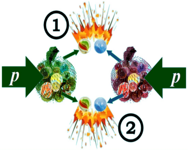
Deutsches Elektronen-Synchrotron (DESY), Hamburg

# Forward and small-x QCD

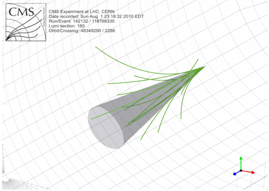
*Paolo Gunnellini*
on behalf of the CMS Collaboration

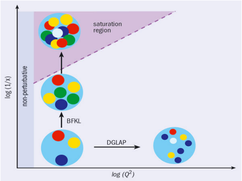


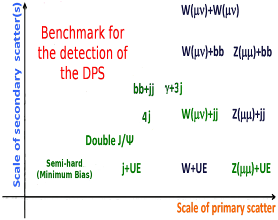

ICNFP Conference
Krete (Greece)
August 2015

# Outline

1. Introduction
2. Inclusive jet measurements
3. Müller-Navelet jet measurements
4. Studies of behaviour of gluon distribution
5. Double parton scattering
6. Summary and conclusion



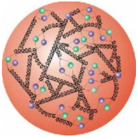



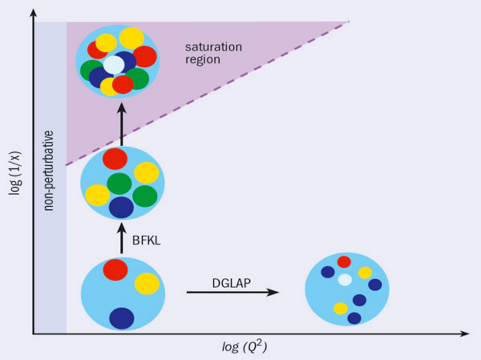
# Introduction

$$\sigma_{ab\to F}(Q^2) = \int dx_1 dx_1' f_a^1(x_1, Q^2) f_b^2(x_1', Q^2) \hat{\sigma}_{ab}(x_1, x_1', Q^2)$$

- Partonic cross section
- Parton Distribution Functions



**Different final states access different scales and $x$ values**




**Small-x: BFKL evolution equation**

**High $Q^2$ and high-x: DGLAP evolution equation**

**CCFM equation bridges between DGLAP and BFKL**

**Saturation effects appearing at very small-x**

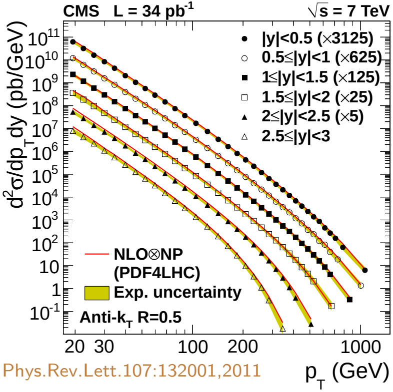
**At the LHC, huge opportunity to study the different regimes**

# Inclusive jet measurement (I)

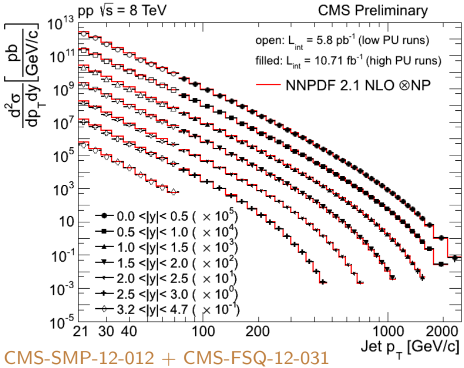
**Double differential cross section measurement in rapidity bins as a function of jet $p_T$**

**Inclusive jet measurements - Event selection**

7 TeV: ak5 - first measurement of inclusive jet cross section at CMS
8 TeV: ak7 - large increase of the phase space in $p_T$ and inclusion of the forward region



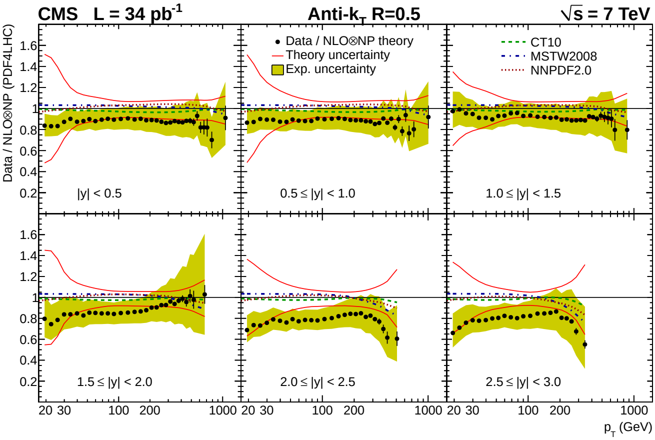

Phys.Rev.Lett.107:132001,2011




CMS-SMP-12-012 + CMS-FSQ-12-031

# Inclusive jet measurement (II)

**Comparisons with theory predictions from NLO calculations with NP corrections**




Phys.Rev.Lett.107:132001,2011

Good agreement in central region but progressive worsening towards forward region

- Effect of pert. corrections (PhysRevD.87.094009)
- Higher sensitivity to dynamics in low-x region

Same trend at 8 TeV

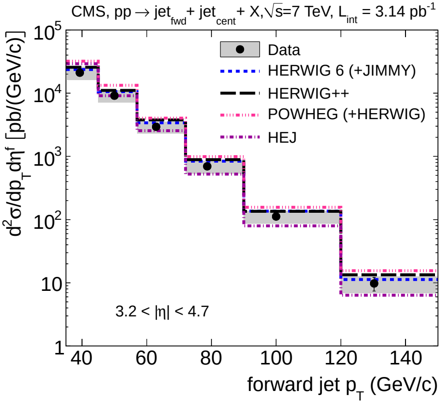
**Soon results at 13 TeV!**

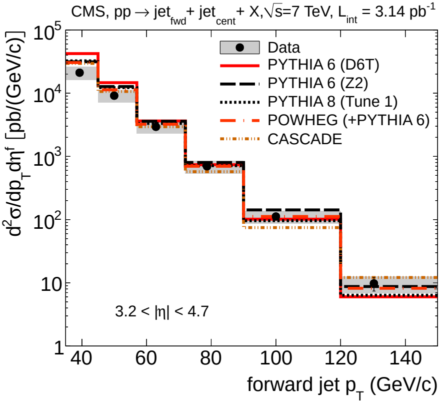
## Going more forward..

JHEP06(2012)036

### Forward-central measurements - Event selection

Proton-proton collisions at 7 TeV: leading central ($|\eta| < 2.8$) jet and leading forward ($3.2 < |\eta| < 4.7$) jet with $p_T > 35$ GeV




Good agreement with (most of) predictions based on different evolution equations

**Little sensitivity to BFKL effects**

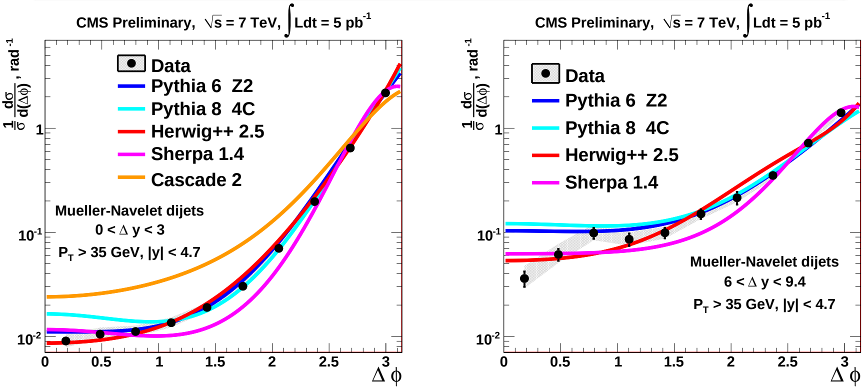
# Searching for BFKL (II)

## Going more forward..

CMS-PAS-FSQ-12-002

### Müller-Navelet jets - Event selection

Proton-proton collisions at 7 TeV:
most forward and most backward jets in $|y| < 4.7$ with $p_T > 35$ GeV



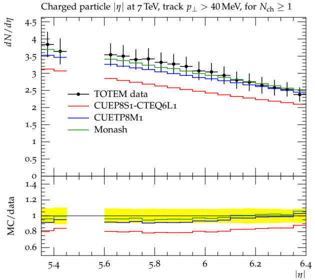

Good agreement with DGLAP-based predictions in every bin of jet rapidity separation

**Same conclusion for measurements of terms of Fourier expansion** (Nucl.Phys.B776 (2007))

No clear evidence for non-DGLAP behaviour!

# Sensitivity to low-x gluon

Low-x gluon distribution affects the forward region! CMS-PAS-GEN-14-001




New tunes available:

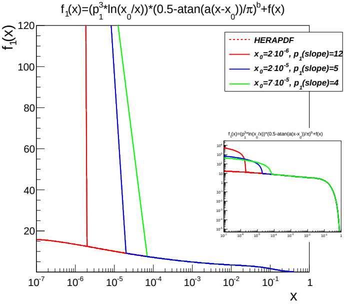
**CUETP8S1 - CTEQ6L1**

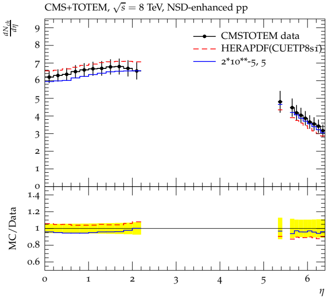
**CUETP8M1 - NNPDF2.3LO**

Very different behaviour at low-$x$ for the two PDFs

$N_{ch}$ in fwd region better described by NNPDF tunes

What happens if one modifies by hand the low-x gluon distribution with an increasing density in e.g. HERAPDF?




We do improve the description at large $\eta$!

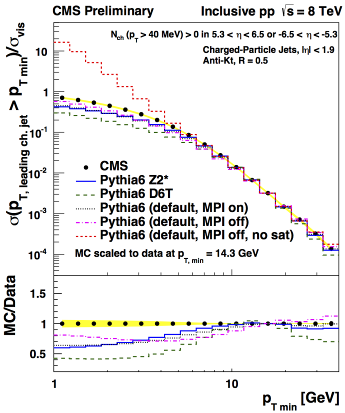
**What happens with saturation?**

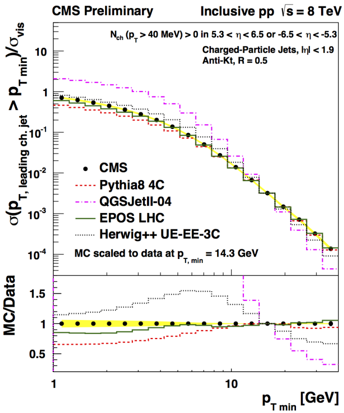
Total partonic 2→2 cross section given by:

$$\sigma(p_{Tmin}) = \int_{p_{Tmin}} dp_T^2 \int_{-\infty}^{\infty} dy \frac{d^2\sigma}{dp_T^2 dy}$$

- Divergent at low $p_T$
- Behaviour tamed in the MC

Measurement of the integrated cross section as a function of the charged mini-jet $p_T$




Sensitivity to MC models and tunes:

standard HEP MC fails to describe the convergence

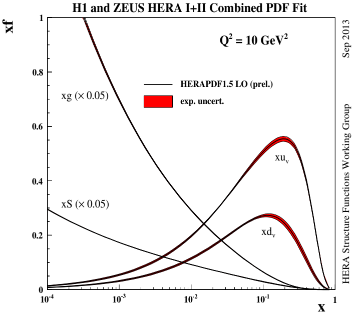
Cosmic Ray MC EPOS describes the data best

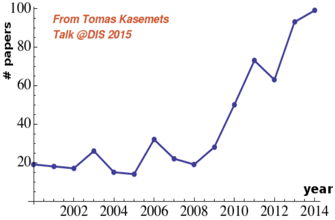
CMS-PAS-FSQ-12-032 (submitted to PRD)

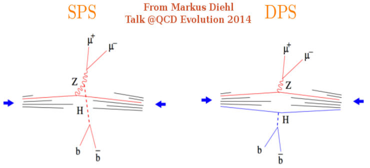
**Saturation effects are shown towards low $p_{Tmin}$ where the cross section converges**

# Hard multiple scatterings become relevant!

- **Increasing contribution at the LHC when going to higher energy**
- **Sizeable background for LHC processes (SM and searches), e.g. Higgsstrahlung**
- **Information about the structure of the proton, i.e. parton correlations**

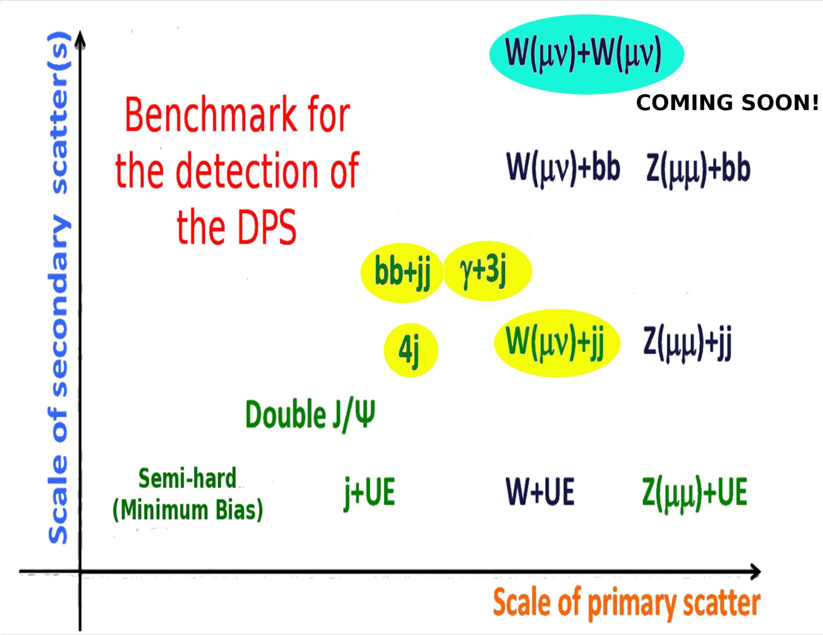



**And...increasing interest and number of entries in Spires!**

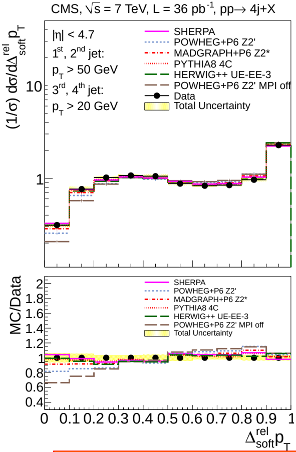
# Choice of physics channels

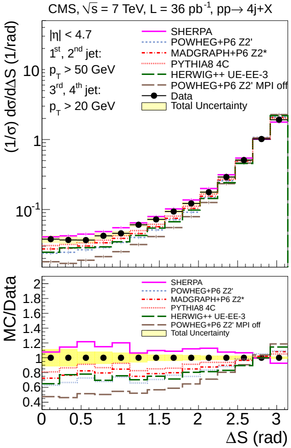


# Measurement of a four-jet final state

## Event selection

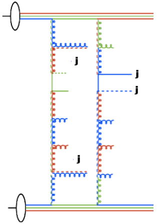
Exactly four jets in the final state in $|\eta| < 4.7$:
2 jets: $p_T > 50$ GeV (hard), 2 jets: $p_T > 20$ GeV (soft)




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

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




Soft jets are expected to be produced also by a $2^{nd}$ scattering

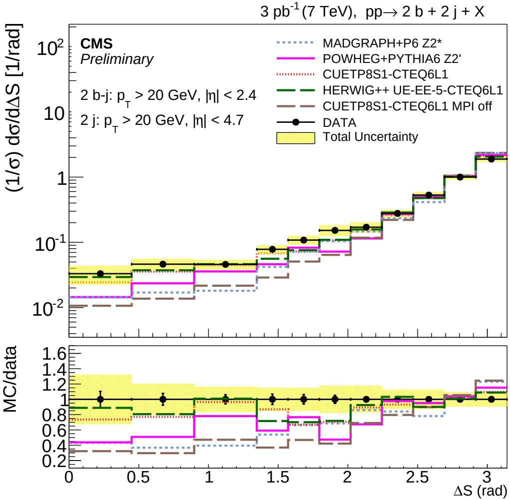
PRD 89 (2014) 092010

$\Delta S$ and $\Delta^{rel}_{soft} p_T$ sensitive to MPI contribution: → ROOM for DPS!

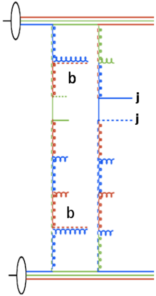
# Measurement of a four-jet final state with b-jets

## Event selection

Selection of at least four jets with $p_T > 20$ GeV:
2 b-jets: $|\eta| < 2.4$, 2 other jets: $|\eta| < 4.7$




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




Additional jets may be produced also by DPS

CMS-FSQ-13-010

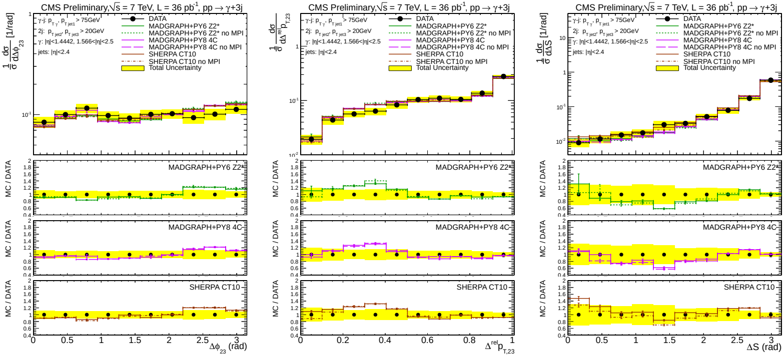
Sensitivity to higher orders..

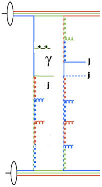
..but also to MPI!

# Measurement of a final state with $\gamma+$ 3 jets

## Event selection

Selection of a photon and at least three jets in $|\eta| < 2.5$:
$\gamma$+1 jet: $p_T > 75$ GeV, 2 jets: $p_T > 20$ GeV




Soft jets may be produced also by a $2^{nd}$ scattering

CMS-FSQ-12-017

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

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

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

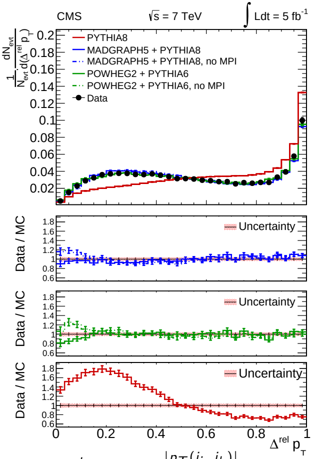
**No difference between predictions with and w/o MPI**

Need for improving sensitivity!

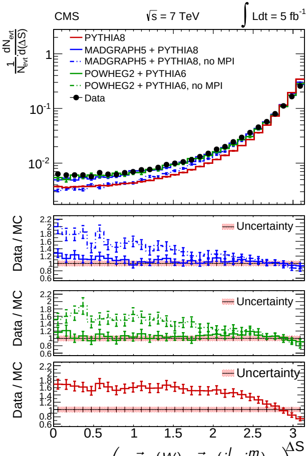
# Measurement of a W+dijet final state

## Event selection

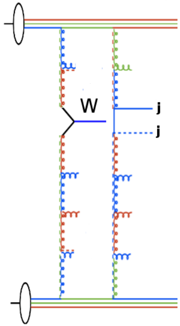
Presence of a muon with $p_T > 35$ GeV in $|\eta| < 2.1$ and $E_T^{miss} > 50$ GeV
+ at least 2 jets: $p_T > 20$ GeV in $|\eta| < 2.0$




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




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



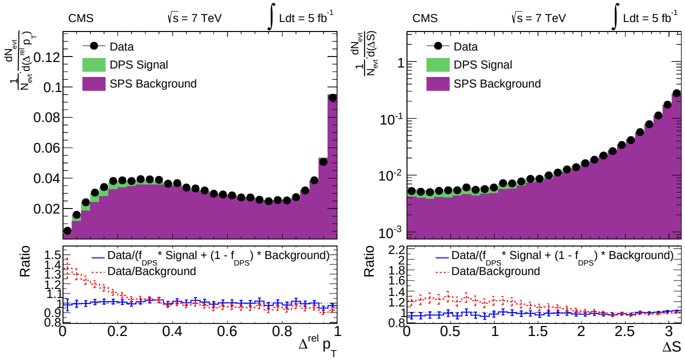

The jets are expected to be produced also by a $2^{nd}$ scattering

JHEP 03 (2014) 032

**Sensitivity to DPS!**

# Extraction of $\sigma_{eff}$ from W+dijet final state

CONSIDERED OBSERVABLES: normalized $\Delta S$ and $\Delta^{rel} p_T$
BACKGROUND: MADGRAPH+P8 with hard MPI above 15 GeV excluded
SIGNAL: Two mixed independent scatterings generated with P8 and MG+P8
DRIVING UNCERTAINTY: model dependence




$$\sigma_{eff} = \frac{N_{W+0j}}{f_{DPS} \cdot N_{W+2j}} \cdot \sigma_{2j}$$

$$f_{DPS} = 5.5\%,$$

$$\frac{N_{W+0j}}{N_{W+2j}} = 27.8$$

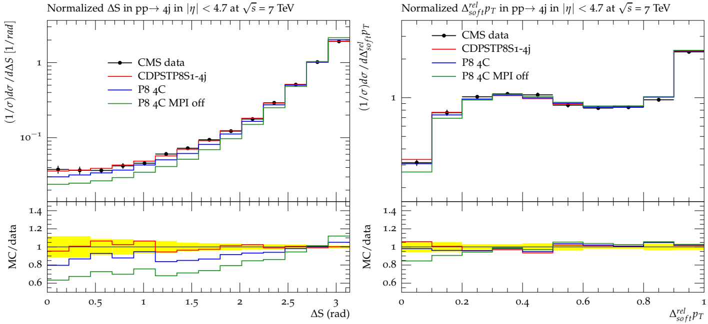
JHEP 03 (2014) 032

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

# Extraction of $\sigma_{eff}$ in four-jet final states

CONSIDERED OBSERVABLES: normalized $\Delta S$ and $\Delta^{rel} p_T$
NEW METHOD USED: inclusive fits to observables
DRIVING UNCERTAINTY: fit uncertainty (no model dependence included)

Minimization of the binned $\chi^2 = \sum_O \sum_{b \in O} \frac{(MC^b - DATA^b)^2}{\Delta_b^2}$




$\sigma_{eff} = 19.0^{+4.7}_{-3.0}$ mb

LEFT: $\Delta S$
RIGHT: $\Delta^{rel}_{soft} p_T$

CMS-GEN-14-001

**A lower value of $\sigma_{eff}$ improves the description of the measurement**

**Values of $\sigma_{eff}$ are compatible between four-jet and W+dijet final states**

# Summary and conclusion

- **CMS has a very rich QCD program investigating processes at different scales, final states, and phase space sensitive to low-$x$ dynamics**

- Good description of QCD processes in central and forward region
- No clear evidence of behaviour disagreeing with DGLAP eq. (yet)
- Saturation of the cross section measured when going to low $p_T$
- Many DPS-sensitive measurements performed with different final states (W+jets, four-jets, two b- + two other jets...)
  - Need for DPS contribution for better data description

- **Future: New energy, sensitivity to lower $x$ values, new phase space!**

# Summary and conclusion

- **CMS has a very rich QCD program investigating processes at different scales, final states, and phase space sensitive to low-$x$ dynamics**
- Good description of QCD processes in central and forward region
- No clear evidence of behaviour disagreeing with DGLAP eq. (yet)
- Saturation of the cross section measured when going to low $p_T$
- Many DPS-sensitive measurements performed with different final states (W+jets, four-jets, two b- + two other jets...)
  - Need for DPS contribution for better data description
- **Future: New energy, sensitivity to lower $x$ values, new phase space!**

THANK YOU!

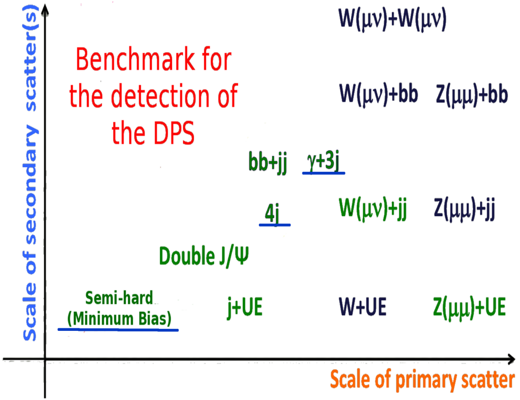

# BACK-UP SLIDES

# Choice of the physics channel

$$\sigma_{AB}^{DPS} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

Internal structure of the proton
DPS background for any physics channel

$\rightarrow$ Which channels can be used to look for DPS signals?

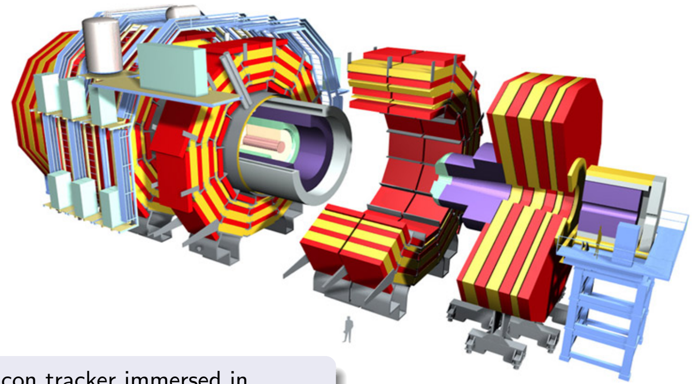



Published by CMS and/or ATLAS

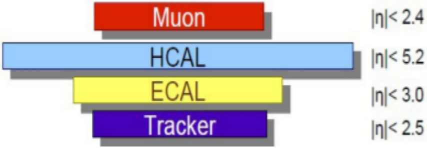
Published by D0 and/or CDF

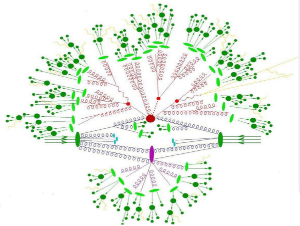
**How can DPS be detected?**

# The Compact Muon Solenoid experiment



- Silicon tracker immersed in a 3.8 T magnetic field
- Wide calorimeter coverage
- Excellent jet energy resolution and muon detection efficiency
- Particle Flow technique for jet reconstruction





Hard scattering

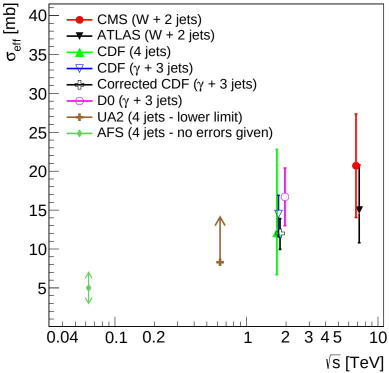
Initial and Final State Radiation

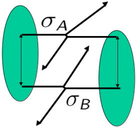
Multiple Parton Interaction (MPI)

Beam-beam remnants

In general, the UE is a softer contribution but.. some MPI can be hard!

## Double Parton Scattering




$$P_A = \frac{\sigma_A}{\sigma_{tot}^{pp}}$$

$$P_B = \frac{\sigma_B}{\sigma_{tot}^{pp}}$$

$$\sigma_{AB}^{DPS} \propto \frac{m}{2} P_A P_B \sigma_{tot}^{pp}$$

$$\sigma_{AB}^{DPS} = \frac{m}{2} \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

$$\sigma_{eff} \ll \sigma_{tot}^{pp}$$

**Need for correlations!**

# The inclusive fit method

## Experimental difficulties of the template method

→ **How to define the background?**

- Good to exclude hard MPI..but no such possibility in some generators

→ **How to define exclusive and inclusive events?**

- $N_{W+0j}$ and $N_{W+2j}$ are sensitive to the jet scales

→ These issues have an impact on the systematic uncertainty!

**Is there a way out?**

## The inclusive fit method

- Run predictions for different choices of UE parameters
- Fit the MC predictions to the considered observables
- Improve the data description with the examined model
- (..look at the corresponding $\sigma_{eff}$..)