Double & multi parton scatterings in p-A collisions at the LHC

Workshop on MPI at the LHC

Tel Aviv University, 17th Oct. 2012

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CERN

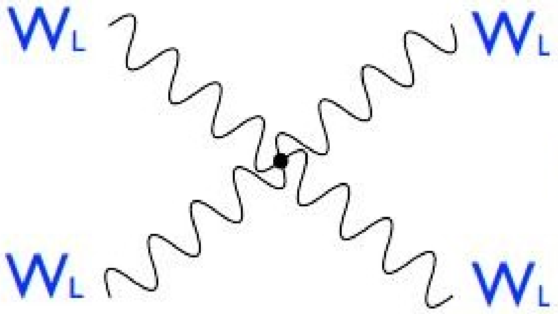
(*) Part of the results based on: Dd'E & A. Snigirev (to be submitted)

Outline

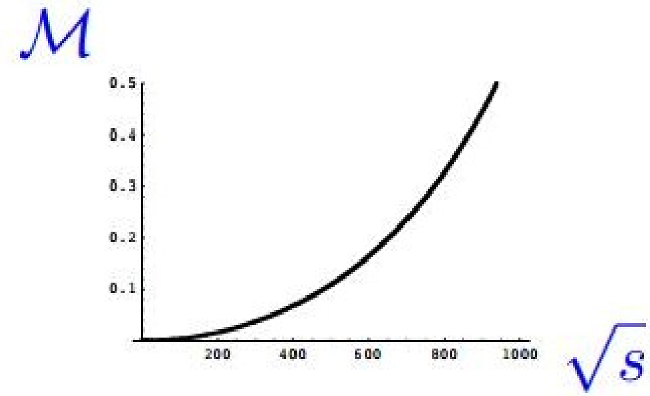
- Introduction:
  - MPI: theoretical basis (unitarity of pQCD x-sections)
  - MPI: experimental evidences in p-p at the LHC (inclusive hadron production, underlying event, “ridge” ?)
  - DPS: theoretical x-section (phenomenological “pocket formula”)
  - DPS: experimental searches in p-p at LHC
- Double-Parton-Scattering in proton-nucleus collisions:
  - (Re)Derivation of DPS x-section “pocket formula” for p-A
  - DPS x-section enhancement factor: ~600 for p-Pb
- Case study: Same-sign WW production in p-Pb at the LHC:
  - Cross-sections (NLO) for signal and background: σ(WW,DPS) ~ 300 pb > σ(WWjj) ~ 100 pb
  - Visible rates N~ 2 – 20 for p-Pb at 8.8 TeV

Unitarity of electroweak cross sections

- SM without a Higgs: Longitudinal W-W scattering explodes at ~1 TeV



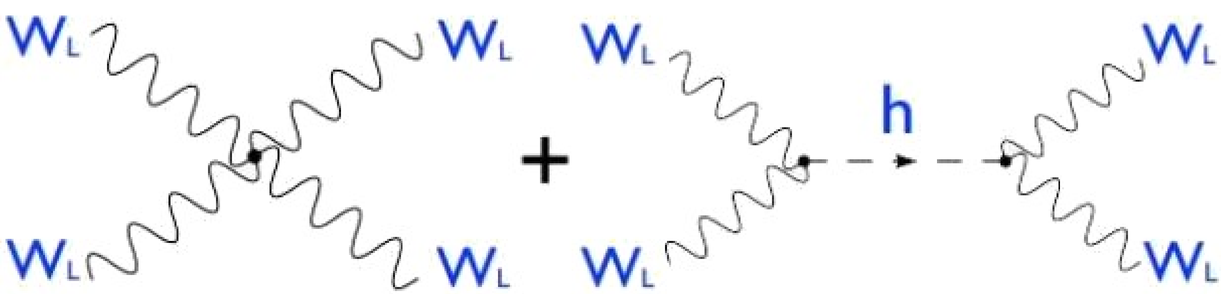
$$\propto \frac{s}{v^2}$$

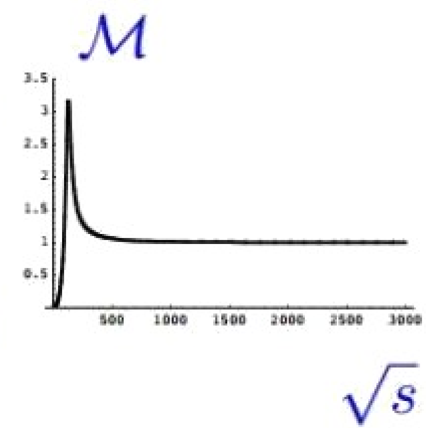


[A.Pomarol, ICHEP'12]

Unitarity is lost at high-energies

- Higgs boson restores finiteness of W-W cross sections:



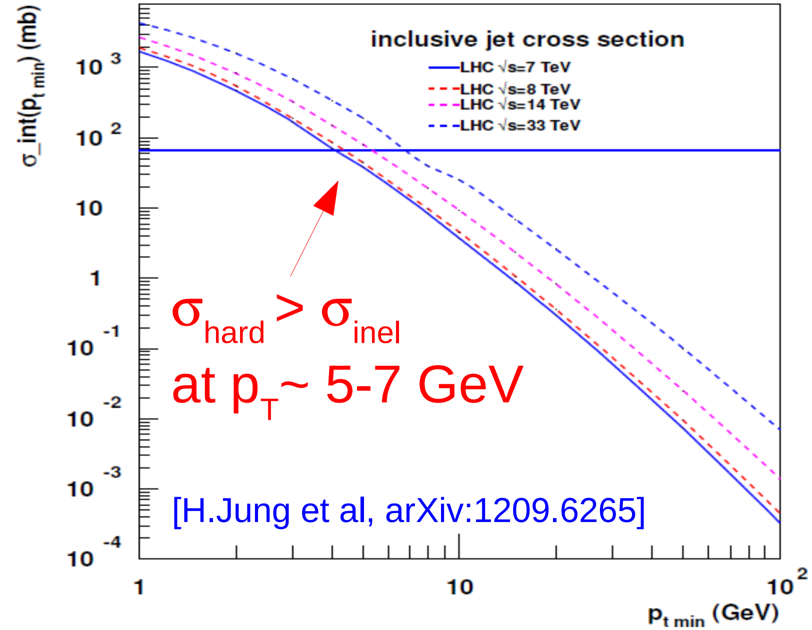


Unitarity of pQCD cross sections

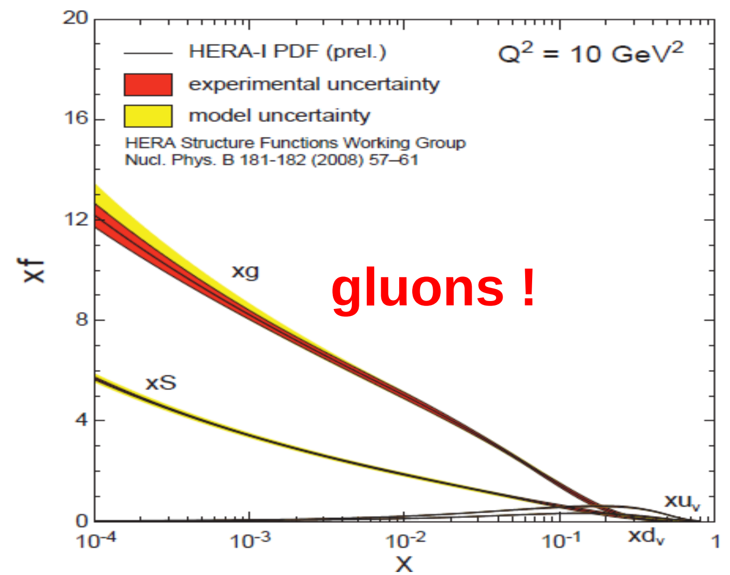
- pQCD (mini)jet production x-section is bigger than total inel p-p x-section for p_{Tmin}~ 5-7 GeV at the LHC !

$$\sigma_{\rm hard}(p_{\perp\rm min}) = \int_{p^2_{\perp\rm min}}^{s/4} \frac{d\sigma}{dp^2_\perp}\, dp^2_\perp$$

... Why this happens ?



- Very high gluon densities at small-x:



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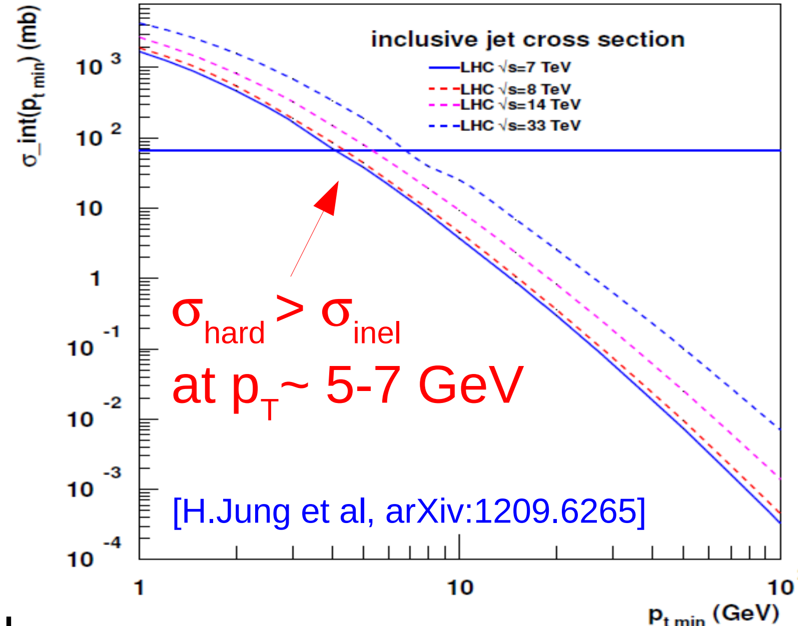
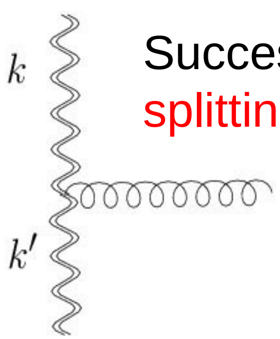
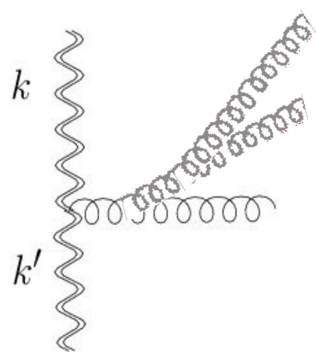
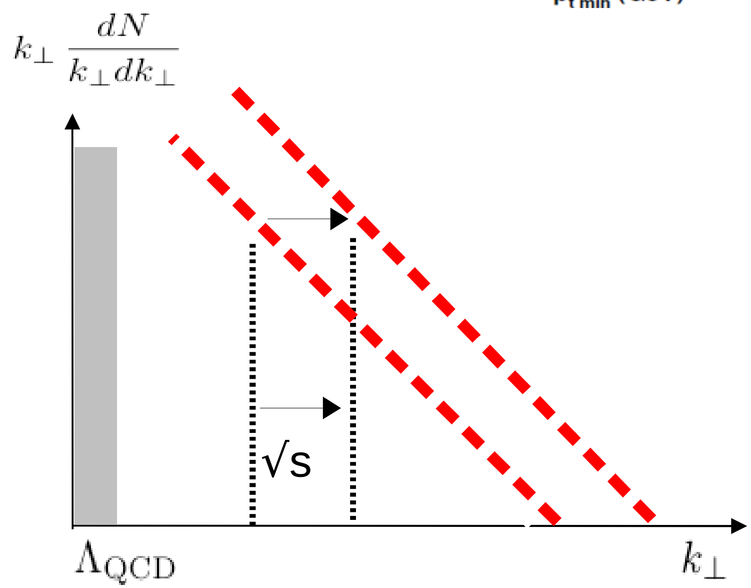


- Very high gluon densities at small-x due to "Malthusian" growth of radiated gluons in linear DGLAP evolution:



Successive parton splitting/branching





Unitarity of pQCD x-sections: gluon saturation

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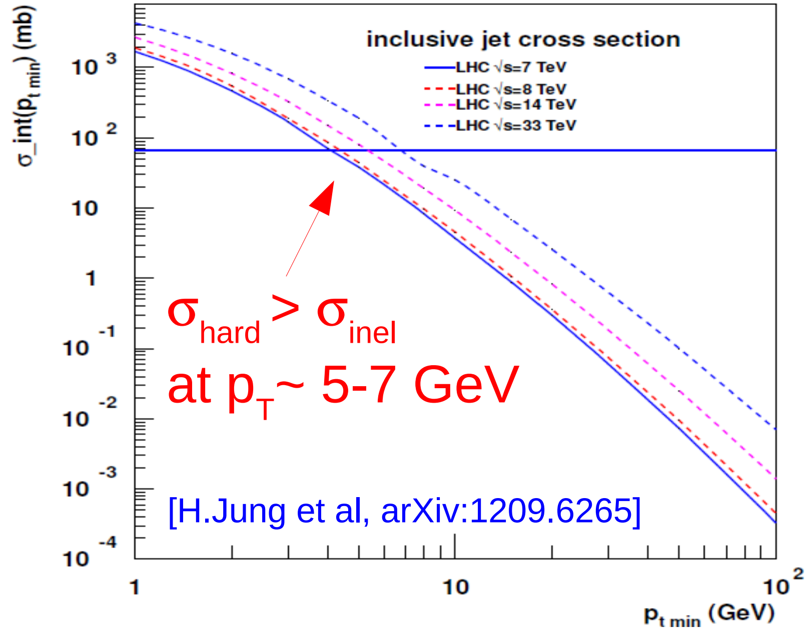
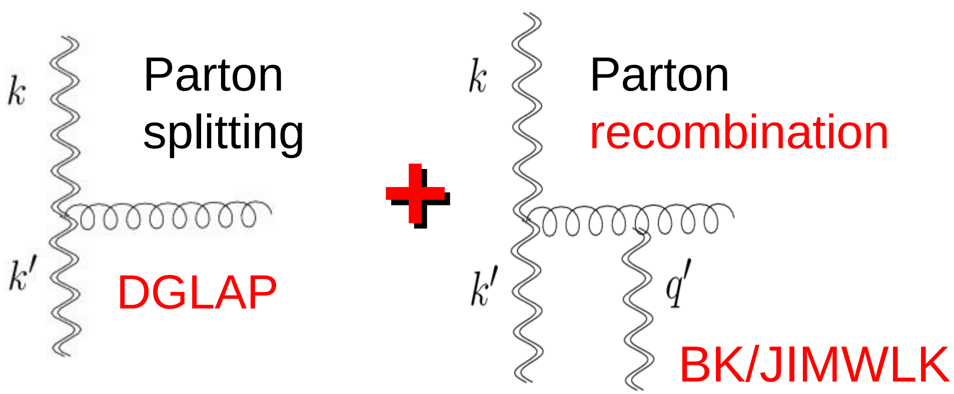
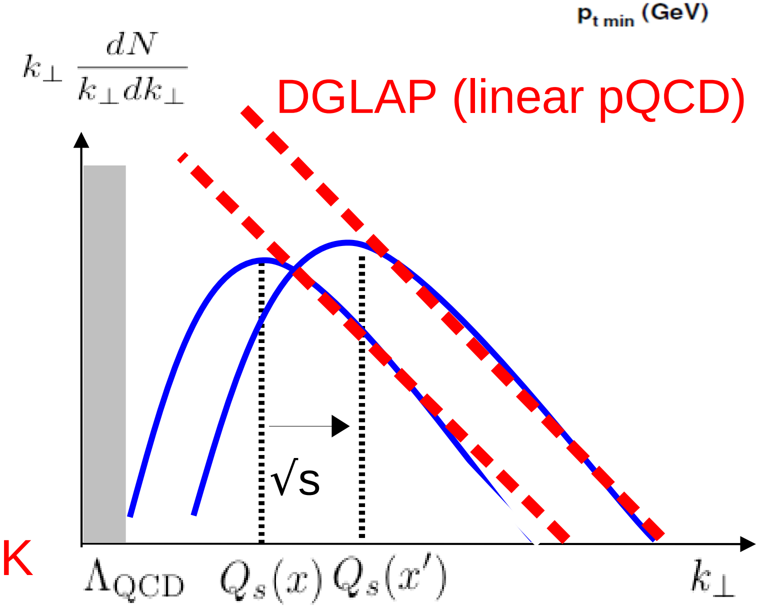


- Very high gluon densities at small-x.
- Solution (1): Gluon saturation
  - Add non-linear QCD evolution eqs.





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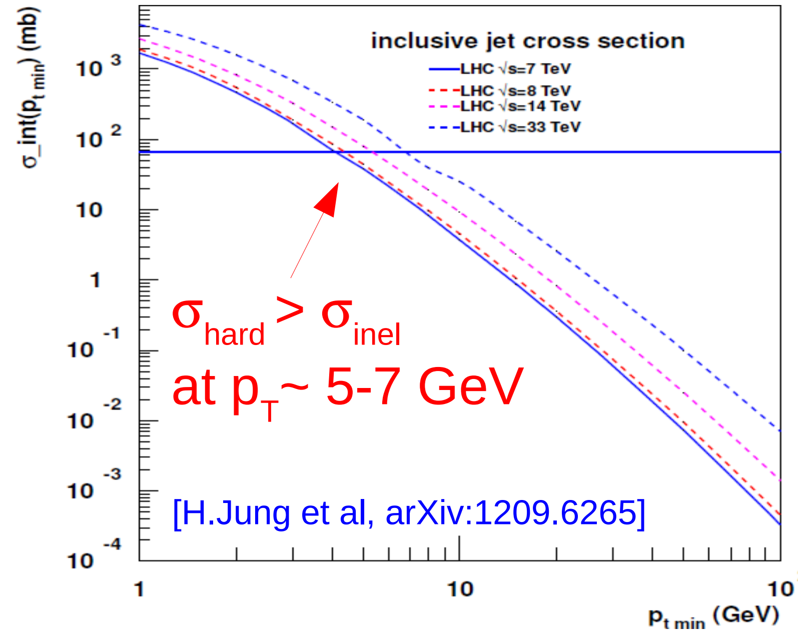
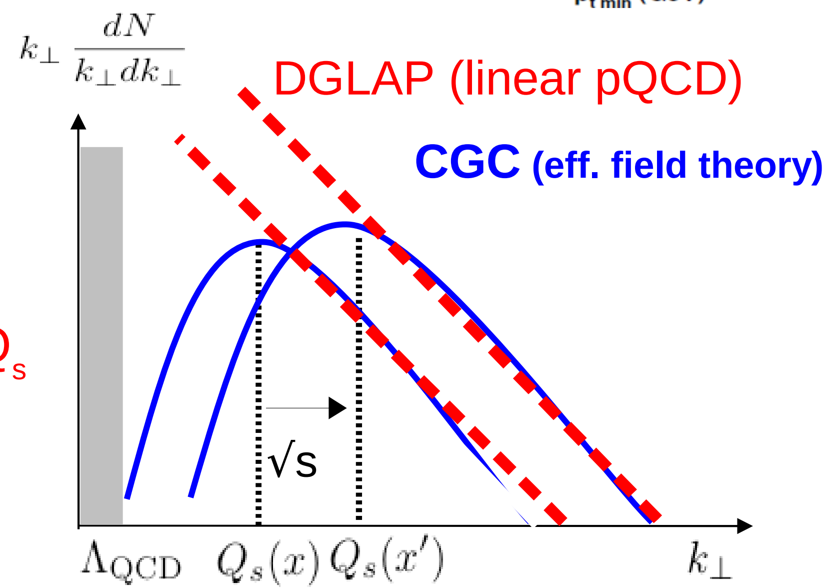


- Very high gluon densities at small-x.
- Solution (1): Gluon saturation
  - Add non-linear QCD evolution eqs.
  - Collinear factorization (leading-twist, incoherent parton scattering) invalid: CGC approach around “saturation scale” Q_s

$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2}$$ ~ 1 – 5 GeV²



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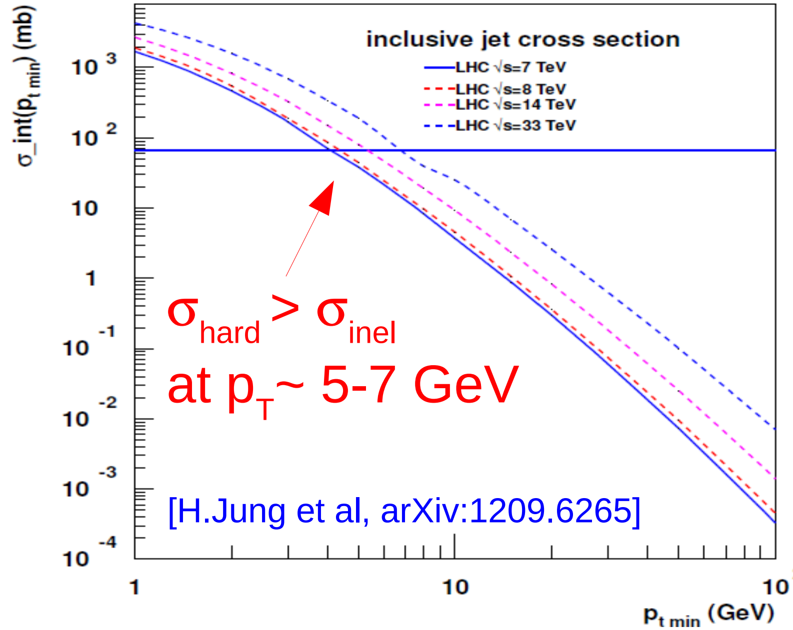
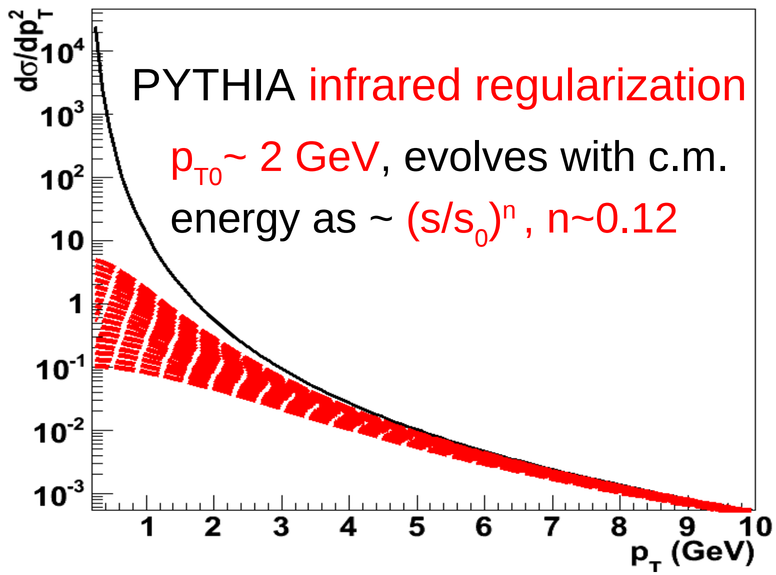


- Very high gluon densities at small-x.
- Solution (1): Gluon saturation around perturbative "saturation scale" Q_s:

$$Q^2_{\rm sat} \propto (1/x)^n \propto (\sqrt{s})^n$$

- Equivalent to (adhoc) PYTHIA p_T-cutoff:

$$\frac{d\hat\sigma}{dp^2_\perp} \propto \frac{\alpha_s^2(p^2_\perp)}{p^4_\perp} \to \frac{\alpha_s^2(p^2_{\perp 0}+p^2_\perp)}{(p^2_{\perp 0}+p^2_\perp)^2}$$



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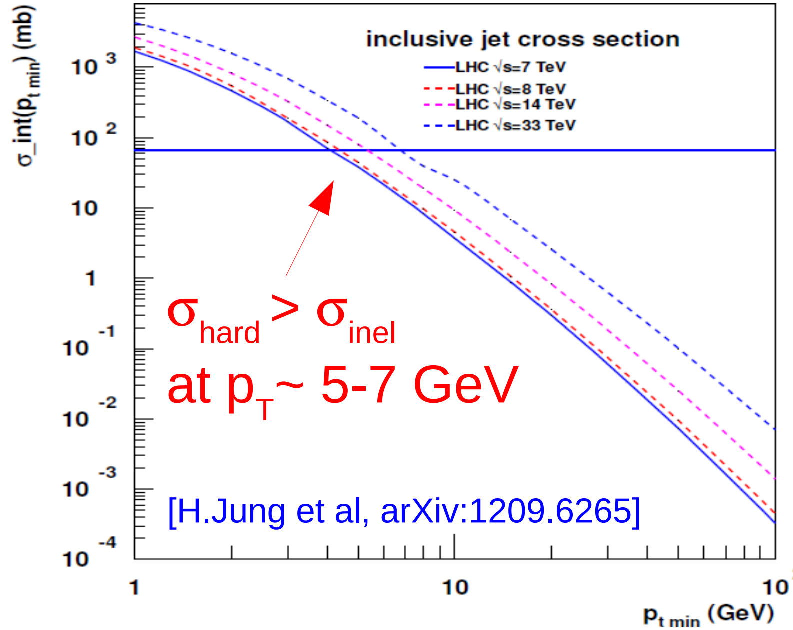
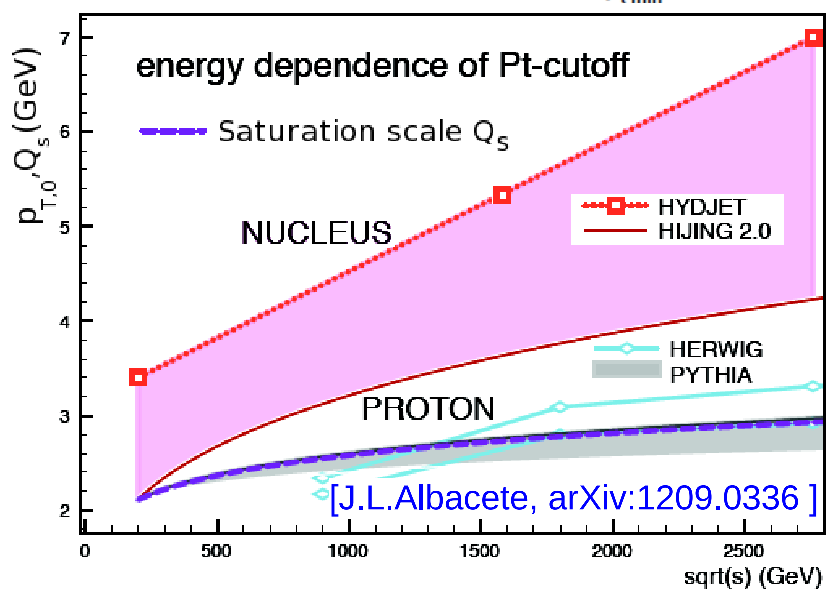


- Very high gluon densities at small-x.
- Solution (1): Gluon saturation around perturbative "saturation scale" Q_s:

$$p^2_{T0} \approx Q^2_{\rm sat} \propto (1/x)^n \propto (\sqrt{s})^n$$

- Enhanced in nuclei (larger g density):

$$Q_s^2 \sim A^{1/3} \sim 6\ (\mathrm{Pb}) \Rightarrow Q_s \sim 3 - 7\ \mathrm{GeV}$$

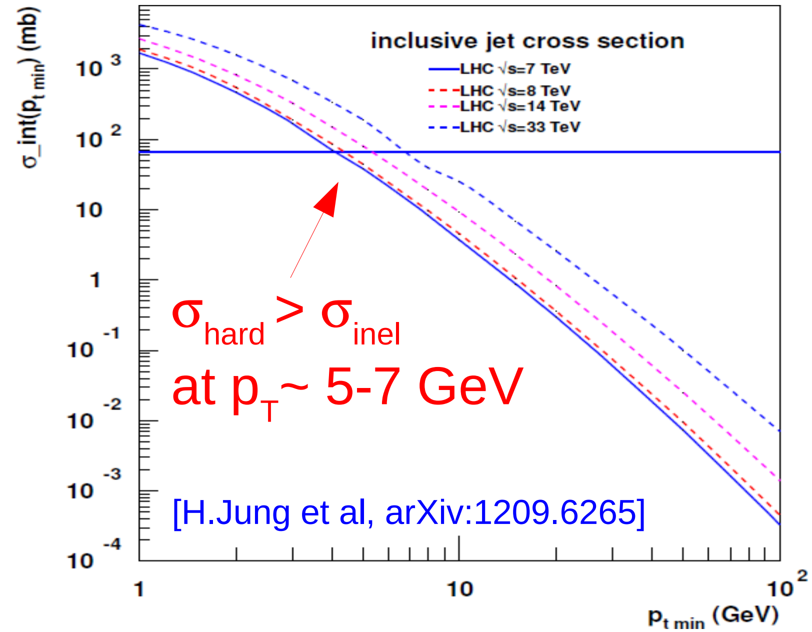


Unitarity of pQCD x-sections: MPI (p-p)

- pQCD (mini)jet production x-section is bigger than total inel p-p x-section for p_{Tmin} ~ 5-7 GeV at the LHC !

$$\sigma_{\mathrm{hard}}(p_{\perp\mathrm{min}}) = \int_{p^2_{\perp\mathrm{min}}}^{s/4} \frac{\mathrm{d}\sigma}{\mathrm{d}p^2_{\perp}}\,\mathrm{d}p^2_{\perp}$$

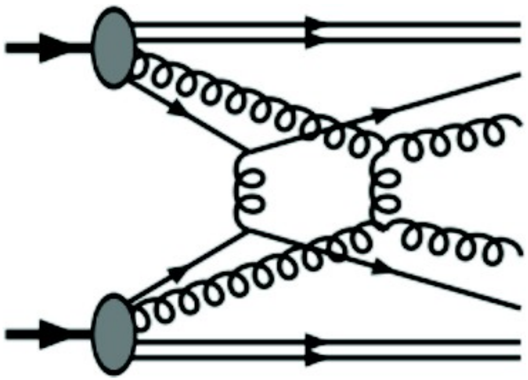
... Why this happens ?



- Very high gluon densities at small-x.
- Solution (2): Multi-parton interactions

Interpret $$\langle n \rangle = \frac{\sigma_{\mathrm{hard}}(p_{\perp\mathrm{min}})}{\sigma_{\mathrm{inel}}}$$

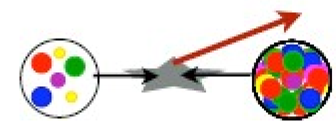
= average number of parton–parton scatterings above $p_{\perp min}$ in an event



- PYTHIA, HERWIG include them via transverse parton density profile.

Multi-parton interactions in proton-nucleus

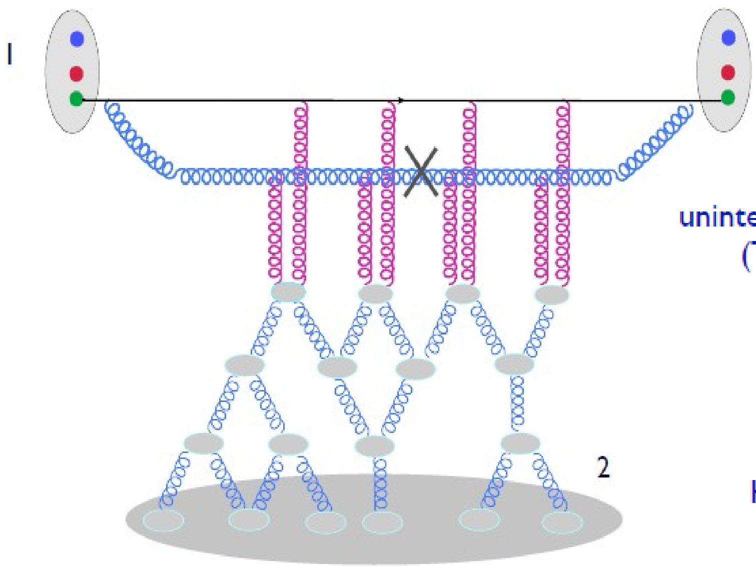
$$x_{1(2)} = \frac{k_t}{\sqrt{s}}\, e^{\pm y_h}$$



- MPIs are significantly enhanced in collisions with nuclei (larger transverse parton density)
- MPI naturally included in gluon-saturation models:

$Q_s^2 \sim A^{1/3} \Rightarrow$ Q_s (Pb)~ 3 – 7 GeV

$$\left.\frac{dN^{gluons}}{d\eta\, d^2b}\right|_{\eta=0} \propto Q_s^2(\sqrt{s}, b) \sim \sqrt{s}^{0.3}\, N_{part}$$



unintegrated gluon distribution: (The 2-point function)
$$\phi(x, k_t) \approx \frac{1}{N_c} \int d^2r\, e^{ik\cdot r} \langle tr(V(r)V^\dagger(0))\rangle_x$$

Kt-factorization: $x_1 \ll$
$$\frac{dN^g}{dy_h d^2k_t} \approx \frac{\alpha_s C_F}{k_t^2}\, \phi_p(x_1, k_t) \otimes \phi_A(x_2, k_t)$$

Hybrid formalism: $x_1 \gg$
$$\frac{dN^g}{dy_h d^2k_t} \approx xq(x_1, k_\perp) \otimes \phi_A(x_2, k_t)$$

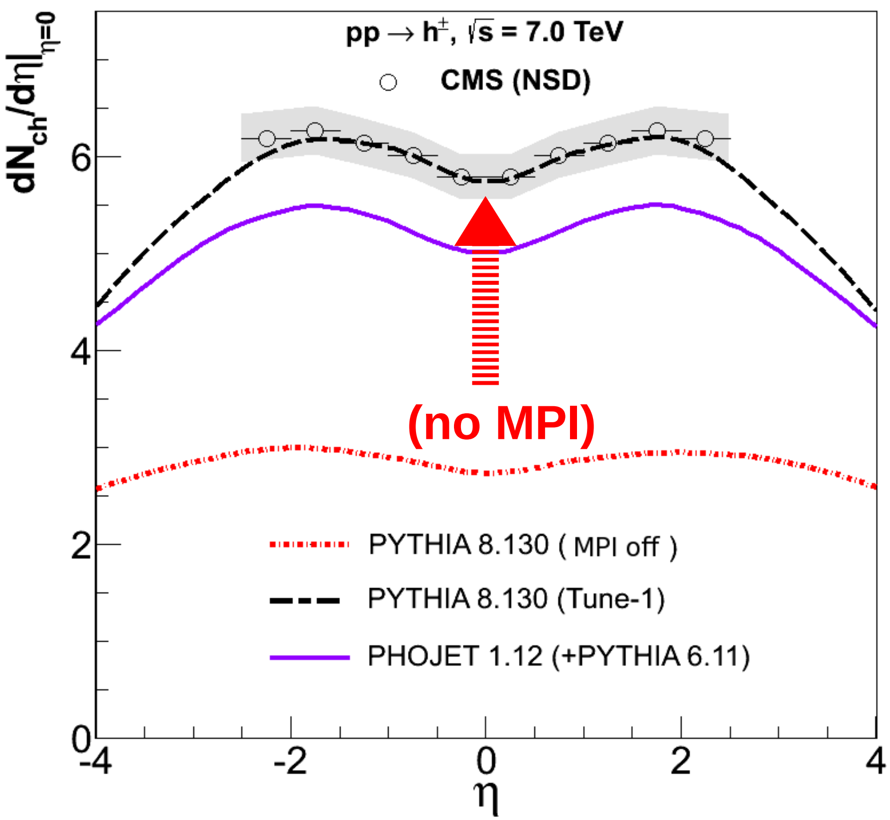
Note: multi-(cut)Pomeron scatterings included also in RFT MCs.

Multiparton interactions:
LHC experimental evidences

MPI evidence (LHC): p-p inclusive hadron prod.

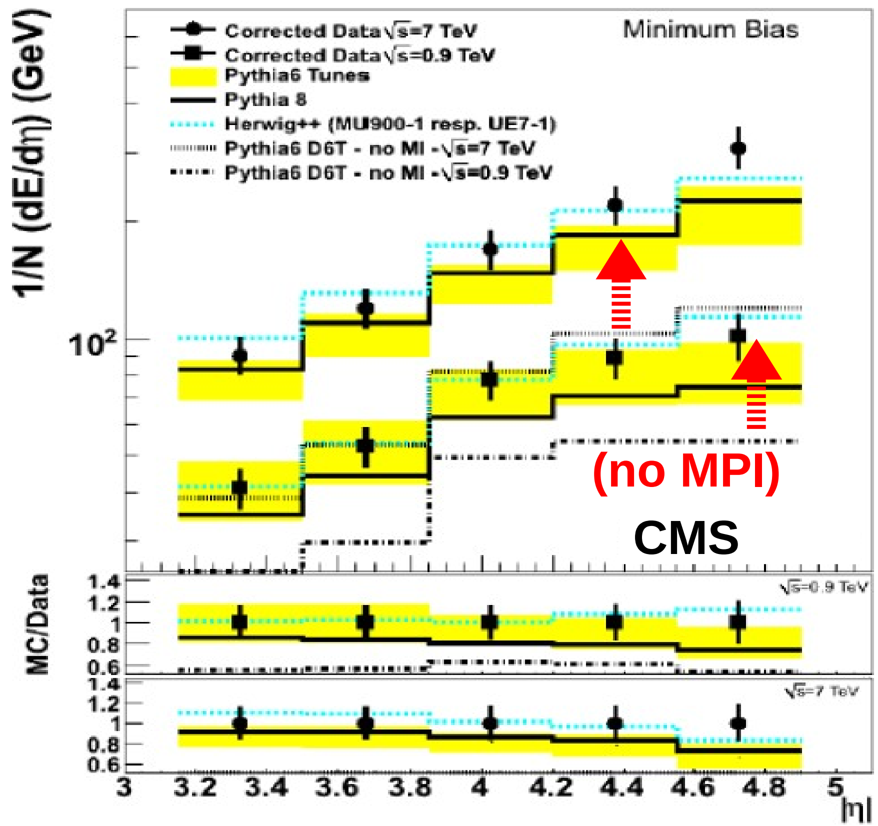
- MPI contributions are unavoidable in MCs to describe total inclusive hadron production in "minimum bias" p-p collisions:

Central particle densities:



CMS data: PRL 105 (2010) 022002
MCs: DdE et al. Astropart. Phys. 35 (2011) 98

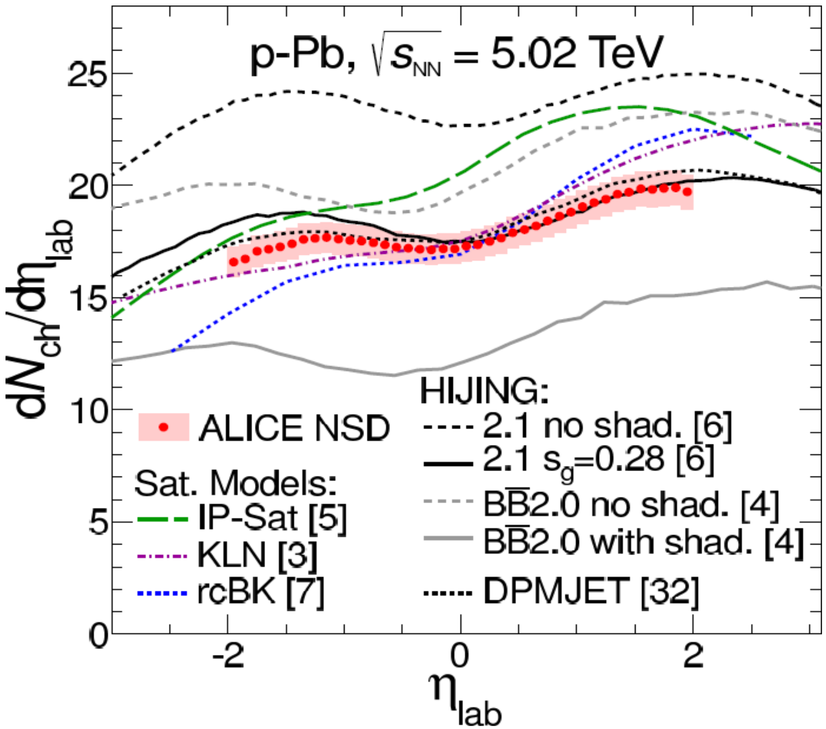
Forward energy flow:



CMS, JHEP 1111 (2011) 148

MPI evidence (LHC): p-Pb inclusive hadron prod.

[ALICE, arXiv:1210.3615]



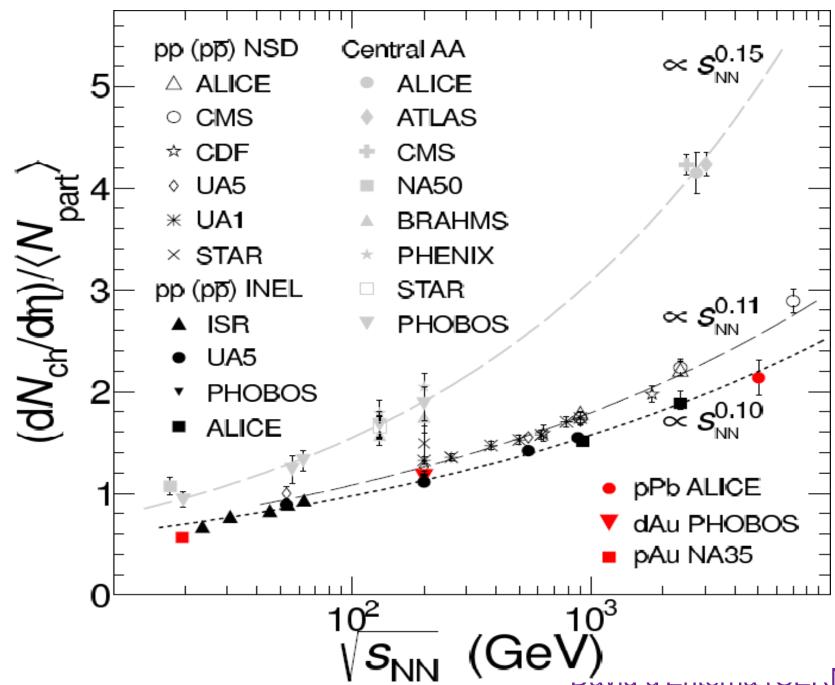
- Inclusive hadron production in p-Pb at 5.02 TeV:

  Models including shadowing/ saturation of Pb gluon PDF reproduce better the data

- Center-of-mass dependence:

  Power-law exponent: n~0.10

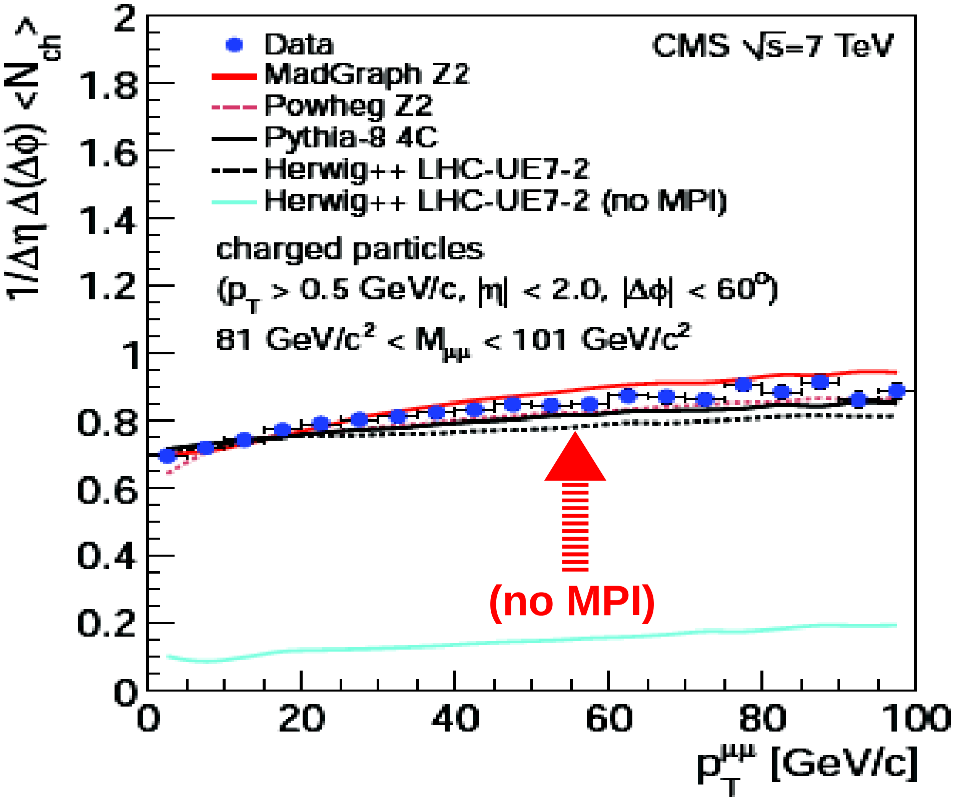
  Naive expectations:
  Gluon sat: n~0.11-0.14
  Pure RFT: n~0.1
  Minijets: n~0.15



MPI evidence (LHC): p-p underlying event

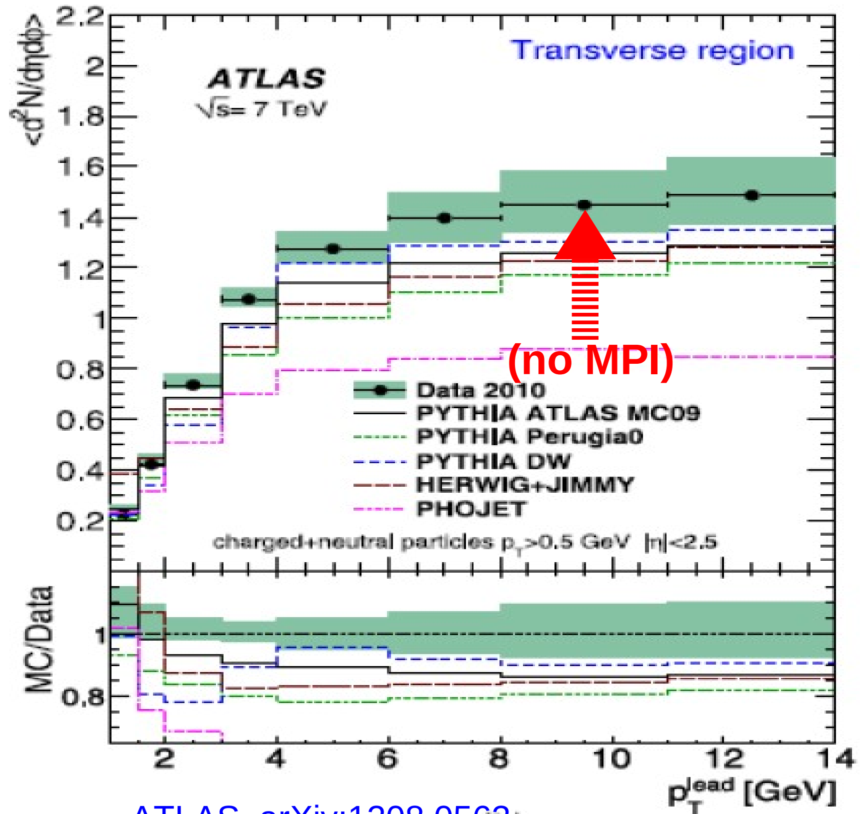
- MPI contributions are unavoidable in MCs to describe characteristics of underlying event in p-p hard scatterings:

"towards" particle density in DY events:



CMS, arXiv:1204.1411

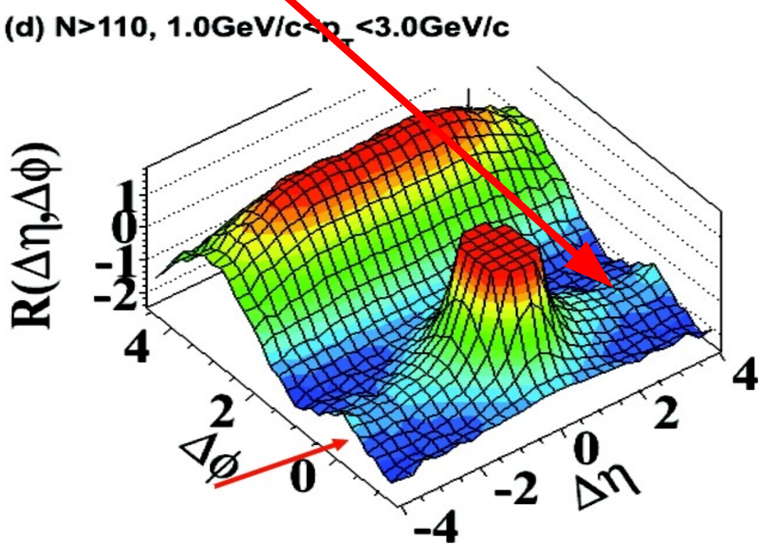
transverse energy in jet events:



ATLAS, arXiv:1208.0563

MPI evidence (LHC): “ridge” in central p-p ?

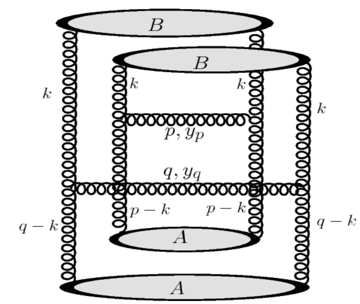
- Observation of long-range (over Δη~8 !) near-side hadron correlations:
  “Ridge” in “central” (high multiplicity) p-p collisions



[CMS, JHEP 1009 (2010) 091]

- Interpretations:
  - Correlated gluons in initial-state ?

$$|\mathbf{k}_\perp| \sim |\mathbf{p}_\perp - \mathbf{k}_\perp| \sim |\mathbf{q}_\perp \pm \mathbf{k}_\perp| \sim Q_s$$



Multi-parton-interactions: α_s^8 enhancement of near-side diagram

[R.Venugopalan et al.]

  - Final-state collective parton-flow ?
    PYTHIA + β_T=0.5 generates structure

- Remains an intriguingly large effect without explanation currently
- Measurement being repeated in CMS p-Pb at 5 TeV (pilot physics run)...

Double Parton Scatterings in p-p and p-Pb at the LHC

Double Parton Scattering x-sections (p-p)

[Treleani, Diehl, Ryskin, Snigirev, Blok, Strikman, Gaunt, ...]

- Hard DPS provides direct quantitative info on transverse parton-density profile & parton correlations in the proton.
- pQCD factorized expression for DPS x-section:

$$\sigma^{\rm DPS}_{(hh'\to ab)} = \left(\frac{m}{2}\right)\sum_{i,j,k,l}\int \Gamma^{ij}_{h}(x_1,x_2;\mathbf{b_1},\mathbf{b_2};Q_1^2,Q_2^2)\times\hat{\sigma}^{ik}_{a}(x_1,x_1',Q_1^2)\,\hat{\sigma}^{jl}_{b}(x_2,x_2',Q_2^2)$$
$$\times\Gamma^{kl}_{h'}(x_1',x_2';\mathbf{b_1}-\mathbf{b},\mathbf{b_2}-\mathbf{b};Q_1^2,Q_2^2)\,dx_1dx_2dx_1'dx_2'd^2b_1d^2b_2d^2b$$

double PDFs = f(x,Q^2,**b**)

- Assuming factorization of transverse & longitudinal components:

$$\Gamma^{ij}_{h}(x_1,x_2;\mathbf{b_1},\mathbf{b_2};Q_1^2,Q_2^2) = D^{ij}_{h}(x_1,x_2;Q_1^2,Q_2^2)\,f(\mathbf{b_1})f(\mathbf{b_2})$$

p-p overlap function: $t(\mathbf{b}) = \int f(\mathbf{b_1})f(\mathbf{b_1}-\mathbf{b})d^2b_1$

$$D^{ij}_{h}(x_1,x_2;Q_1^2,Q_2^2) = D^{i}_{h}(x_1;Q_1^2)\,D^{j}_{h}(x_2;Q_2^2)$$

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double PDFs = f(x,Q^2,**b**)

- DPS x-section commonly approximated by:

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

p-p overlap function

$$\sigma_{\rm eff} = \left[\int d^2b\,t^2(\mathbf{b})\right]^{-1} \approx 13\pm 2\ \ \text{mb}$$

ISR,SppS Tevatron

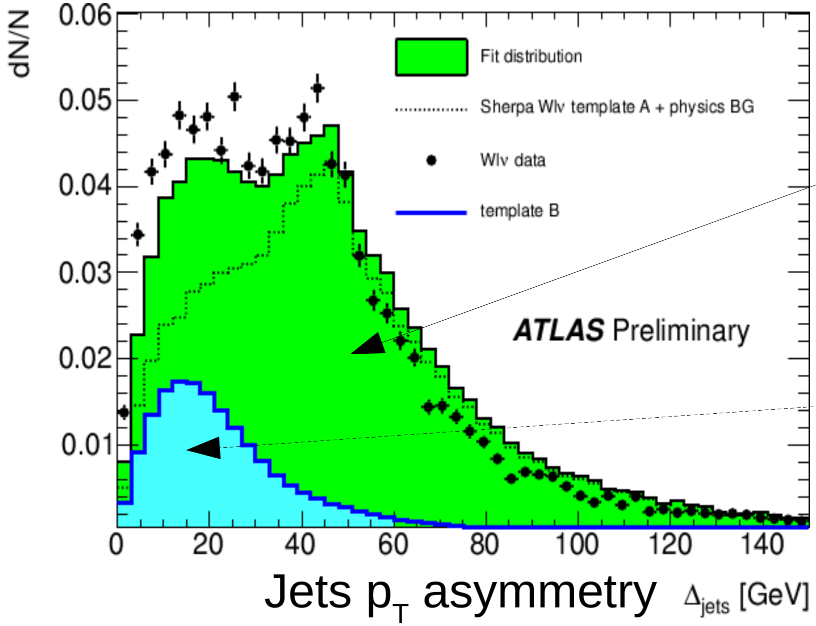
- Parton transverse profile in proton (CDF'97):

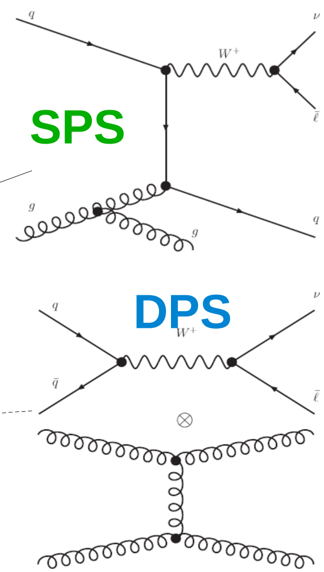
Effective DPS radius smaller than e.m. one

Model for density	Form of density, dN/d^3r	Predictions rms r	Predictions $\sigma_{\rm eff}$	Measurements Scale (fm)
Solid sphere	Constant, $r<r_p$	$\sqrt{3/5}r_p$	$4\pi r_p^2/4.6$	$r_p=0.73$
Gaussian	$e^{-r^2/2\Sigma^2}$	$\sqrt{3}\Sigma$	$4\pi\Sigma^2$	$\Sigma=0.34$
Exponential	$e^{-r/\lambda}$	$\sqrt{12}\lambda$	$35.5\lambda^2$	$\lambda=0.20$
Fermi, $\lambda/r_0=0.2$	$(e^{(r-r_0)/\lambda}+1)^{-1}$	$1.07r_0$	$4.6r_0^2$	$r_0=0.56$

DPS searches (LHC): p-p → W^{+}+2j, J/ΨJ/Ψ, ...

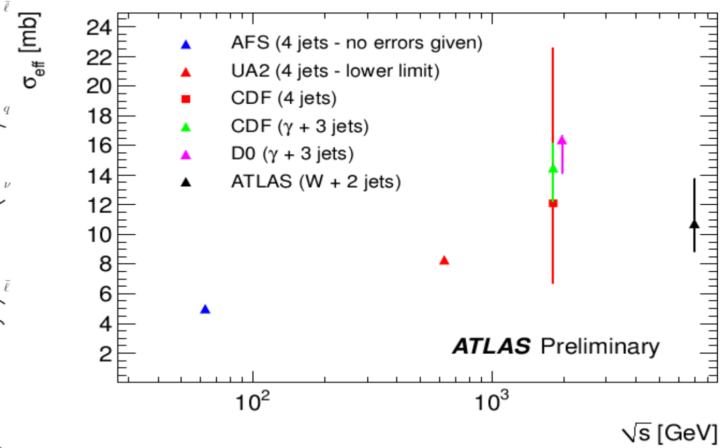
- Ongoing searches in W+2jets production ...

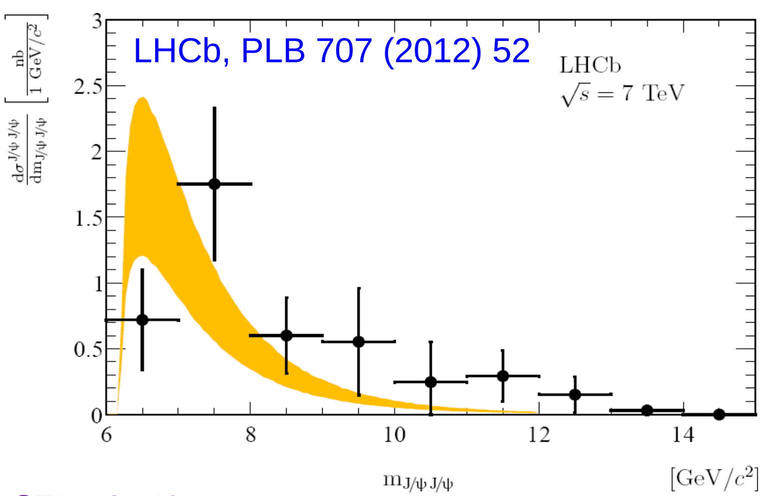




ATLAS-COM-CONF-2011-16

$\sigma_{eff} = 11 \pm 1\ ^{+3}_{-2}$ mb





- ... and double J/Ψ production:

  $\sigma_{J/\psi J/\psi}$ = 5.1±1.0± 1.1 nb

  $\sigma_{SPS}^{J/\psi J/\psi} + \sigma_{DPS}^{J/\psi J/\psi} \sim$ 4 nb + 2 nb = 6 nb

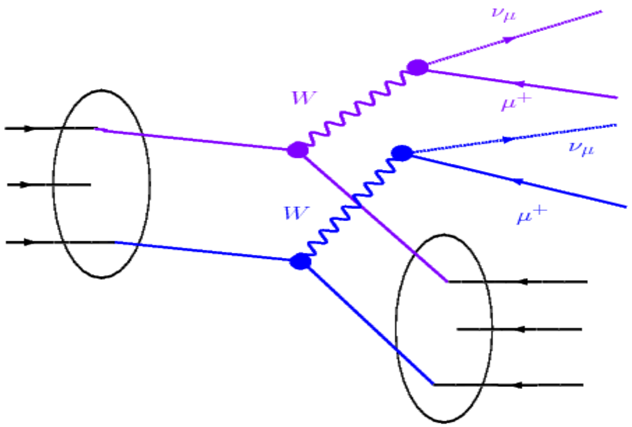
- Uncertainties on SPS (higher-order) contributions: No “smoking gun” of double hard parton-parton scattering, yet ...

DPS "golden channel" (LHC): p-p → W^+W^+, W^-W^-

[Kulesza, Stirling, Gaunt, Treleani, Del Fabbro, ...]

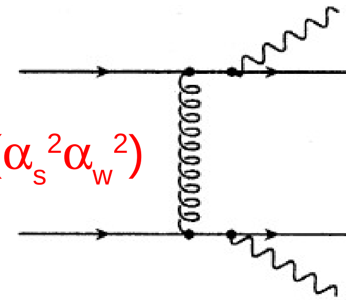
- Same-sign W-W production from 2 independent hard scatterings is an excellent DPS signature:

  - well controlled pQCD x-sections.
  - clean final-state:
    2 like-sign leptons + MET

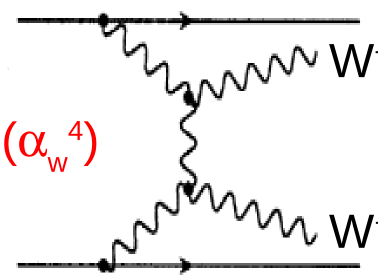


- Backgrounds: same-sign W-W production in single parton scatterings (SPS) occurs only with 2 extra jets:

QCD ($\alpha_s^2\alpha_w^2$)



EWK (α_w^4)

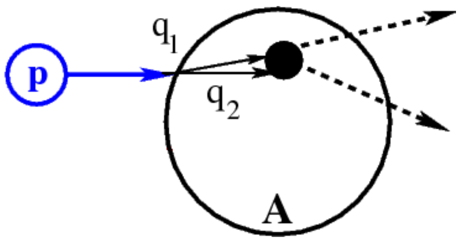


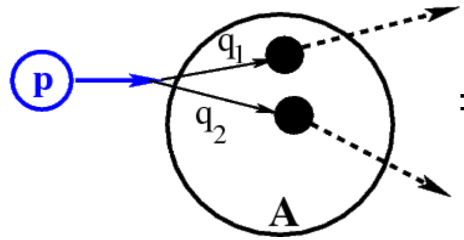
- σ(WW,DPS)~1/3 σ(WWjj,SPS), but SPS background reducible by more than x20 applying jet cuts.

Double Parton Scattering x-sections (p-Pb)

[Treleani, Strikman, , ...]
[DdE, Snigirev, in prep.]

- DPS x-section enhanced in proton-nucleus collisions:





$$\Rightarrow \sigma^{DPS}_{(pA)} = \sigma^{DPS,1}_{(pA)} + \sigma^{DPS,2}_{(pA)}$$

$$\sigma^{DPS,1}_{(pA\to ab)} = A \cdot \sigma^{DPS}_{(pN\to ab)} \qquad \sigma^{DPS,2}_{(pA\to ab)} = \sigma^{DPS}_{(pN\to ab)} \cdot \sigma_{\text{eff,pp}} \cdot F_{pA}$$

p-A overlap function

$$\text{with } F_{pA} = \int d^2r\, T^2_{pA}(\mathbf{r})$$

Pb Woods-Saxon density:
r=6.62 fm, a=0.546 fm

F_{pA}=30.4 mb^{-1}

- ► Factorized expression for DPS p-A x-section:

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

(p-Pb, 13±2mb)

$$\sigma_{\text{eff,pA}} = \frac{\sigma_{\text{eff,pp}}}{A + \sigma_{\text{eff,pp}} F_{pA}} = 21.5 \pm 1.1\ \mu b$$

- ► Ratio of DPS p-Pb/p-p x-sections: $\sigma_{\text{eff,pp}} / \sigma_{\text{eff,pA}} \approx 600$!

- DPS processes are large and can be unambiguously observed in p-A.
- Pb transverse density better known than proton: determine $\sigma_{\text{eff,pp}}$?

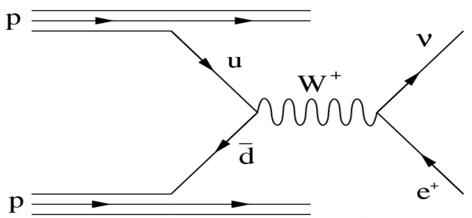
Case study: p-Pb → W^+W^+, W^-W^-

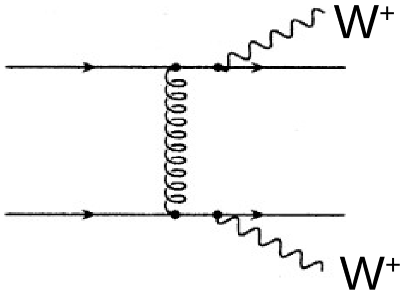
[DdE, Snigirev, in prep.]

■ Theoretical setup:

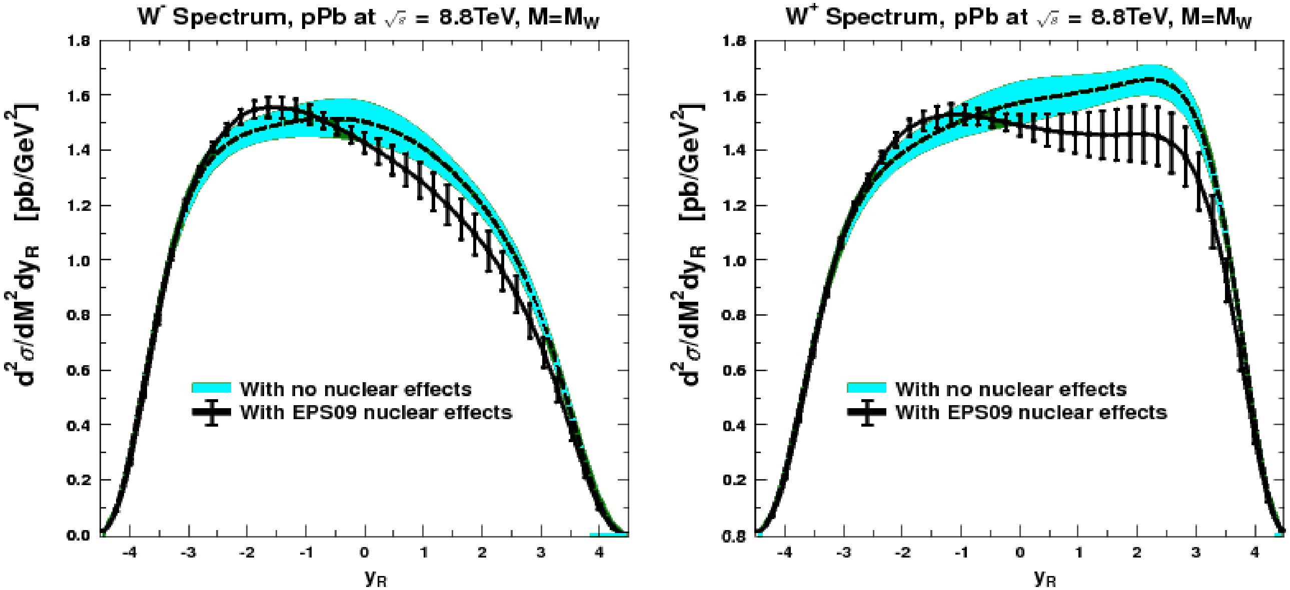
► MCFM 6.2: single-parton W^+,W^-
W^+W^+jj (QCD) background

- NLO accuracy.
- Scales: $\mu(W) = m_W$, $\mu(WW)$=150 GeV
- CT10 proton PDF, EPS09 Pb nuclear PDF:





~10% effects due nuclear (anti-)shadowing alone:



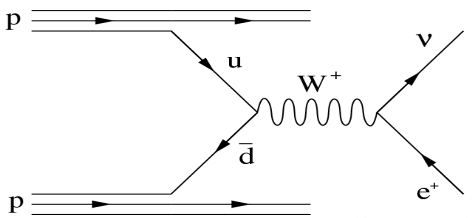
[Paukkunen&Salgado JHEP 1103 (2011) 071]

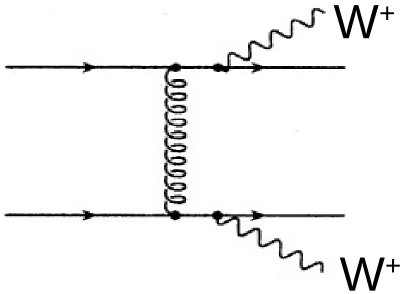
Isospin+shadow. effects on total inclusive x-sections:
W^- : +7%
W^+ : -15%
compared to p-p

Case study: p-Pb → W^+W^+, W^-W^-

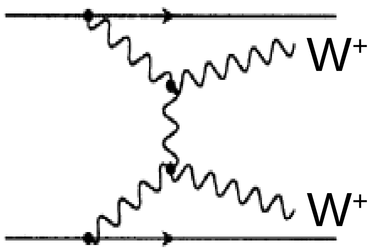
[DdE, Snigirev, in prep.]

- Theoretical setup:
  - MCFM 6.2: single-parton W^+,W^-
    W^+W^+jj (QCD) background
    - NLO accuracy.
    - Scales: $\mu(W) = m_W$, $\mu(WW)$=150 GeV
    - CT10 proton PDF, EPS09 Pb nPDF
    - Uncertainties: ~10% (W)





  - VBFNLO 2.6.0: W^+W^+jj (EWK) background
    - NLO accuracy
    - Scales: $\mu^2 = t_{W,Z}$
    - CT10 PDF
    - Uncertainties: <10%



- Results:

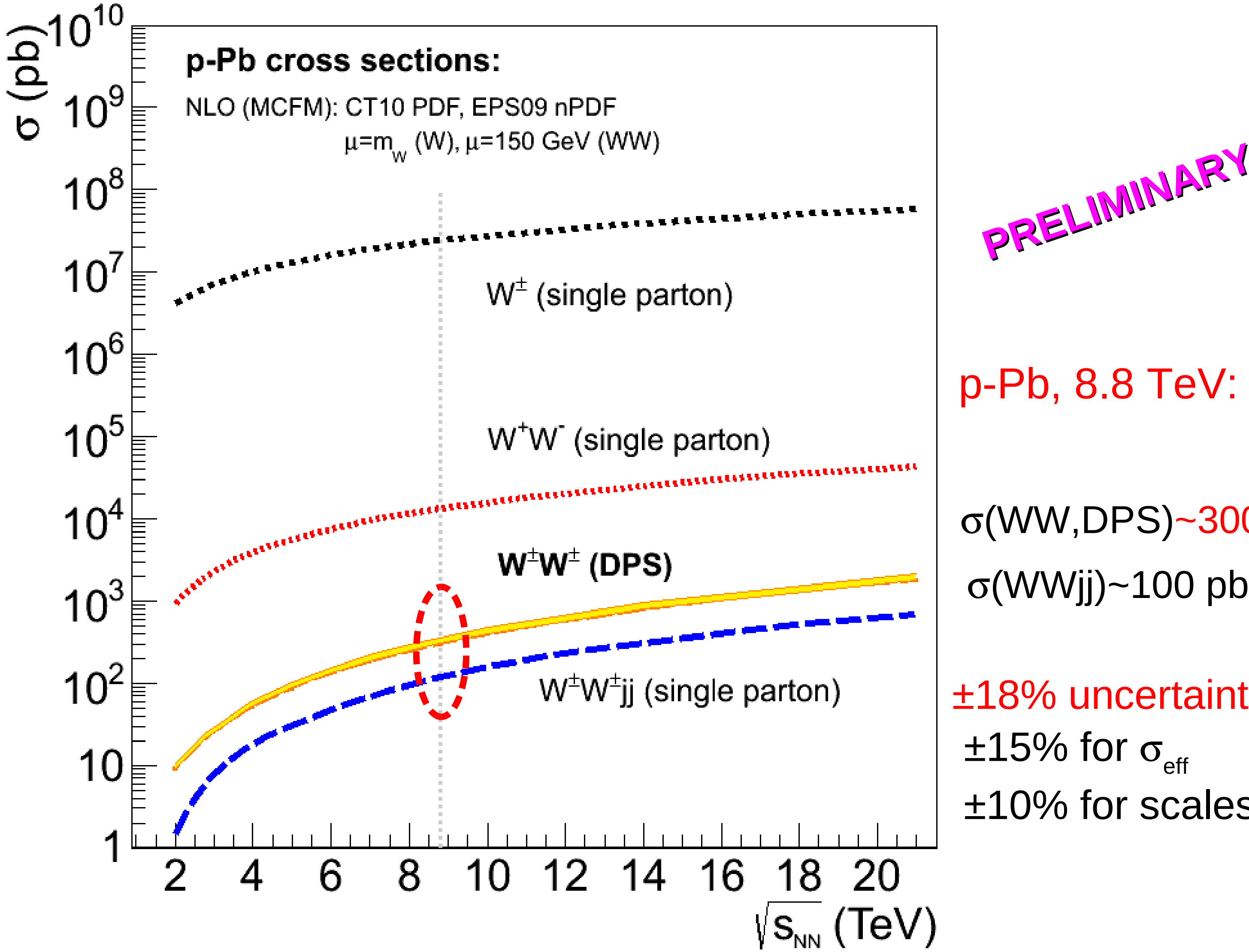
p-Pb final-state:	W^+	W^-	W^+W^-	W^+W^+jj (QCD)	$W^\pm W^\pm jj$ (VBF)	$W^\pm W^\pm$ (DPS)
Code (process #):	MCFM (1)	MCFM (6)	MCFM (61)	MCFM (251)	VBFNLO (250,260)	Eq. (15)
Order (σ units):	NLO (μb)	NLO (μb)	NLO (nb)	NLO' (pb)	NLO (pb)	NLO (pb)
$\sqrt{s_{NN}}$ = 5.0 TeV	6.85 ± 0.68	5.88 ± 0.59	5.48 ± 0.55	12.1 ± 1.2	12.4 ± 0.6	88. ± 16.
$\sqrt{s_{NN}}$ = 8.8 TeV	12.6 ± 1.3	11.1 ± 1.1	13.0 ± 1.3	40.4 ± 4.0	50.0 ± 2.0	303. ± 54.

PRELIMINARY

Results: p-Pb → W^+W^+, W^-W^-

[DdE, Snigirev, in prep.]

- Cross sections for all relevant SPS and DPS processes vs sqrt(s):



p-Pb, 8.8 TeV:

σ(WW,DPS)~300 pb

σ(WWjj)~100 pb

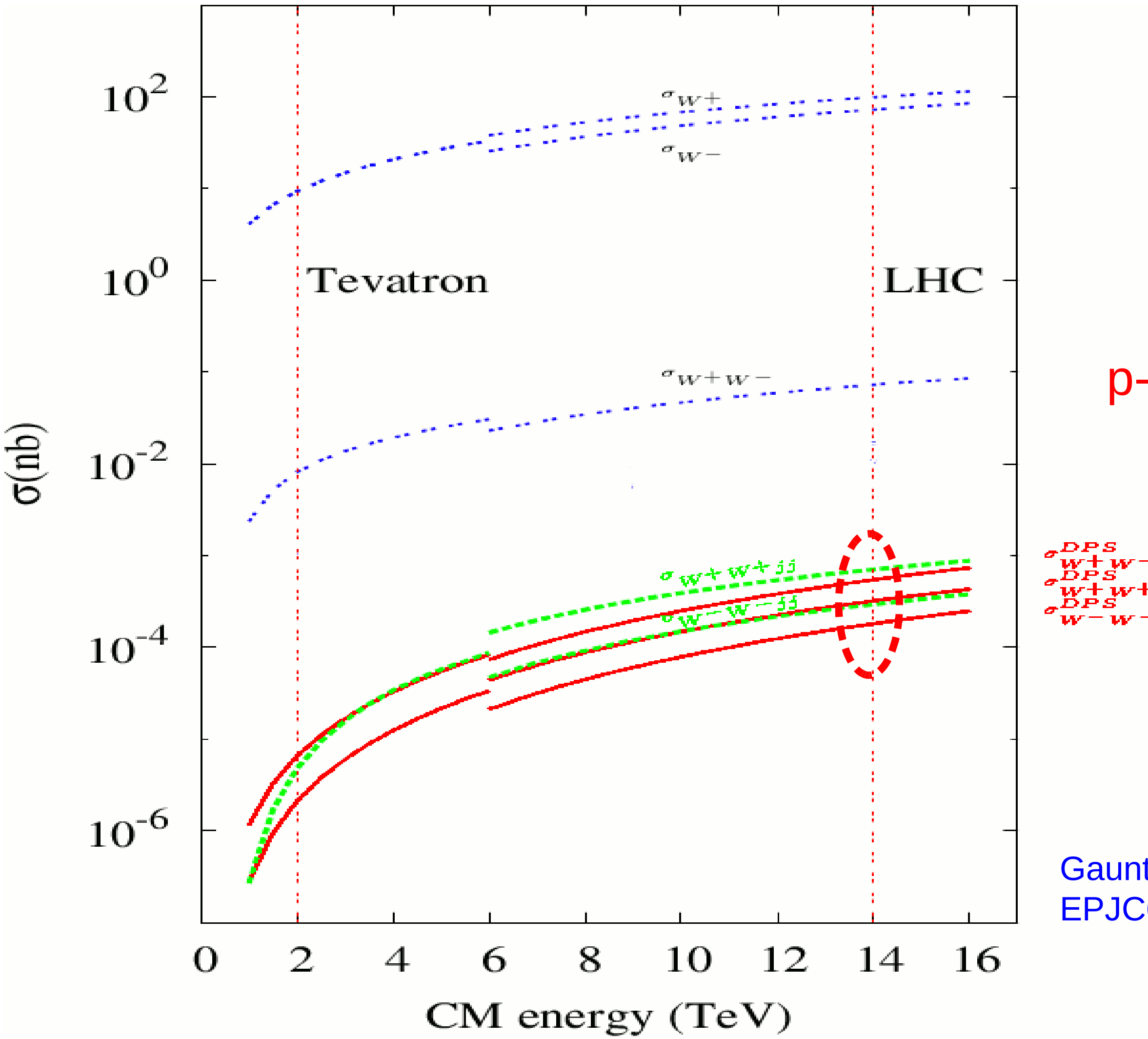
±18% uncertainties:

±15% for σ_{eff}

±10% for scales&PDFs

Compare to ... Results: p-p → W^+W^+, W^-W^-

- Cross sections for all relevant SPS and DPS processes vs sqrt(s):



p-p, 14 TeV:

σ(WW,DPS)~0.5 pb

σ(WWjj)~1 pb

Gaunt, Kulesza, Stirling, EPJC69 (2010) 53

Results: p-Pb → W^+W^+, W^-W^-

[DdE, Snigirev, in prep.]

- Measurable final-states:
  - ► W's branching ratios:
    - BR($W\rightarrow l\nu$) ~ 3 $\times$1/9, BR($W\rightarrow qq$) ~ 2/3
    - Both leptonic: 4 final-states ($\mu\mu$, ee, eμ, μe): $(4/9)^2$ ~ 1/20
    - 1 leptonic + 1 hadronic (jet-charge): $(2/9 \times 4/3)^2$ ~ 0.3
  - ► Typical ATLAS/CMS acceptances & efficiencies:
    - Leptons: |y|<2.5, p_T >15 GeV $\Rightarrow \varepsilon_{WW}$ ~ 40%
- LHC p-Pb luminosities:
  - ► $\mathcal{L}_{\rm int}$ = 0.2 – 2 pb^{-1} (increase to nominal p intensity, reduce beam size)
- Expected (purely leptonic) rates including yield loses & luminosity:

$$\mathcal{N} = \sigma^{\rm DPS}_{pPb\rightarrow WW}/(\varepsilon \cdot \mathcal{L}_{\rm int}) \approx$$ 2 – 20 same-sign WW pairs/year

(factor ~10 more in 1 lepton + 1-jet channel ?)

Summary

- MPI are an unavoidable consequence of:
  (i) extended nature of hadronic objects
  (ii) unitarity of perturbative QCD cross sections

- MPI are unavoidable to understand many LHC p-p measurements:
  (i) ~50% of inclusive particle production
  (ii) all details of underlying event in hard scatterings
  (iii) long-range "η ridge" in the near-side of trigger hadrons ?

- MPI ⇒ Double hard parton scatterings (existing pQCD description)
  Yet, no incontrovertible experimental proof of DPS observation ...

- DPS x-section in proton-nucleus collisions:

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

(p-Pb, 13±2 mb)

$$\sigma_{\rm eff,pA} = \frac{\sigma_{\rm eff,pp}}{A+\sigma_{\rm eff,pp}\,{\rm F}_{\rm pA}} = 21.5 \pm 1.1\ \mu{\rm b}$$

Enhanced DPS p-Pb x-sections: $\sigma_{\rm eff,pp}/\sigma_{\rm eff,pA} \approx 600$!

- DPS can be unambiguously observed in p-A (determine $\sigma_{\rm eff,pp}$?)
- Case study: p-Pb → W^+W^+, W^-W^- , NLO, nuclear PDFs
  σ(same-sign WW,DPS) ~ 300 pb (2 – 20 counts/year)

Backup slides