well
- **The absolute values can not be described by Monte Carlo event generators**

Result : σ_{inel} = 71.3 ± 0.5 (exp.) ± 2.1 (lum.) ± 2.7 (ext.) mb

- CMS result consistent with ATLAS [ATLAS-CONF-2015-038]

$\sigma(\xi > 10^{-6})$ = 65.2 ± 0.8 (exp.) ± 5.9 (lum.) mb
σ_{inel} = 73.1 ± 0.9 (exp.) ± 6.6 (lum.) ± 3.8 (ext.) mb

- Both results below the predictions

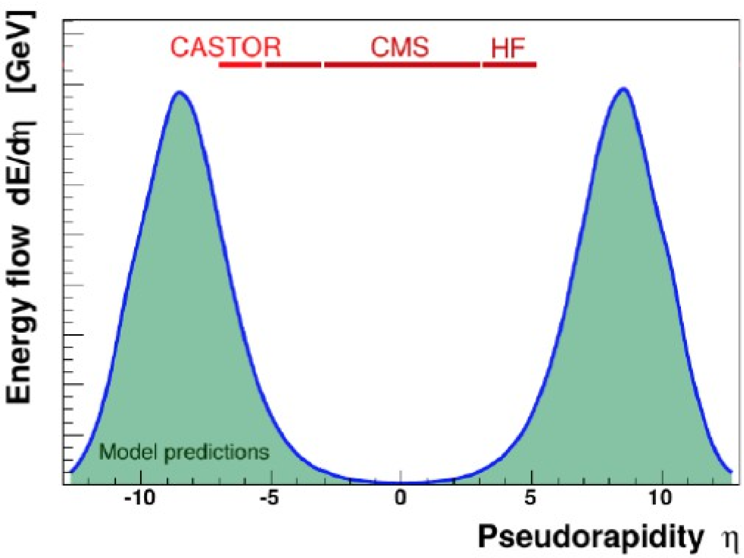


Forward energy flow & limiting fragmentation @ 13 TeV

CMS PAS FSQ-15-006

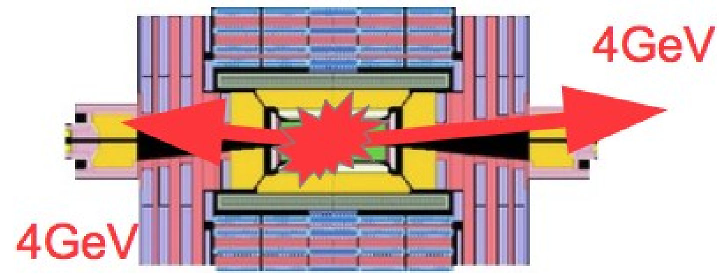
- **Motivation:**
  - measure the underlying activity for hard processes as well as the new & exciting physics
  - requirement for precision high p_T measurement in QCD and EWK sectors
  - useful input to the tuning of hadronic interaction models
  - better undestanding of QCD dynamics

Most of the energy in the forward rapidities in HF or CASTOR.

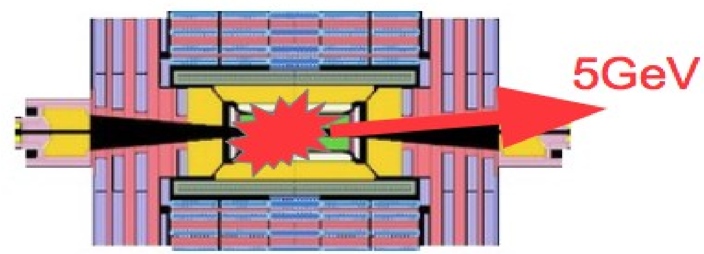


- **Analysis strategy:**
  - Use low pile-up runs from 2015 with B = 0 T
  - perform the measurement in $3.15 < |\eta| < 6.6$.
  - sum up calorimeter energies for two event classes
    - Soft-inclusive events (single-arm)
    - Non-single-diffractive-enhanced (NSD) events (double-arm)
- **Observables:**
  - $dE / d\eta$ (sum of particle energies in each η bin)
  - $dE_T / d\eta'$ ($\eta' = \eta - y_{beam}$)
- **Correction to particle level:**
  - stable particles with $c\tau > 10$ mm, excl. μ and ν
  - noise from non-colliding bunches and pile up correction applied

Non-single diffractive events (HF AND)
Double sided collision event activity

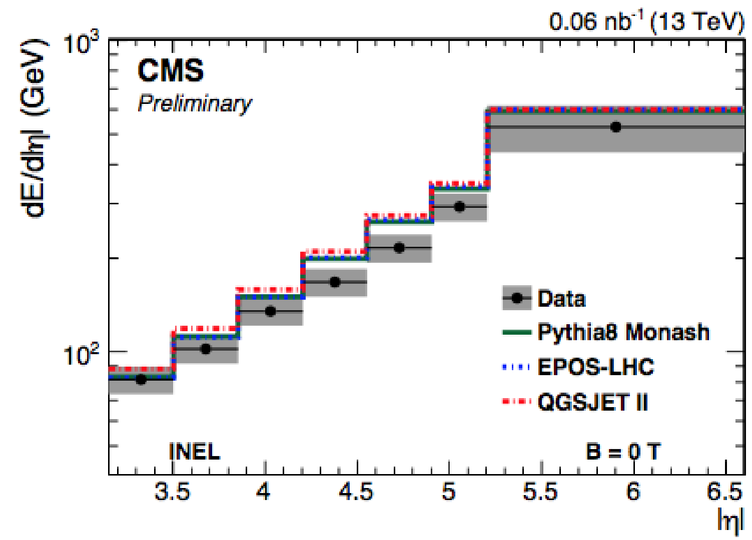


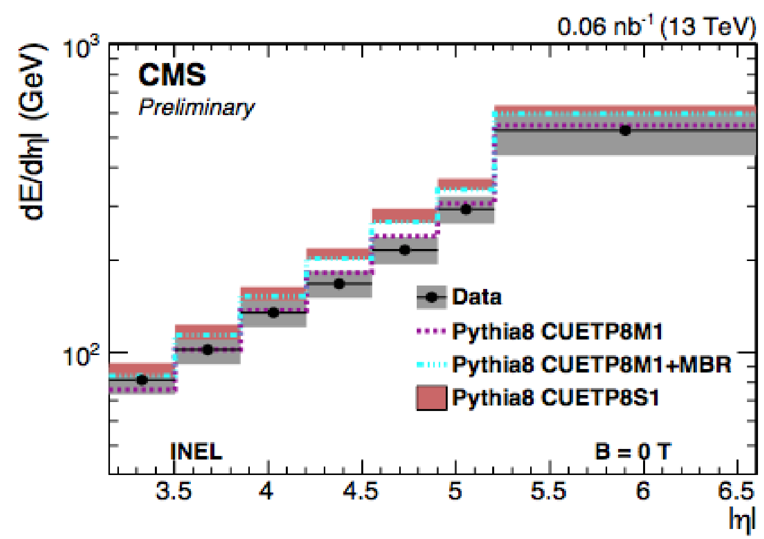
Soft Inclusive Inelastic events (HF OR)
Single sided collision event activity



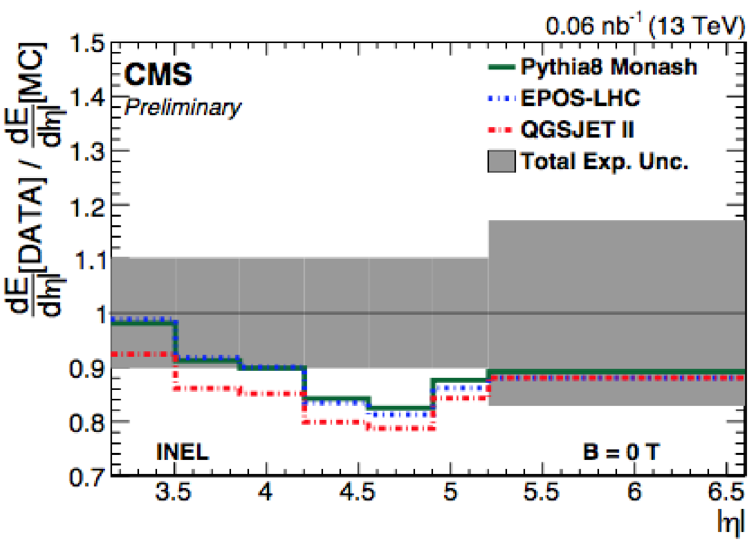
dE/dη Soft-Inclusive Events

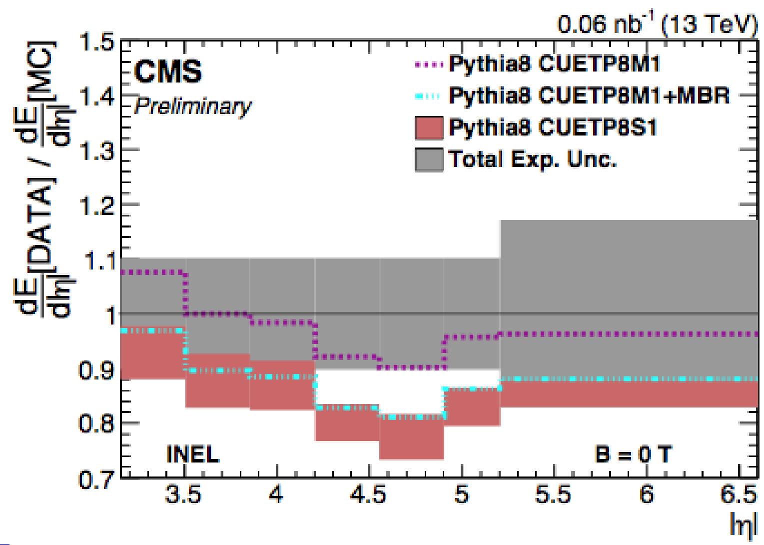
CMS PAS FSQ-15-006





$\xi > 10^{-6}$

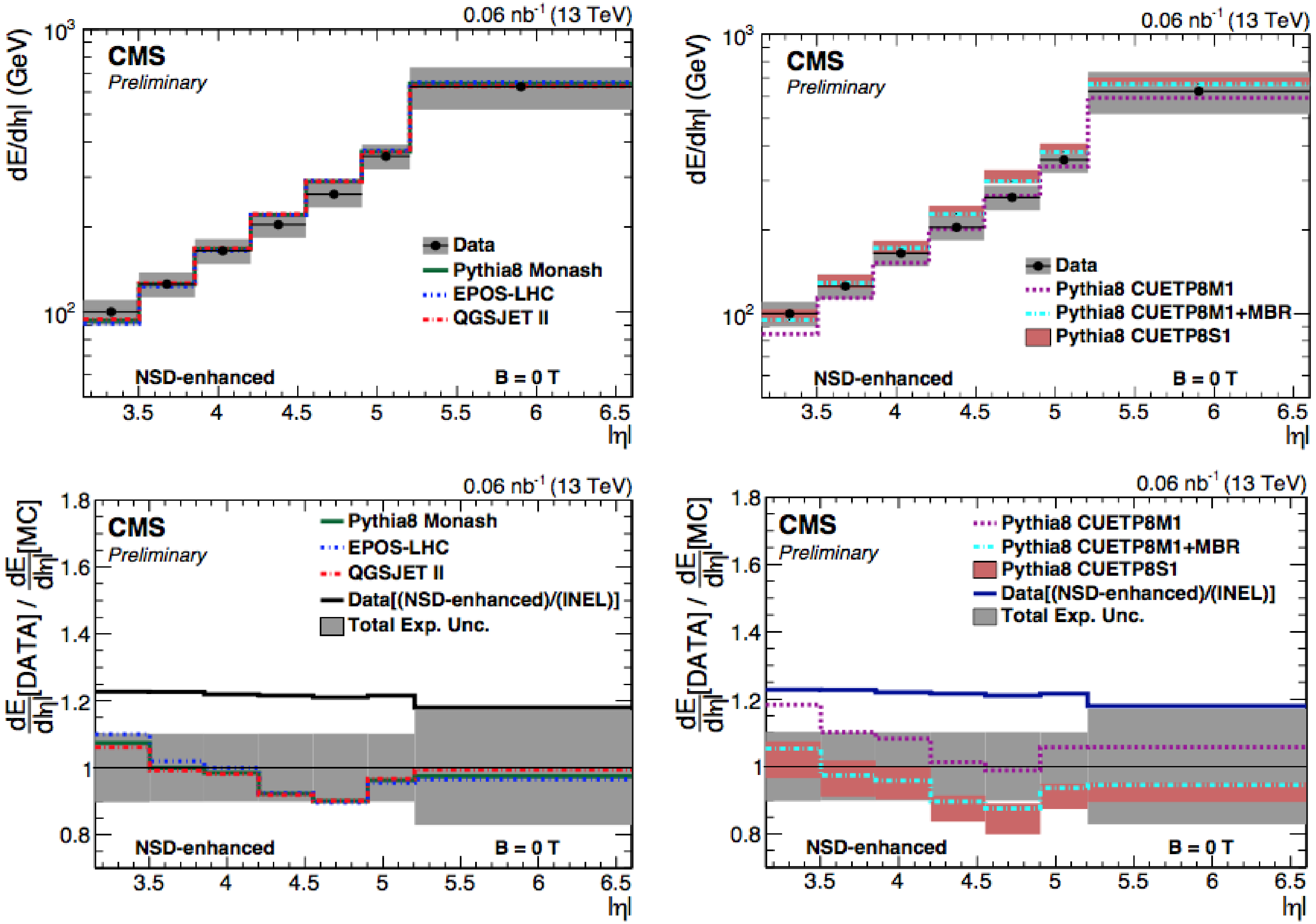




- Model predictions show large spread in HF region, $3.15 < |\eta| < 5.2$
- Best agreement at low η and in the CASTOR region ($5.2 < |\eta| < 6.6$).
- Pythia8 Monash vs EPOS/QGSJET: provides comparable result
- CUETP8M1 vs CUETP8M1+MBR: effect of variation of diffractive parameters
- CUETP8S1+uncertainties: dominant contribution from color reconnection parameters

dE/dη NSD-enhanced Events

CMS PAS FSQ-15-006

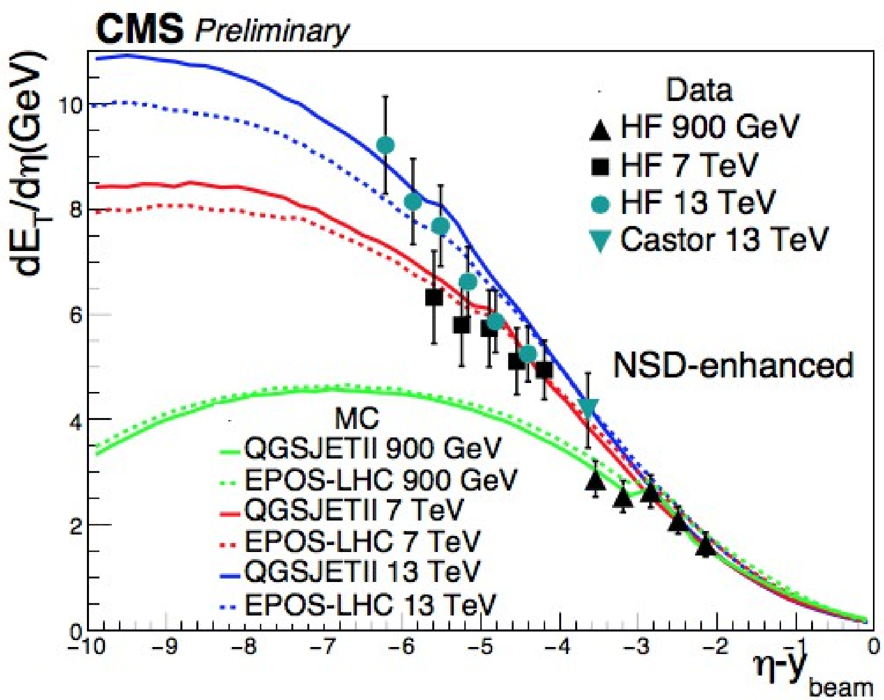


ξ > 10^{-6}

Limiting fragmentation $dE_T/d\eta'$

CMS PAS FSQ-15-006

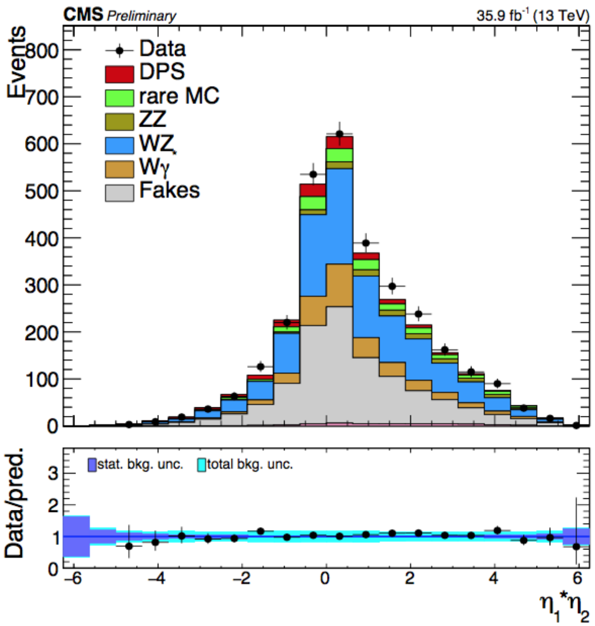
- Shifted pseudorapidity variable; η' = η - ybeam (ybeam = beam rapidity)

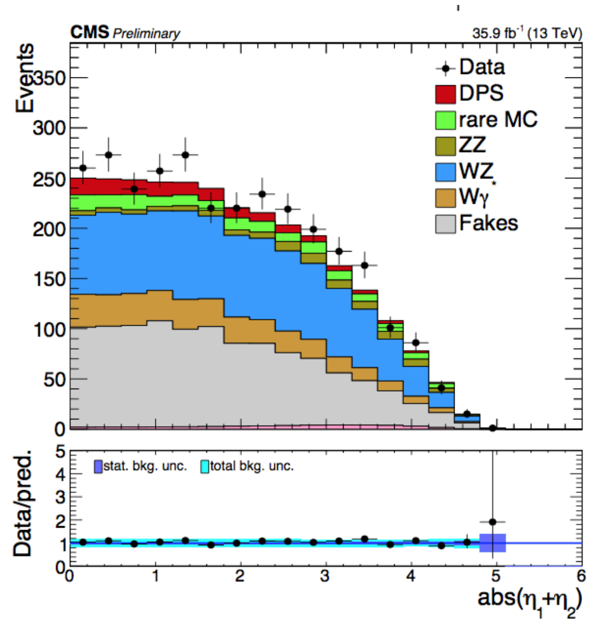


- Comparison with earlier CMS measurement at different centre-of-mass energies (0.9, 7), JHEP 11 (2011) 148.
- Simple geometry factors to get E_T from E; particle level definition adjusted to agree with previous data

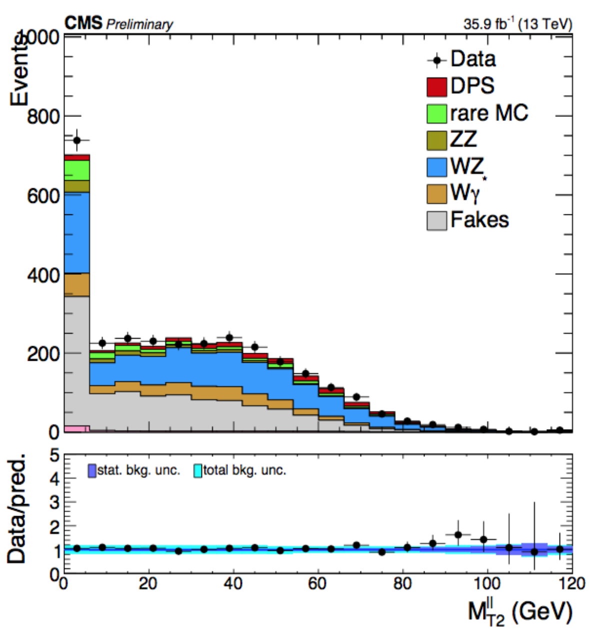
Input variables to BDT

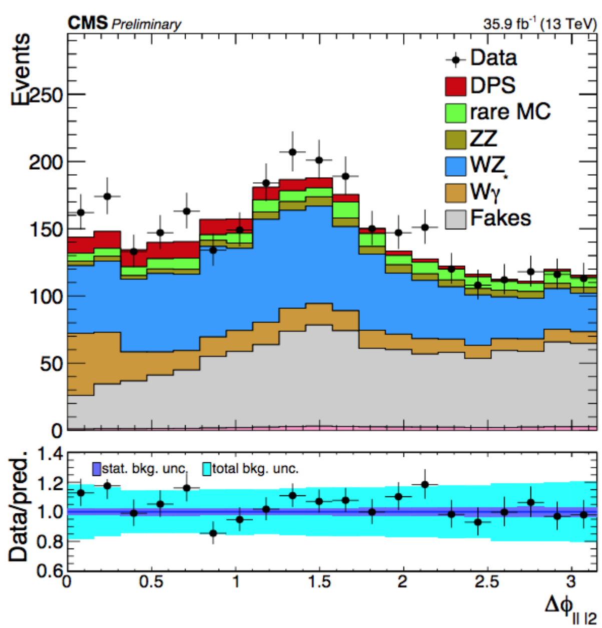
CMS PAS-FSQ-16-009





- Good agreement in input variables
- Perform binned maximum
- likelihood for BDT algorithm in 4 categories: $\mu^+\mu^+$, $\mu^-\mu^-$, $e^+\mu^+$, $e^-\mu^-$





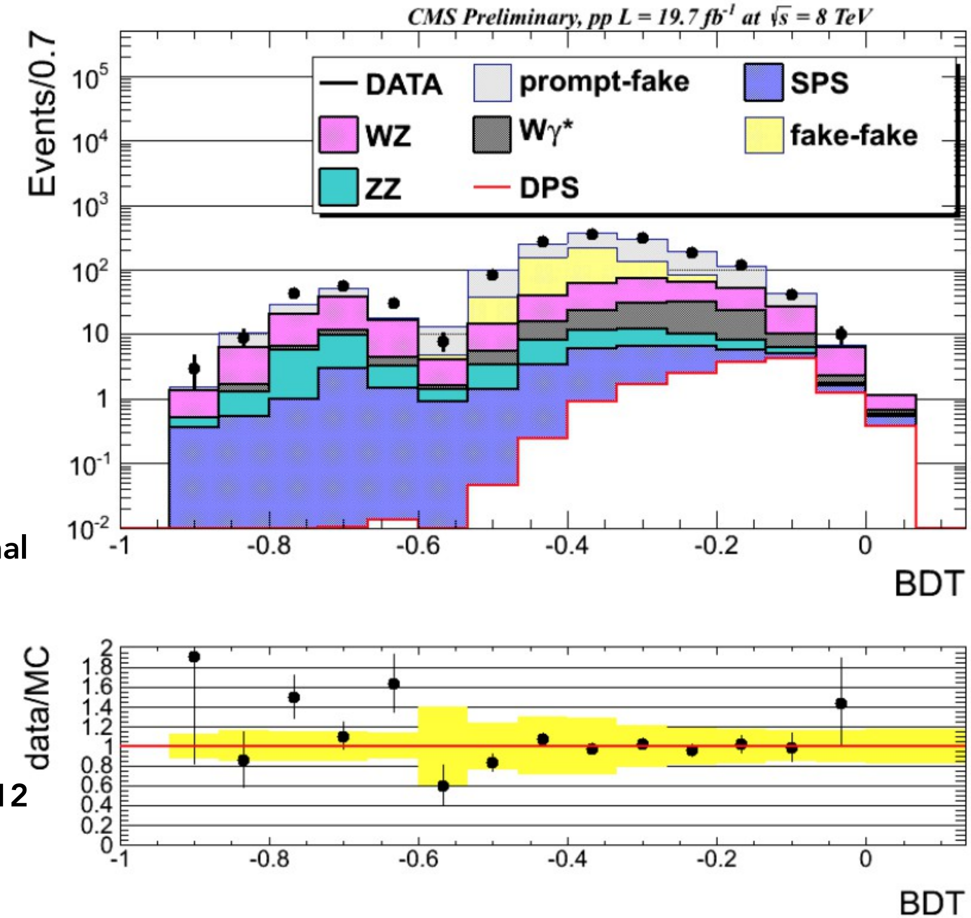
Results : same sign WW production @ 8 TeV

CMS PAS-FSQ-13-001

- **Boosted decision tree (BDT) algorithm input variables:**

leading muon (μ_1) p_T
subleading muon (μ_2) p_T
E_T^{miss}
$M_T(\mu_1, \mu_2)$ di-muon invariant transverse mass
$\Delta\phi(\mu_1, \mu_2)$
$\Delta\phi(\mu_1, E_T^{miss})$
$\Delta\phi(\mu_2, E_T^{miss})$
$\Delta\phi(\mu_1 + \mu_2, E_T^{miss})$: where $\mu_1 + \mu_2$ is the vector sum of muon four-momenta

$$m_T(W_{1/2}) = \sqrt{2 \cdot p_T^{\mu_{1/2}} \cdot E_T^{miss} \cdot (1 - cos(\Delta\phi(\mu_{1/2}, E_T^{miss})))}$$



- Signal strength (ratio of observed to expected signal events), r < 1.9
- DPS/SPS contributions comparable
  - Observed value of r, corresponds to DPS < 1.12 pb.
- W suffers from contamination

Same sign WW production @ 8 TeV (cont'd)

CMS PAS-FSQ-13-001

Jet-MET Base Selection

- PFJets reconstructed with anti-k_T having R = 0.5
- Loose jet ID
- ME_T corrections applied with ME_T > 20 GeV

Muon Base Selection

- Global Muon & PF Muon with > 5 hits in tracker layers
- Atleast one pixel hit, ndof < 20, dz < 0.1 cm, d0 < 0.02 cm
- PF based isolation with isolation variable, (I) < 0.15
- $|\eta(\mu)| < 2.4$

- Opposite sign leptons; leading lepton p_T > 20 GeV/c and sub-Leading lepton p_T > 10 GeV/c
- 3rd Lepton Veto; No third identified and isolated lepton within acceptance (p_T > 10 GeV/c)
- To suppress WZ and ZZ backgrounds
  - M_{inv}(dilepton) > 20 GeV/c (suppress low mass resonances)
  - p_T(lepton 1) + p_T(lepton 2) > 45 GeV/c (suppress W+Jets background)
  - For same flavour final state: 75 > M_{inv} (di-lepton) > 105 (suppress DY processes)

Effective Cross Section

- The cross-section for a generic process that involves DPS:

$$\sigma^{DPS}_{(hh'\to ab)} = \left(\frac{m}{2}\right)\frac{\sigma^{SPS}_{(hh'\to a)}\cdot\sigma^{SPS}_{(hh'\to b)}}{\sigma_{\text{eff}}}$$

  - m is number of "distinguishable partonic subprocesses"
    - m = 1 when a = b, m = 2 when a ≠ b
  - σ_{eff}, regarded as an important link to the theories.

$$\sigma_{\text{eff}} = \left(\frac{m}{2}\right)\frac{\sigma^{SPS}_{(hh'\to a)}\cdot\sigma^{SPS}_{(hh'\to b)}}{\sigma^{DPS}_{(hh'\to ab)}}$$

- Before LHC: Results available for collision energy from 63 GeV (AFS) to 1.96 TeV (Tevatron).
  - focus on photon+jets
- LHC Measurements: from ATLAS and CMS collaborations (7 TeV and 8 TeV).
  - Focus on photon+3jets, +4jets, W+2j, same-sign WW processes.

- Measure of the matter overlap in hadron-hadron interactions, input for theoretical models.
- DPS play important role
  - when several particles in final state (typically 4 or more)
  - high-energy hadron collisions (probing low-x)