QCD AT CMS

Daniele Fasanella, on behalf of CMS Collaboration

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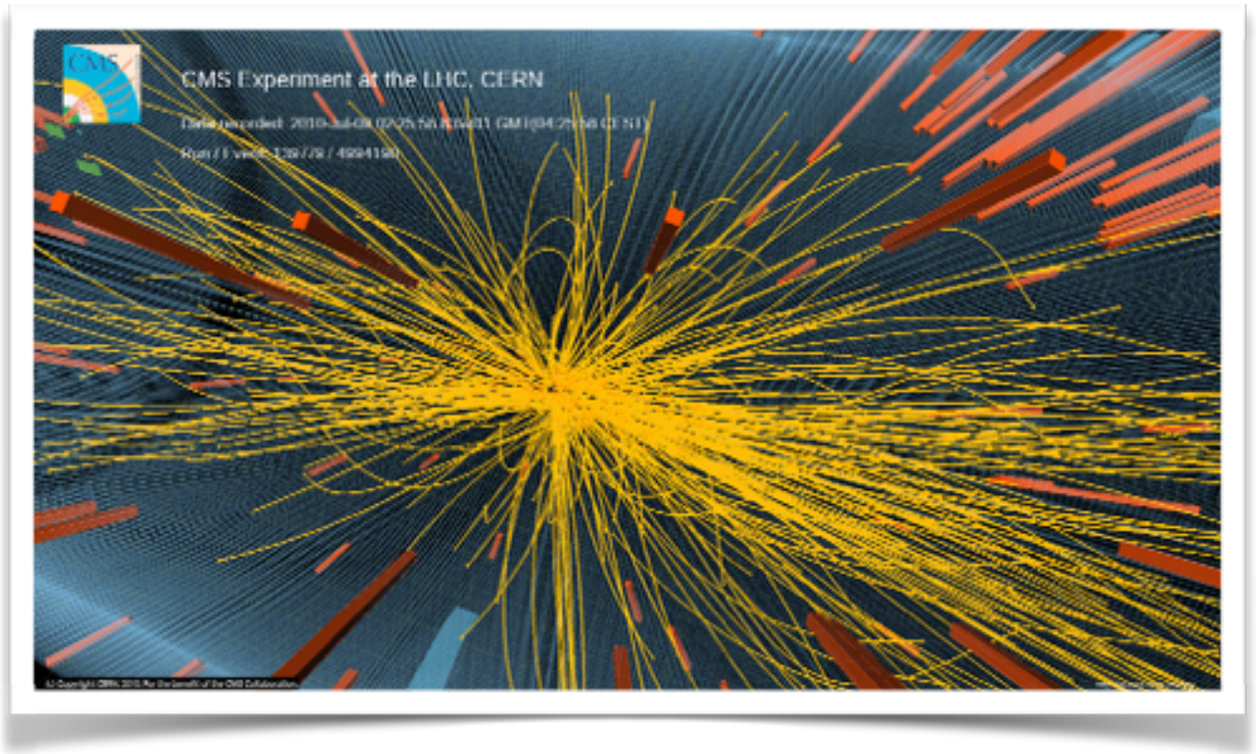
Outline

- **QCD at CMS**

- **Jets studies at CMS**
  - Jet Reconstruction
  - Inclusive Cross Sections at 8 TeV
  - Events shapes and PDF constraints from 7TeV data
  - 3 Jets Mass Cross Section
  - 4 Jet Production
  - Determinations of α_S



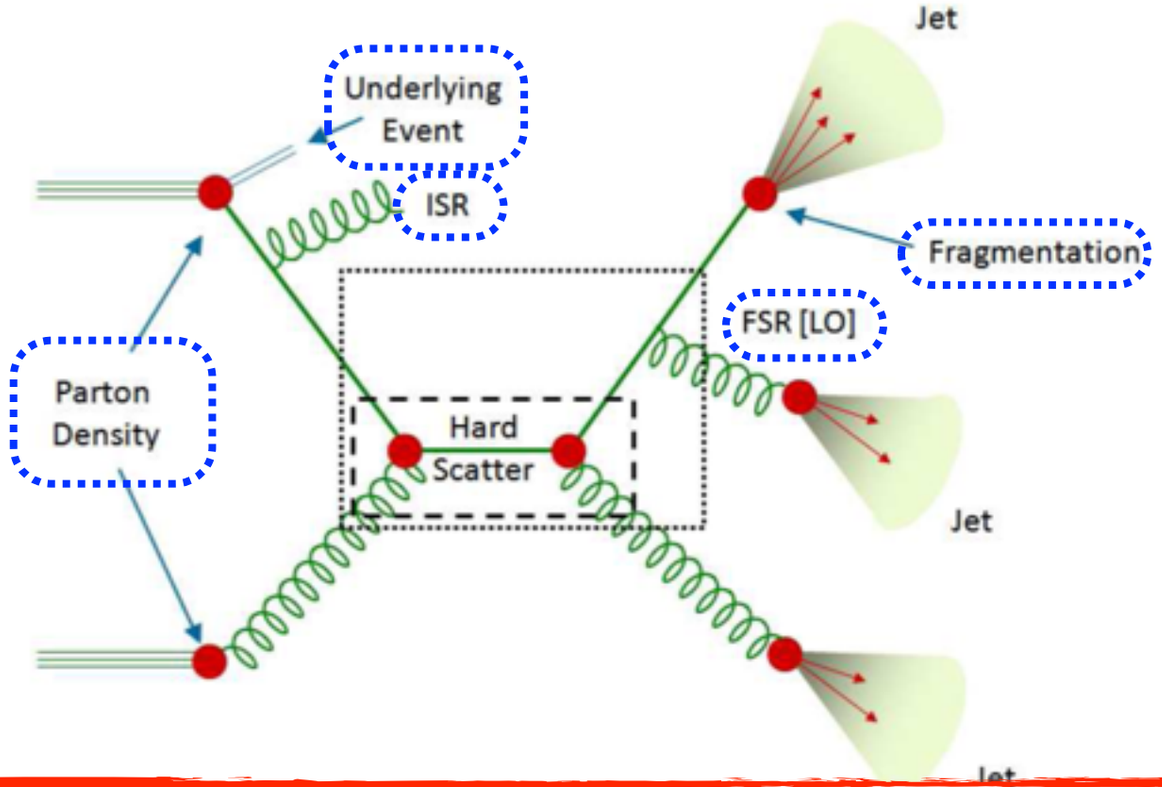
- **Evaluation of DPS**
  - W+2 jets
  - Double J/ψ

- **NRQCD description**
  - Quarkonium Polarization for Y(nS), J/ψ and ψ(2S)

QCD at LHC

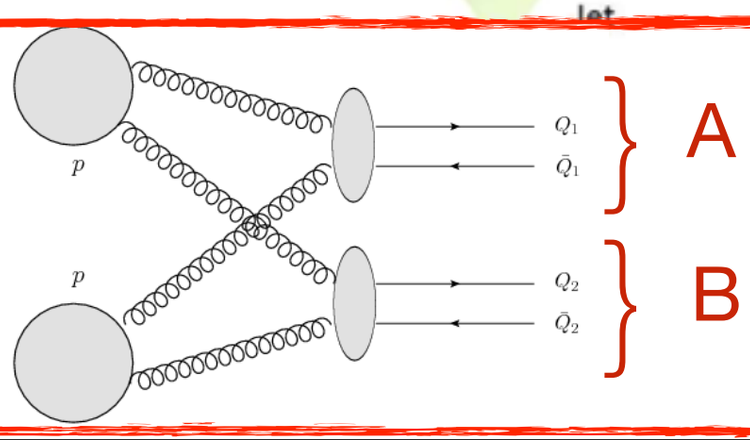
QCD measurements are of great importance at LHC:

- pQCD can be tested at a totally unexplored kinematic region
- Monte Carlo generator can be tuned to better describe data
- QCD is an ubiquitous source of background for any new physic signal, that need to be studied and understood.



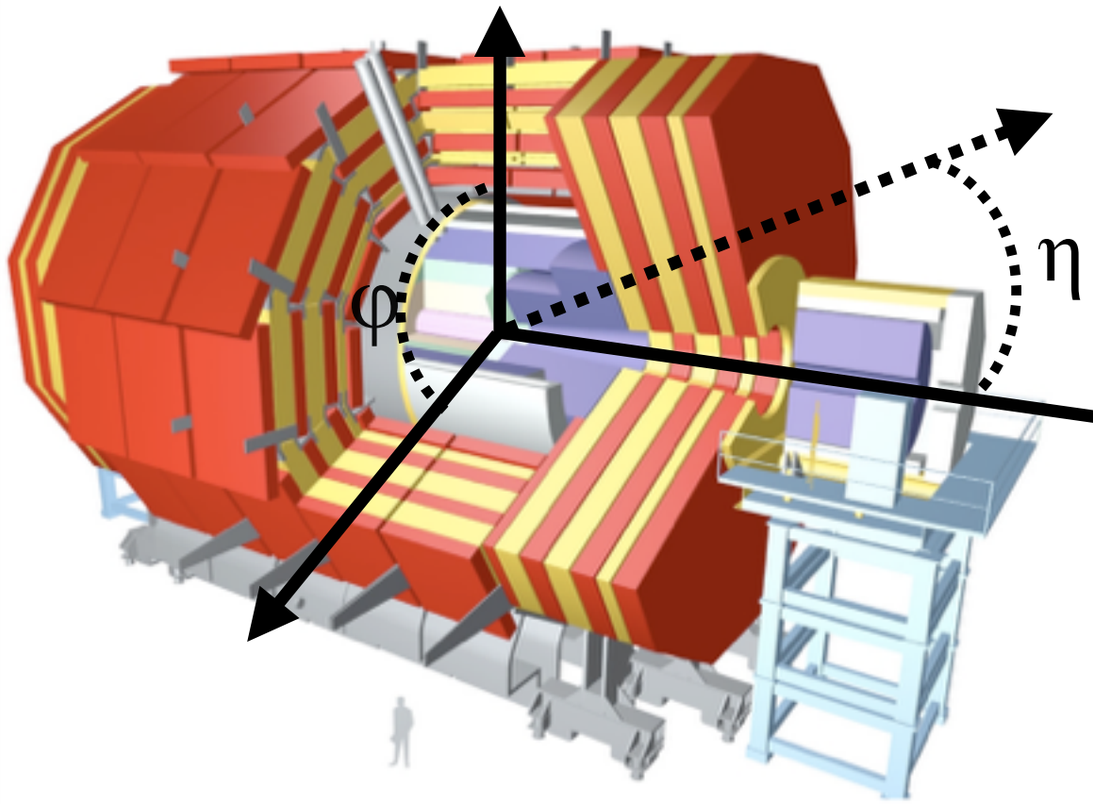
A lot of ingredients are needed to have the complete picture or a Single Parton Scattering (SPS).

And not to forgot DPS!



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

QCD at CMS



CMS is well suited for QCD measurement thanks to the large pseudorapidity coverage:

For **|η|<2.4**:

- **High precision** Silicon Tracker
- Crystal electromagnetic calorimeter (**ECAL**)
- Brass/scintillator hadron calorimeter (**HCAL**)
- **Redundant** muon detection system

In the very forward region 3<|η|<5:

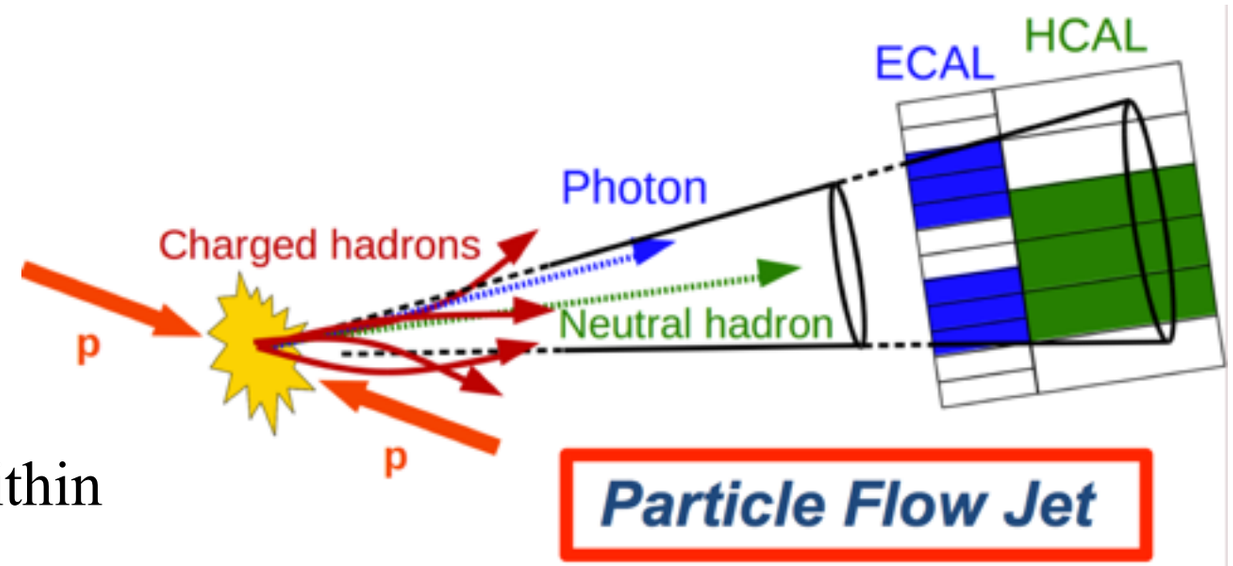
- Cherenkov-light Hadronic Forward calorimeter (**HF**)

Jets are reconstructed using ***particle flow:***

- Inclusion of all the information from all the subdetectors

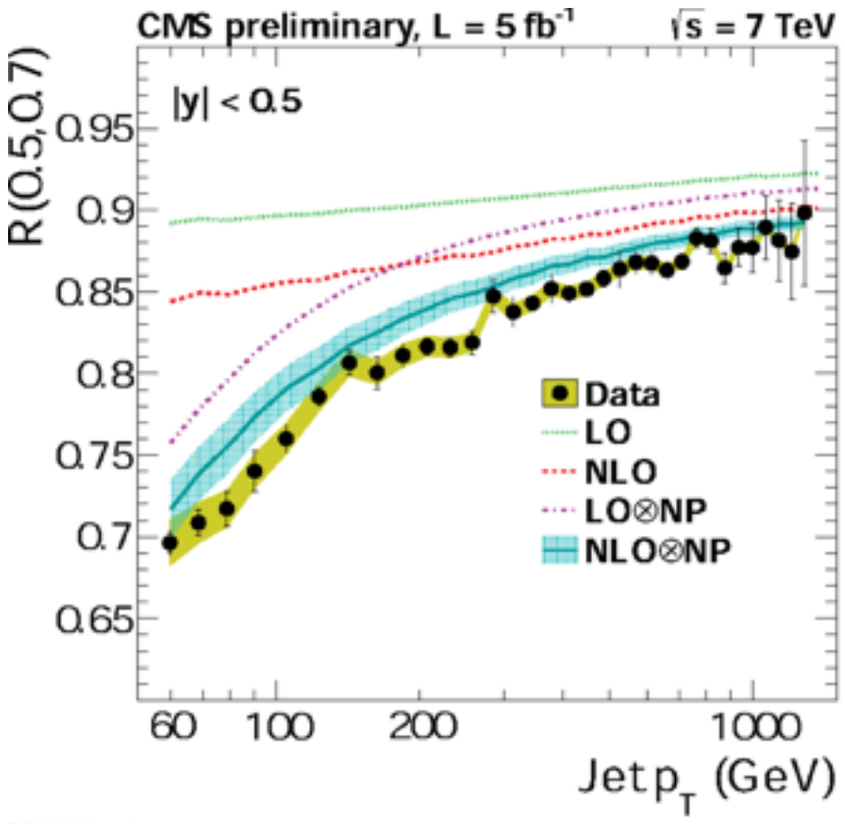
Jet clustering is done with the ***anti-kt*** algorithm:

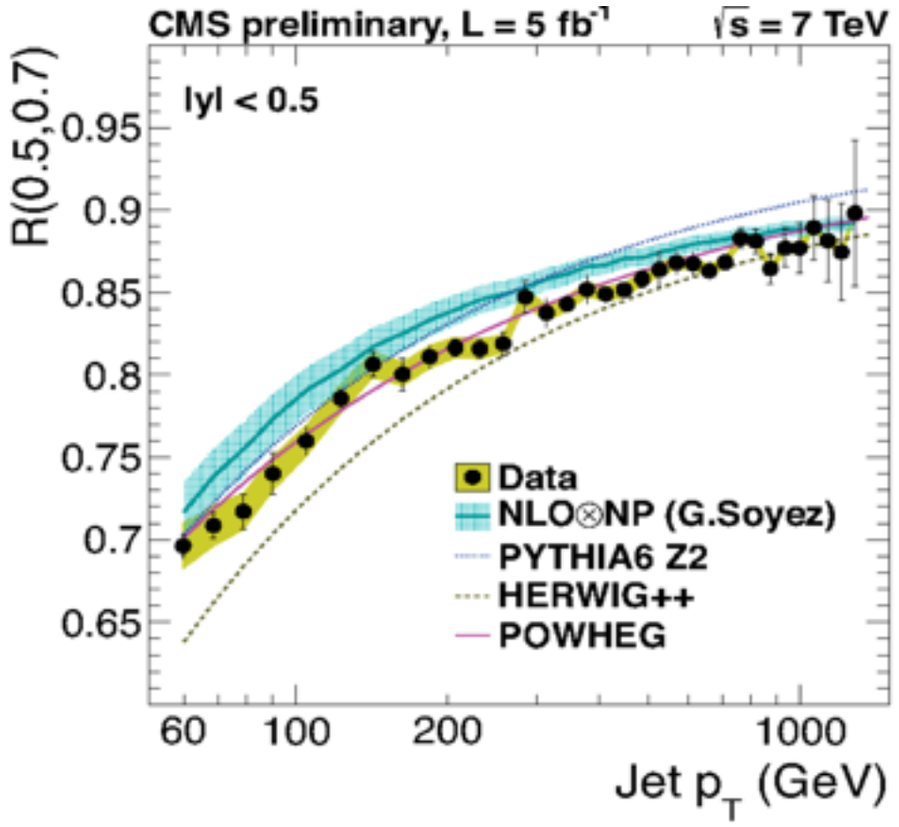
- **R** is the **clustering parameter**
- hard particle accumulates all the soft particles within a circle of radius R.



Inclusive jet AK5/AK7 cross section ratio at 7 TeV

- Ratio of cross section of jets with different radius parameter **R=0.5 (AK5) and 0.7 (AK7)**
- Performed with 2011 data as function of p_T, in 6 rapidity bins
- Several systematic uncertainties cancel in ratio



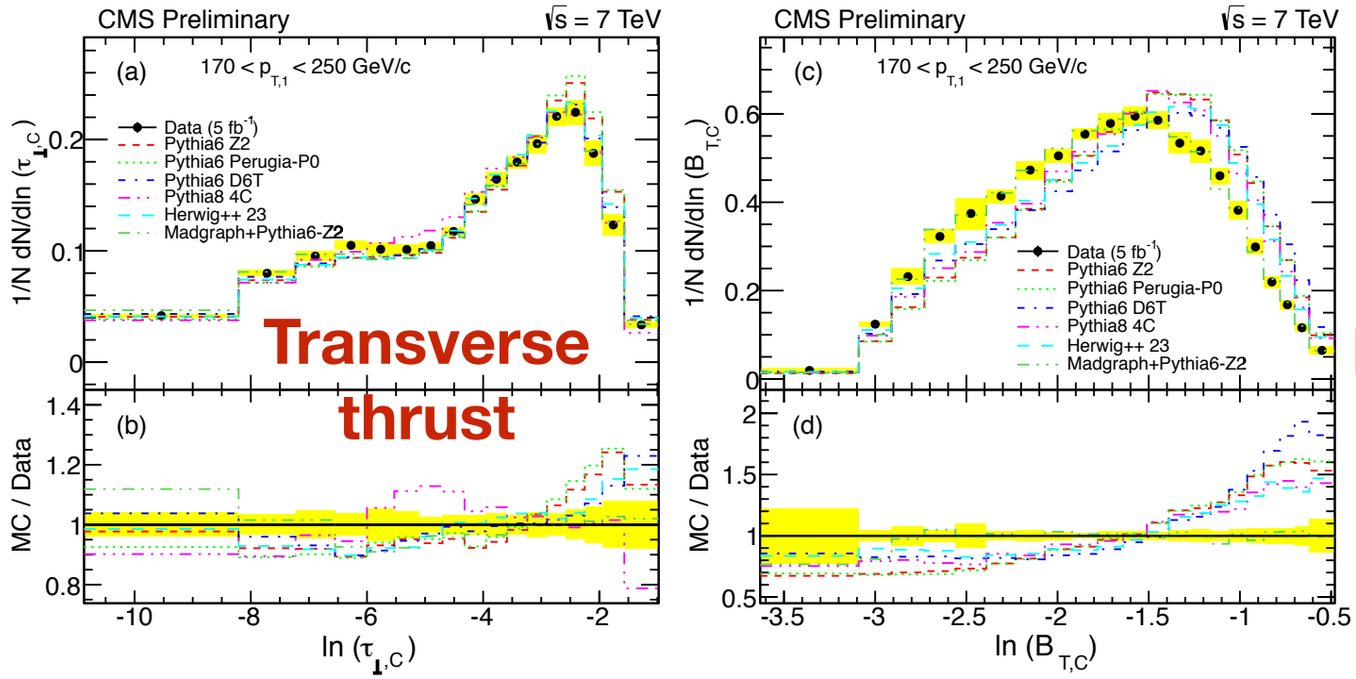


- The ratio gradually increases towards unity with increasing Jet-p_T
- No dependence on rapidity for |y|<2.5
- **Perturbative QCD prediction are systematically above**, data, improving at higher order.
- POWHEG(NLO+PS) Monte Carlo prediction has the describes the data best
- **Higher order corrections needed for R = 0.5, in particular FSR**

CMS-PAS-SMP-12-022

Hadronic events shapes at 7 TeV

- Event shape variables are geometric properties of the energy flow in hadronic final states.
- Analysis on **2011 data**, studying different variable in bins of the leading jets p_T



Jet broadening spectra

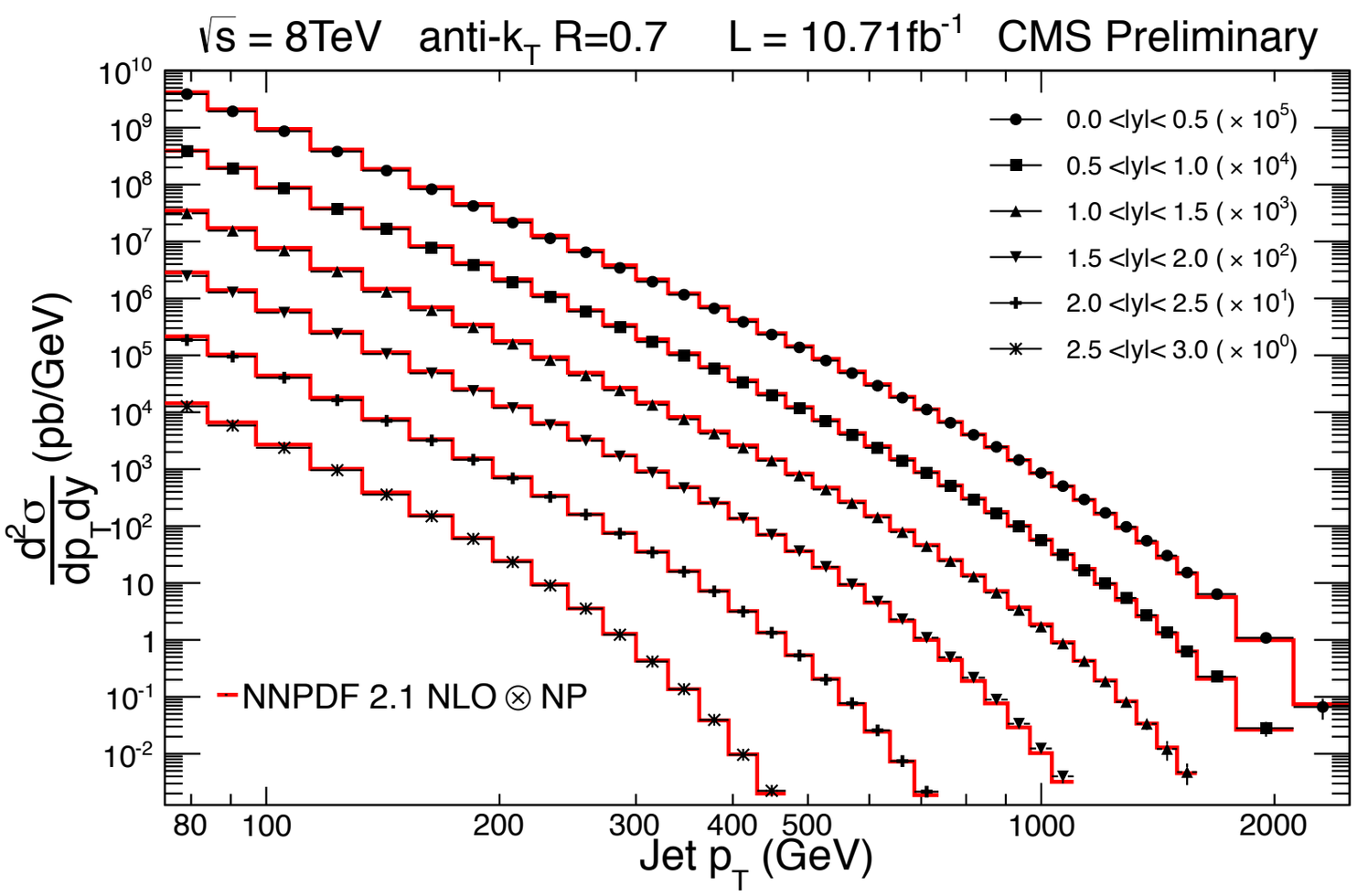
Total transverse jet mass

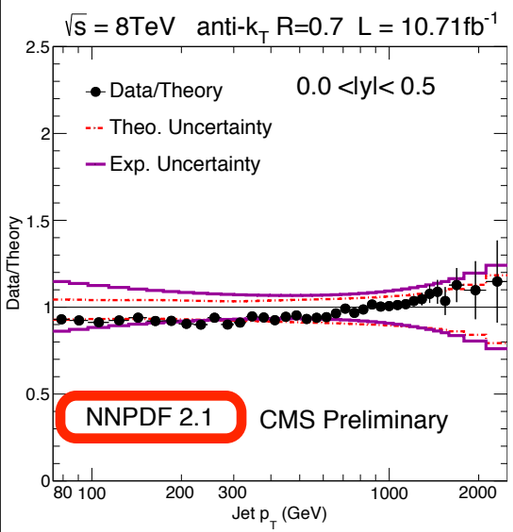
- For the central thrust, all generators show an overall agreement with data within 10%
- Variables sensitive to longitudinal energy flow show a larger disagreement
- Modeling of **color connection** between soft scatters and beam remnants, **ISR**, and **FSR** are the major sources of the discrepancies.

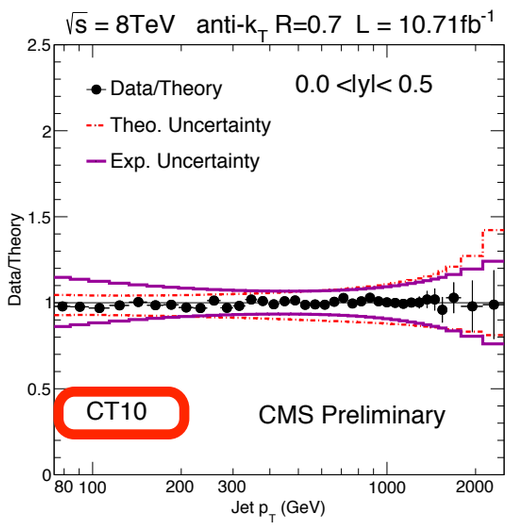
CMS-PAS-SMP-12-012

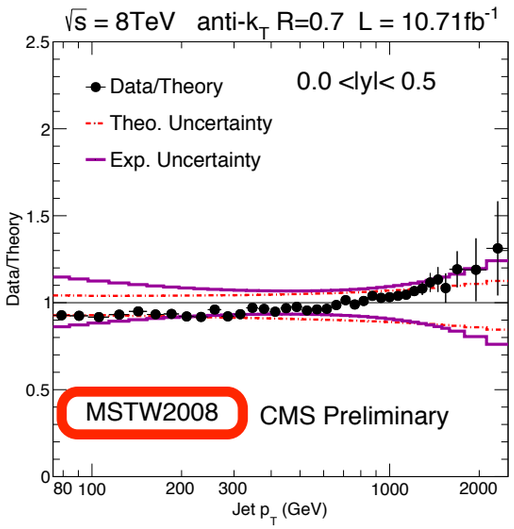
Inclusive jet cross section at 8 TeV

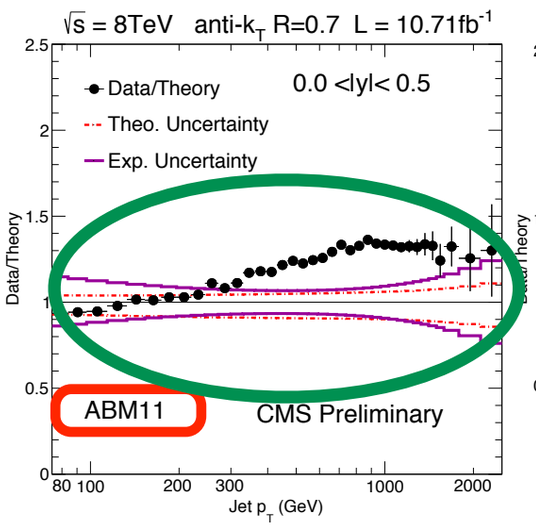
- Preliminary results on half of 2012 dataset for |y|<3
- Potential for PDF constrains thanks to lower experimental uncertainties (15%-40%) w.r.t. theory.
- Comparison with 5 PDFs sets
- Data are in agreement with NLO calculations within systematic uncertainties fin al cases except for ABM11 PDF at high p_T

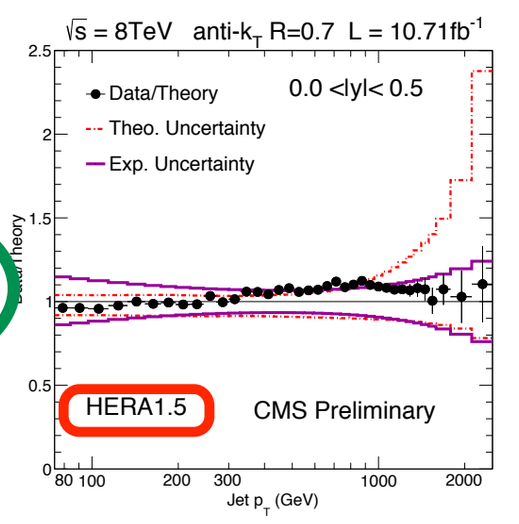








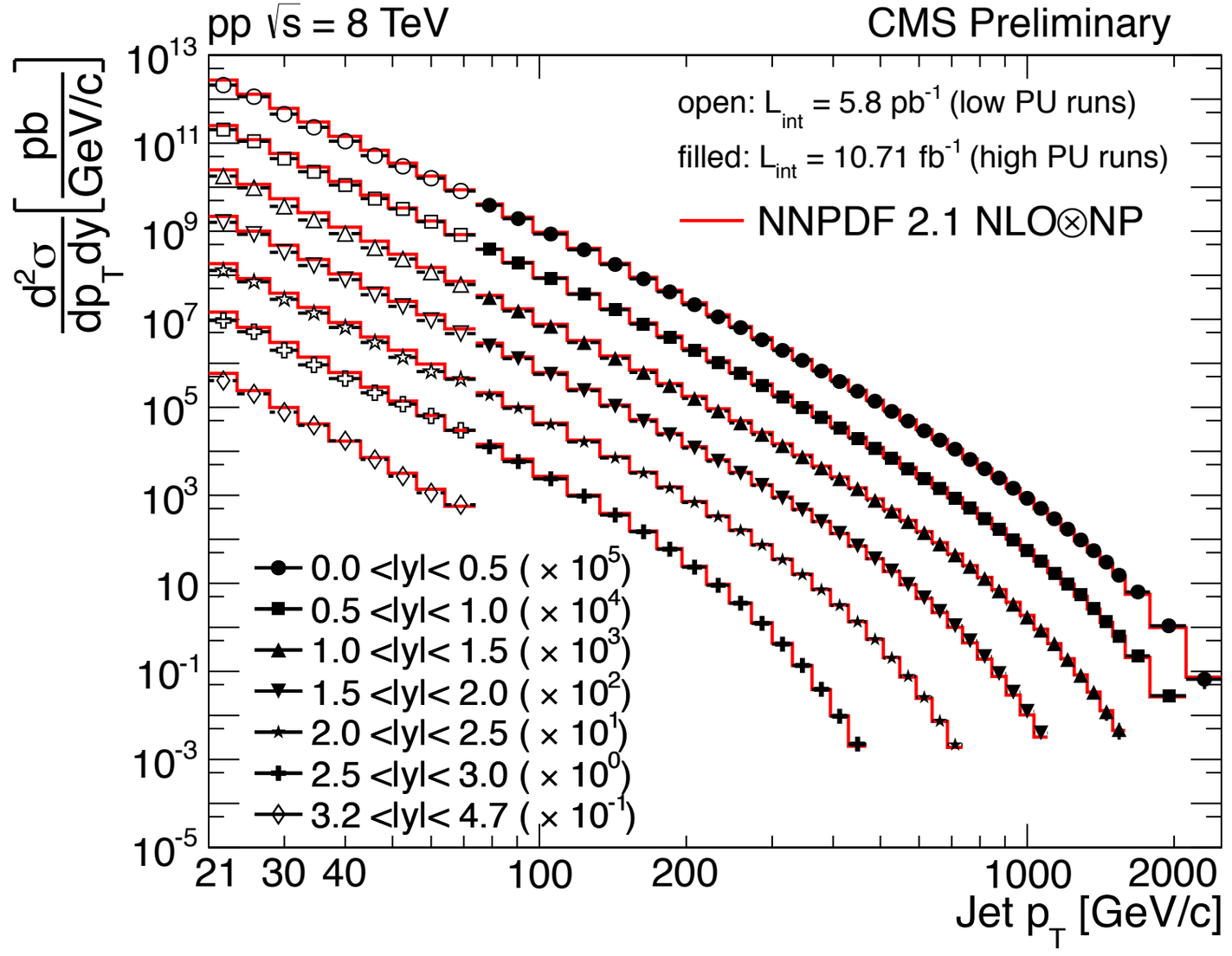


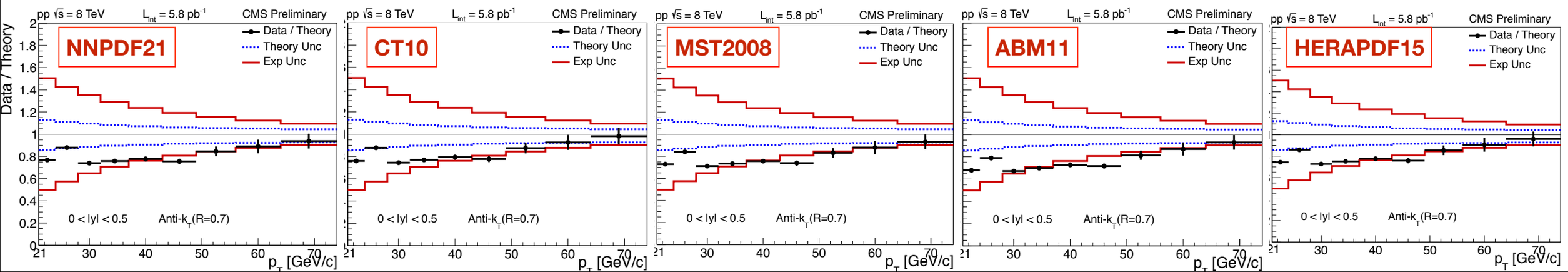


Low p_T jet cross section at 8 TeV

CMS-PAS-FSQ-12-031

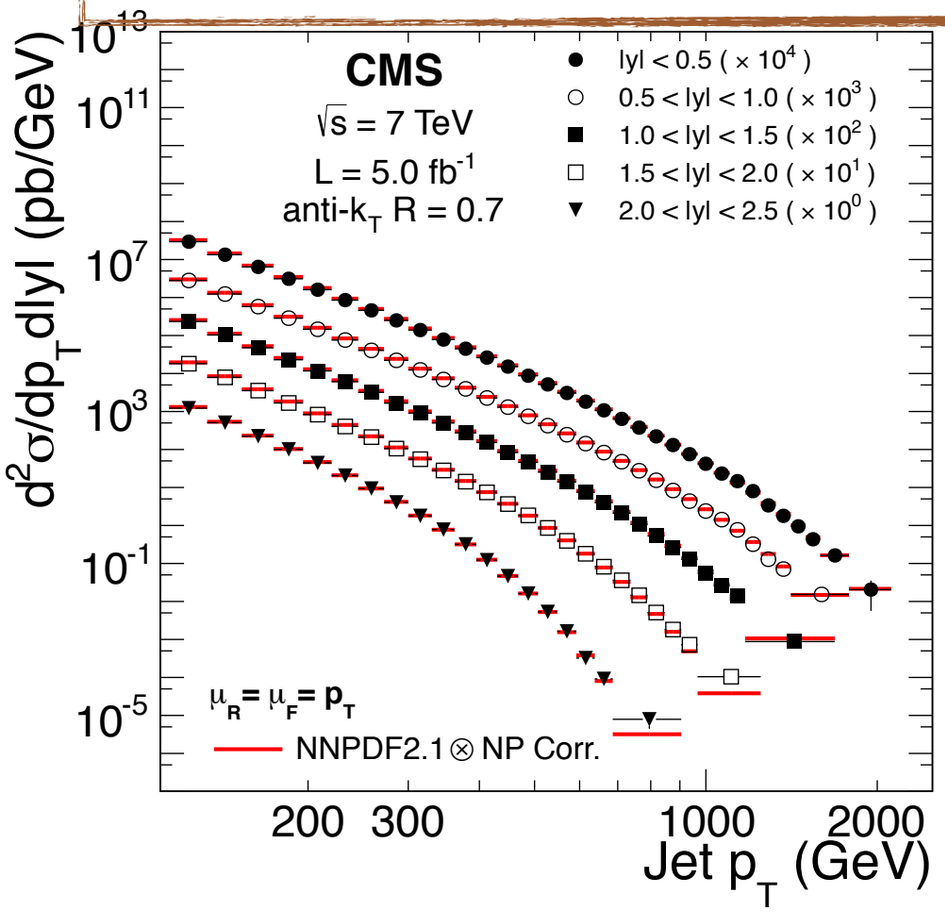
- Additional study in the low-p_T region data thanks to low-pile up runs (5.8 pb^{-1})
- Explored the region starting from p_T = 20 GeV and reaching |y|=4.7
- Combining the 2 studies very good agreement with the theory (5 PDFs sets) in a wide phase-space
  - **2** orders of magnitude in p_T
  - **14** orders of magnitude in the cross section





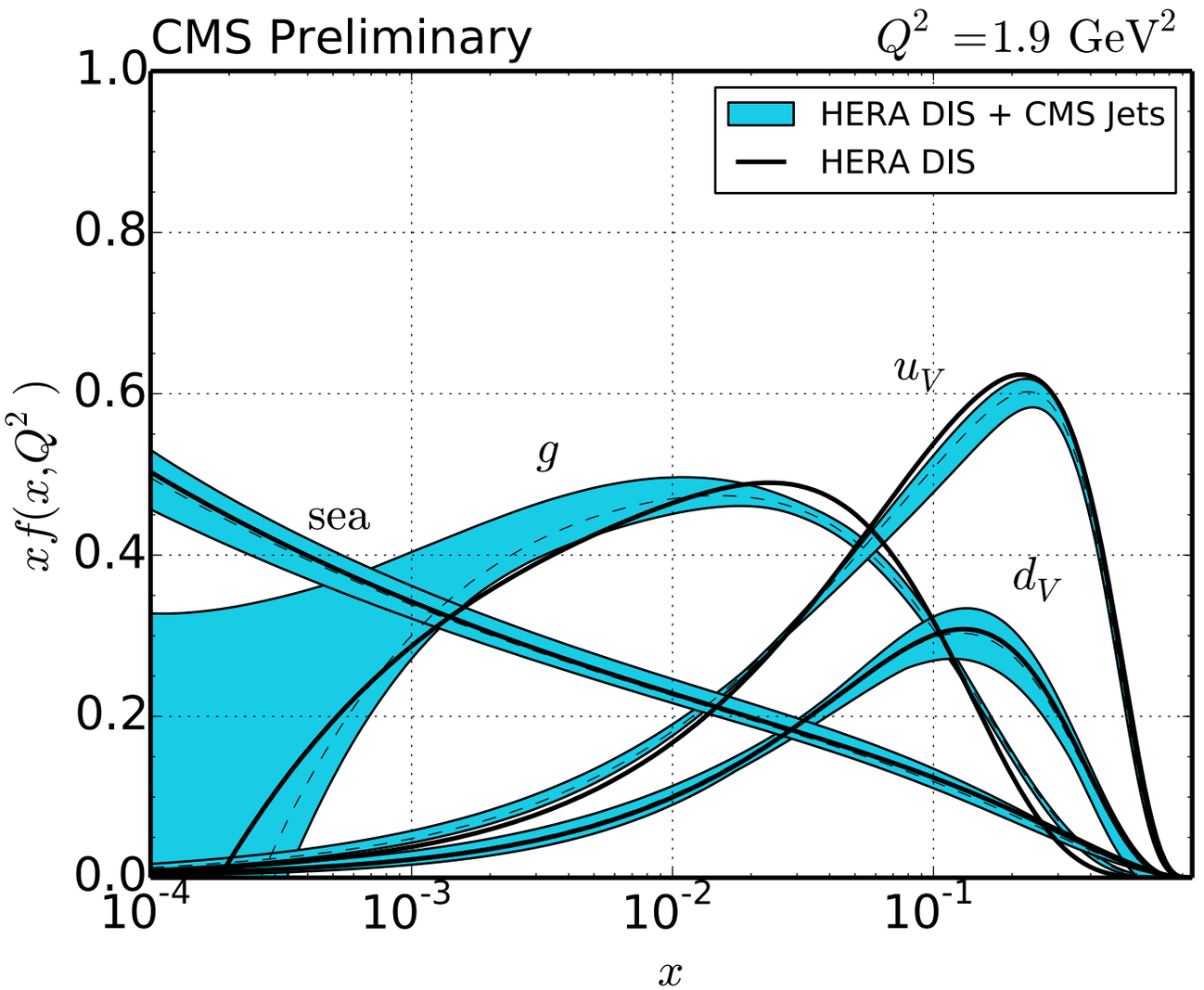
PDF constraints from inclusive jet cross section at 7 TeV

Phys. Rev. D 87 (2013) 112002



- Published CMS **inclusive jet cross section** on 2011 data:
  - wide range of transverse momentum and rapidity
  - experimental uncertainties smaller than in previous publications
  - possibility to constrain the parton distribution of the proton

- Parton distribution obtained using HERAFitter tool
- Inclusion of the CMS inclusive jet data in comparison to HERA inclusive DIS data alone significantly reduces the uncertainty
  - on the gluon for x ≳ 0.01
  - on the up and down quark for x ≳ 0.3



3-jet mass cross section

CMS-PAS-12-027

- Measurement of double differential cross section as a function of **3-jet mass**, defined as:

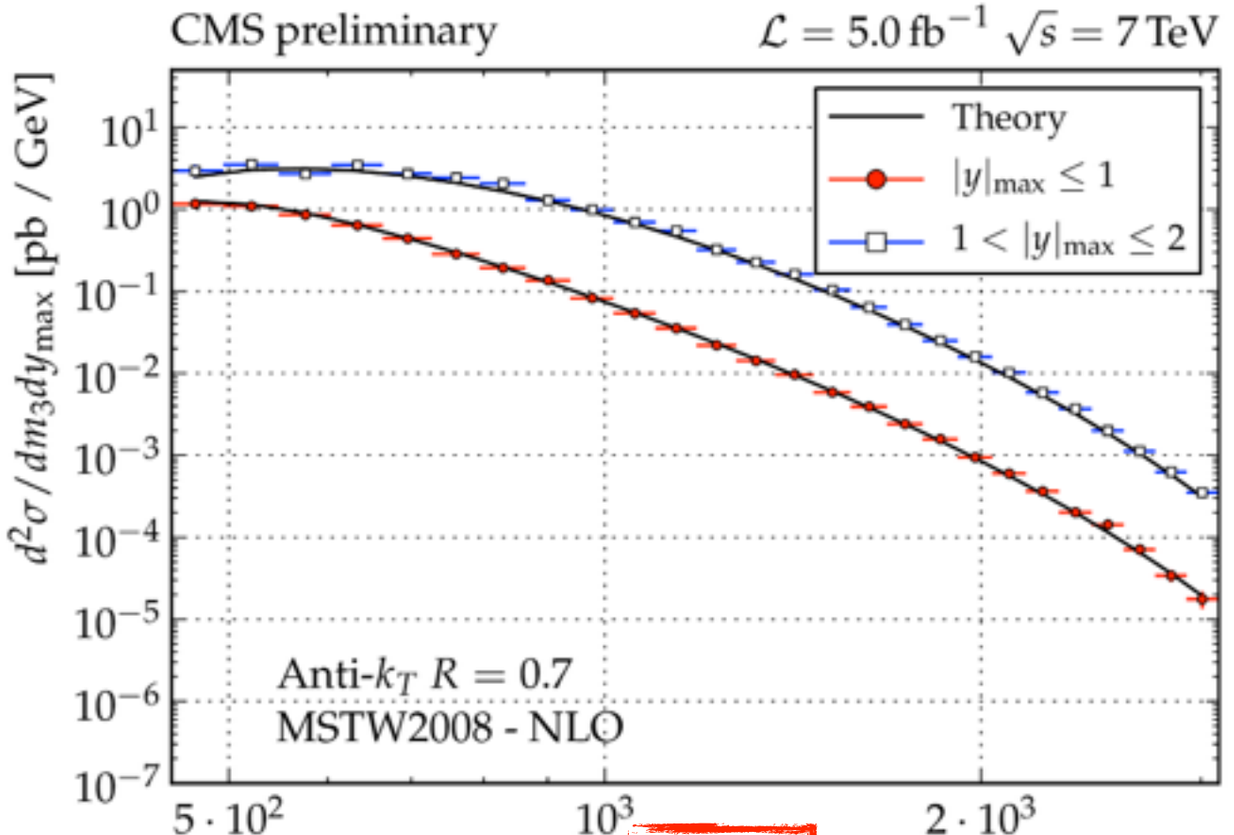
$$m_3^2 \;=\; (p_1 + p_2 + p_3)^2$$

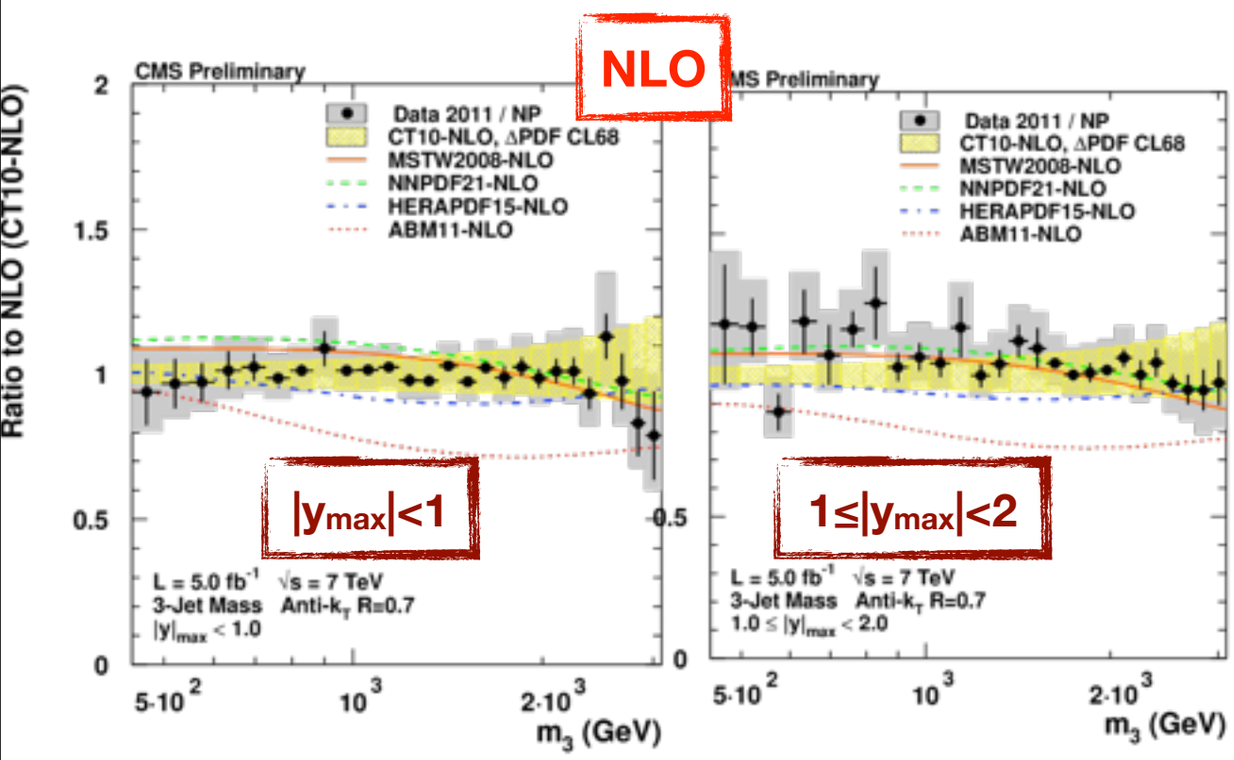
- in two $\mathbf{y_{max}}$ rapidity regions

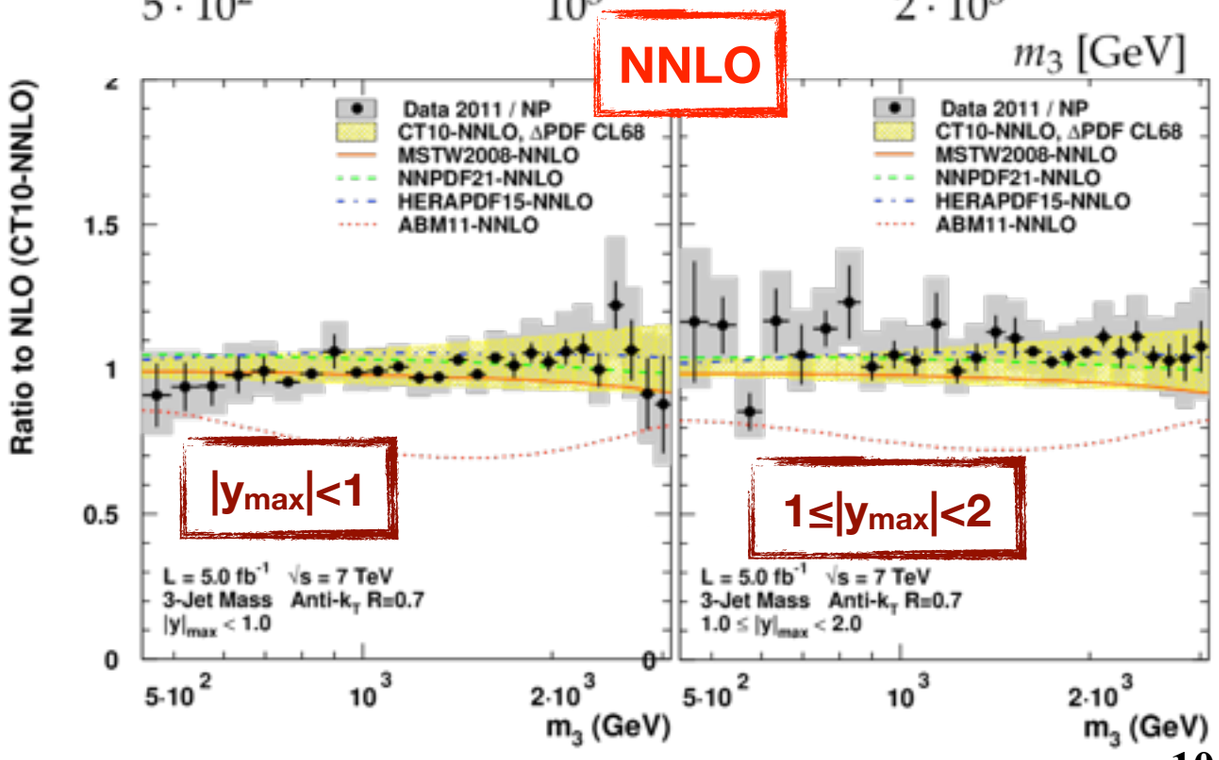
$$y_{\max} \;=\; \mathrm{sign}(|\max(y_1, y_2, y_3)| - |\min(y_1, y_2, y_3)|) \cdot \max(|y_1|, |y_2|, |y_3|)$$

- **Good Agreement with pQCD @ NLOxNP up to $m_3 = 3$ TeV**

- Deviations observed for NLO + ABM11 PDF







Determination of α_S

CMS-PAS-12-027
CMS-PAS-SMP-12-028

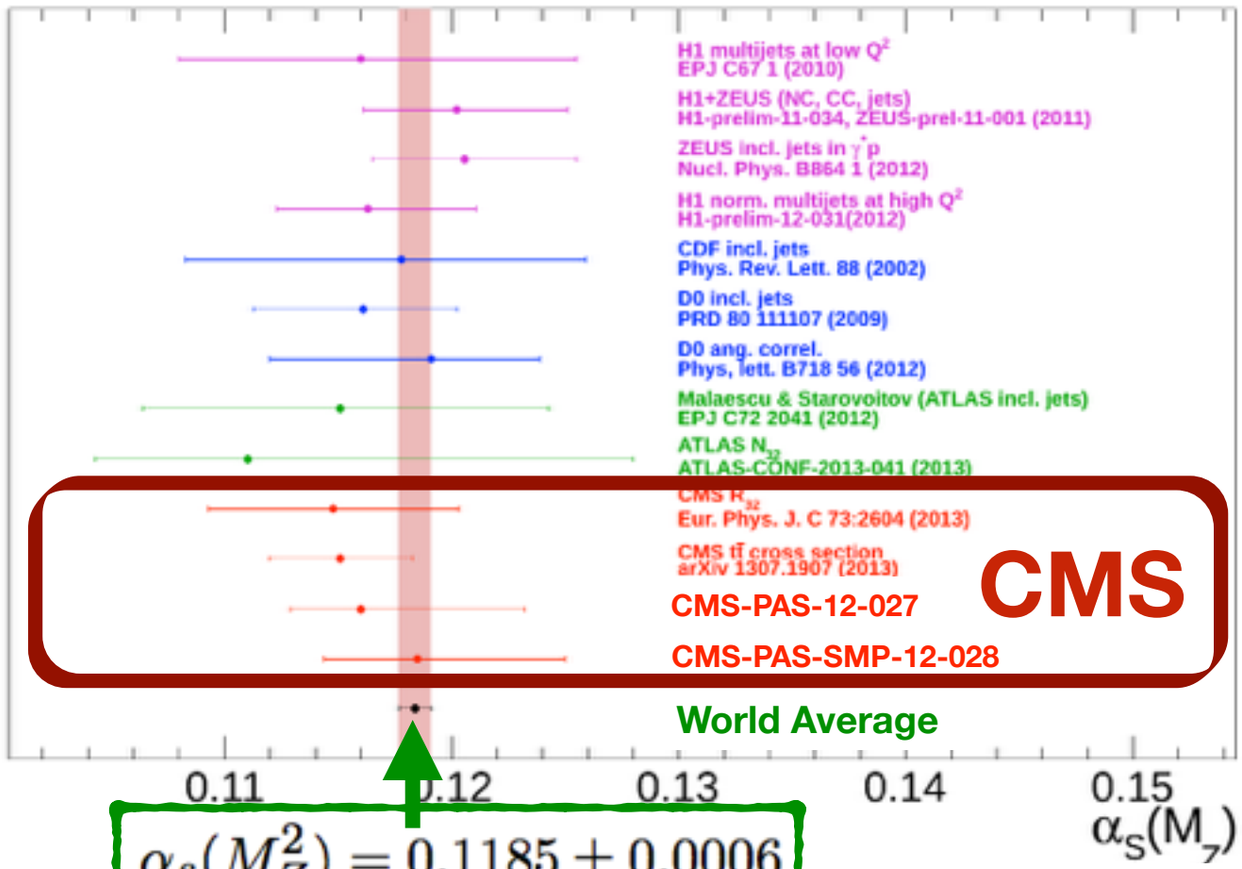
- α_S has been determined:
  - adding it as a free parameter in addition to the PDF in the fit from inclusive jet production:

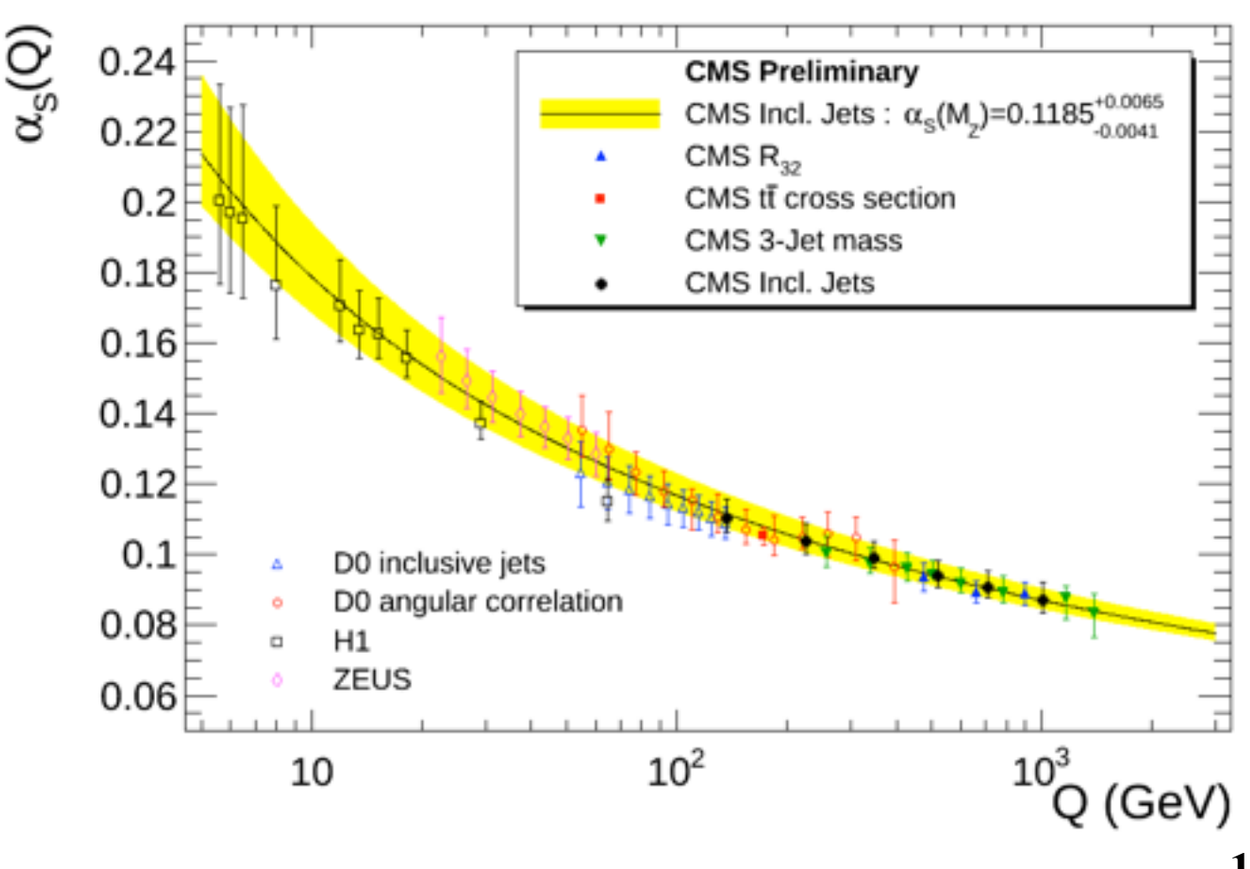
$$\alpha_S(M_Z) = 0.1185 \pm 0.0019\,(\text{exp.}) \pm 0.0028\,(\text{PDF}) \pm 0.0004\,(\text{NP})\,^{+0.0055}_{-0.0022}\,(\text{scale})$$

  - from comparison to theory of 3-jet mass distribution

$$\alpha_S(M_Z) = 0.1160\,^{+0.0025}_{-0.0023}\,(\text{exp, PDF, NP})\,^{+0.0068}_{-0.0021}\,(\text{scale})$$

- behavior vs Q **is consistent** with the dependence predicted by the renormalization group equation of QCD and extend the H1, ZEUS, and D0 results to the 1 TeV region





arXiv:1312.6440

Measurement of 4-jet production

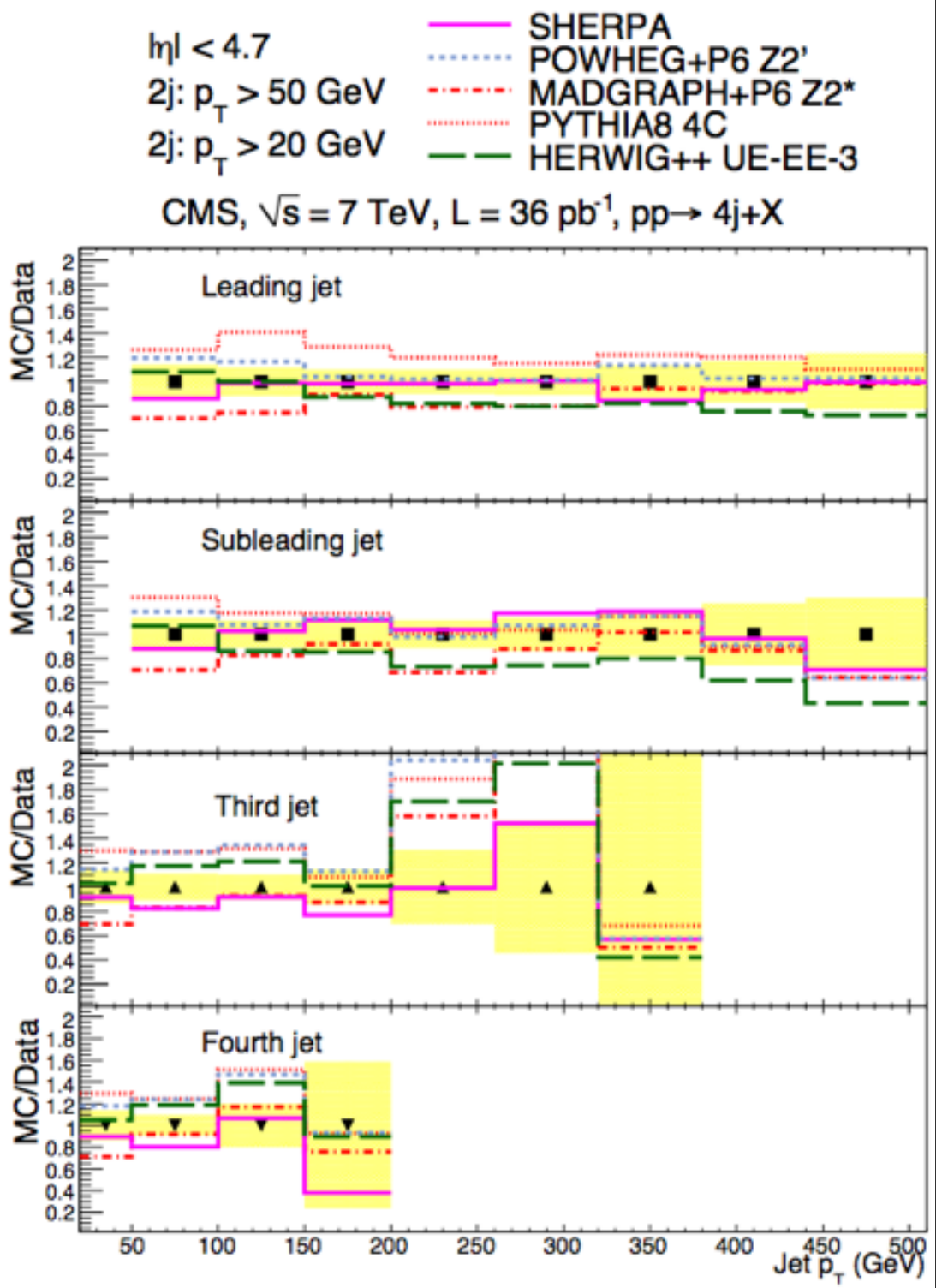
- In **SPS** processes production of a pair of partons at high-p_T and their evolution results in additional jets at lower p_T
  - crucial test for higher-order QCD calculations and the parton shower formalism.

- In the ***low-x region***, parton densities are large and **DPS** processes play an important role

- The **SPS** tends to have a strongly correlated configuration.
- **DPS** events generally have uncorrelated topologies.

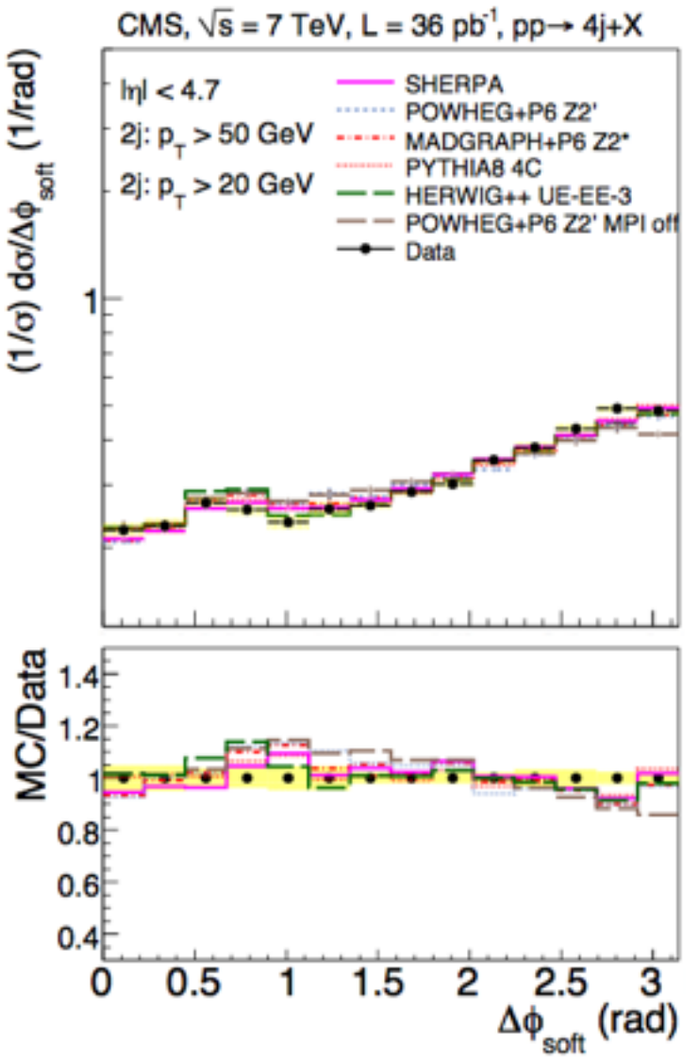
- cross section at large p_T is reasonable
- significant differences arise at smaller p_T values, especially for the subleading and soft jets

MC/Data

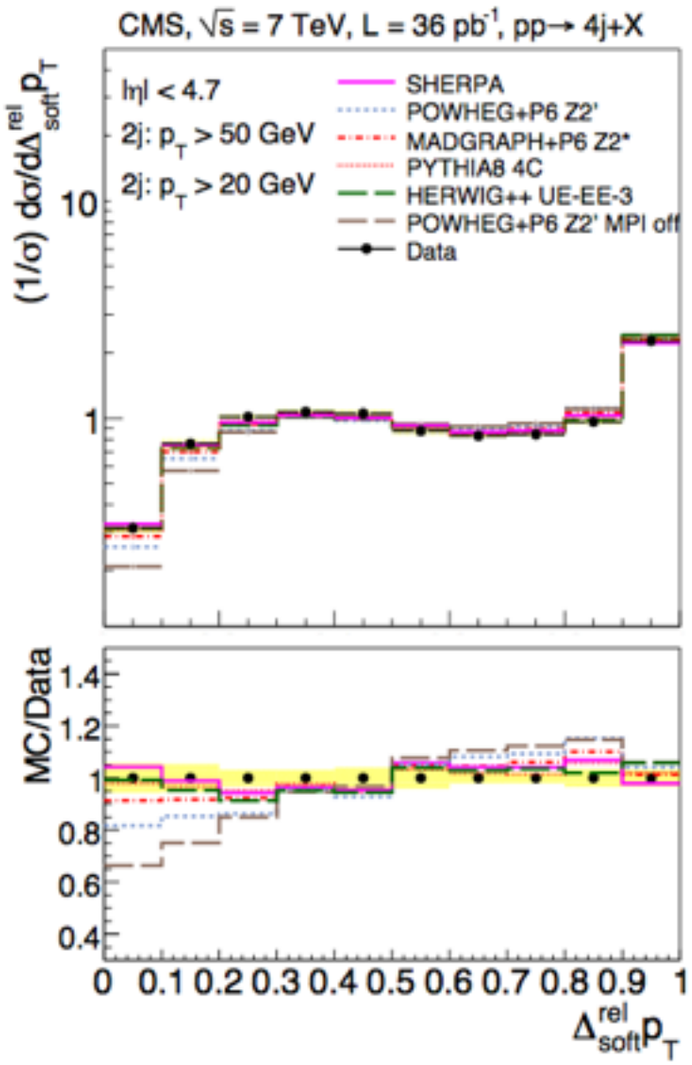


4-jet topological quantities

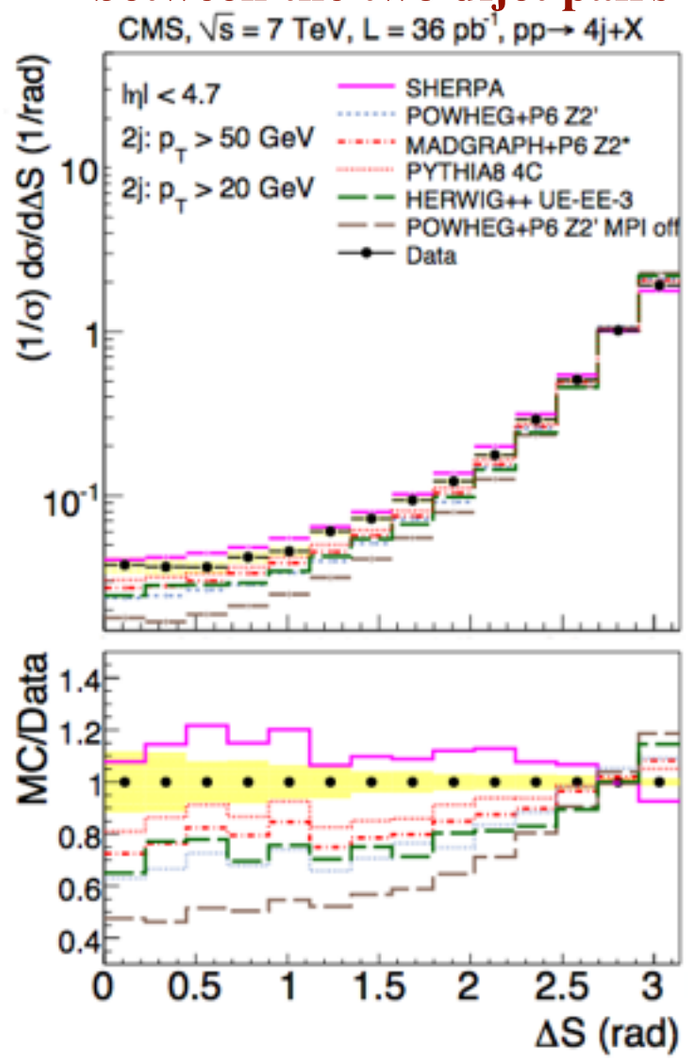
Azimuthal angular differences of soft pair jets



Balance in p_T of the two soft jets



Azimuthal angle ΔS between the two dijet pairs



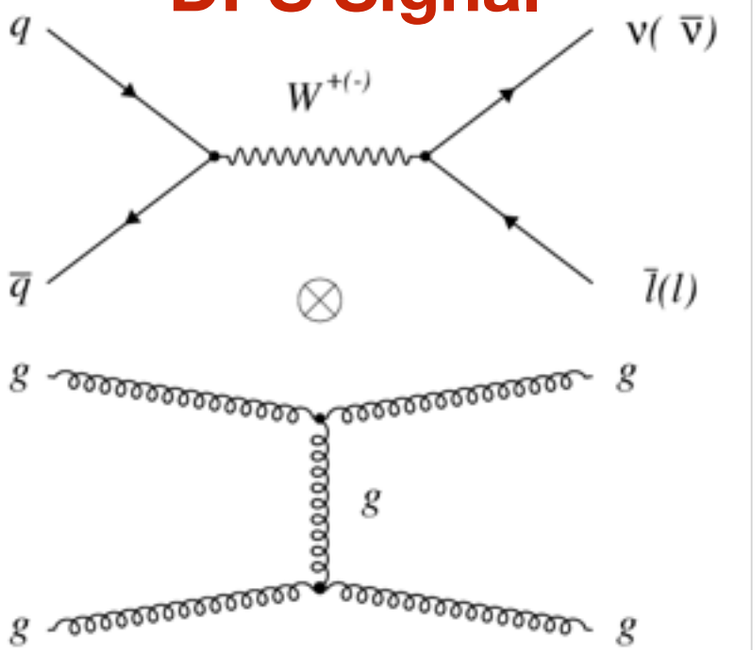
Calculations including MPI agree within uncertainties only in some regions of the phase space.

- contributions from **SPS** can be improved by higher order calculations
- predictions with **MPI** need to be validated before a direct extraction of the **DPS** contribution can be performed.

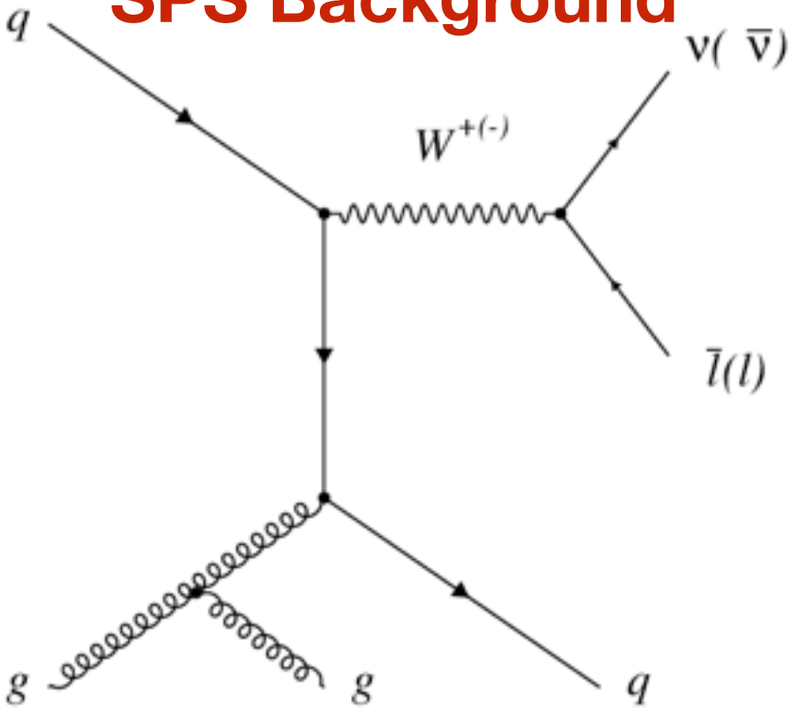
arXiv:1312.5729

Study of W+2 jets production

DPS Signal



SPS Background



Attractive channels for observing DPS thanks to:

- Clean tag coming from the muonic decay of the W
- Large dijet production cross section

σ_{eff} is extracted from an **exclusive selection** by considering the events with one W boson and exactly two jets:

$$\sigma_{\text{eff}} = \frac{N'_{\text{W+0j}}}{N'^{\text{DPS}}_{\text{W+2j}}} \cdot \sigma'_{\text{2j}} \qquad f_{\text{DPS}} = \frac{N'^{\text{DPS}}_{\text{W+2j}}}{N'_{\text{W+2j}}} \qquad R = N'_{\text{W+0j}} / N'_{\text{W+2j}}$$

$$\sigma_{\text{eff}} = \frac{R}{f_{\text{DPS}}} \cdot \sigma'_{\text{2j}}$$

2010 data

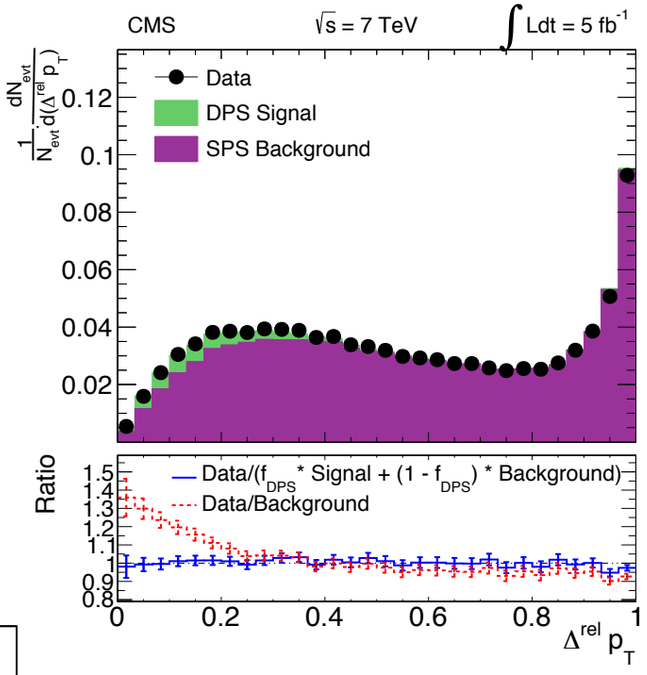
Determination of σ_{eff}

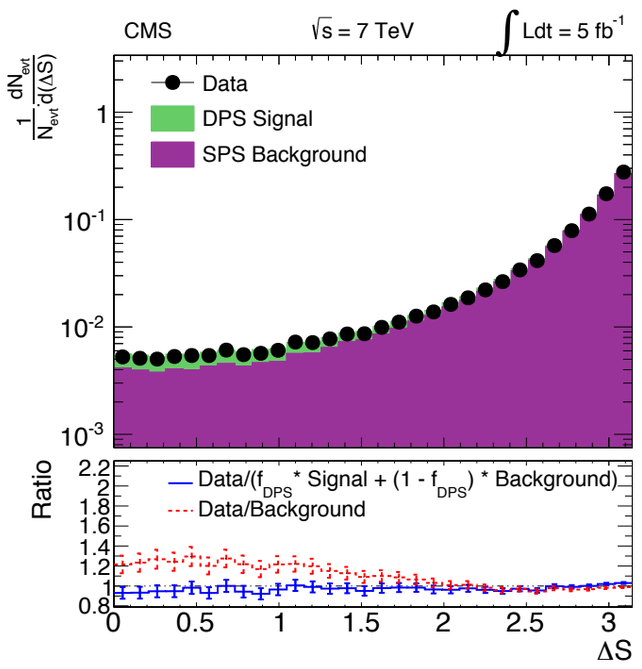
Simultaneous fit to two discriminating variables

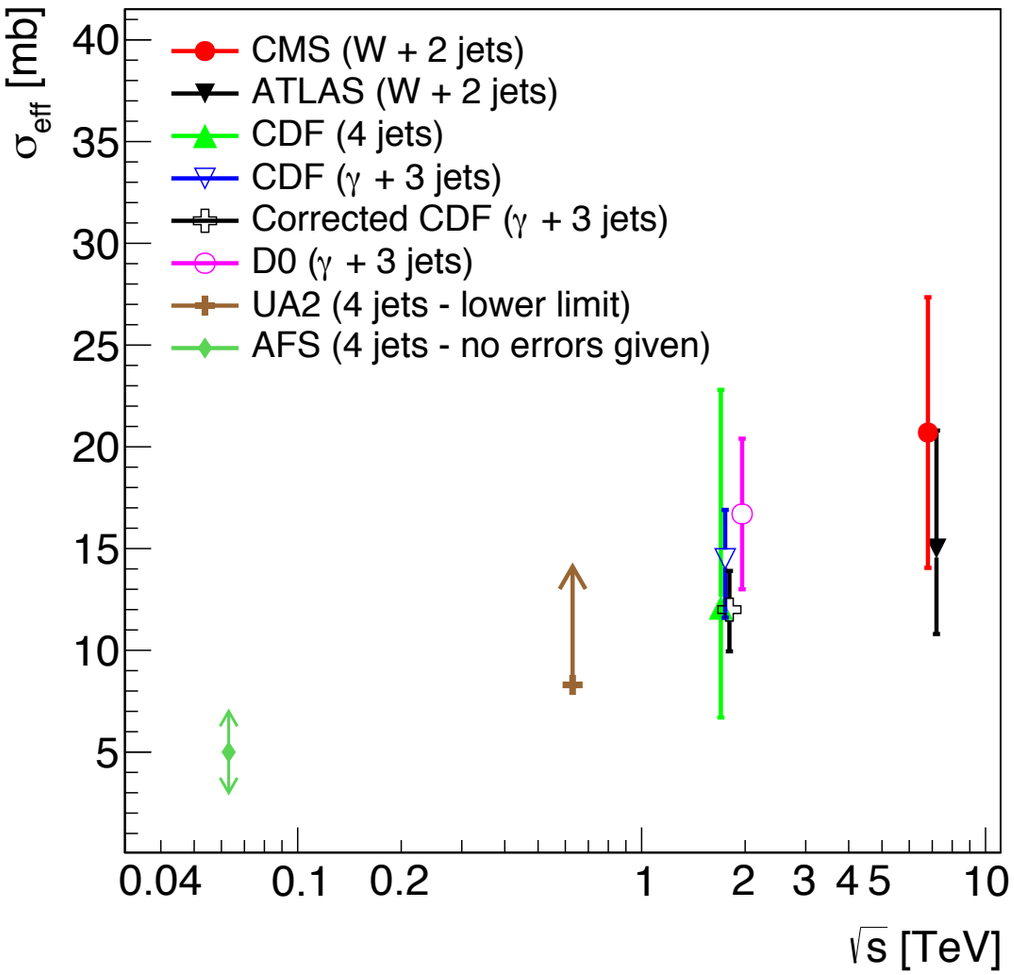
- relative p_T-balance between the two jets
- azimuthal angle between the W-boson and the dijet system

by use of MC templates

$$f_{DPS} = 0.055 \pm 0.002\,(\text{stat.}) \pm 0.014\,(\text{syst.})$$







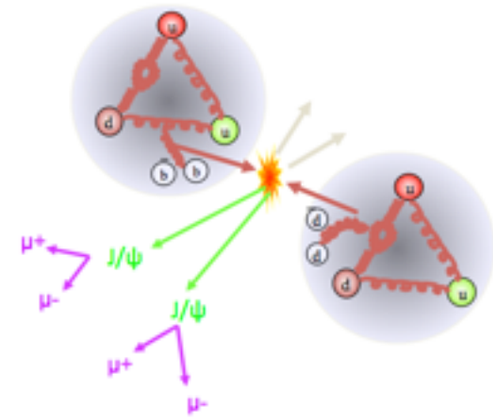
$$\sigma_{eff} = 20.7 \pm 0.8\,(\text{stat.}) \pm 6.6\,(\text{syst.})\ \text{mb}$$

- The measurement is consistent with Tevatron and ATLAS
- Is also consistent with predictions from PYTHIA of 20–30 mb (depending on the tune)

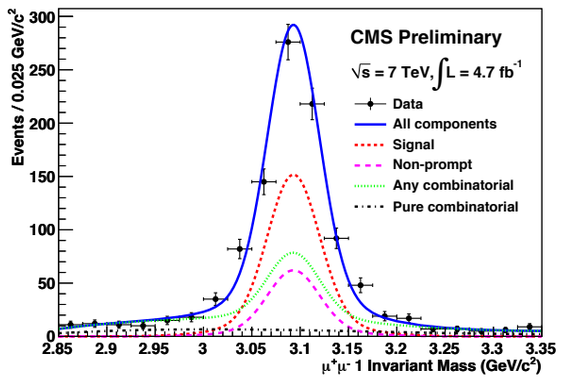
Double J/ψ Cross Section

CMS-PAS-BPH-11-021

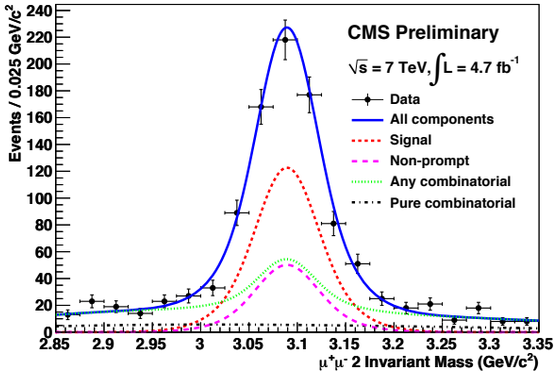
- Clean final state to probe for **DPS**
- Interesting to look for resonances: η_b , tetra quark states, Higgs in NMSSN
- Signal is extracted from a binned maximum likelihood fit on four discriminating variables



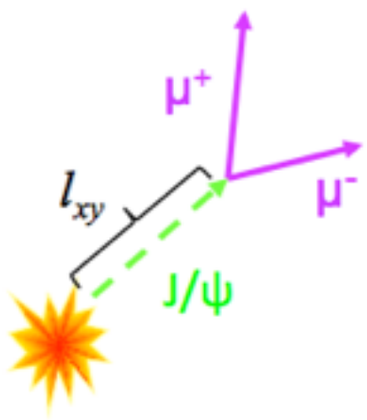
- $\mu^+\mu^-$ ***invariant mass*** *M1 of the high-p_T J/ψ*

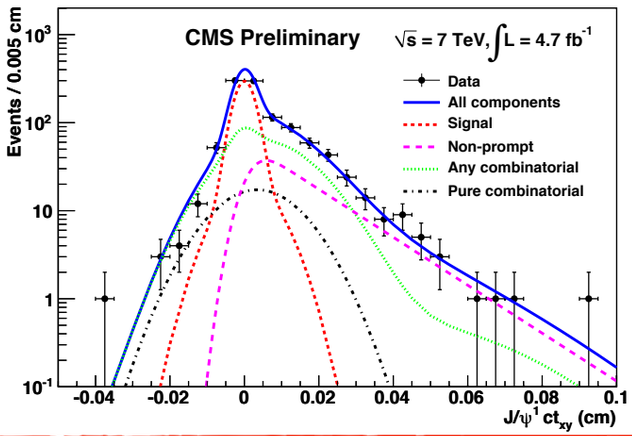


- $\mu^+\mu^-$ ***invariant mass*** *M2 of the low-p_T J/ψ*

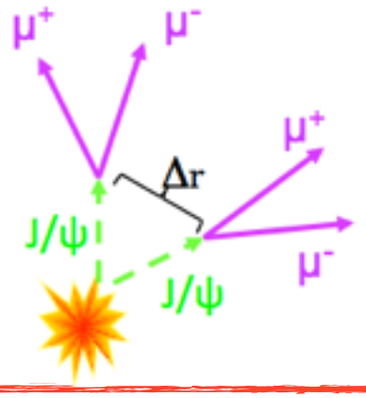


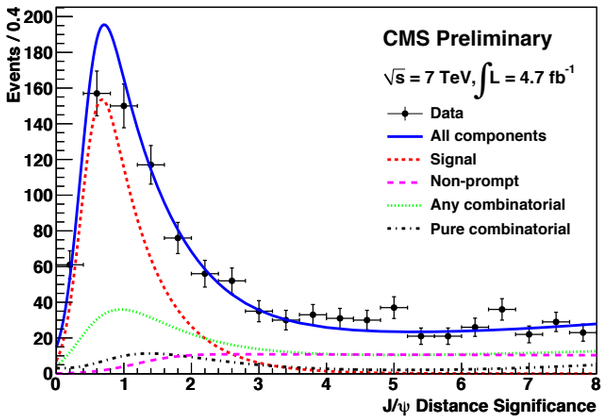
- ***proper decay length*** *of the high-p_T J/ψ*





- ***separation significance*** *between the two J/ψ*



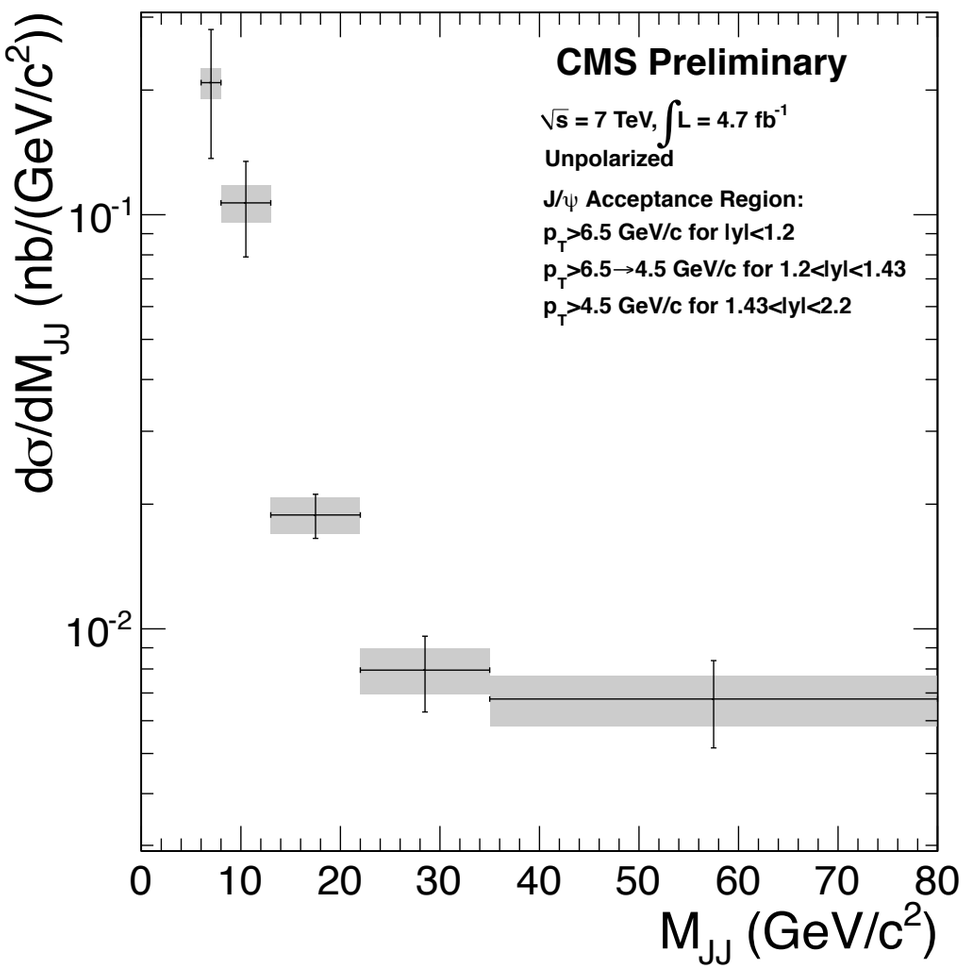


Double J/ψ Cross Section Results

Observed **446 ± 23** events of signal.
For unpolarized J/ψ the total cross section measured at CMS resulted:

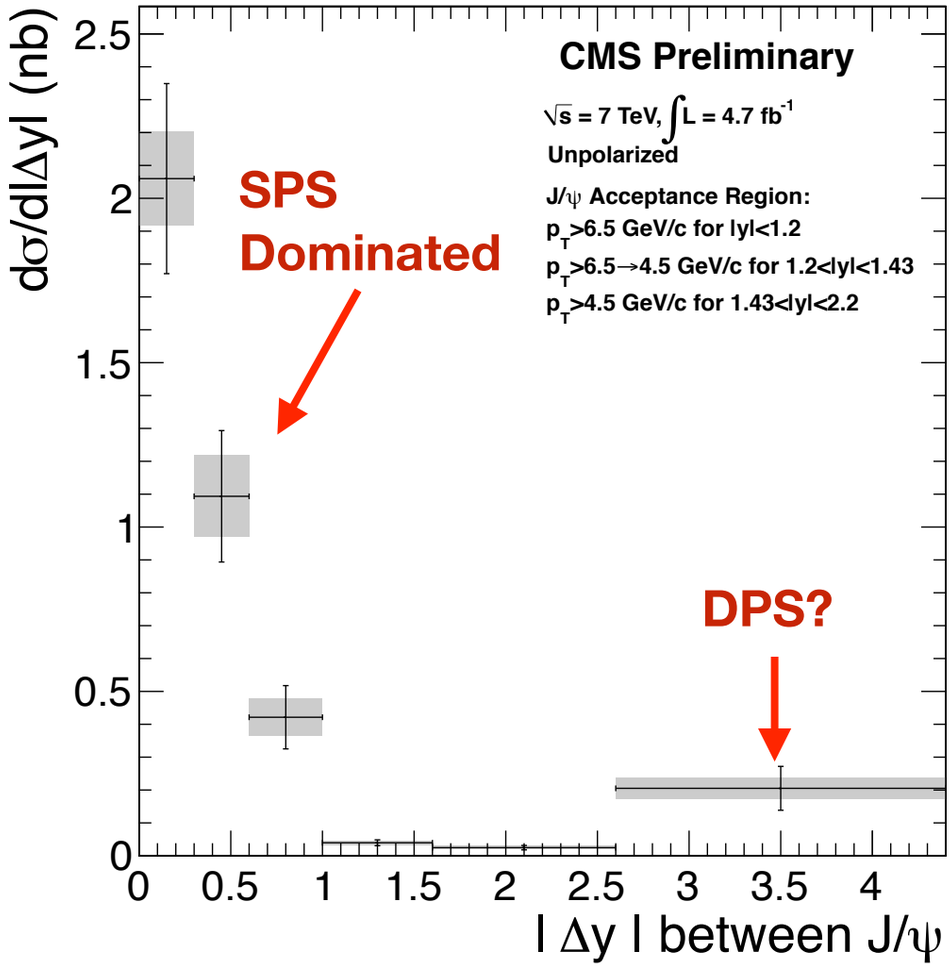
$$\sigma(pp \to J/\psi\, J/\psi + X) = 1.49 \pm 0.07 \pm 0.14 \text{ nb}$$

Differential vs total invariant mass



Found non evidence of resonant production in 2011 data

Differential vs rapidity difference



Excess found $|\Delta y| > 2.6$.
DPS Contribution?

Quarkonium Polarization

- The Standard Model for hadron formation is (non-perturbative) QCD
  - NRQCD = effective theory devoted to high-p_T quarkonium production

- Thanks to the large statistic collected in 2011, CMS performed the polarization measurement for wide range of quarkonium states decaying in a muon pair.

Polarization is measured through the average angular decay distribution:

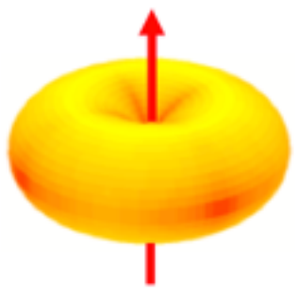
$$W(\cos\vartheta, \varphi|\vec{\lambda}) = \frac{3/(4\pi)}{(3+\lambda_\vartheta)}(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi)$$

where $\lambda\theta$, $\lambda\varphi$, $\lambda\theta\varphi$ are the polarization parameters

Extreme decay distributions:

Longitudinal polarization

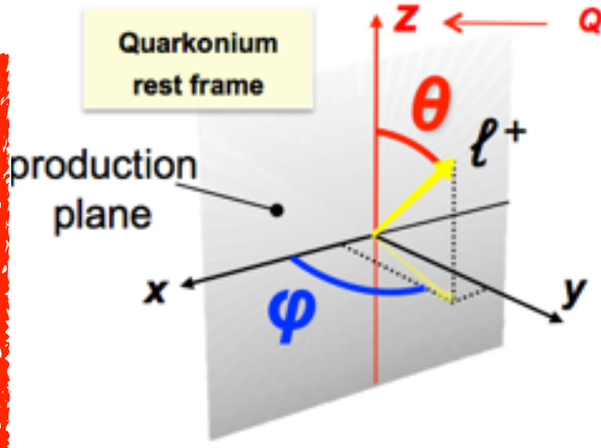
$\lambda_\vartheta = -1$
$\lambda_\varphi = 0$
$\lambda_{\vartheta\varphi} = 0$

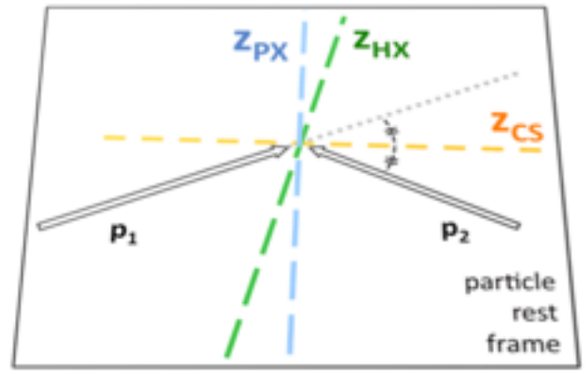


Transverse polarization

$\lambda_\vartheta = +1$
$\lambda_\varphi = 0$
$\lambda_{\vartheta\varphi} = 0$

Reference frames:





Helicity axis (HX): direction of quarkonium momentum

Collins-Soper axis (CS): direction of relative velocity of colliding particles (p_1, p_2)

Perpendicular helicity axis (PX): perpendicular to CS

Quarkonium Polarization vs theory

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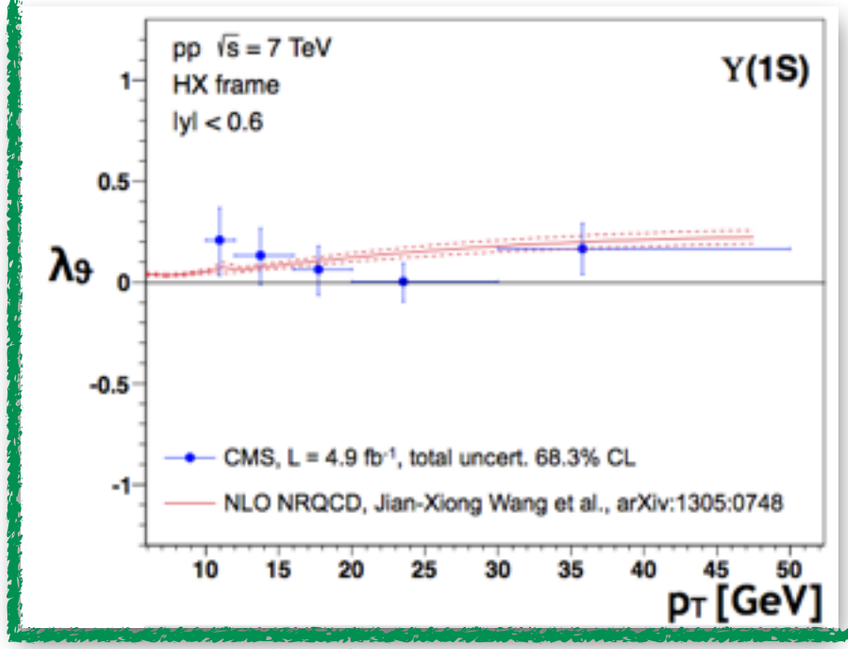

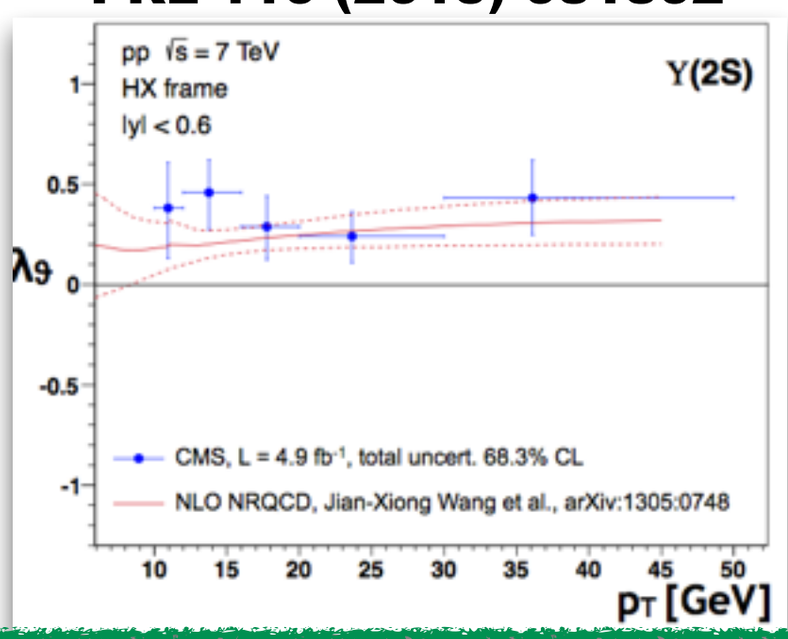

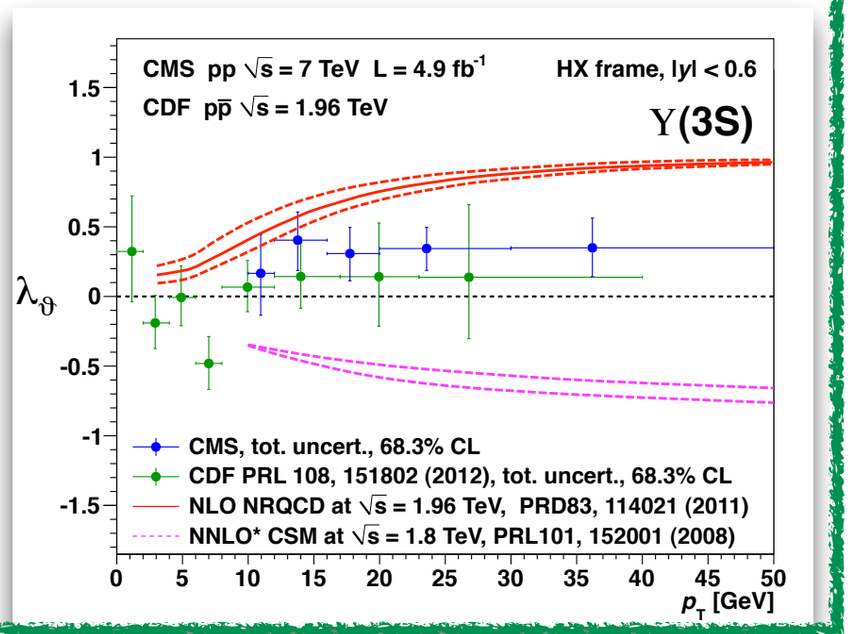

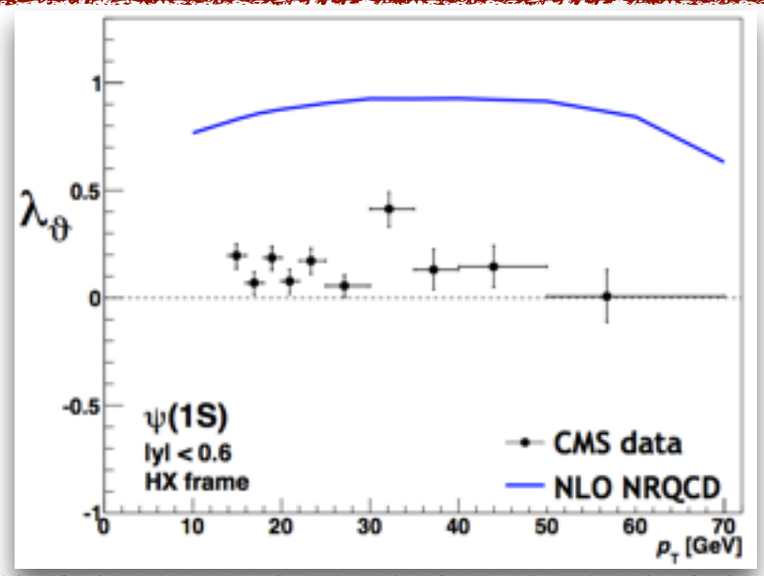

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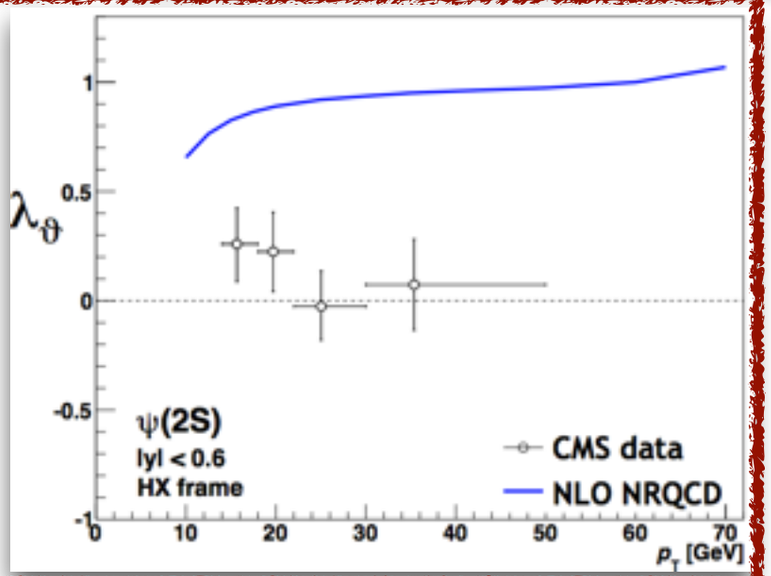


- NLO NRQCD calculations using a global fit of color octet matrix elements as well as hadroproduction data. Include polarization results for Y(nS).
- **Calculations fails to describe CMS results for charmonium**

Conclusions

- Significant **ongoing effort** in CMS improve the understanding of QCD
- Only a small selection of results has been proposed in this talk

DPS fraction from W+2 jets events

3-jet mass cross section

Hadronic event shapes

Double J/ψ

Quarkonium Polarization

Determination of α_S

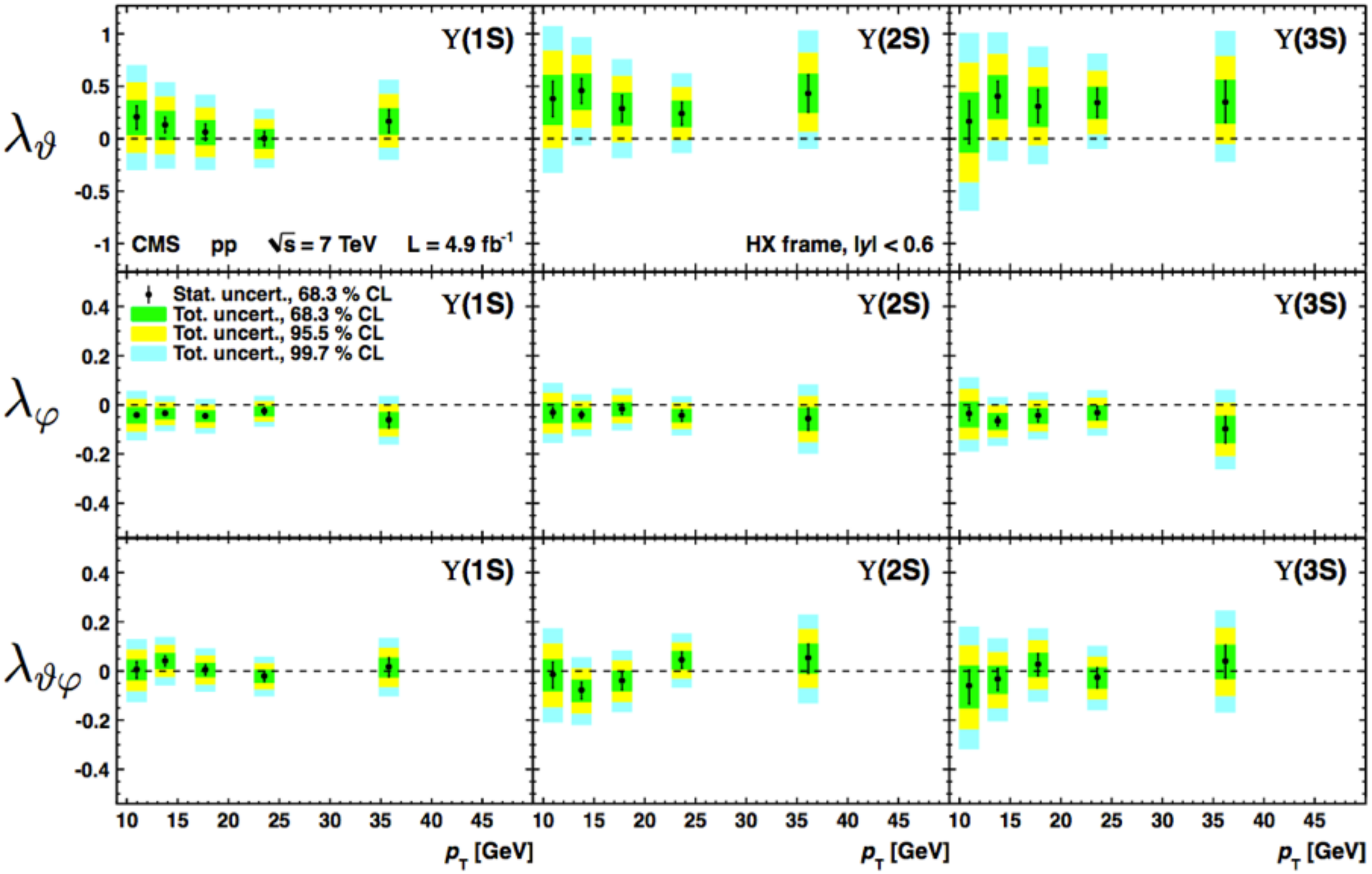
Topology of 4-jet

Inclusive jet cross section at 8 TeV

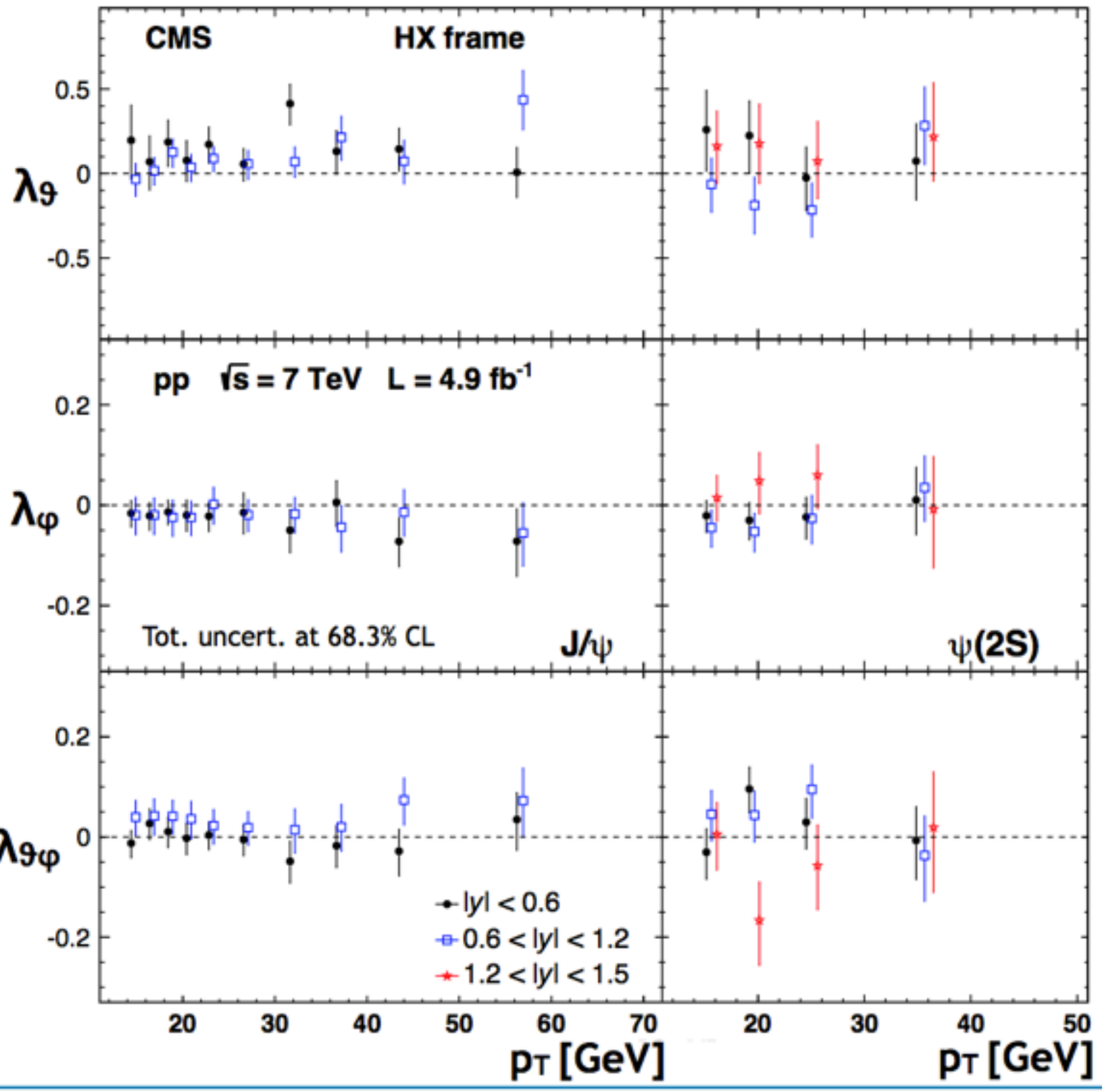
- QCD results are public available from different working group in CMS:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFSQ
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

BACKUP

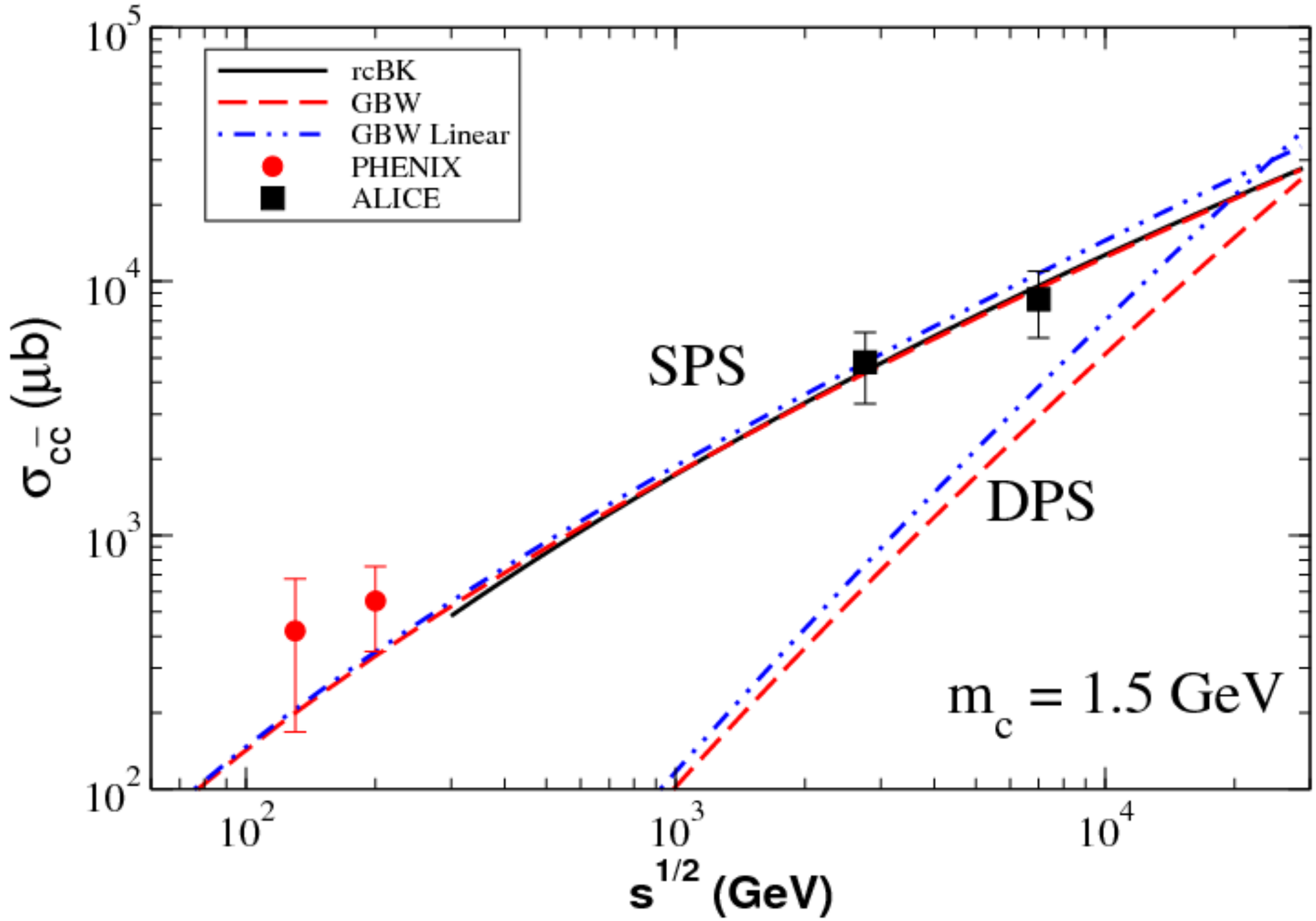
Y(nS) Polarization



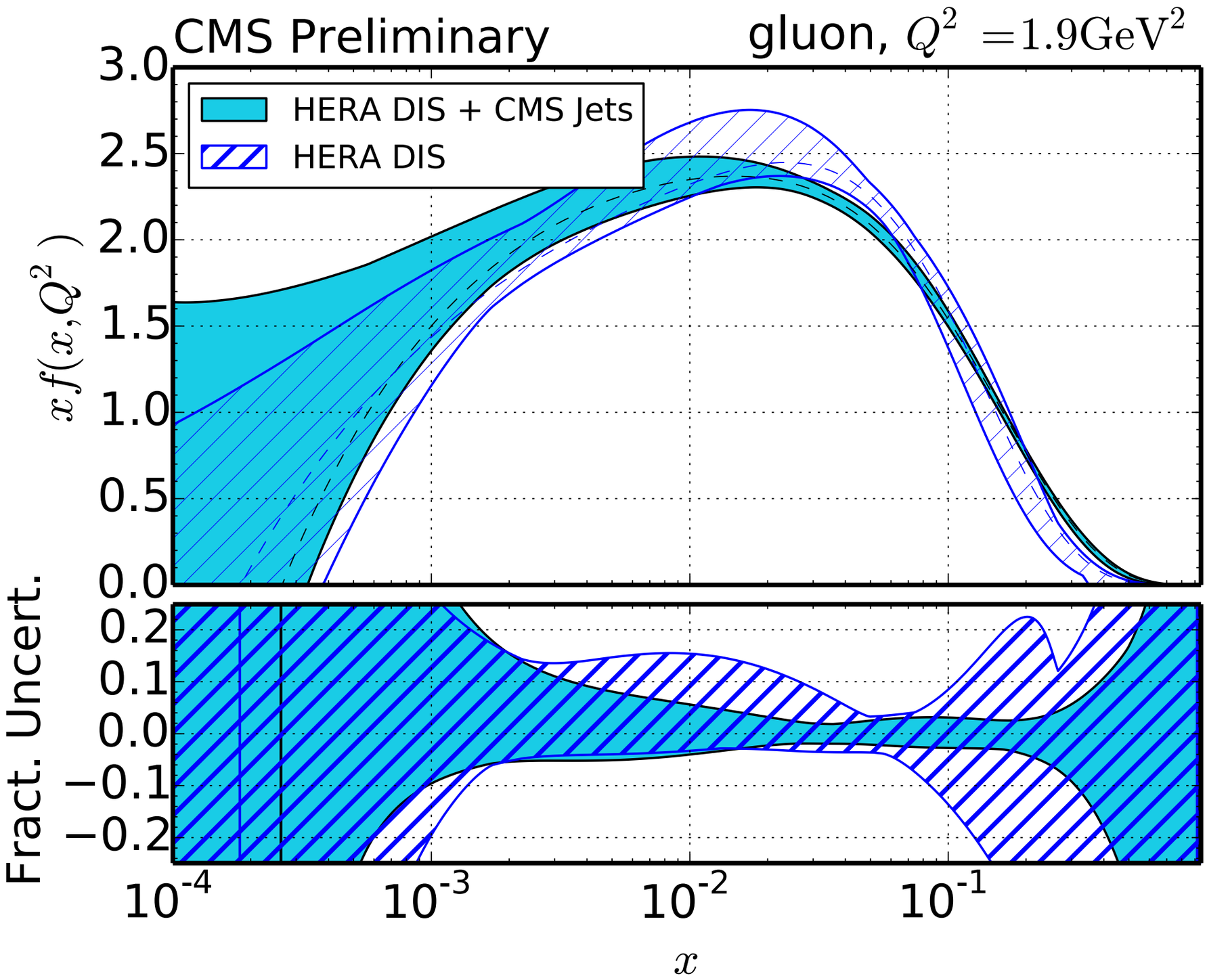
Charmonium Polarization



DPS effect on charmonium production



Gluon PDF


CMS Preliminary
gluon, $Q^2 = 1.9\mathrm{GeV}^2$
HERA DIS + CMS Jets
HERA DIS
$x f(x,Q^2)$
Fract. Uncert.
x
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.2
0.1
0.0
−0.1
−0.2
10^{-4}
10^{-3}
10^{-2}
10^{-1}