Review of QCD physics in LHC Run-1 [2010–2013]

Hirschegg 2014: Hadrons from Quarks and Gluons

13th January 2013

David d'Enterria (CERN)

Outline

- Introduction:
  - Studies of the SM and QCD at the LHC
- Perturbative QCD:
  - LHC extraction of PDFs via jets, isolated-γ, W,Z, top
  - LHC measurement of α_s at O(1-2 TeV)
- Semi-hard QCD:
  - LHC searches of gluon saturation & «beyond DGLAP» dynamics
  - LHC evidences for multi-parton-interactions & double-parton-scatterings
- Non-perturbative QCD:
  - LHC measurements of elastic & inelastic cross sections
  - Issues with hadronization & fragmentation functions
  - Impact on ultra-high-energy cosmic rays physics
- QCD matter:
  - «Ridge» in central p-p, perturbative probes (Υ, jets, isolated-γ, W,Z) of QGP
- Summary

Standard Model of particles & interactions

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu})$$

[Gauge interactions: $U_Y(1)$, $SU_L(2)$, $SU_c(3)$]

$$+(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}\nu_L\\ e_L\end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + (\text{h.c.})$$

[Lepton dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi}\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix}-e_L\\ \nu_L\end{pmatrix}\right]$$

[Lepton masses]

$$+(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix}u_L\\ d_L\end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + (\text{h.c.})$$

[Quark dynamics]

$$-\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi}\begin{pmatrix}u_L\\ d_L\end{pmatrix}\right] - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix}-d_L\\ u_L\end{pmatrix}\right]$$

[Quark masses]

$$+\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2.$$

[Higgs dynamics & mass]

- Gauge-fermion dynamics via covariant derivatives:

$$D_\mu\begin{pmatrix}\nu_L\\ e_L\end{pmatrix} = \left[\partial_\mu - \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}, \quad D_\mu\begin{pmatrix}u_L\\ d_L\end{pmatrix} = \left[\partial_\mu + \frac{ig_1}{6}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu + ig\mathbf{G}_\mu\right]\begin{pmatrix}u_L\\ d_L\end{pmatrix},$$

$$D_\mu\nu_R = \partial_\mu\nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1 B_\mu]\,e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R,$$

$$D_\mu\phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi.$$

- Gauge-boson field strength tensors:

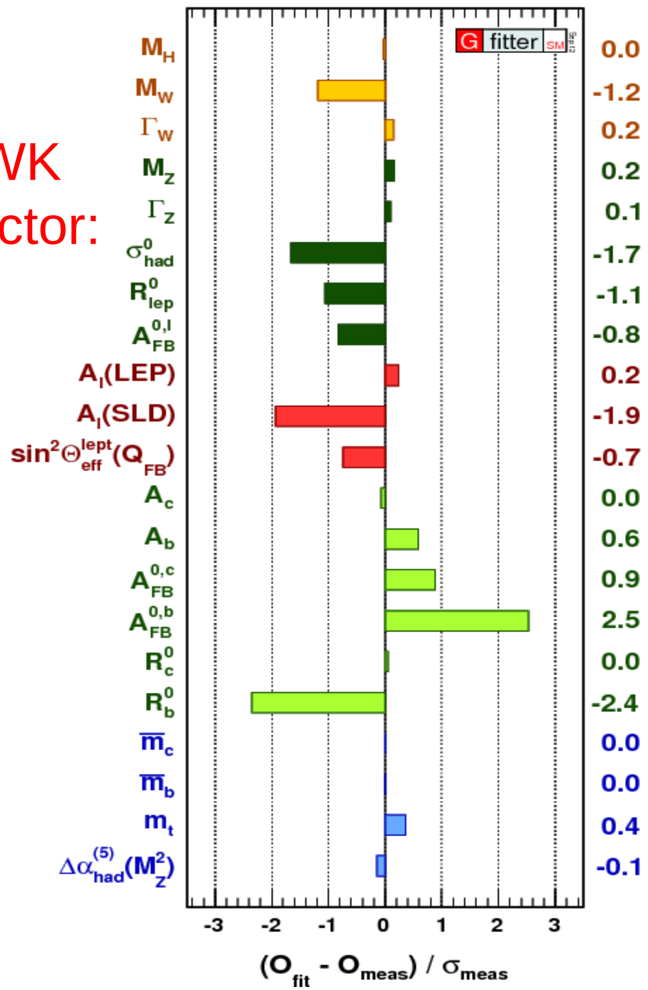
$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad \mathbf{W}_{\mu\nu} = \partial_\mu\mathbf{W}_\nu - \partial_\nu\mathbf{W}_\mu + ig_2(\mathbf{W}_\mu\mathbf{W}_\nu - \mathbf{W}_\nu\mathbf{W}_\mu)/2, \quad \mathbf{G}_{\mu\nu} = \partial_\mu\mathbf{G}_\nu - \partial_\nu\mathbf{G}_\mu + ig(\mathbf{G}_\mu\mathbf{G}_\nu - \mathbf{G}_\nu\mathbf{G}_\mu).$$

19 parameters: gauge couplings, H mass&vev, H-f Yukawa coupl., CKM mixings, CP phases

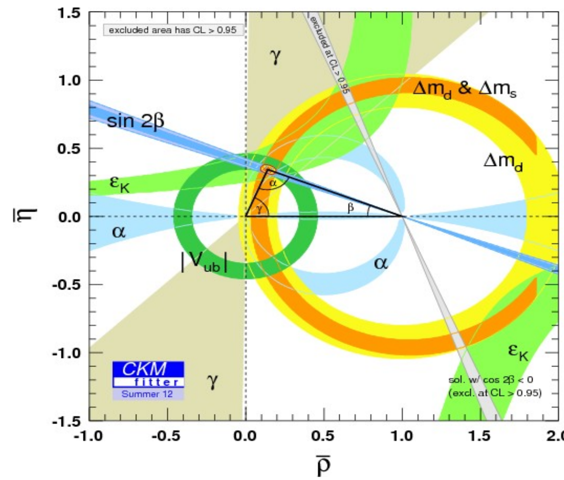
Standard Model of particles & interactions

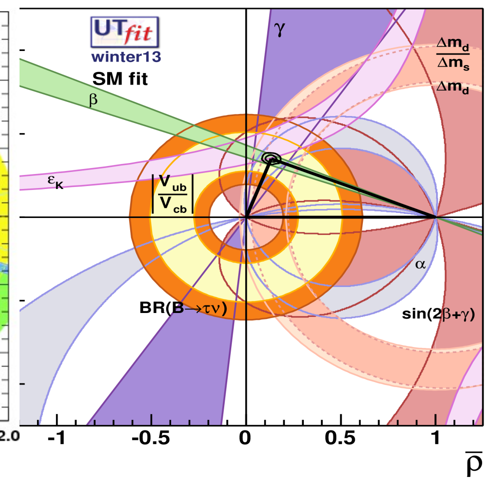
- SM: Renormalizatible QFT whose internal consistence & predictive power has been & is being experimentally confirmed to great precision:

EWK sector:

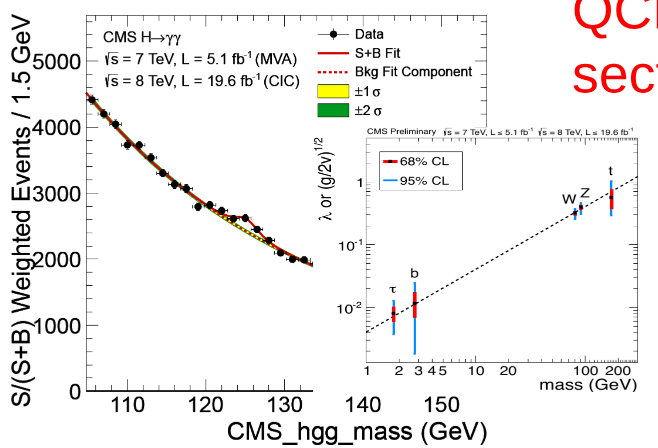


Flavour sector:

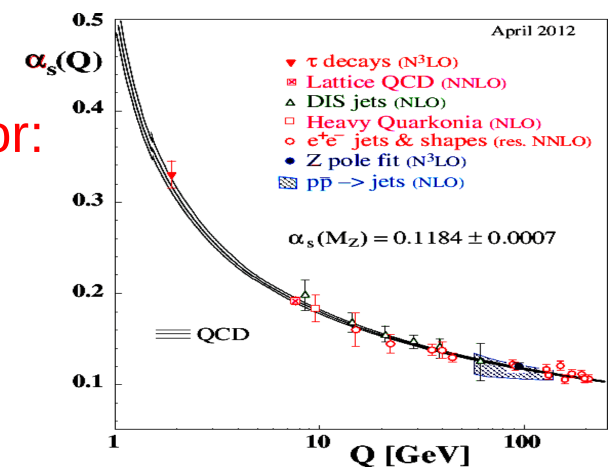




Higgs (2012!) sector:



QCD sector:



- Issues: matter-antimatter, ν masses, hierarchy (m_H unprotected), dark matter, gravity...

Quantum Chromodynamics

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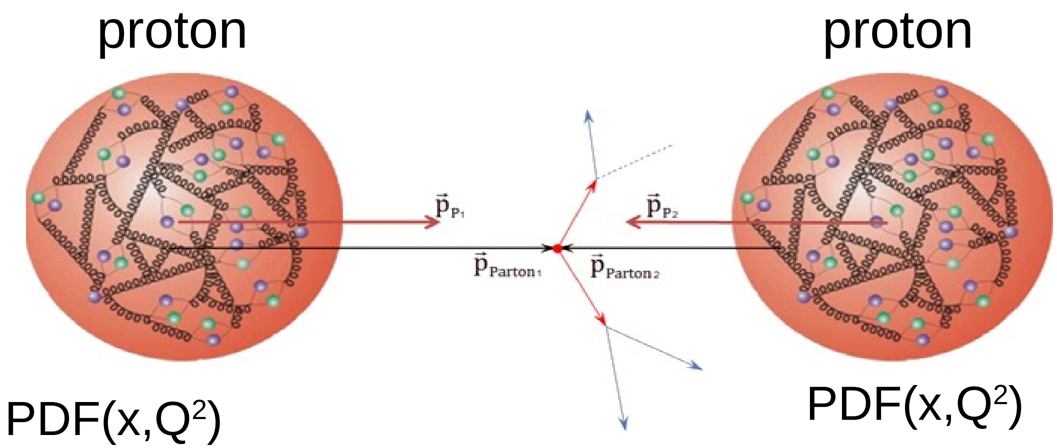
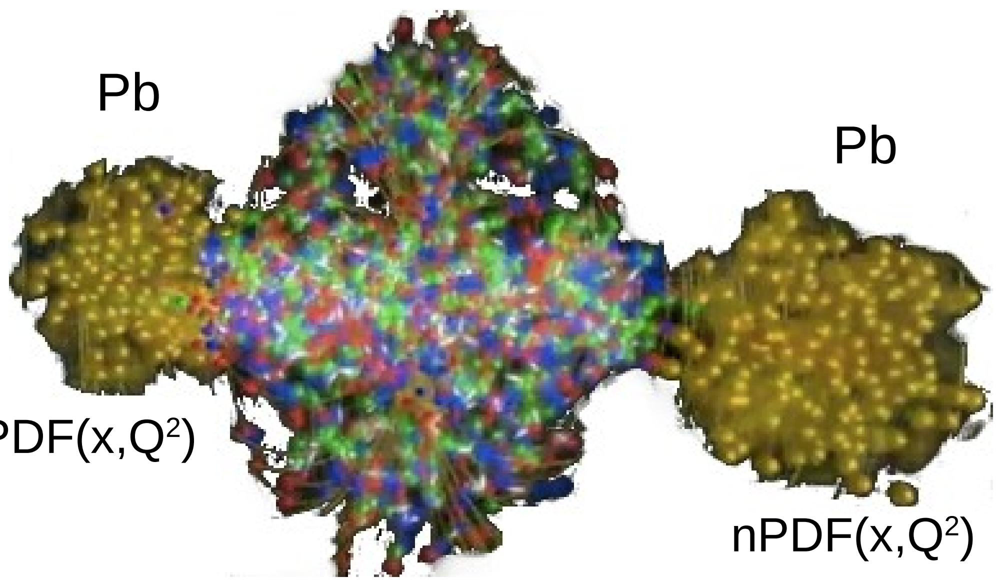
«Issues»: no CP-violation (axion?), confinement, non-perturbative structure/dynamics,...

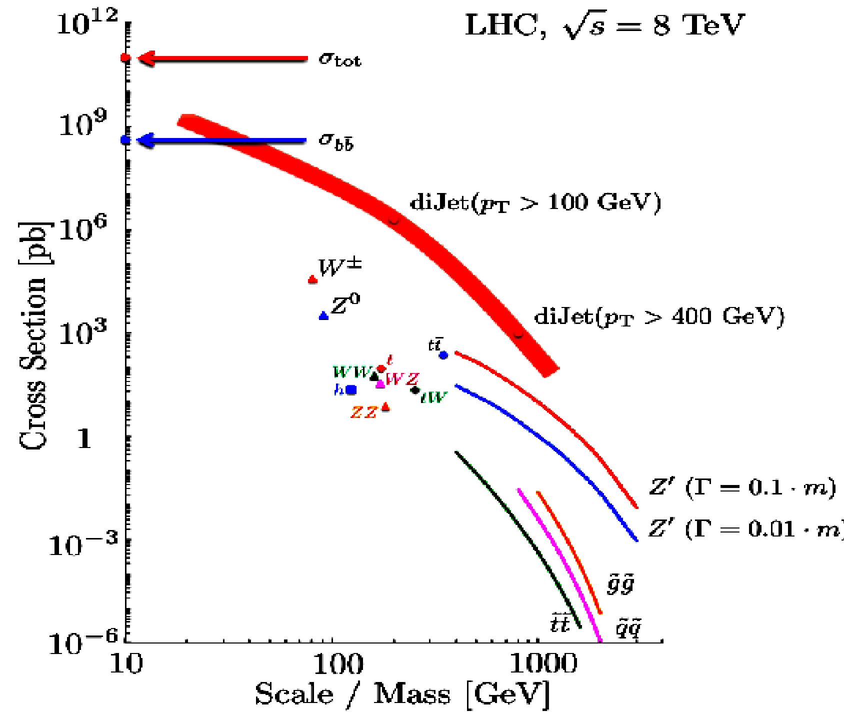
“All” LHC physics “is” QCD physics

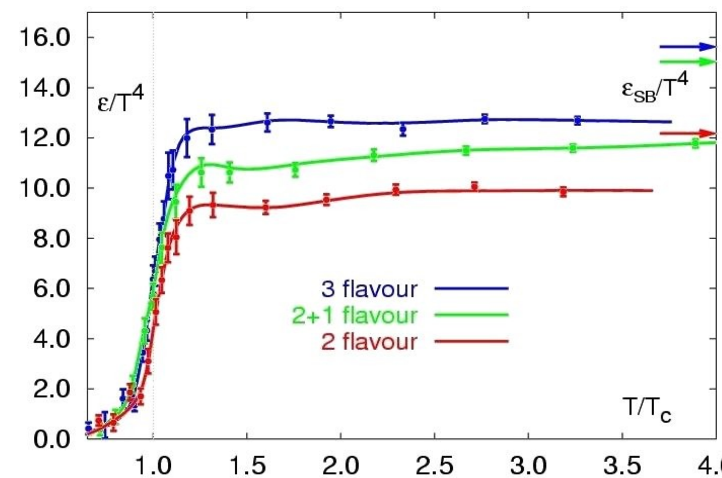


Precision SM & New physics searches



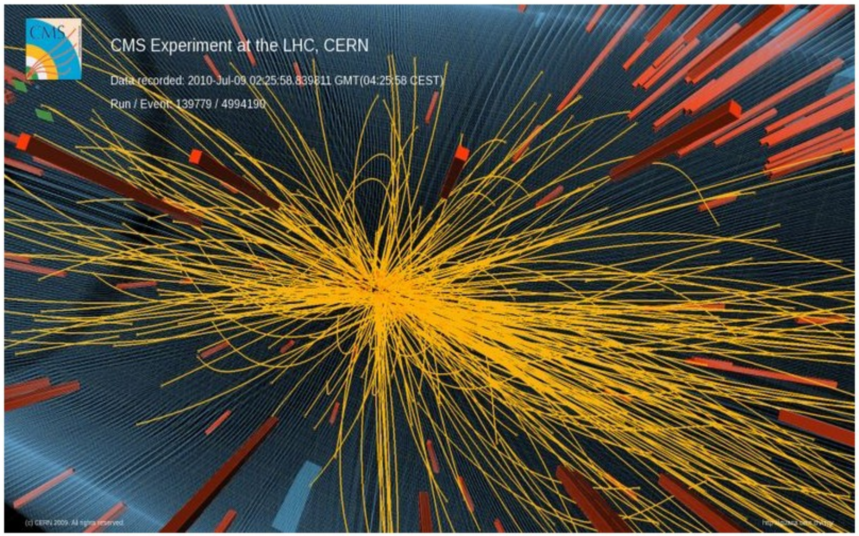
QGP, QCD thermodynamics



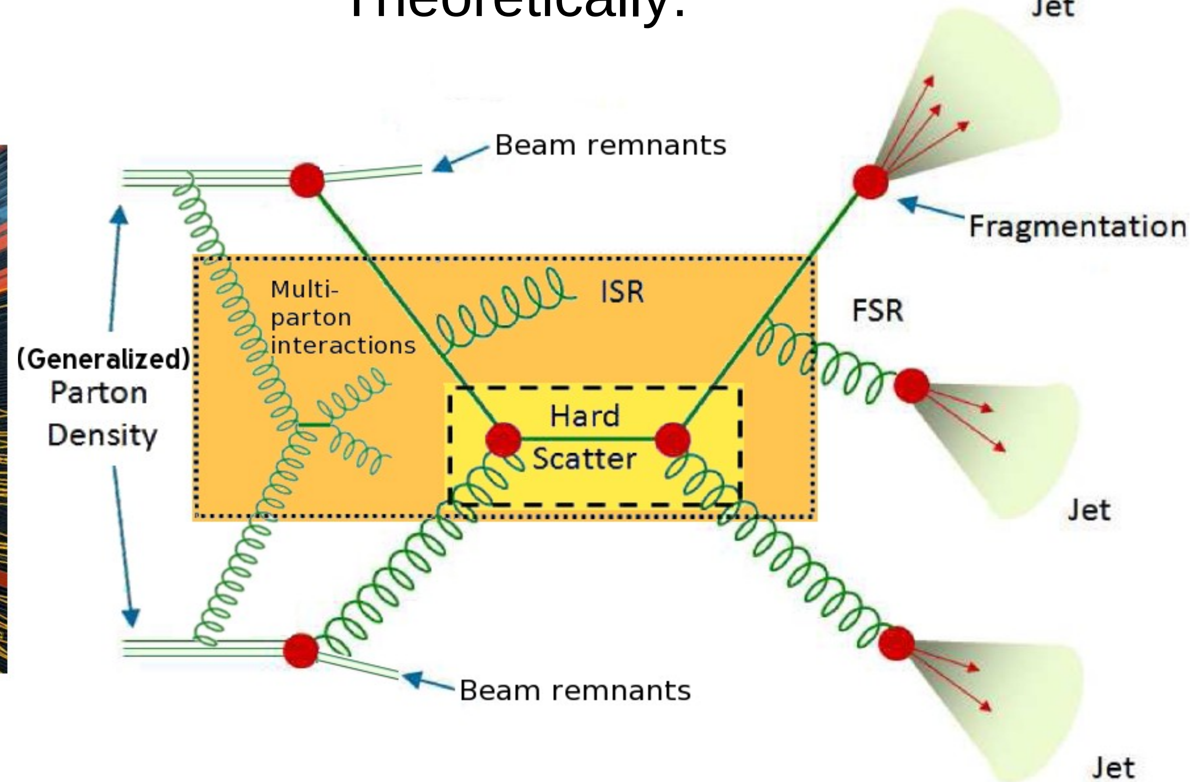


Typical p-p collision at the LHC

Experimentally:



Theoretically:



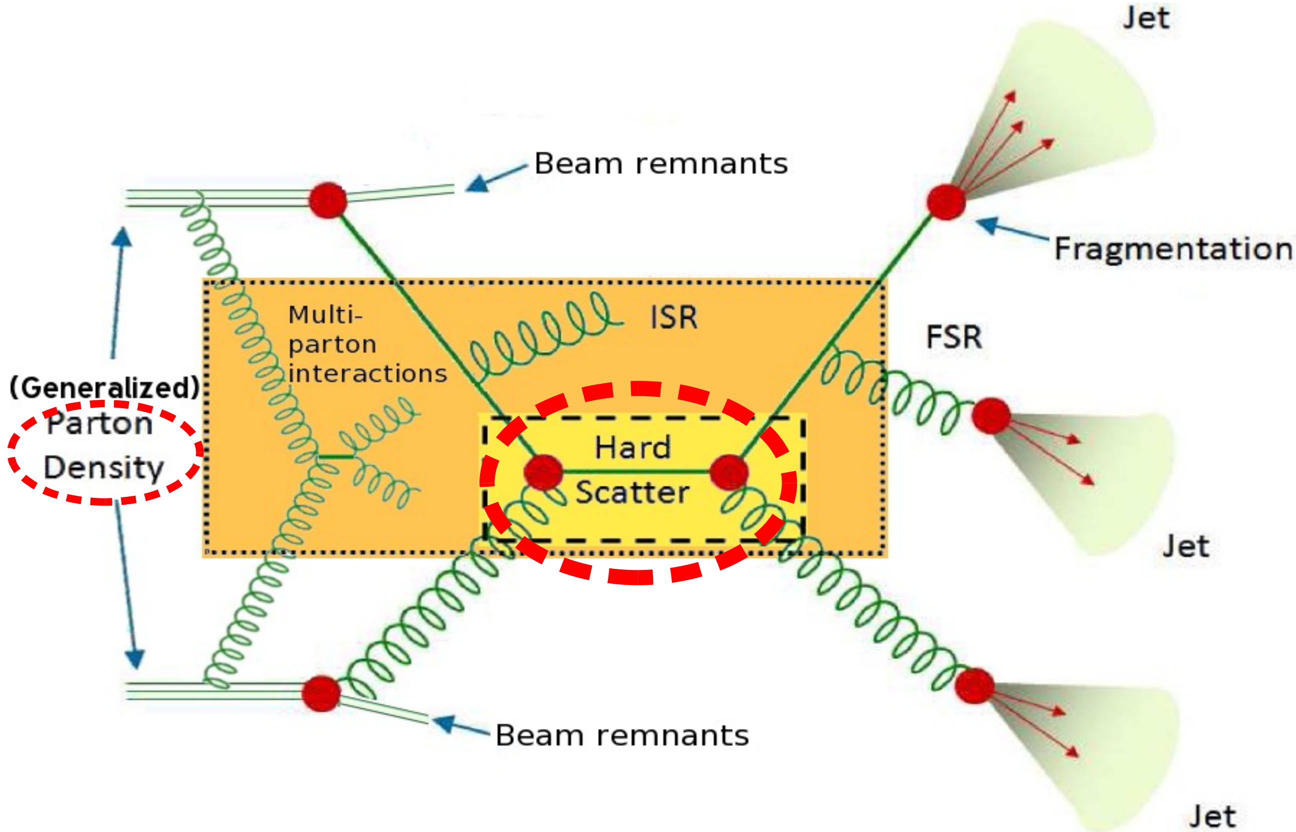
Full Quantum Cromodynamics at work !

(1) Perturbative: Matrix elements, evolution, resummations, PDFs

(2) Semi-hard: Gluon saturation, Multi-Parton Ints., Generalized PDFs

(3) Soft: Hadronization, beam-remnants, diffraction

Perturbative QCD at the LHC



Hard cross sections: pQCD factorization

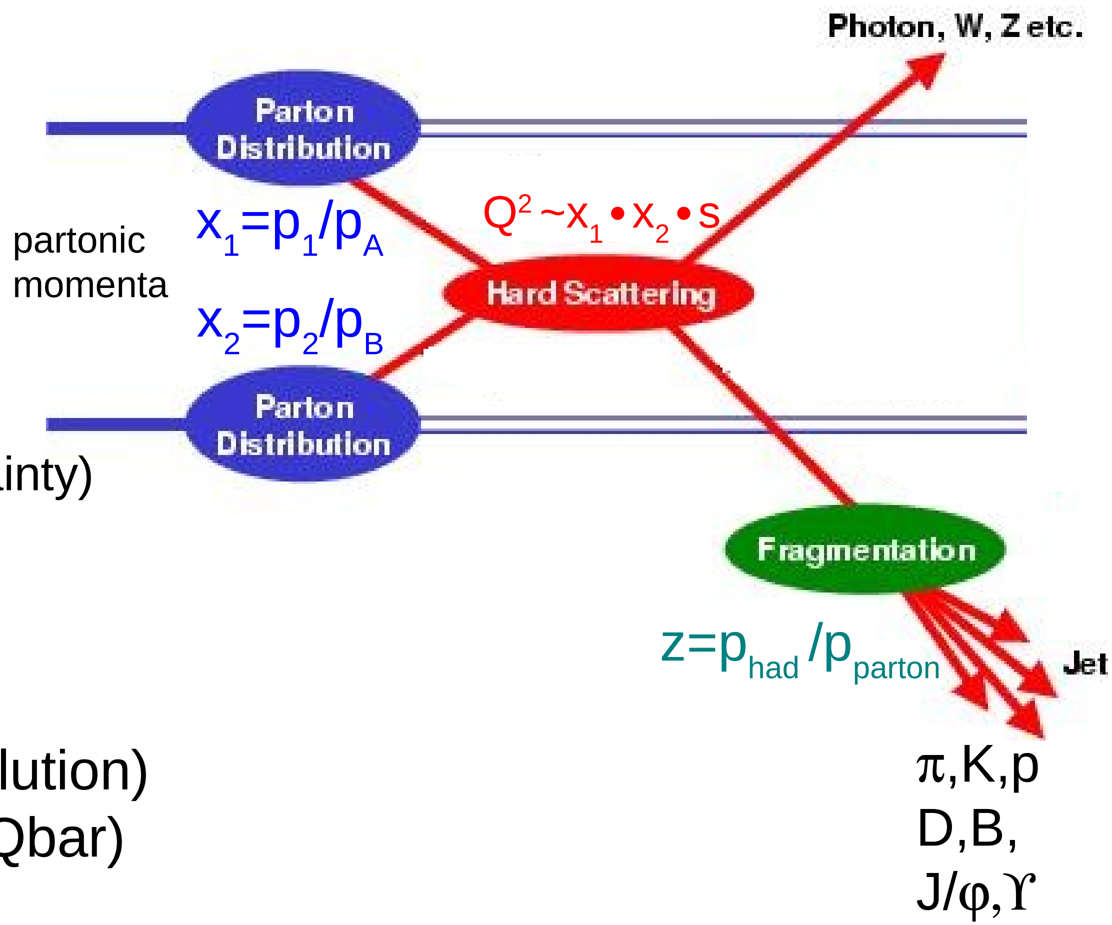
- Convolution of non-perturbative objects + parton-parton matrix elements:

$$\sigma^{AB\to h} = f_A(x_1,Q^2)\otimes f_B(x_2,Q^2)\otimes \sigma(x_1,x_2,Q^2)\otimes D_{i\to h}(z,Q^2)$$

- Initial state:
  Universal PDFs
  (+ DGLAP evolution)

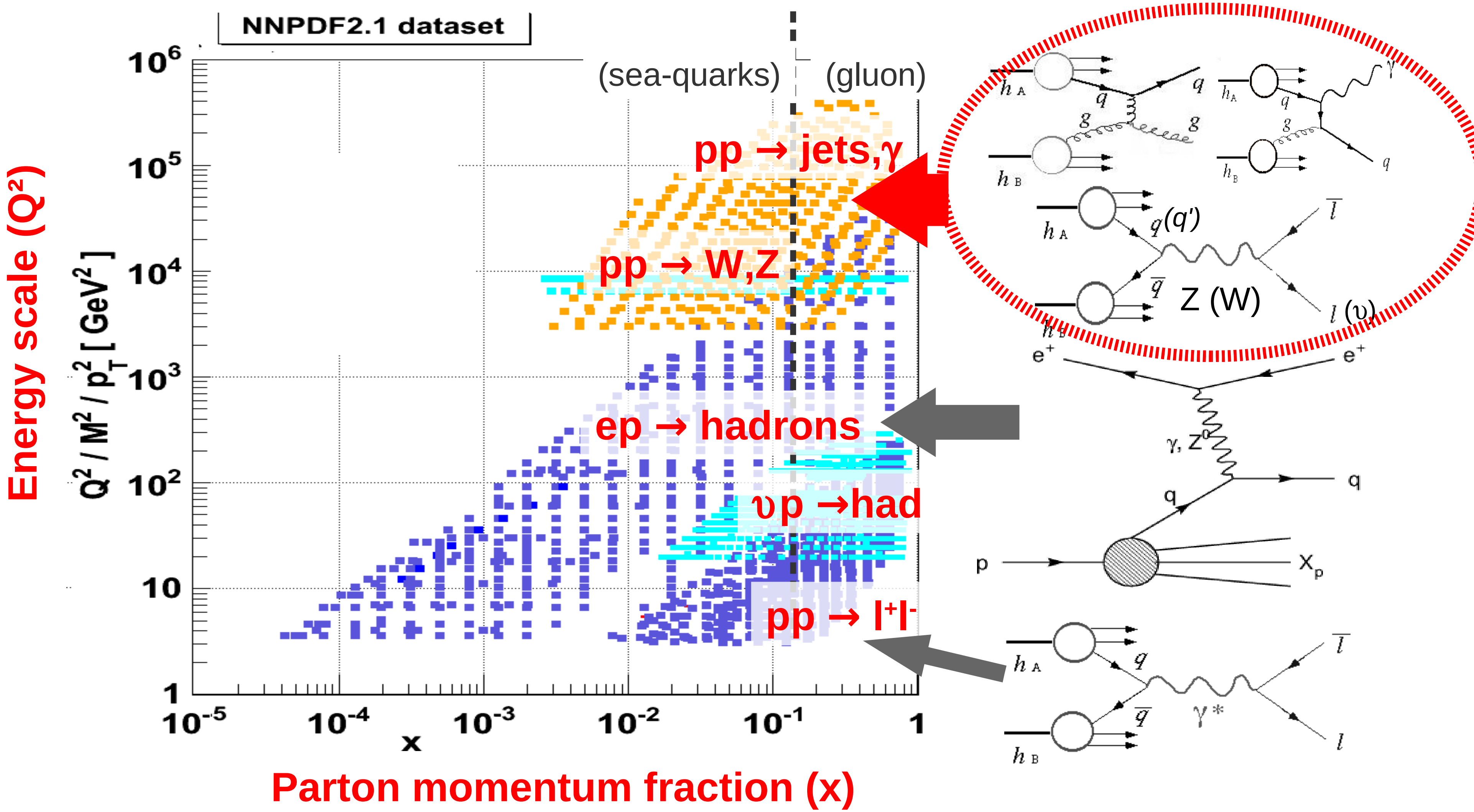
- Hard scattering:
  Matrix elements computed
  at (N)NLO in α_s expansion
  (1000s diags., <10% scale uncertainty)
  + NLL, NNLL resummation
  of log-enhanced terms

- Final-state hadronization:
  Universal FFs (+ DGLAP evolution)
  Bound-state formation (for QQbar)



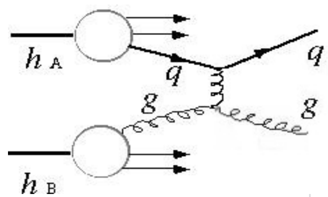
Extraction of PDF via global fits

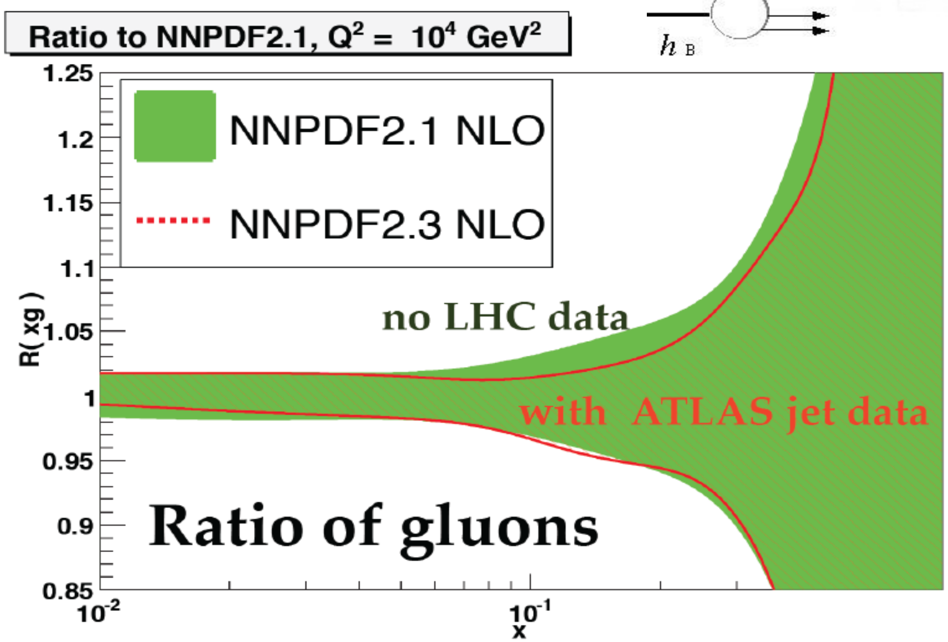
- e,υ-p DIS, p-p (fixed-target,collider) data vs pQCD: $\sigma_{data} \sim \sigma_{partons} \otimes PDF_{(fitted)}$

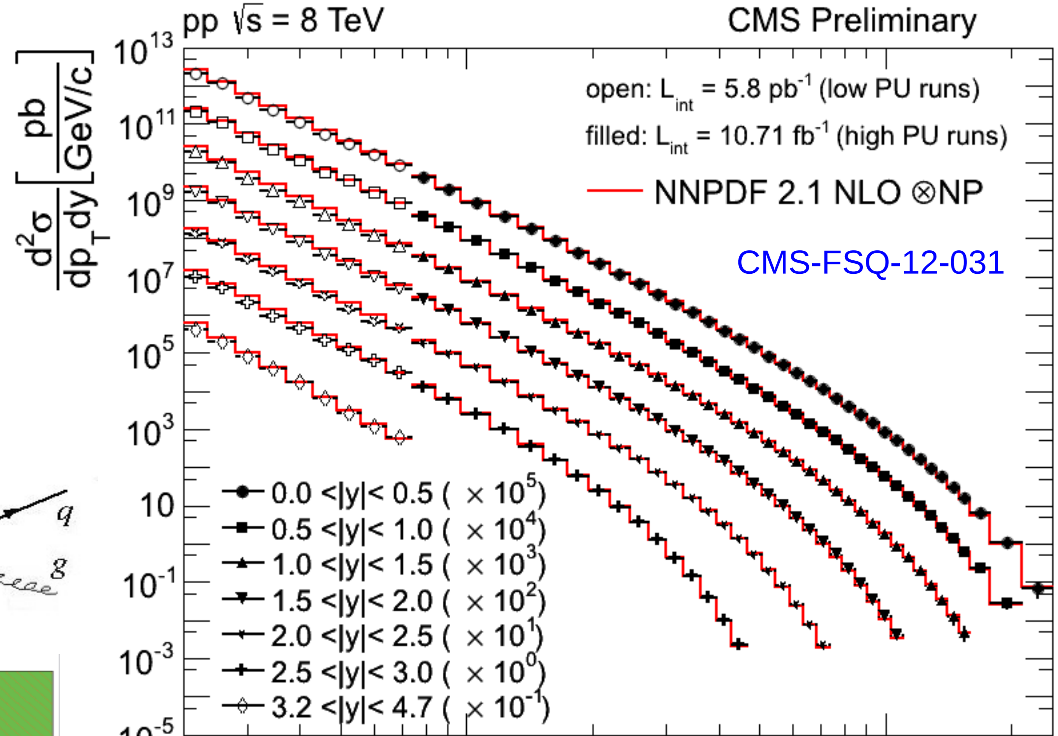


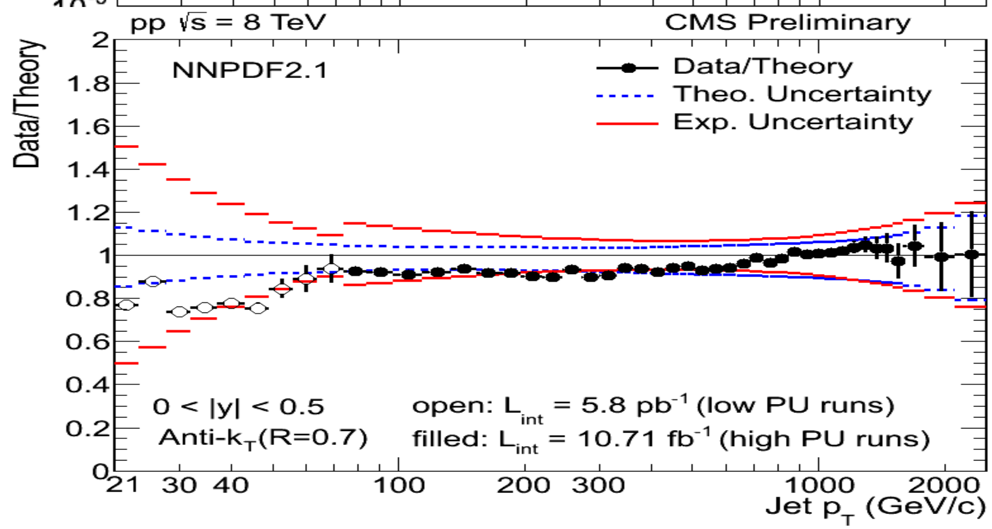
PDF constraints via light-quark & gluon jets

- Inclusive jet p_T spectra:
  p_T = 20 GeV up to 2-3 TeV !
  Exp. uncertainty: ~10% (JES)
- NLO pQCD describes data over 14 orders-magnitude !
- Impact on gluon PDF:



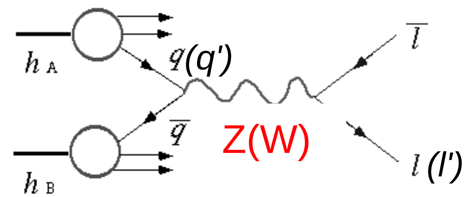


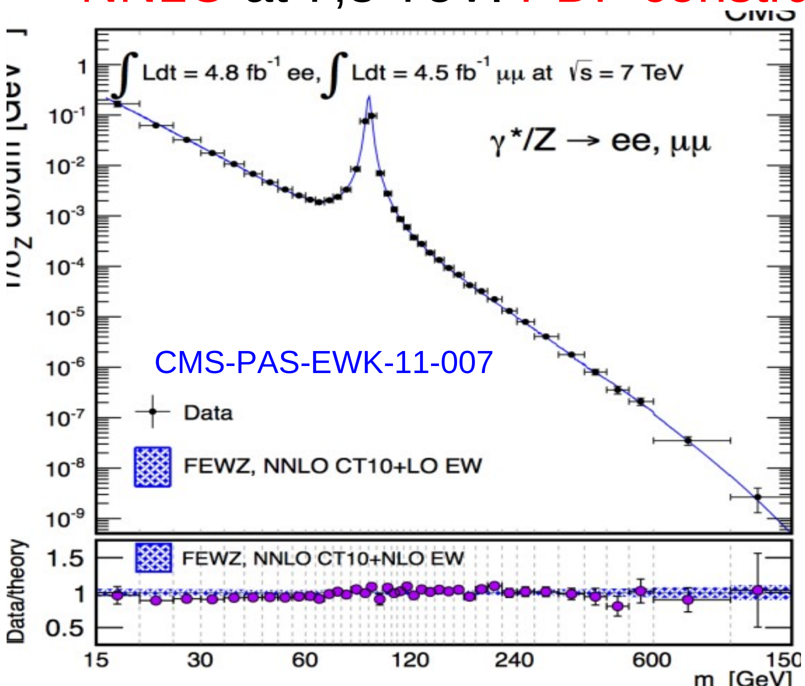




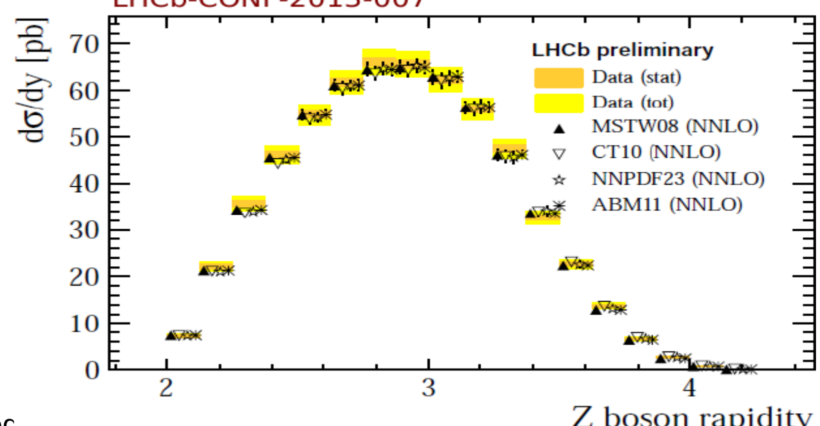
PDF constraints via W,Z "standard candles"

- Differential DY+Z x-section in agreement with NNLO at 7,8 TeV. PDF constraints at low m_{ll}



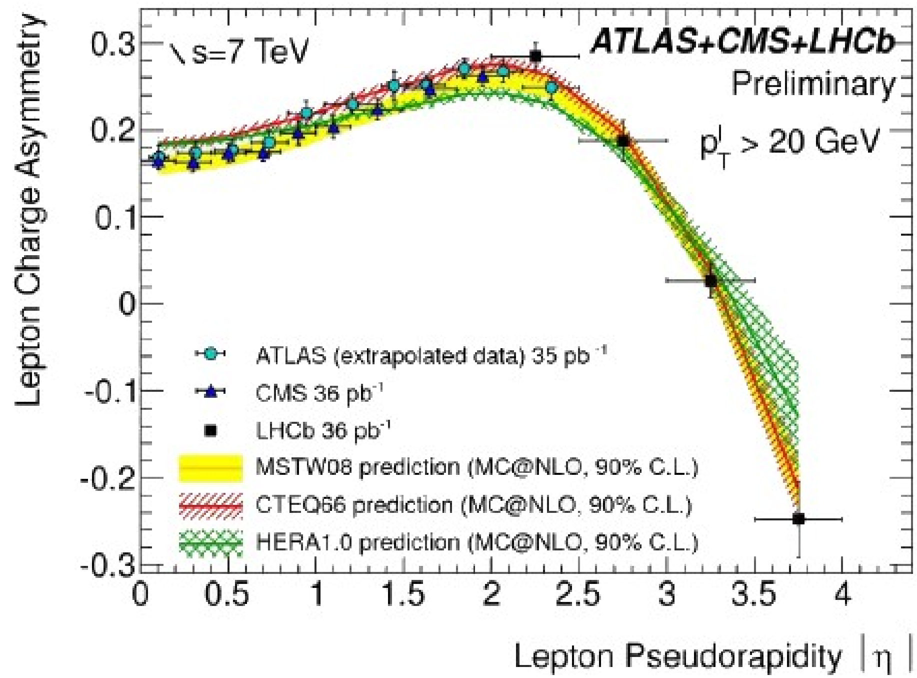


LHCb-CONF-2013-007



- W electron charge asymmetry vs |η| measured to ~1%. Many uncertainties cancel in ratio. Constrains u/d PDF ratio

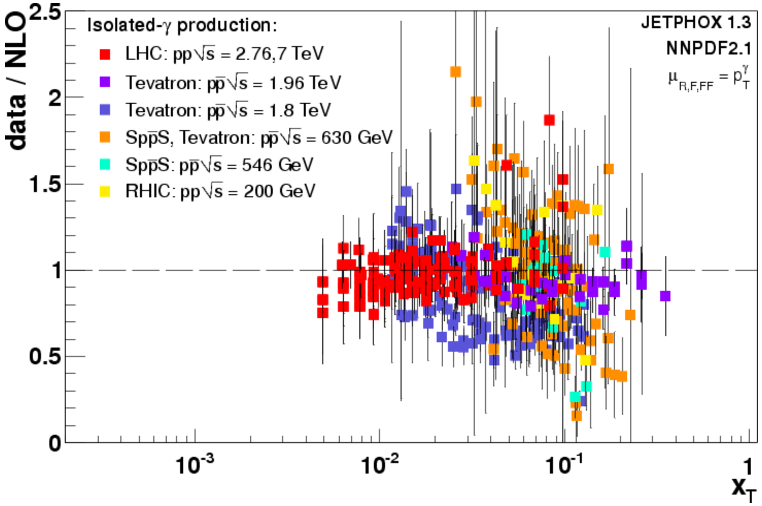
$$\mathcal{A}(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}$$

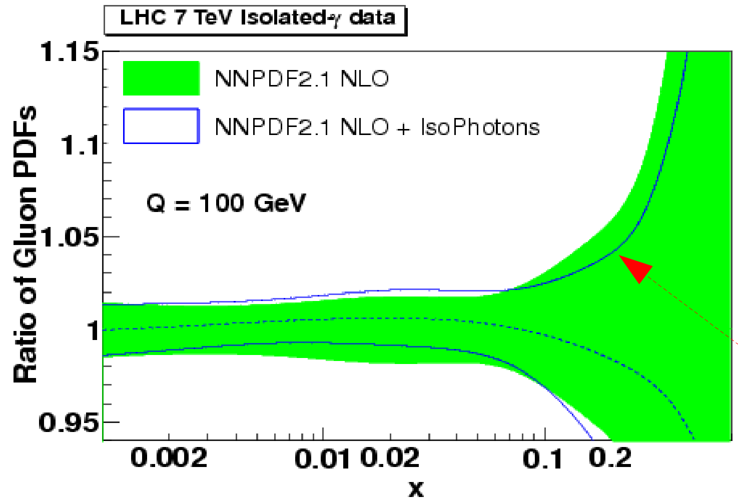


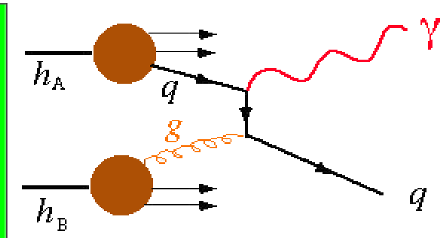
Other PDF constraints: isolated-γ, top, ...

- Isolated-γ sensitive to gluon NLO PDF in wide x range:

DdE&Rojo,NPB 860(2012)311

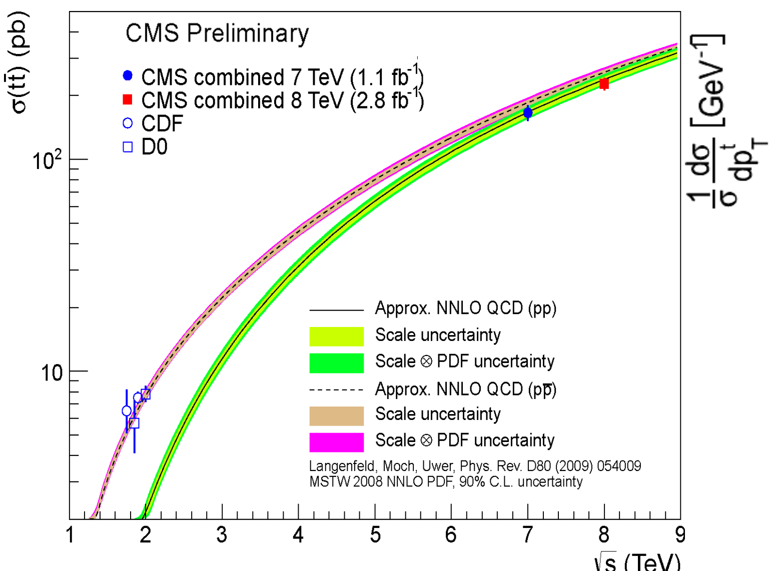


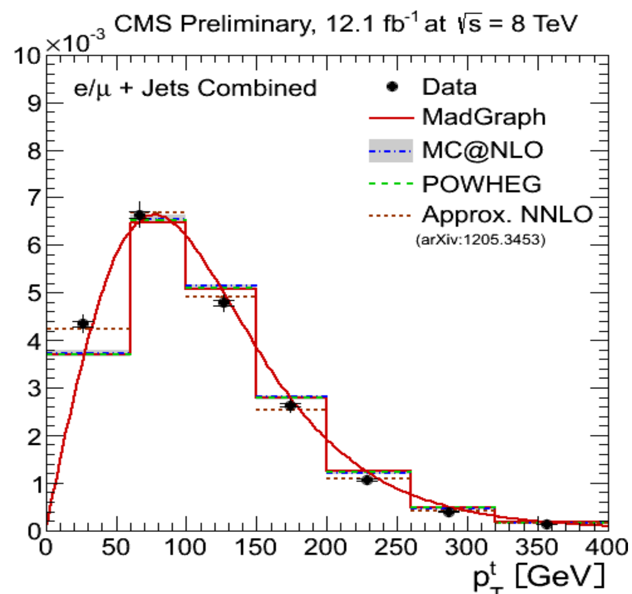


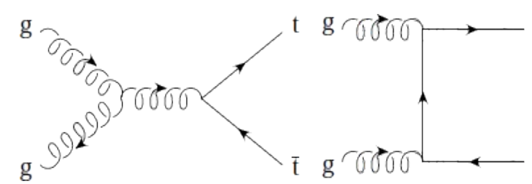


Reduced $xG(x,Q^2)$ uncertainties

- Top (and bottom) x-sections in good agreement with (N)NLO:





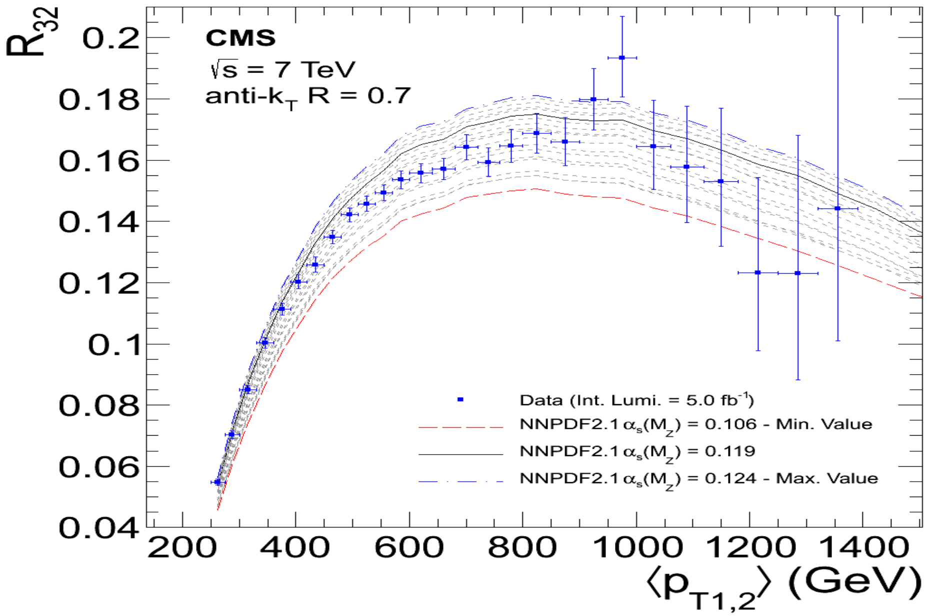


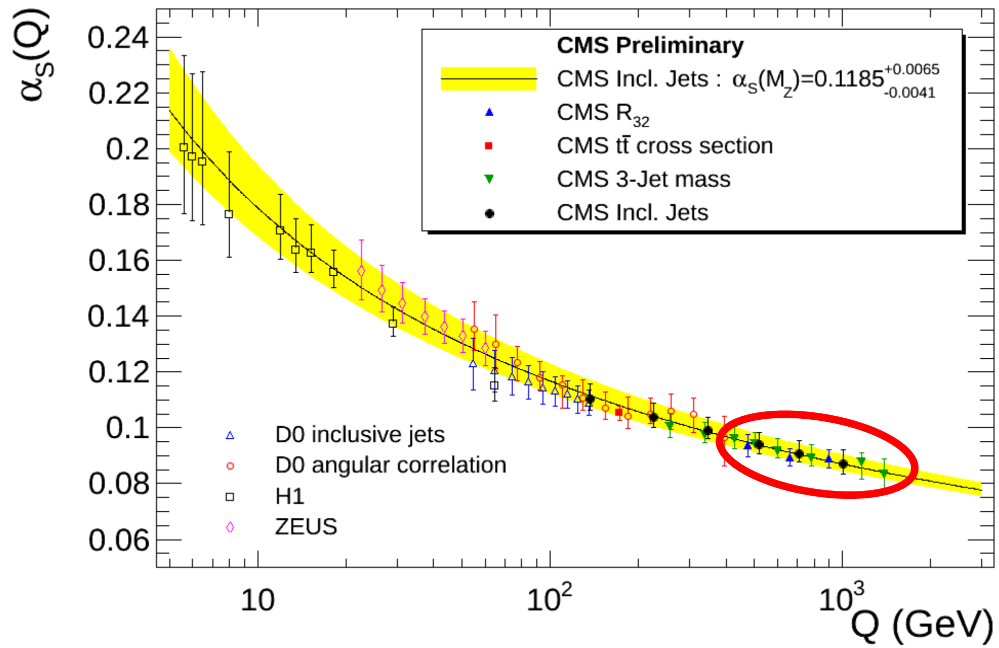
Quality of differential top x-sections constrain (1st time) gluon (N)NLO PDF

Strong α_s coupling from jets x-sections

- Ratio of 3-jets of 2-jets & 3-jet mass x-sections constrain α_s at so-far unprobed scales up to Q ~ 1.4 TeV:

CMS-QCD-11-003





NNPDF21: $\alpha_s(M_Z) = 0.1148 \pm 0.0014$

CT10: $\alpha_s(M_Z) = 0.1135 \pm 0.0019$

MSTW2008: $\alpha_s(M_Z) = 0.1141 \pm 0.0022$

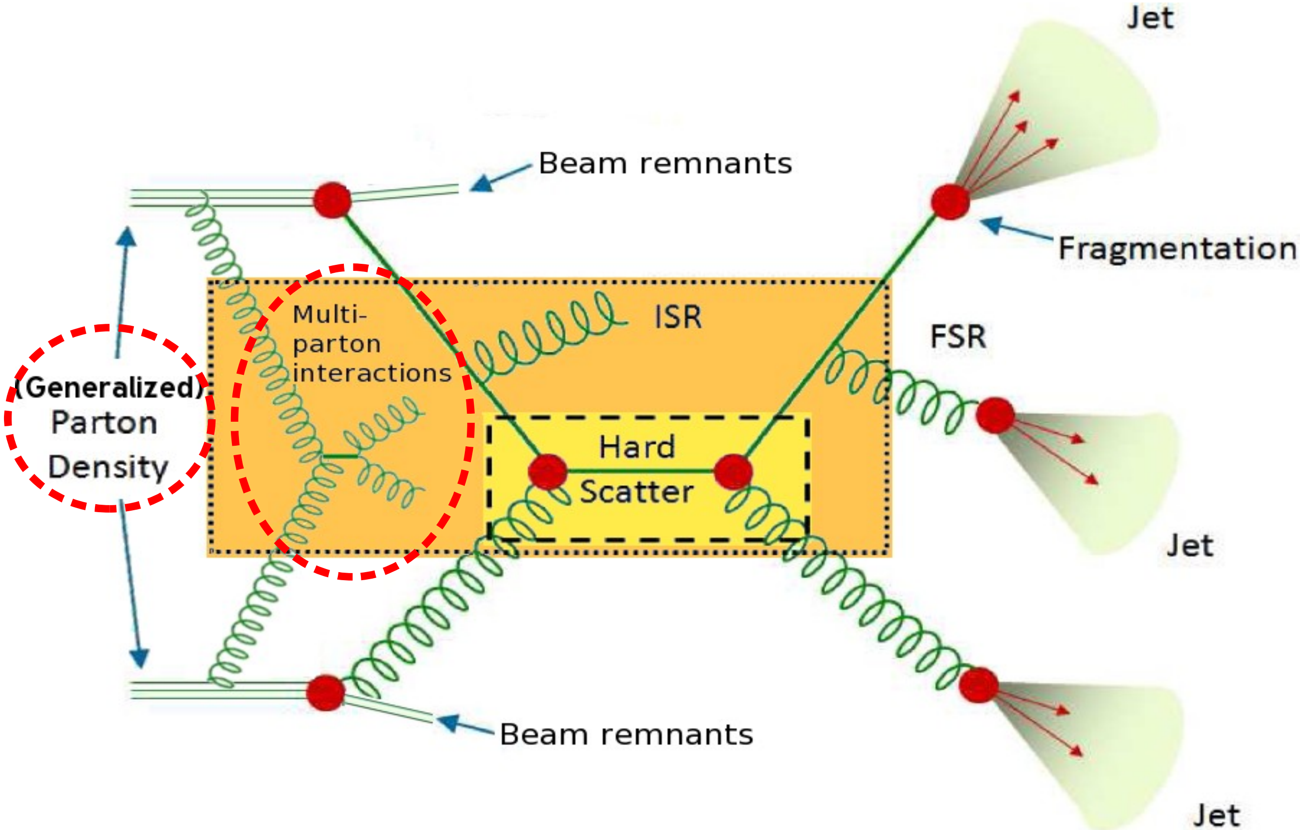
(ABM11: $\alpha_s(M_Z) = 0.1214 \pm 0.0020$**)**

Measurement dominated by TH uncertainty: PDF & (asymmetric) scale uncertainty

$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\,(\mathrm{exp}) \pm 0.0018\,(\mathrm{PDF}) \pm^{0.0050}_{0.0000}\,(\mathrm{scale})$$

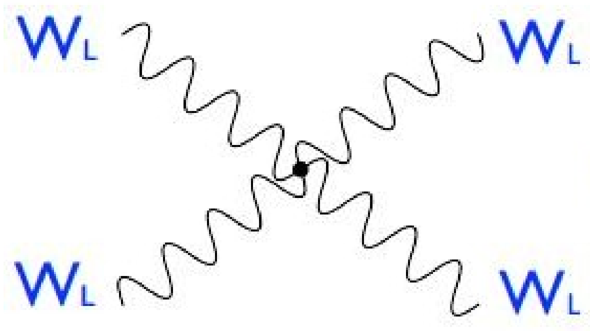
- Test of asymptotic freedom mostly: Uncertainties still large in extracted α_s

Semi-hard QCD at the LHC

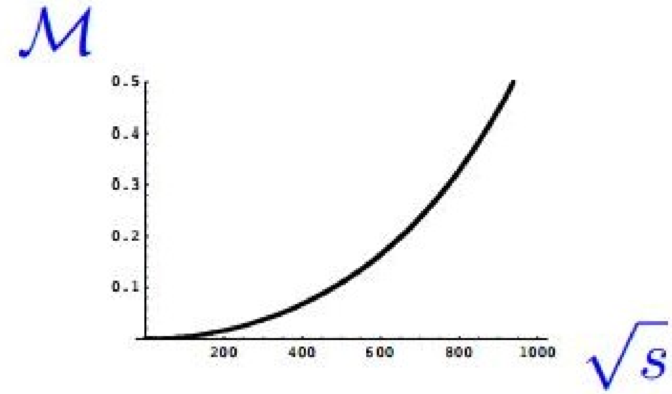


Unitarity of electroweak cross sections

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



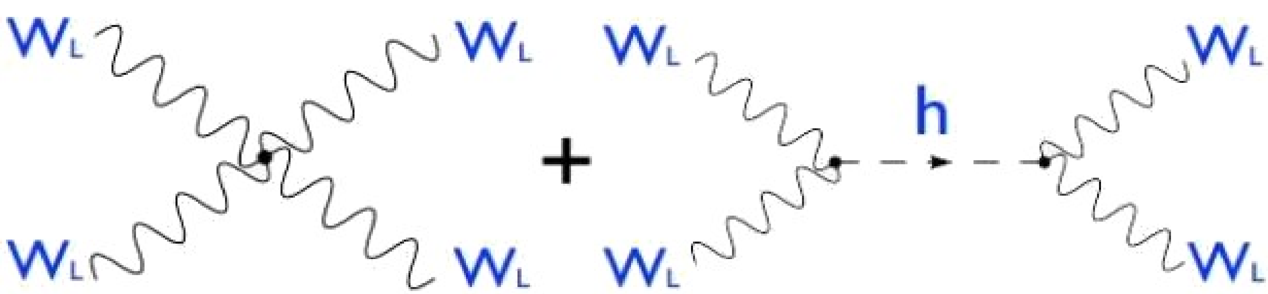
$$\propto \frac{s}{v^2}$$

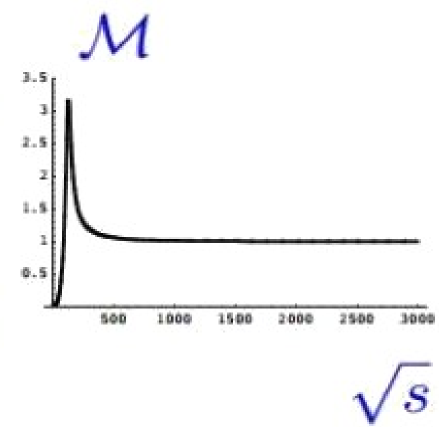


Unitarity is lost at high-energies

[A.Pomarol, ICHEP'12]

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



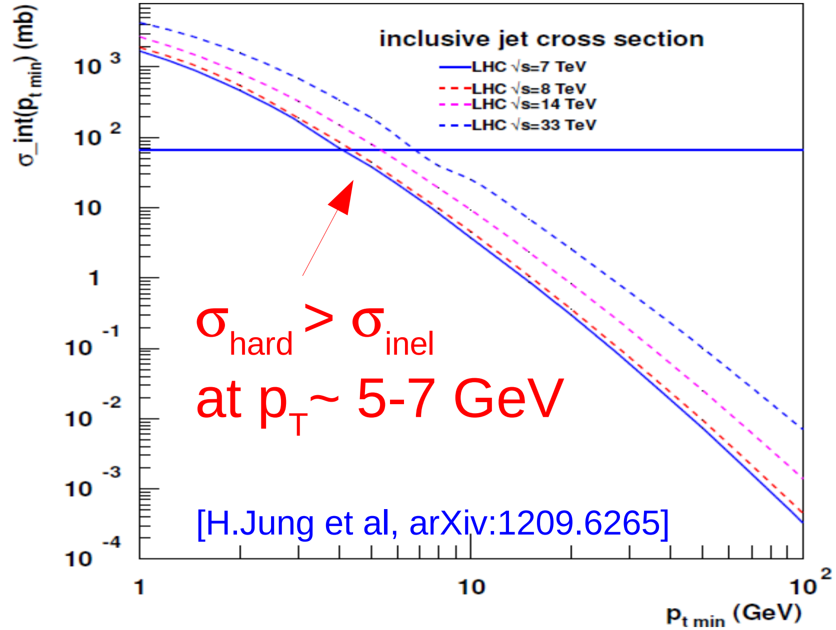


Unitarity of pQCD cross sections

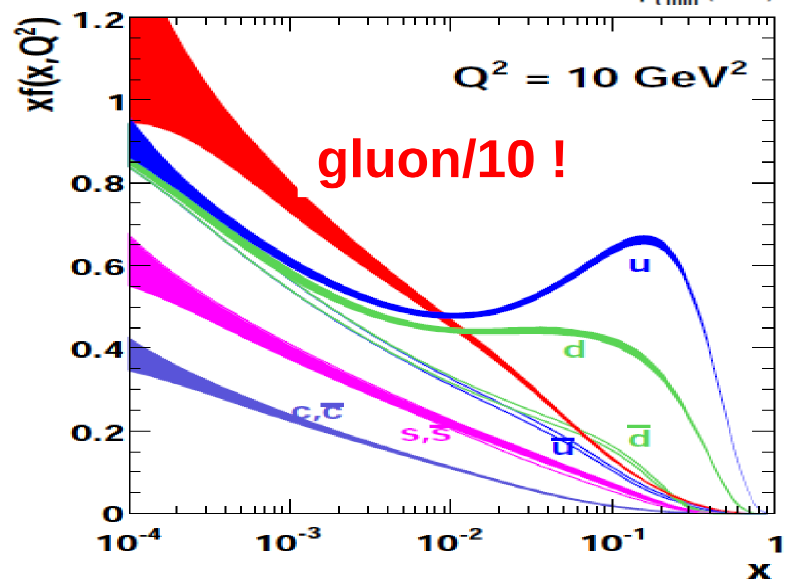
- pQCD (mini)jet production x-section is bigger than total inel p-p x-section for p_{Tmin}~ 5-7 GeV at the LHC !

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

... Why this happens ?



- Very high gluon densities at small-x:



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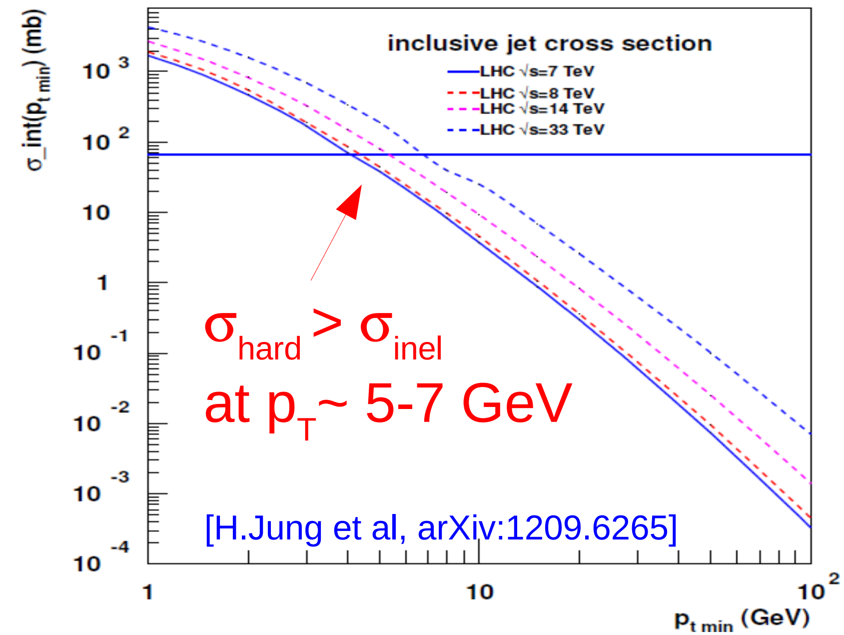
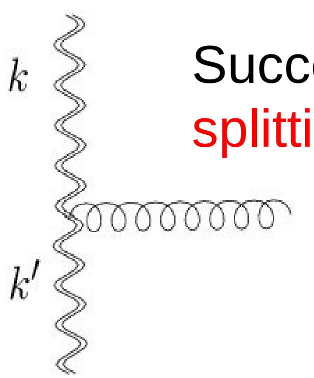
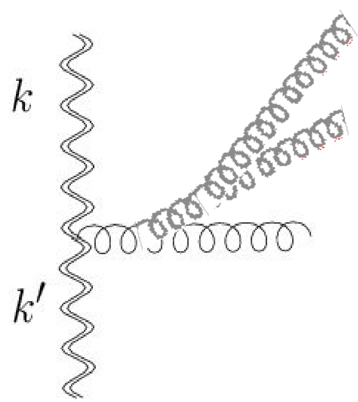
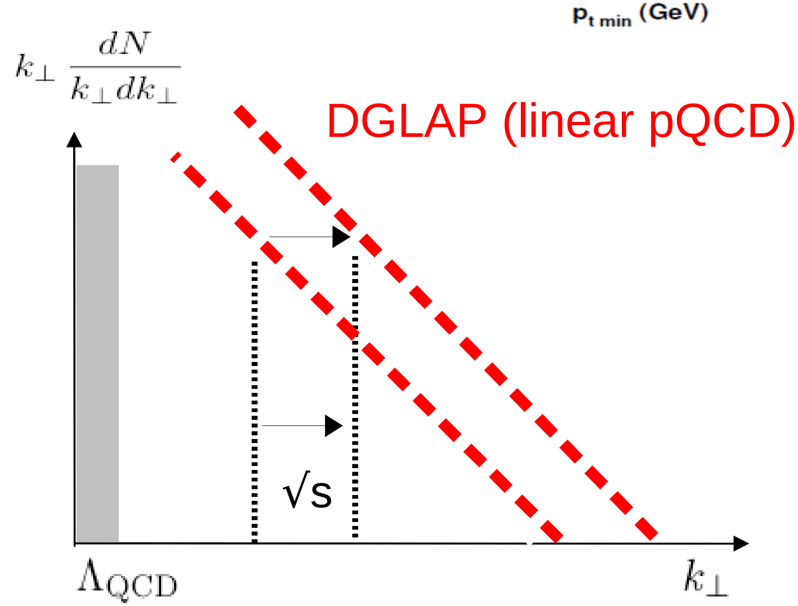


- Very high gluon densities at small-x: "Malthusian" growth of radiated gluons in linear DGLAP evolution:



Successive parton splitting/branching:



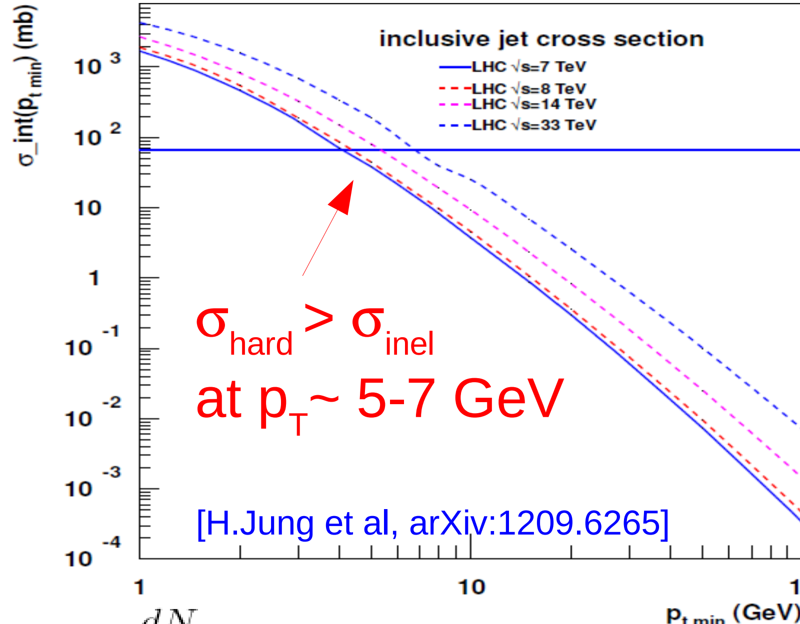


Unitarity of pQCD x-sections: gluon saturation

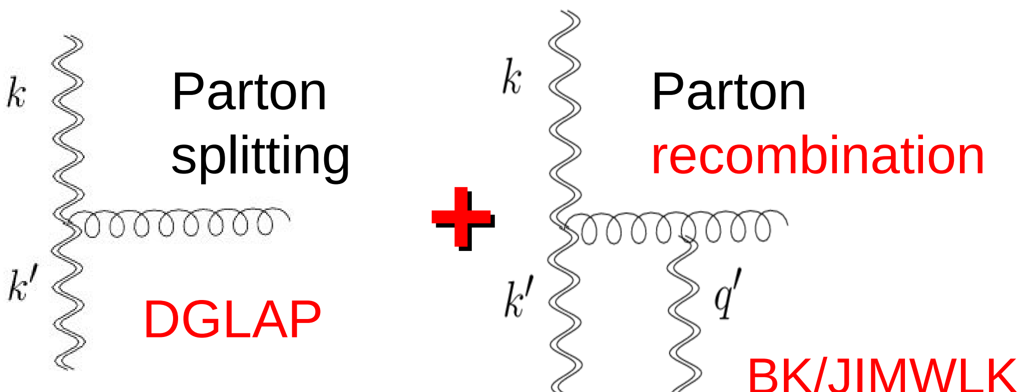
- pQCD (mini)jet production x-section is bigger than total inel p-p x-section for p_{Tmin}~ 5-7 GeV at the LHC !

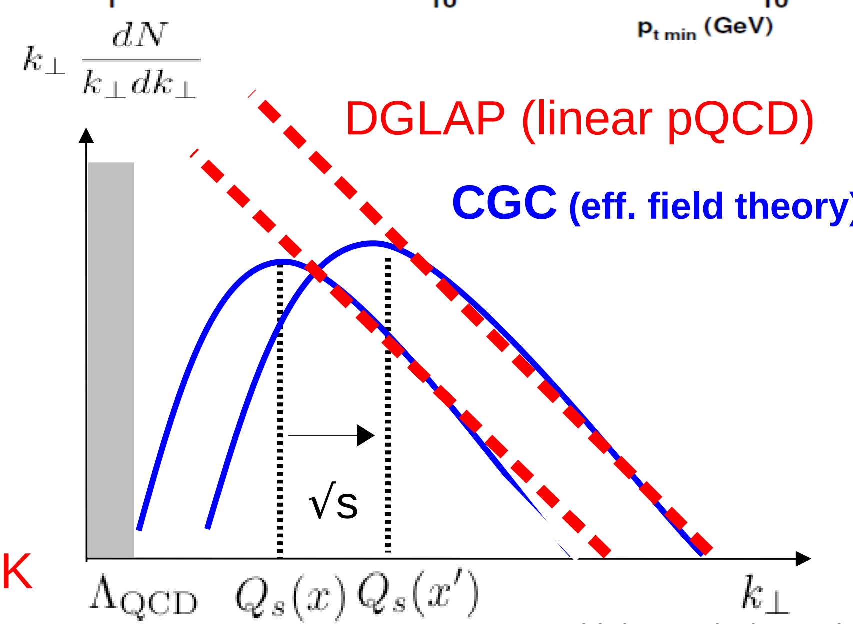
$$\sigma_{\rm hard}(p_{\perp\rm min}) = \int_{p^2_{\perp\rm min}}^{s/4} \frac{{\rm d}\sigma}{{\rm d}p^2_\perp}\,{\rm d}p^2_\perp$$

... Why this happens ?



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





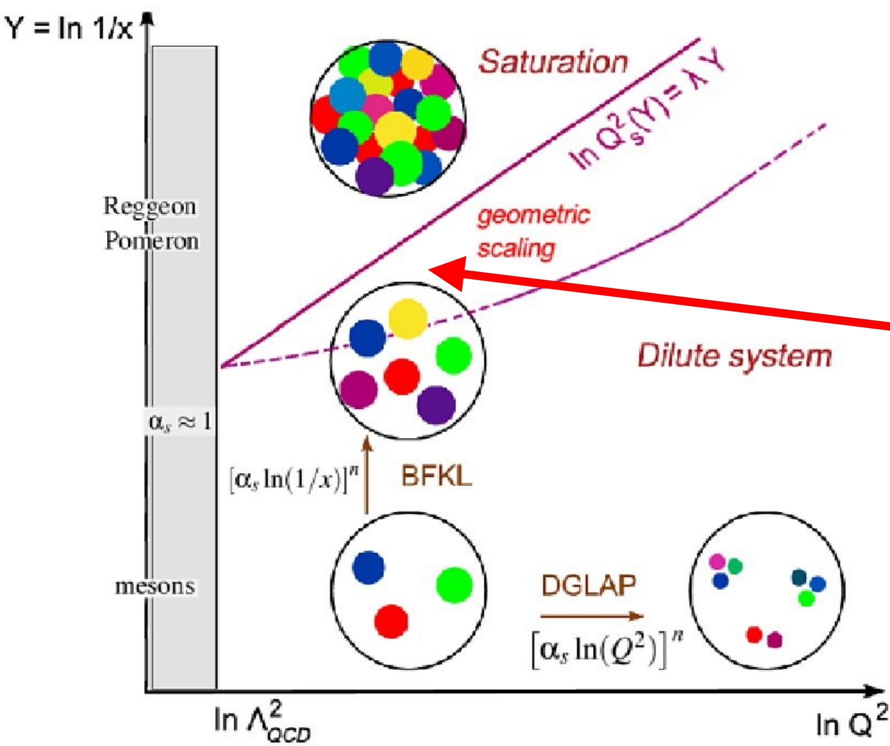
Searches of “Beyond DGLAP” evolution

- DGLAP equations describe parton radiation as a function of Q^2:

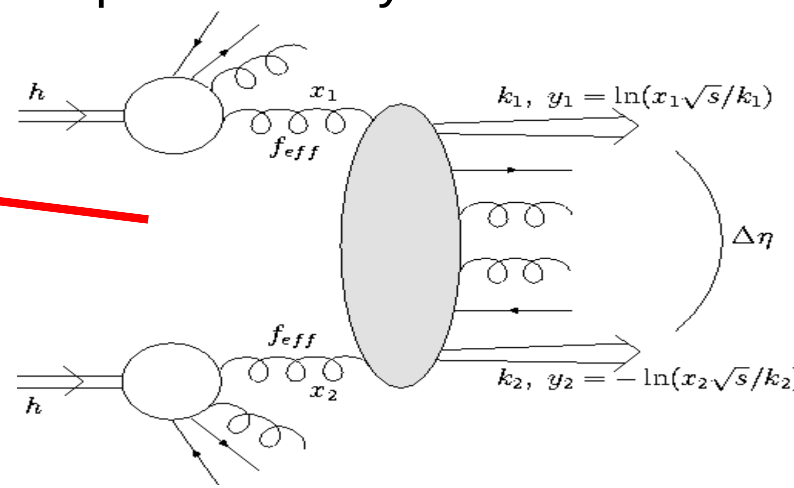
  $f(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$ [fixed-order PDFs, collinear factorization]

- BFKL, saturation evolutions: At low-x & mid Q^2, parton emission in p_L,η

  $f(x) \sim \alpha_s \ln(1/x)^n$ [uPDFs, k_T-factorization]



- Mueller-Navelet dijets with large y separation very sensitive to BFKL:

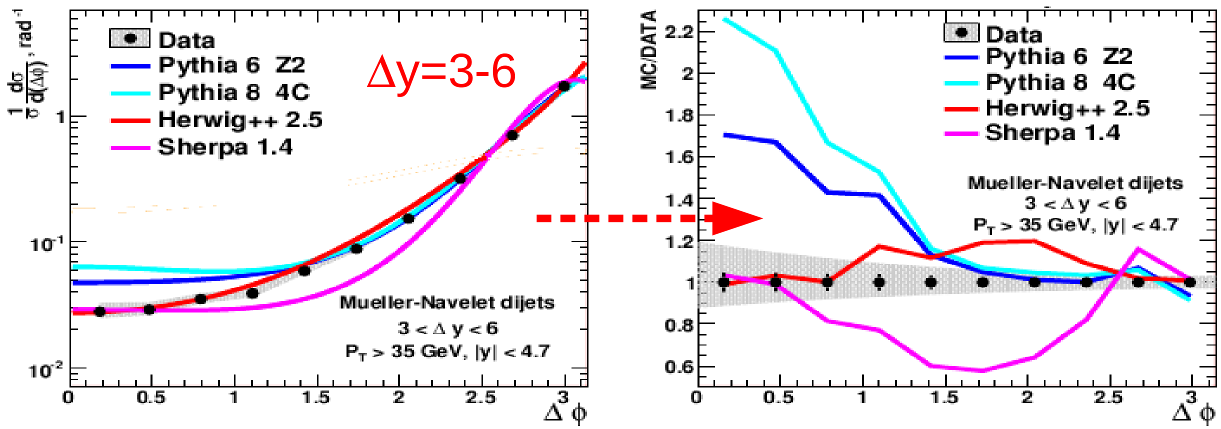


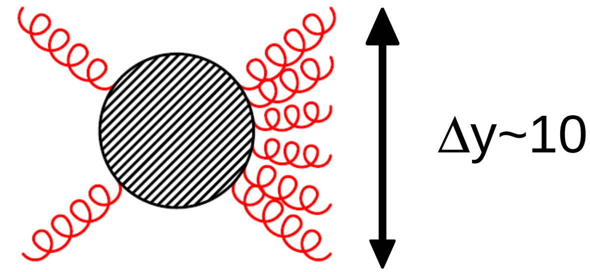
Δη ~10
(Atlas,CMS)

- Extra radiation in rapidity ?
- Enhanced azimuthal decorrelation ?

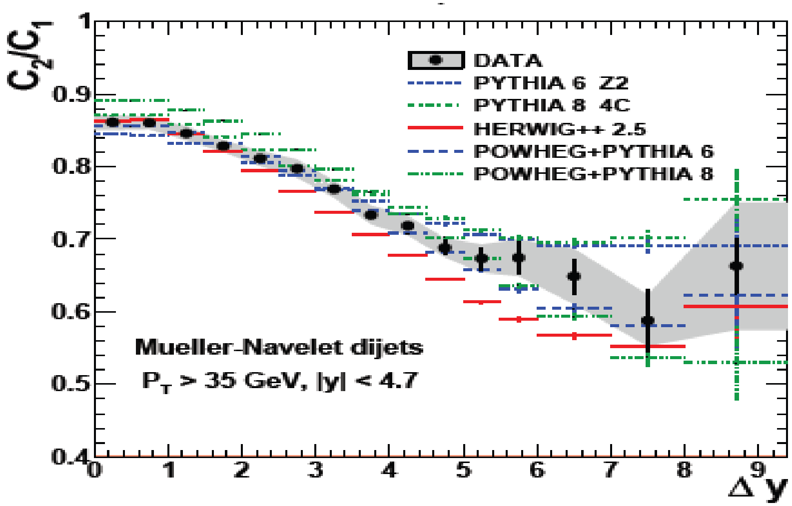
"Beyond DGLAP" in LHC Mueller-Navelet dijets?

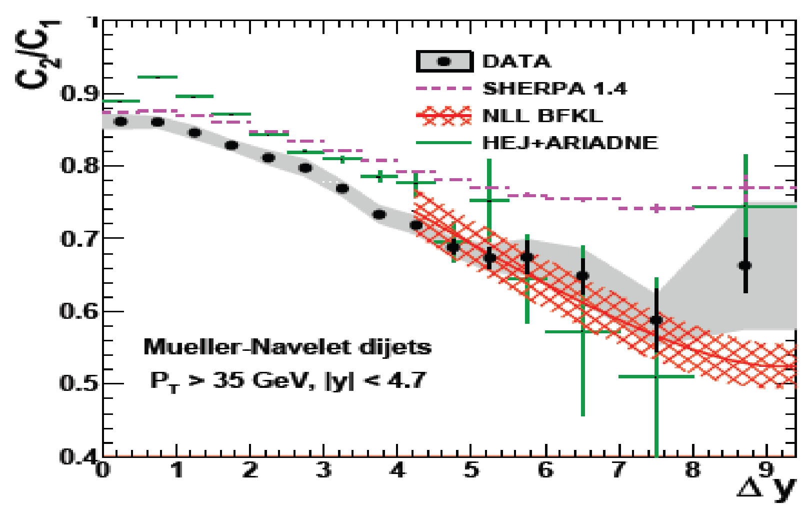
- MN dijet azimuthal decorrelations over large Δy: Absolute $\Delta\phi$ distributions & ratio moments vs Δy





- HERWIG = DGLAP + (N)LL parton-shower not doing bad ...





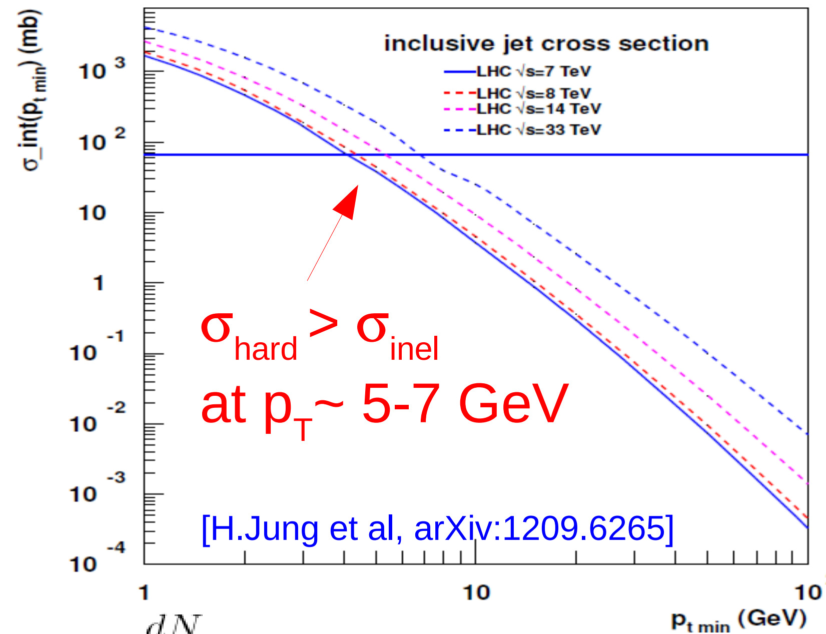
- Latest NLL+ BFKL also consistent with results... Final word at lower p_T ?

Unitarity of pQCD x-sections: saturation scale

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

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

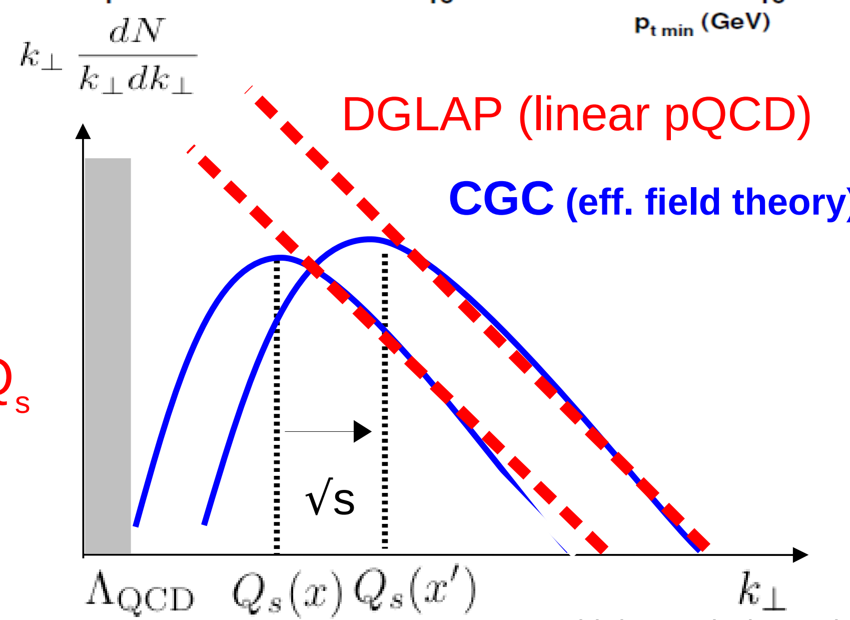
... Why this happens ?



- Very high gluon densities at small-x
- 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

$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2} \quad \sim 1-5\ \mathrm{GeV}^2$$



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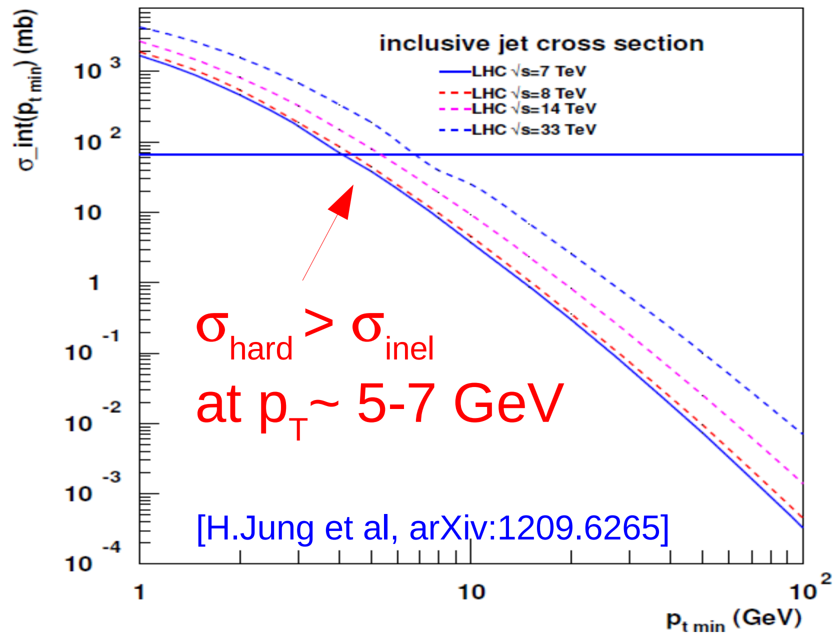
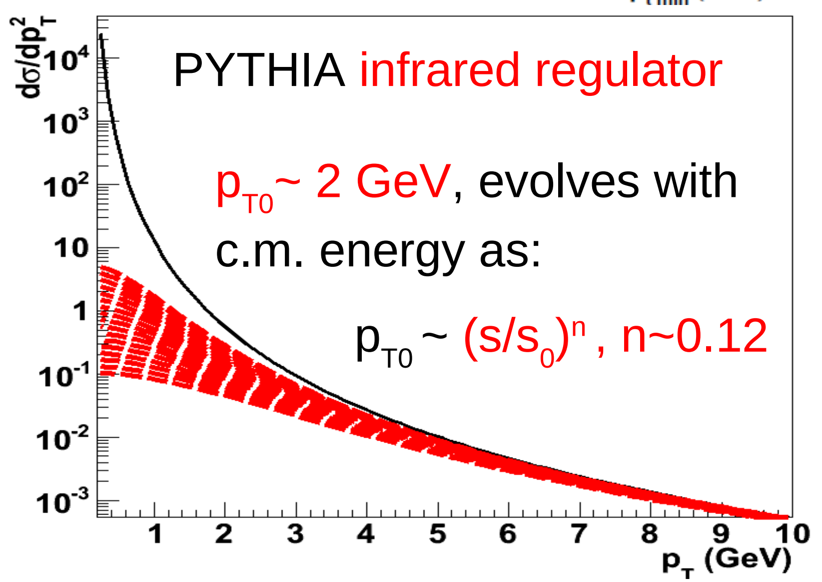


- Very high gluon densities at small-x
- Solution (1): Gluon saturation around perturbative "saturation scale" Q_s:

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

- Equivalent to (adhoc) PYTHIA p_T-cutoff:

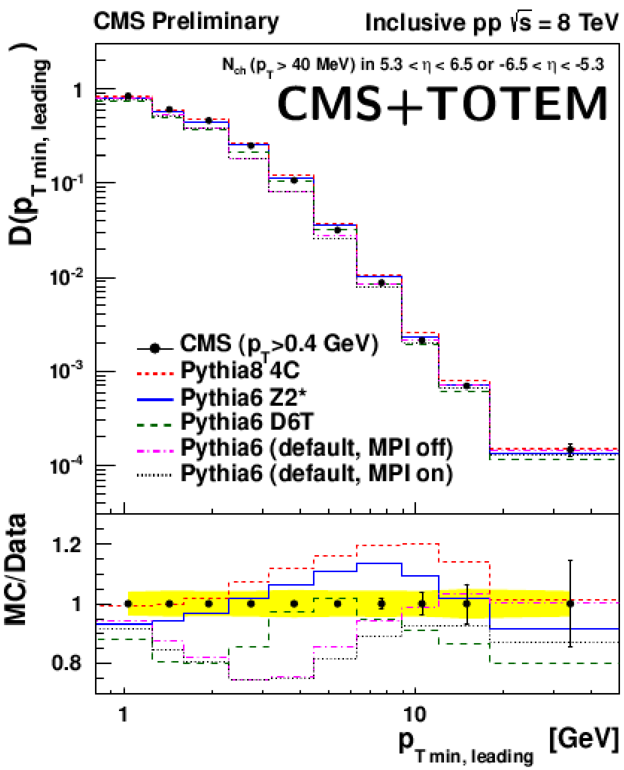
$$\frac{{\rm d}\hat{\sigma}}{{\rm d}p^2_\perp} \propto \frac{\alpha_s^2(p^2_\perp)}{p^4_\perp} \rightarrow \frac{\alpha_s^2(p^2_{\perp 0}+p^2_\perp)}{(p^2_{\perp 0}+p^2_\perp)^2}$$

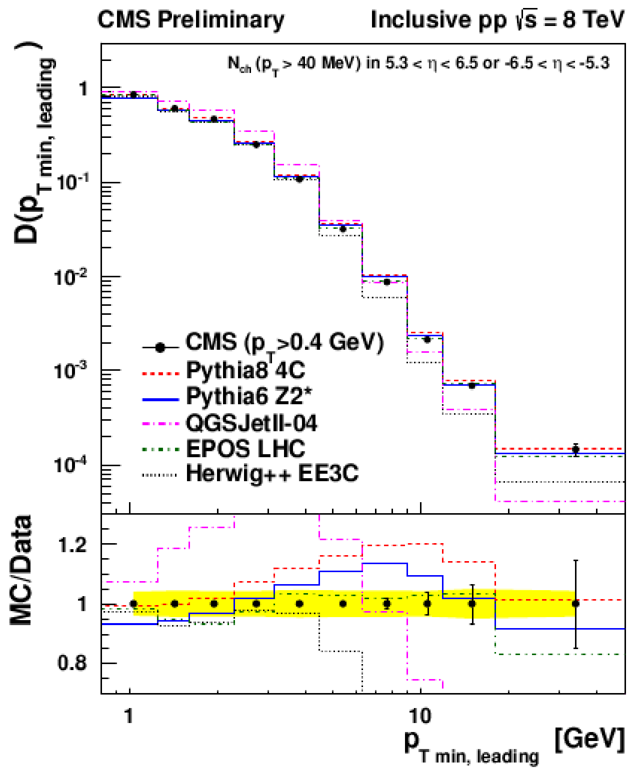


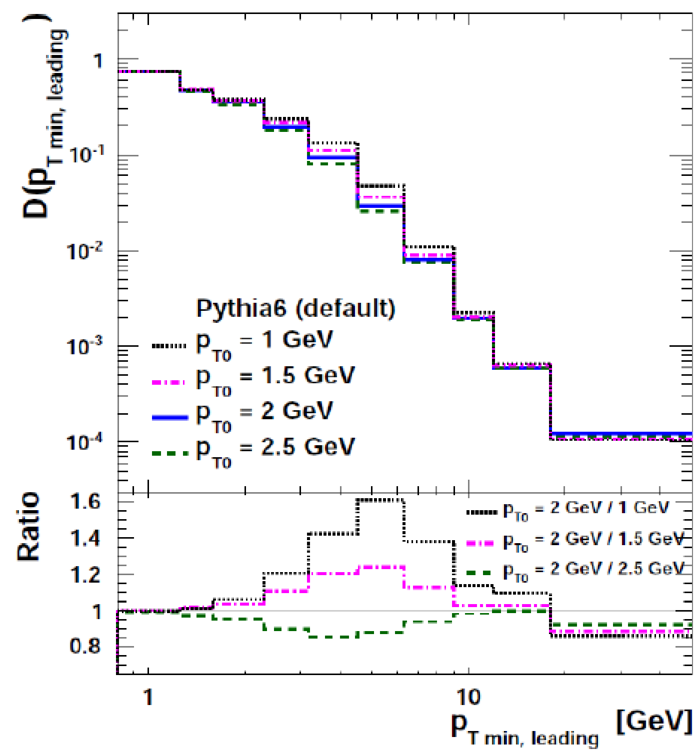
LHC leading minijets x-section at O(1 GeV)

- Leading charged-jet & leading track cross sections

down to $p_T \sim 1$ GeV/c: $D(p_{T\,min}) = \frac{1}{N}\int_{p_{T\,min}} dp_{T,leading} \frac{dn}{dp_{T,leading}}$







→ First direct test of minijet x-section behavior approaching unitarity limit.

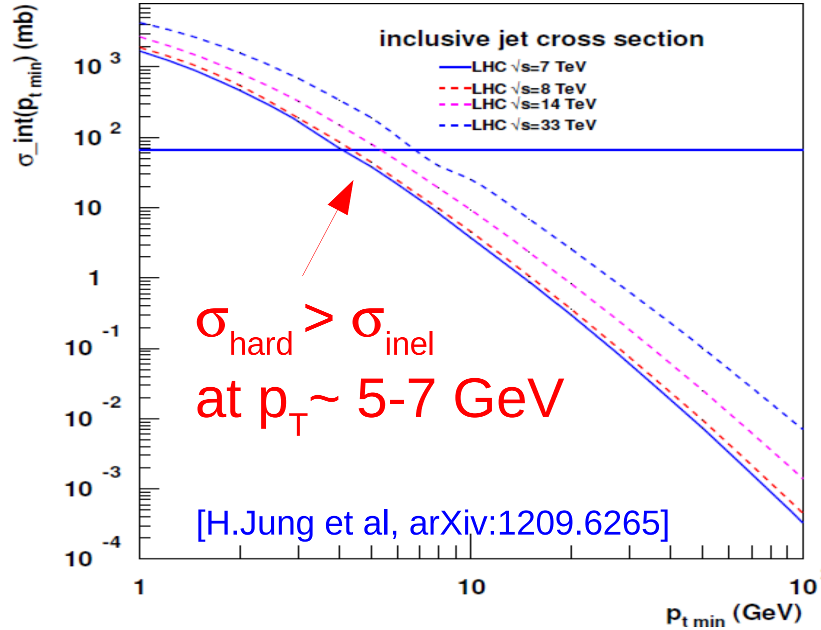
→ Strong constraints on p_T-cutoff regulator ($\sim Q_{sat}$) in Monte Carlos

Unitarity of pQCD x-sections: Multi-parton interactions

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

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

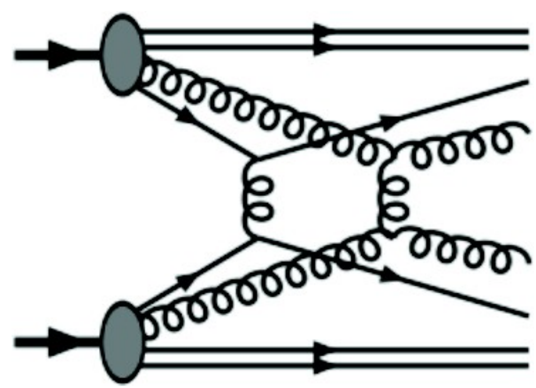
... Why this happens ?



- Very high gluon densities at small-x
- Solution (1): Multi-parton interactions

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

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

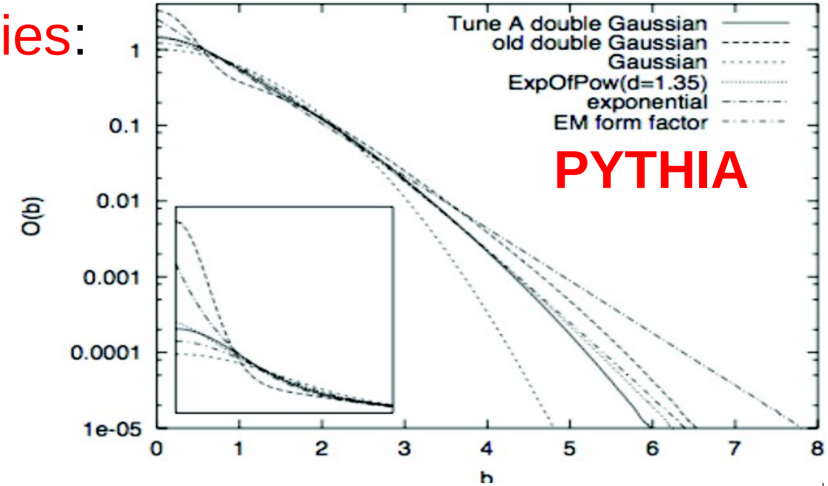


- PDF(x,Q^2) densities need generalization in transverse direction: GPD(x,Q^2,b)

Partonic transverse structure in the proton

- Empirical MC parton transverse densities:

  Double Gaussian
  Exponential of power
  Fermi-Dirac
  E.M. form-factor (measured in low-Q e-p)

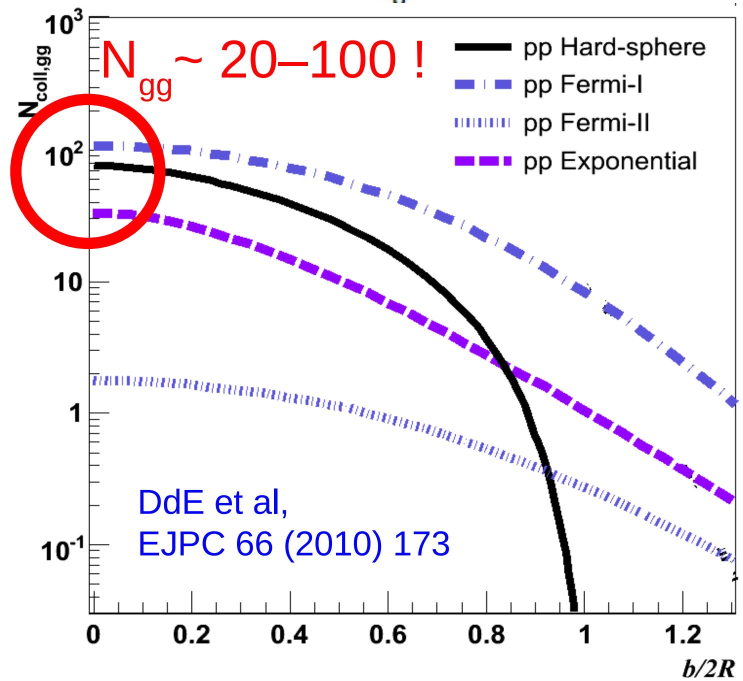


- Proton-proton overlap function:

$$\mathcal{O}(b) = \int \mathrm{d}^3\mathbf{x}\,\mathrm{d}t\;\rho^{\mathrm{boosted}}_{1,\mathrm{matter}}(\mathbf{x},t)\,\rho^{\mathrm{boosted}}_{2,\mathrm{matter}}(\mathbf{x},t)$$

Underlying parton activity at b proportional to *O*(b)

Number of glue-glue collisions at 14 TeV:

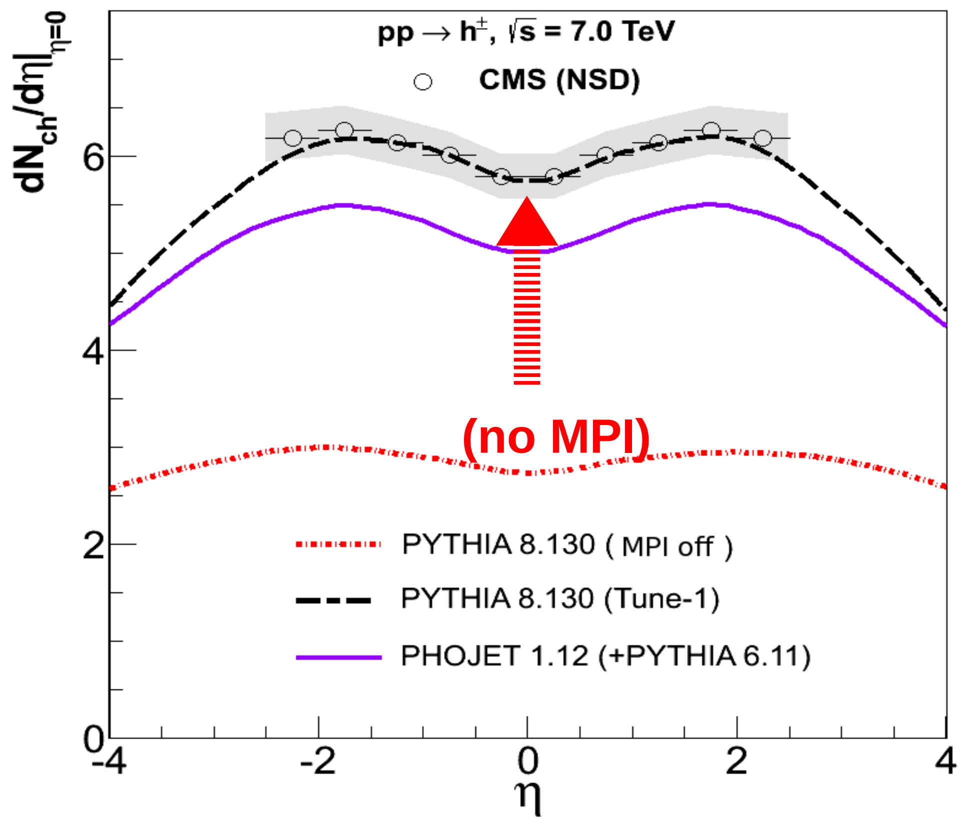


- Explaining perturbatively (GPDs?)
  √s-evolution of transverse proton profile
  is key to properly describe MPI, DPS, ...

MPI at the LHC: Inclusive p-p hadron production

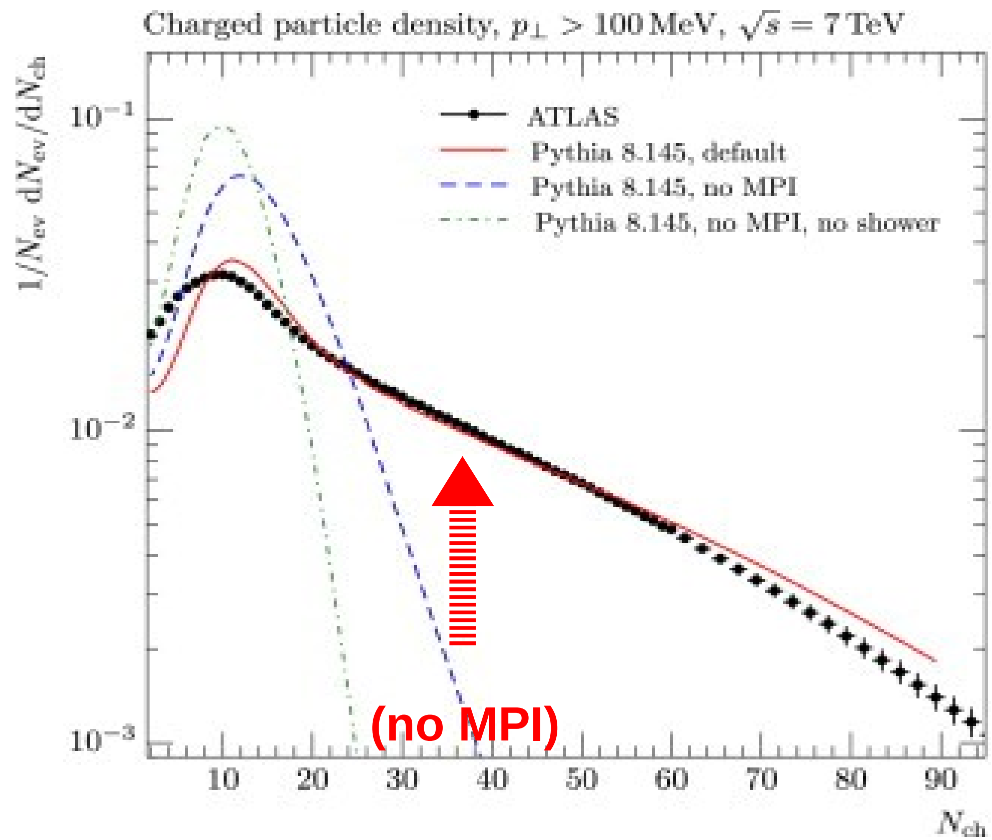
- MPI contributions are unavoidable in MCs to describe total inclusive hadron production in "minimum bias" p-p collisions:

Central particle densities:



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

Charged particle multiplicities:

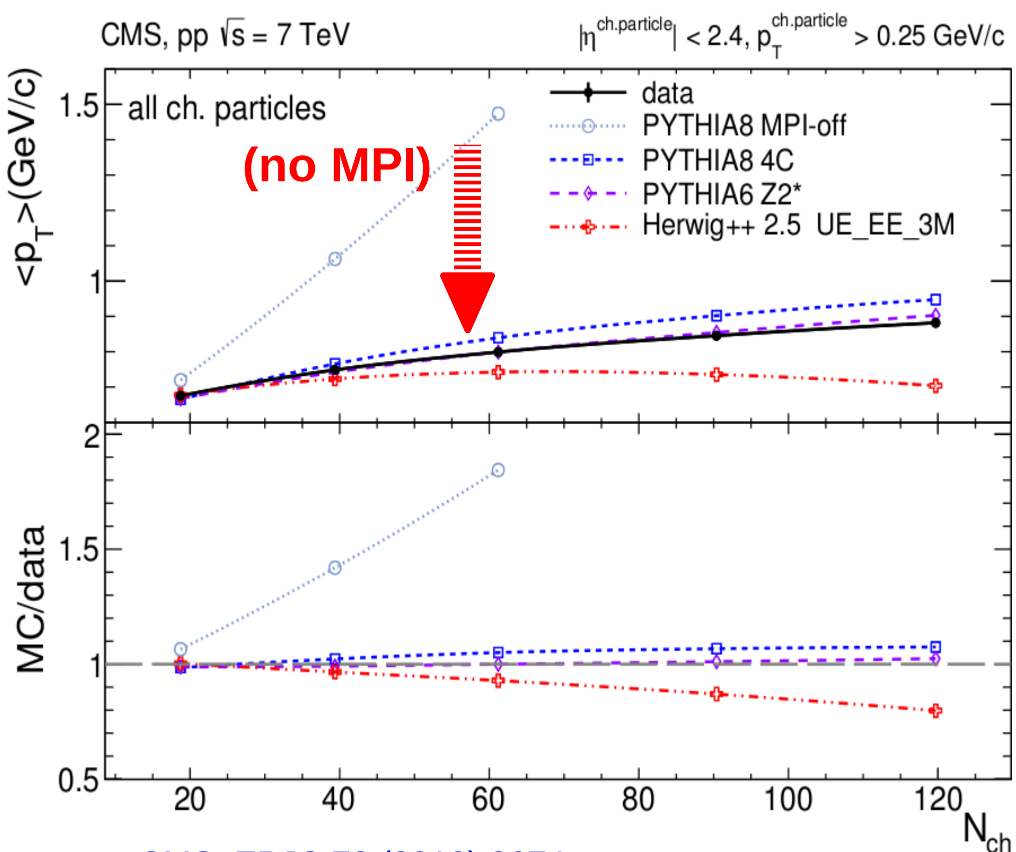


ATLAS, arXiv:1012.5104

MPI at the LHC: <p_T> vs N_{ch}, fwd energy flow

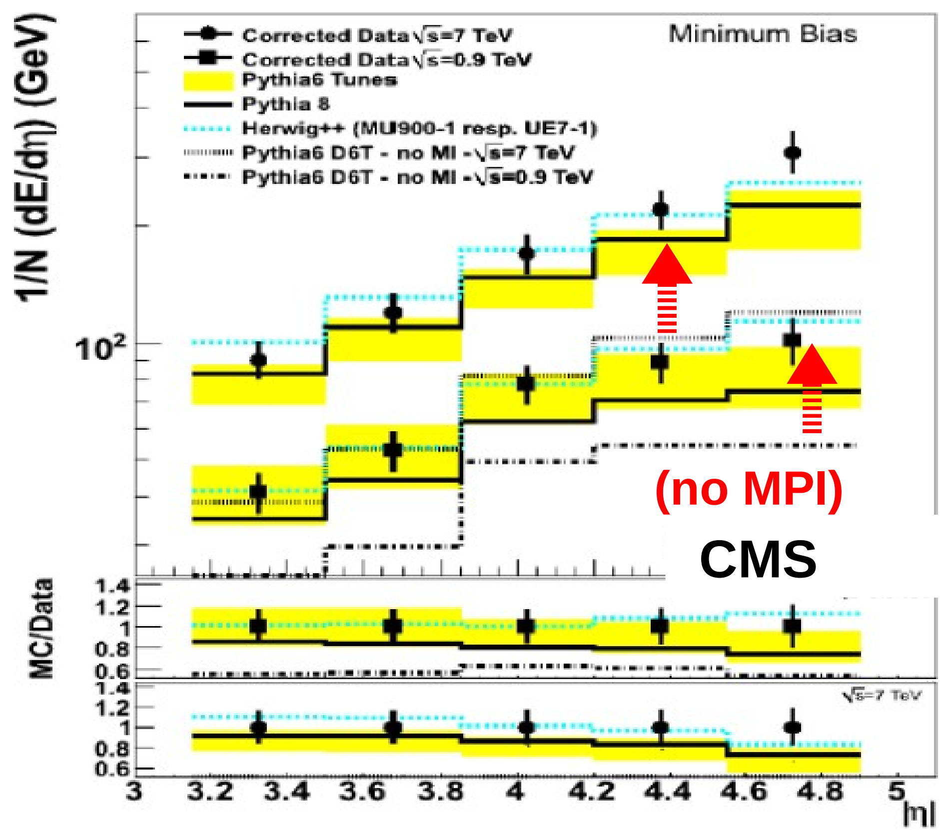
- MPI contributions are unavoidable in MCs in order to describe <p_T> versus Nch and forward energy flow in p-p collisions:

Mean transverse momentum vs N_{ch}:



CMS, EPJC 73 (2013) 2674

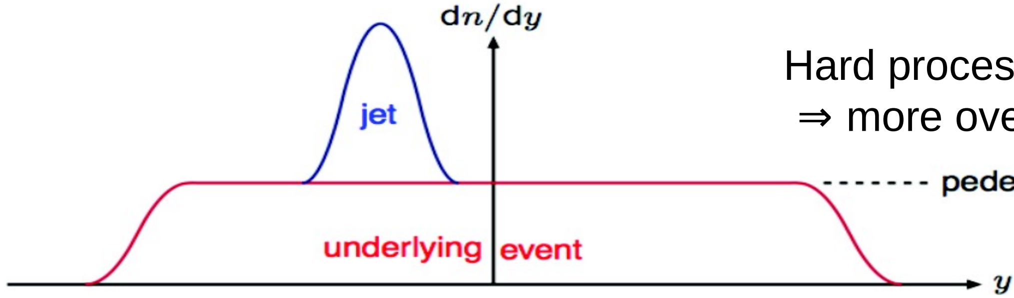
Forward energy flow:



CMS, JHEP 1111 (2011) 148

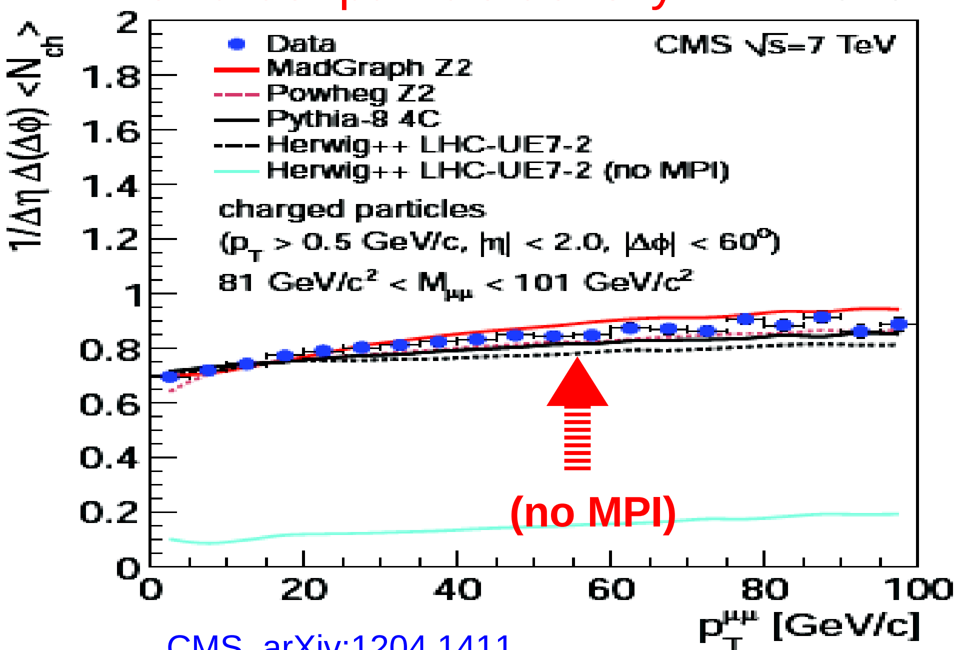
MPI at the LHC: p-p underlying event

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



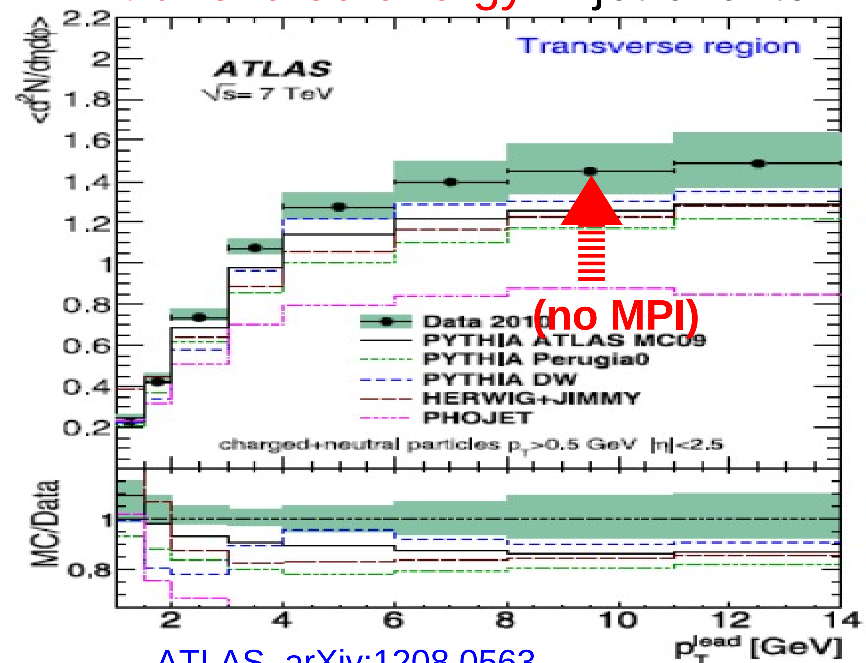
Hard process = more "central" pp collision
⇒ more overlap ⇒ more MPIs ⇒ more activity

"towards" particle density in DY events:



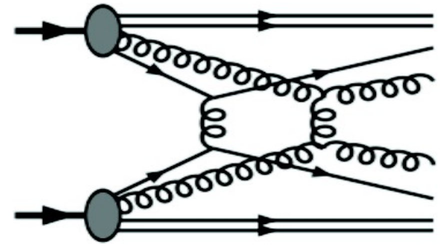
CMS, arXiv:1204.1411

transverse energy in jet events:



ATLAS, arXiv:1208.0563

Double Parton Scattering cross sections



- MPI O(1-3 GeV) are unavoidable to explain:
  - O(50%) of total particle production
  - Underlying event activity in hard scatterings

► Double hard parton scatterings O(3-100 GeV) should also take place.

- pQCD expression for DPS x-section:

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

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

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

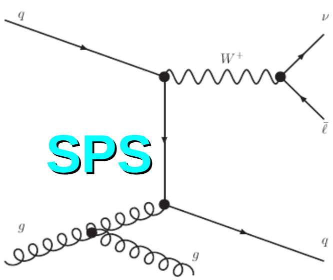
Effective DPS radius:
r~0.3 – 0.7 fm
smaller than e.m. one

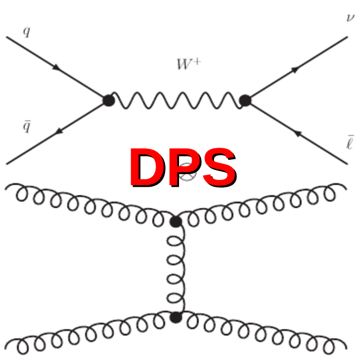
Model for density	Form of density, dN/d^3r	Predictions rms r	Predictions $\sigma_{\rm eff}$	Measurements Scale (fm)
Solid sphere	Constant, $r<r_p$	$\sqrt{3/5}r_p$		$r_p=0.73$
Gaussian	$e^{-r^2/2\Sigma^2}$	$\sqrt{3}\Sigma$	~14.5 mb	$\Sigma=0.34$
Exponential	$e^{-r/\lambda}$	$\sqrt{12}\lambda$		$\lambda=0.20$
Fermi, $\lambda/r_0=0.2$	$(e^{(r-r_0)/\lambda}+1)^{-1}$	$1.07r_0$		$r_0=0.56$

DPS searches: p-p → W⁺+2j

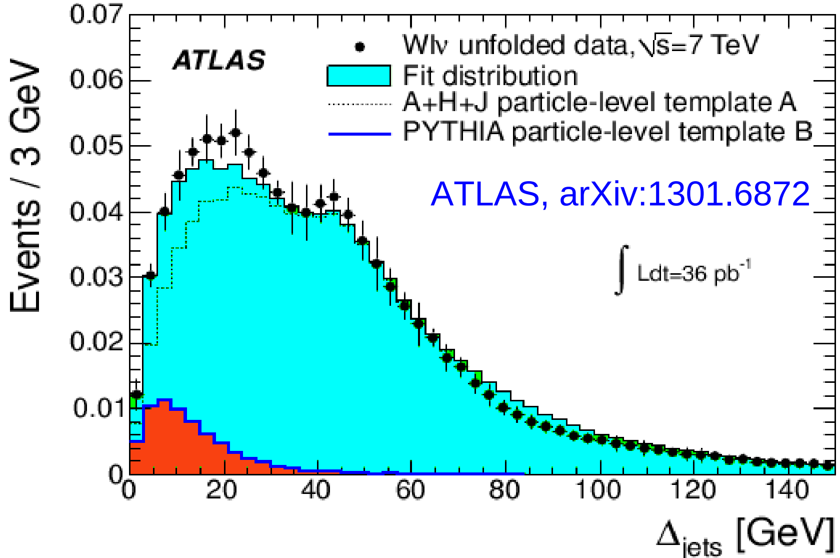
- Signal in W+2jets via di-jet asymetry observables sensitive to DPS:

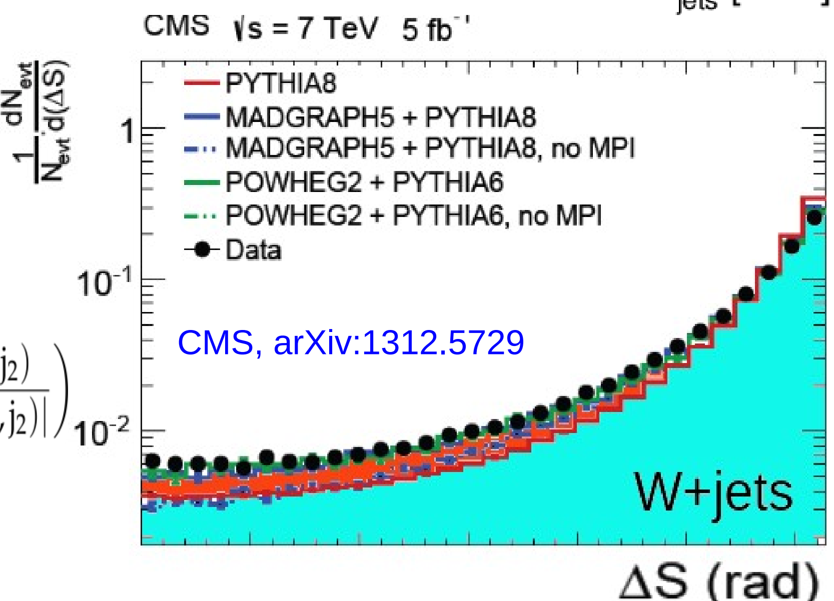
$$\Delta^{\mathrm{rel}} p_T = \frac{|\vec{p}_T(j1) + \vec{p}_T(j2)|}{|\vec{p}_T(j1)| + |\vec{p}_T(j2)|}$$





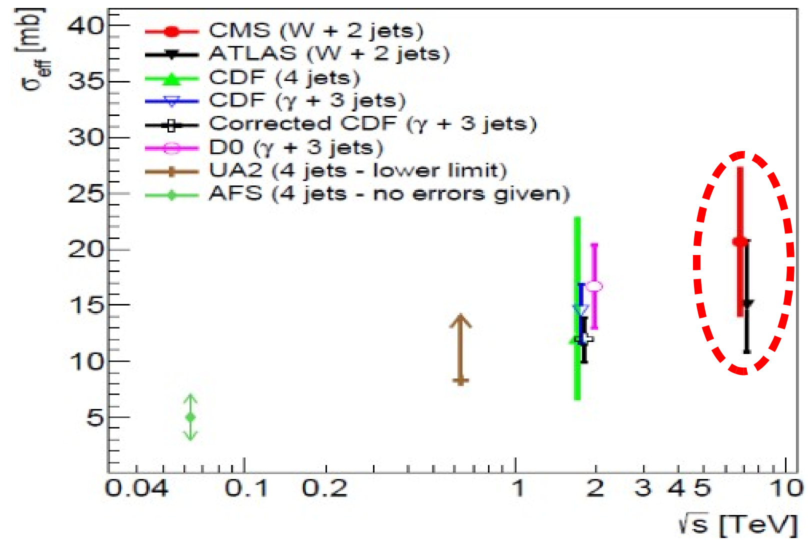
$$\Delta S = \arccos\left(\frac{\vec{p}_T(\mu, \not{E}_T)\cdot\vec{p}_T(j_1, j_2)}{|\vec{p}_T(\mu, \not{E}_T)|\cdot|\vec{p}_T(j_1, j_2)|}\right)$$





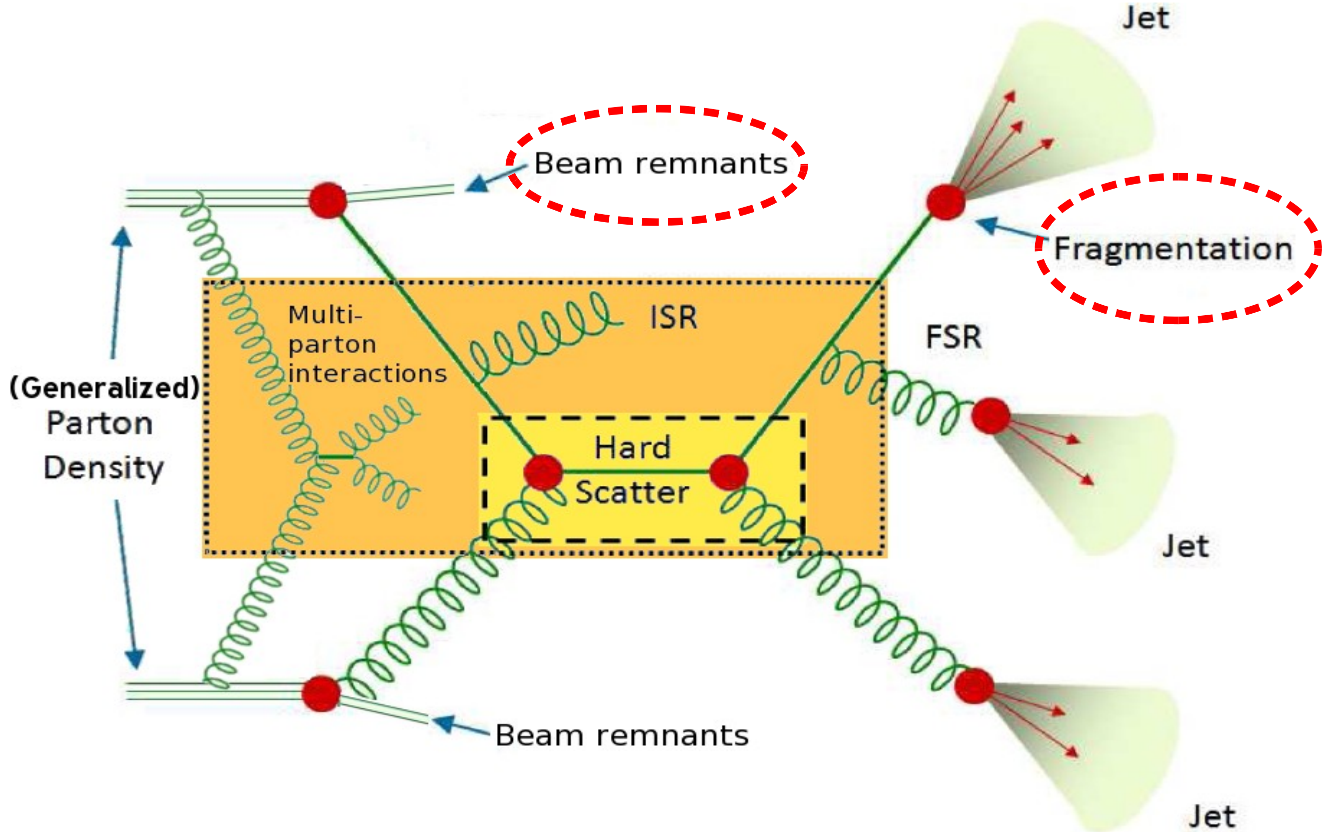
- Extracted σ_{eff} = 15 – 21 mb

(larger σ_{eff} than at smaller √s, more consistent with MPI proton profile)



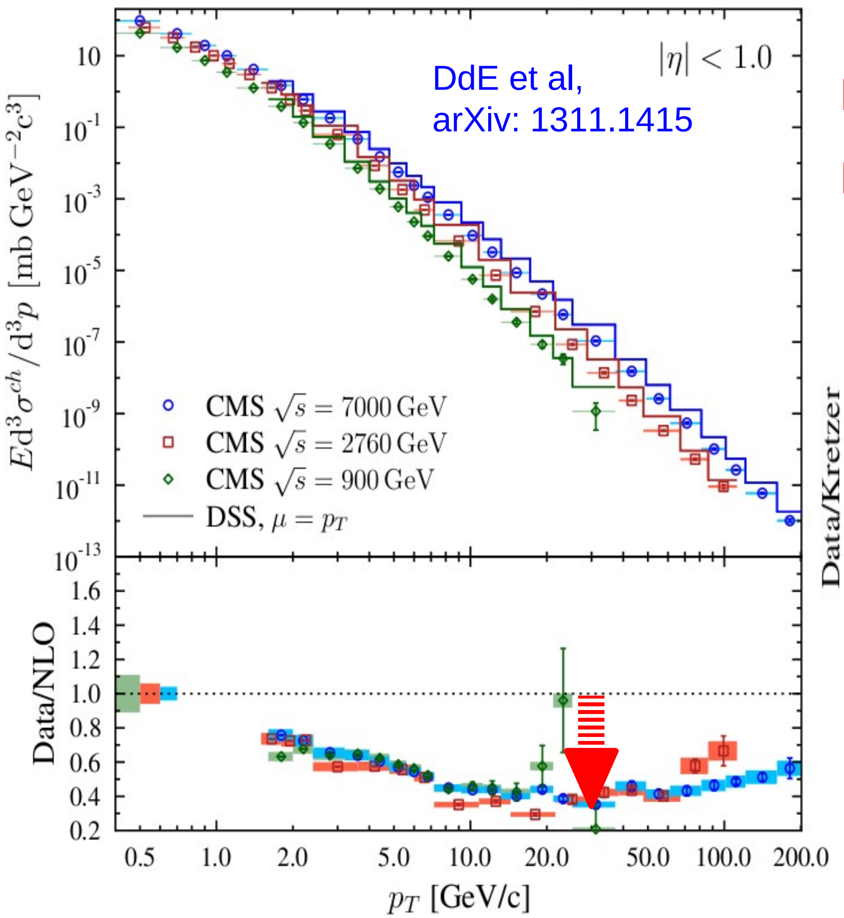
- Theoretical uncertainties:
  - Higher-order SPS contrib.
  - ME-jets & MPI-jets matching

Non-perturbative QCD at the LHC

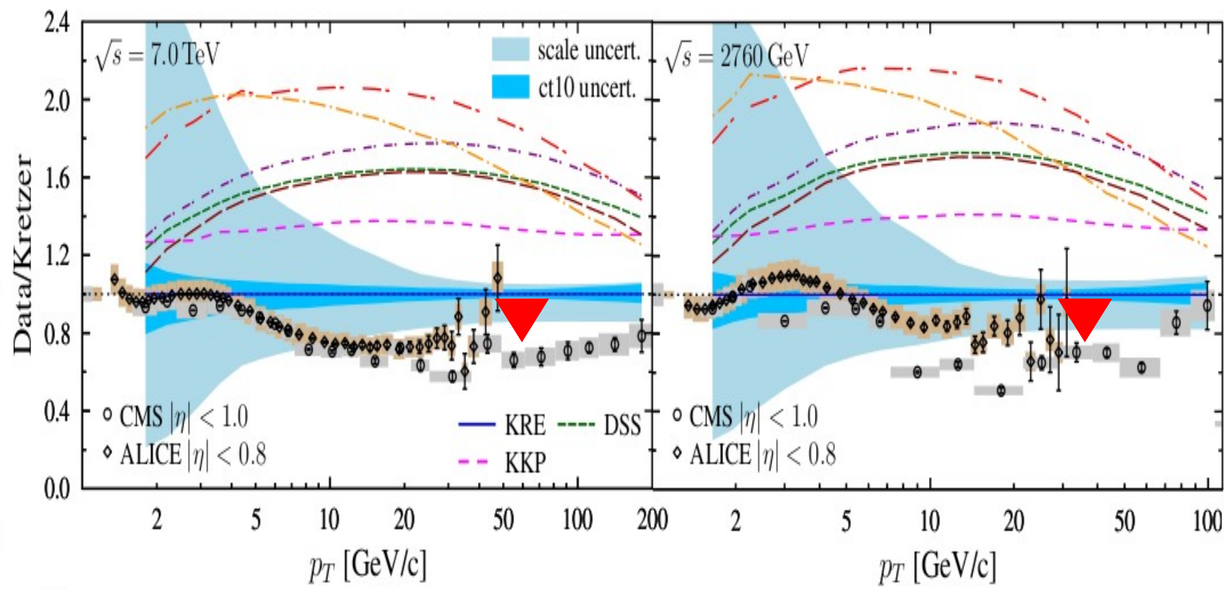


Parton fragmentation: LHC high-p_T hadrons

- NLO calculations overpredict high-p_T hadrons by factor x2 at Tevatron/LHC:



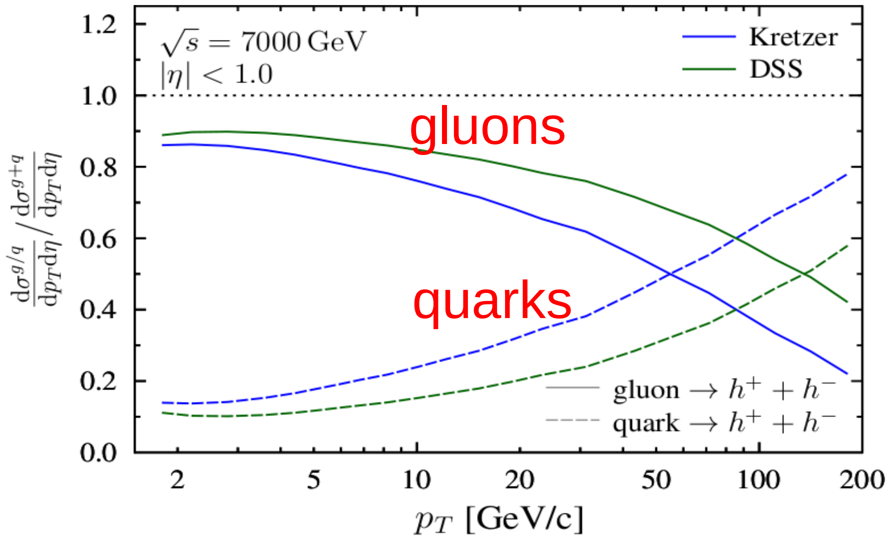
- All FFs fail. Disagreement increases √s=0.9-7 TeV
- “Old” Kretzer FF shows best agreement:

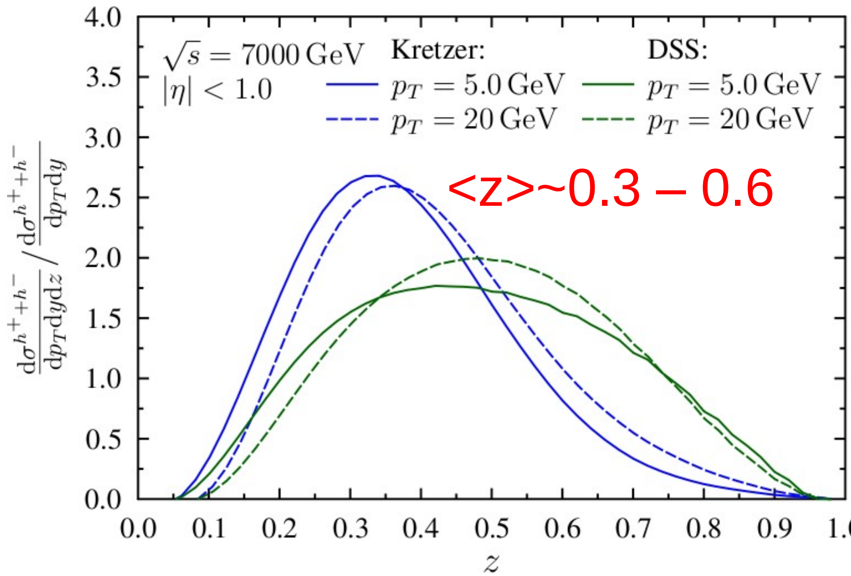


- Same NLO calculations reproduce well high-p_T jet and photon spectra: Problems in the modern parton-to-hadron FFs (refitted with RHIC data)

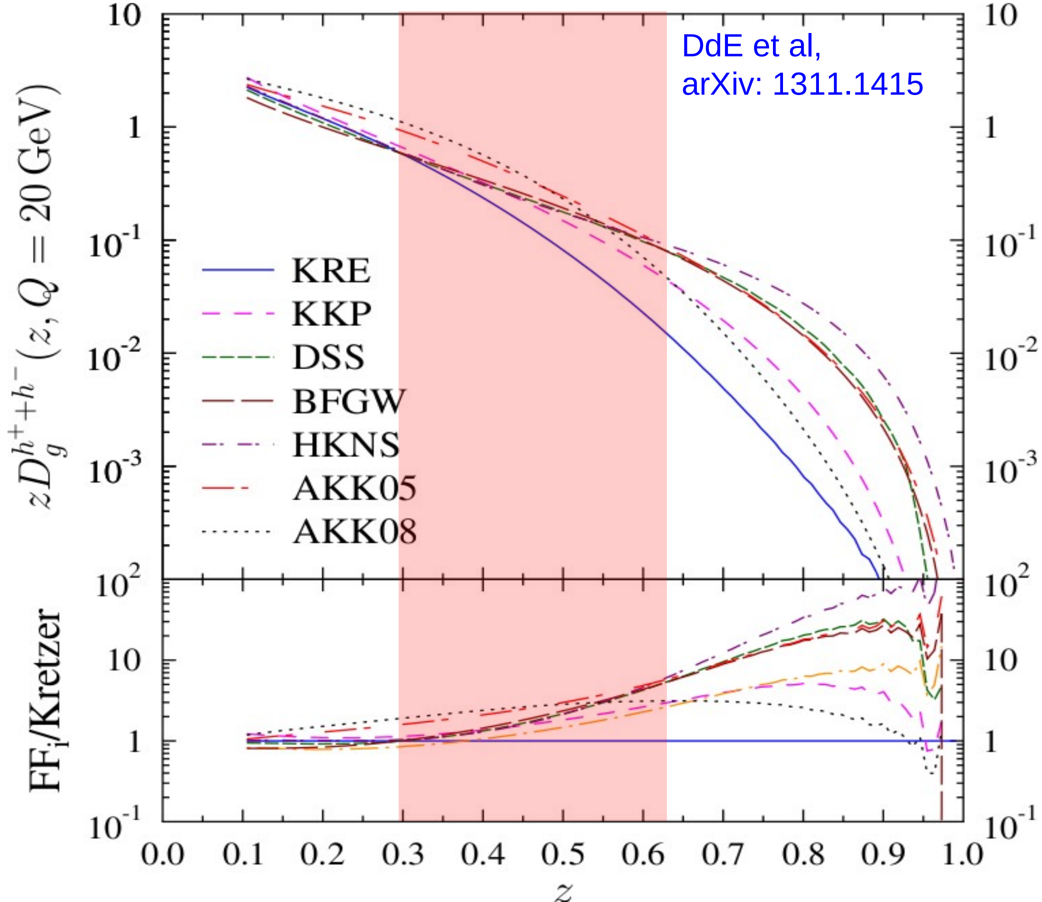
Parton fragmentation: unknown gluon FFs

- Dominant gluon production&fragmentation up to p_T~50 GeV with <z>~0.3–0.6





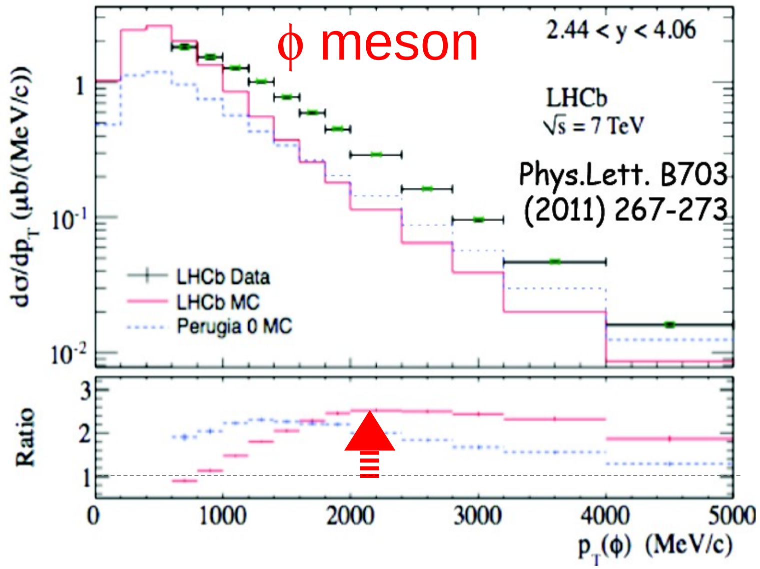
Very large differences on gluon-to-hadron FFs

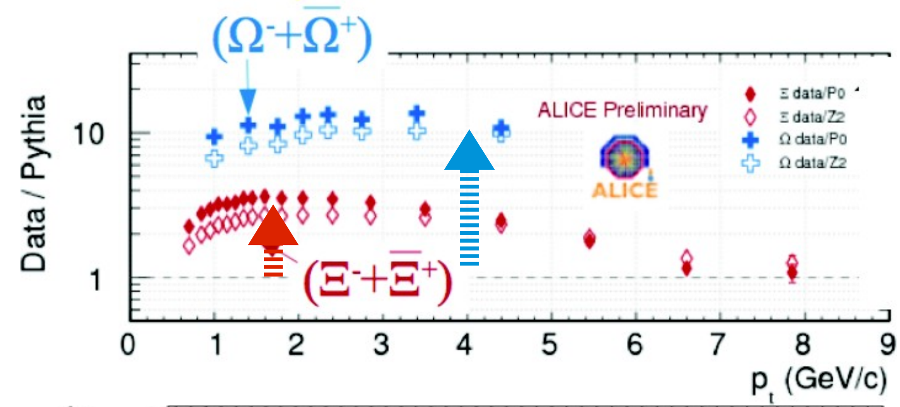


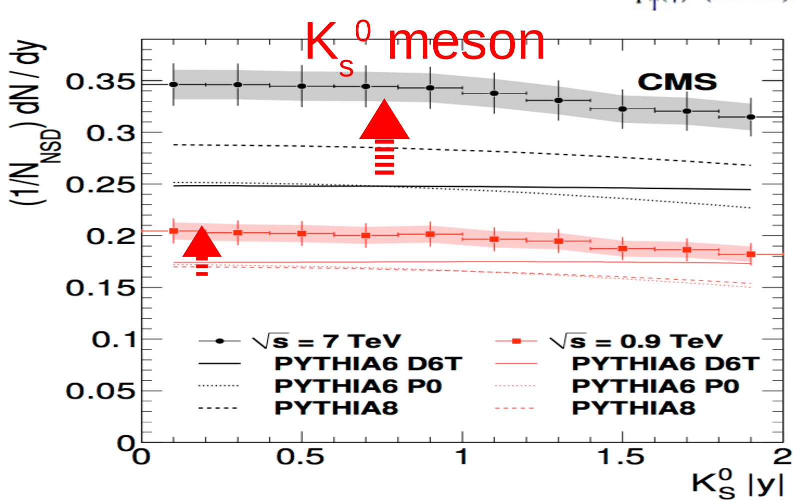
- Modern gluon FFs are too hard.
  Need to refit them with LHC data.

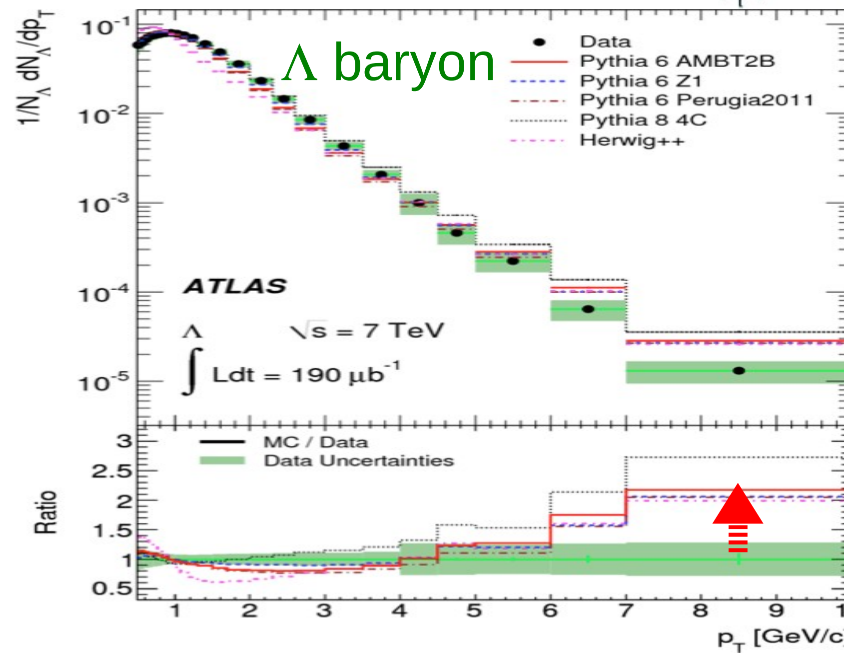
Parton fragmentation: LHC identified hadrons

- LEP-tuned MCs ~OK for π,p but not for most strangeness & baryons:









- Extra final-state effects in p-p ? Is hadronization "universal" ?

Cross sections in p-p collisions

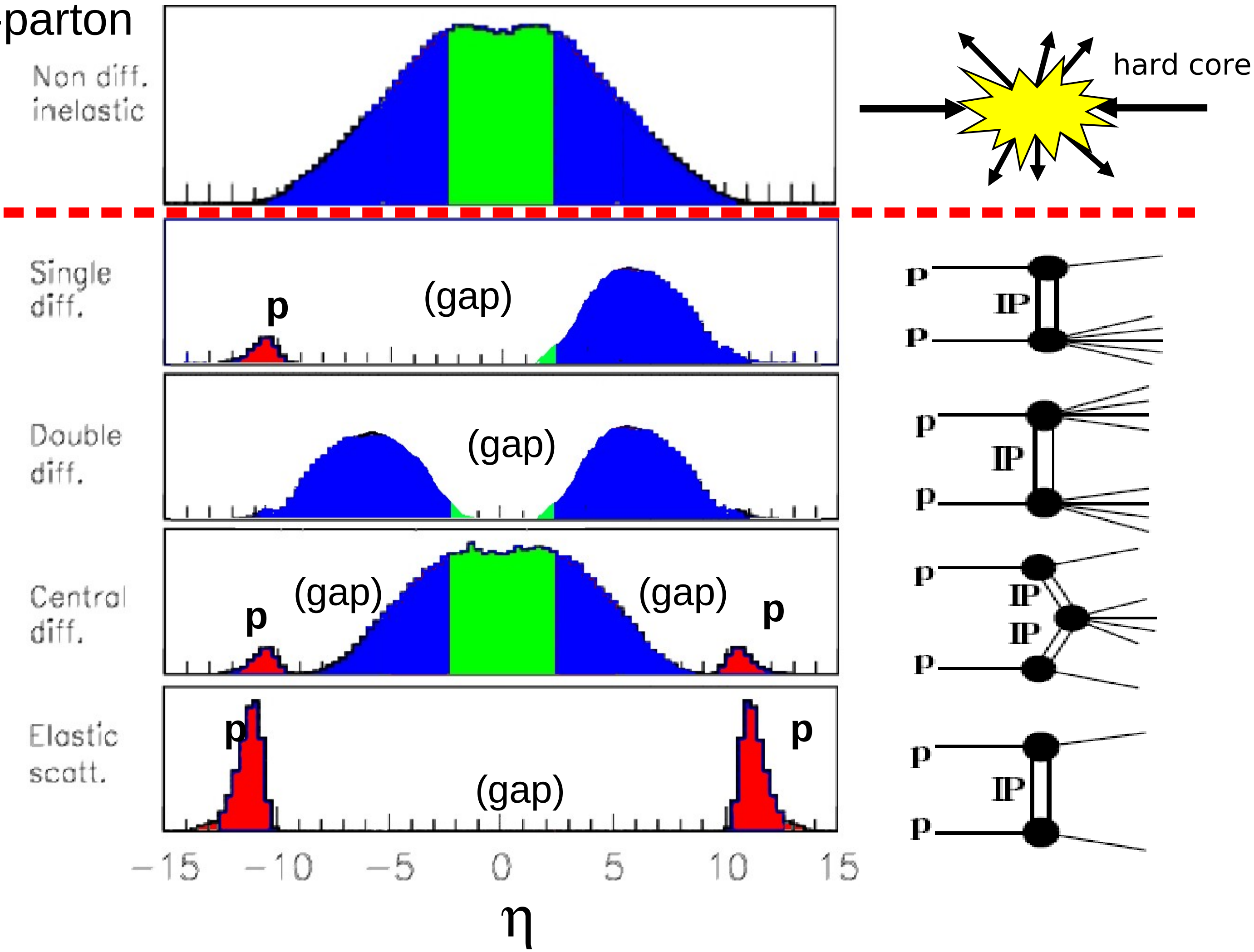
(1) Perturbative parton-parton collisions

~60%

(2) Diffractive + elastic

~40%

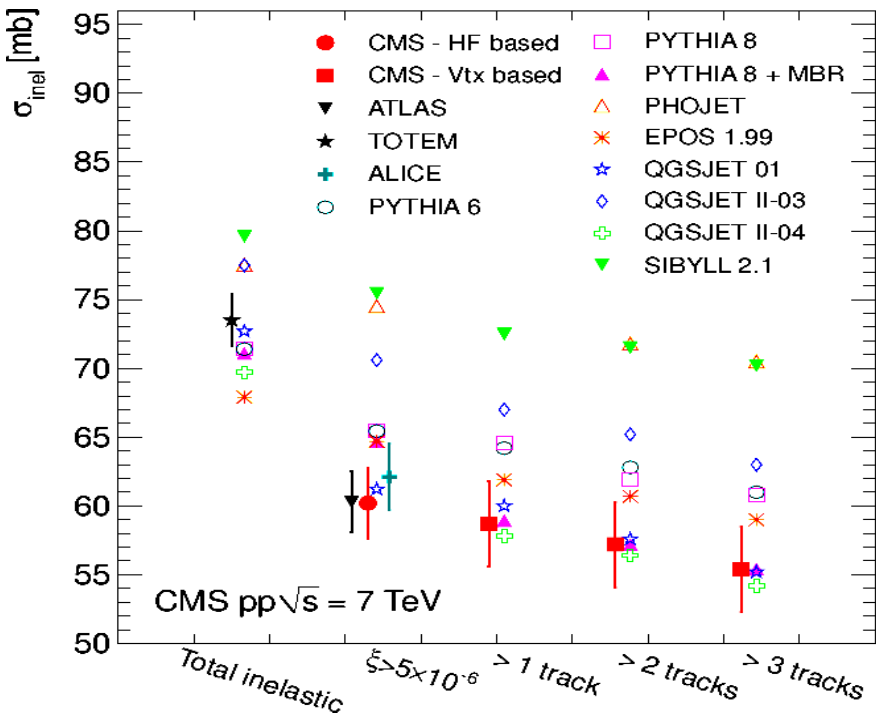
- 1 or 2 protons intact. + 1 or 2 rapidity gaps:
- No colour flux.
- Colourless exchange with vacuum $J^{PC}=0^{++}$ quantum-numbers: |Pomeron = 2-gluons in colour-singlet state.

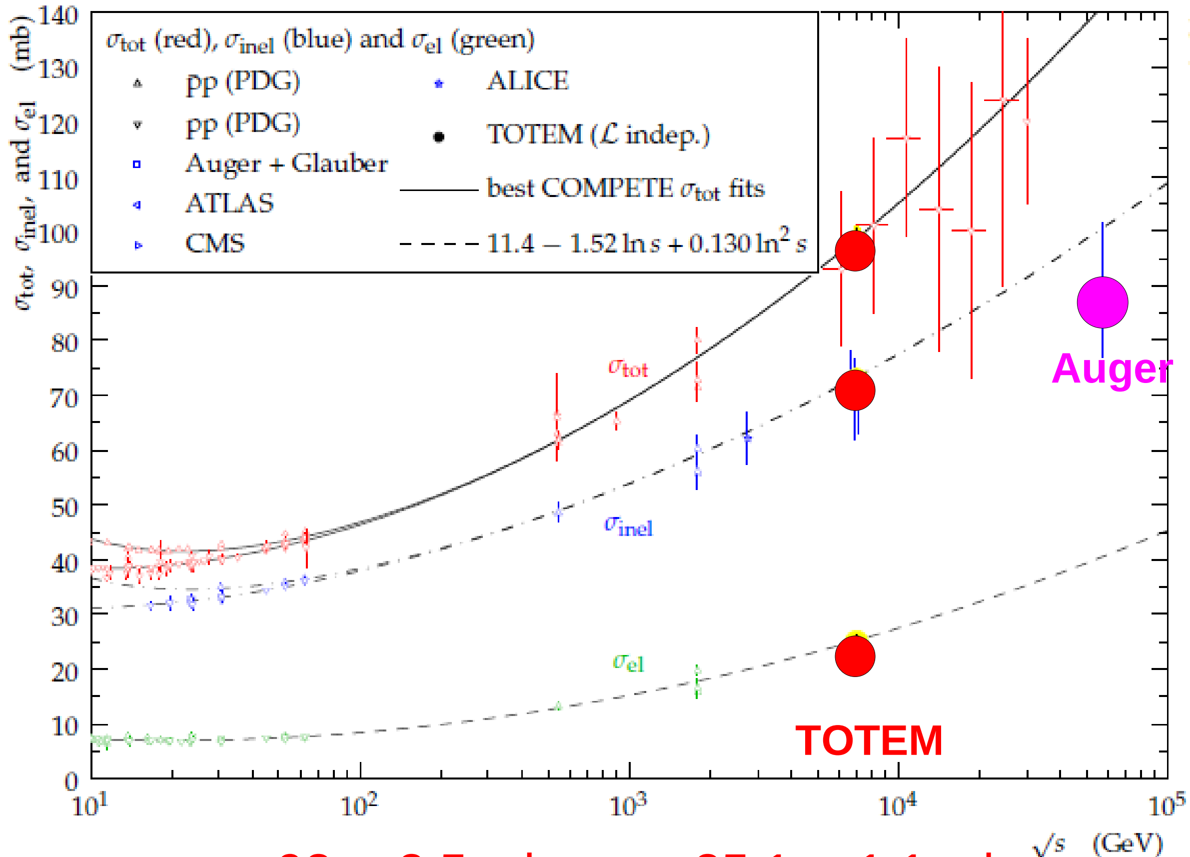


- pQCD (~60 mb) + elastic (~25 mb) + diffractive (~15mb) ~ 100 mb at the LHC.

Inelastic, elastic & total p-p x-sections at 7 TeV

- Non-computable from QCD Lagrangian (maybe lattice?), but constrained by fundamental QM relations: Froisart bound, optical theorem, dispersion relations.





Inelastic: $\sigma_{TOTEM} \sim 73$ mb

Visible inelastic: $\sigma_{Atlas,CMS} \sim 60$ mb

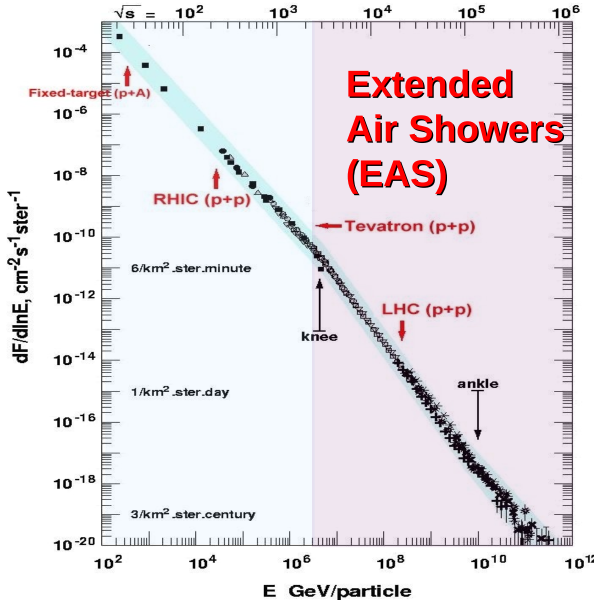
$\sigma_{TOT} = 98 \pm 2.5$ mb, $\sigma_{el.} = 25.1 \pm 1.1$ mb

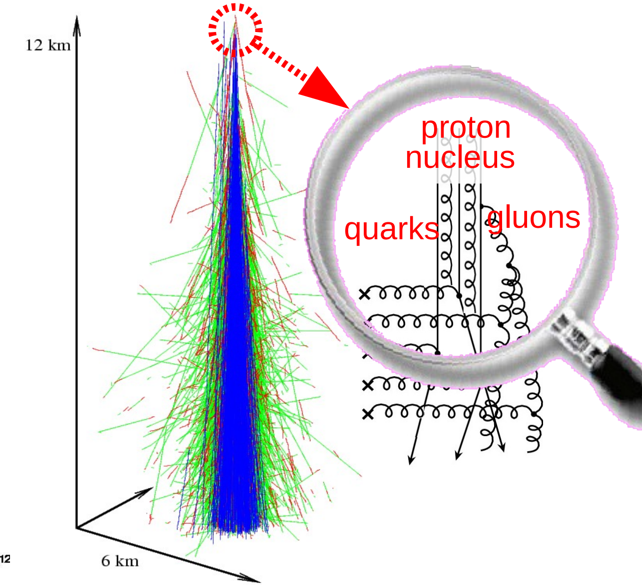
- Most MCs over(under)estimate high(low)-mass diffraction

  New data provide extra constraints on hadronic MCs

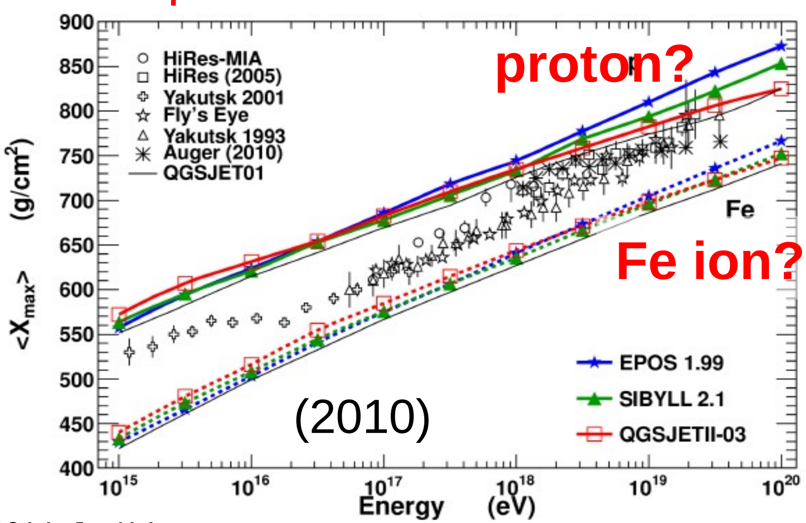
Soft QCD at LHC: Impact on UHE cosmic ray MCs

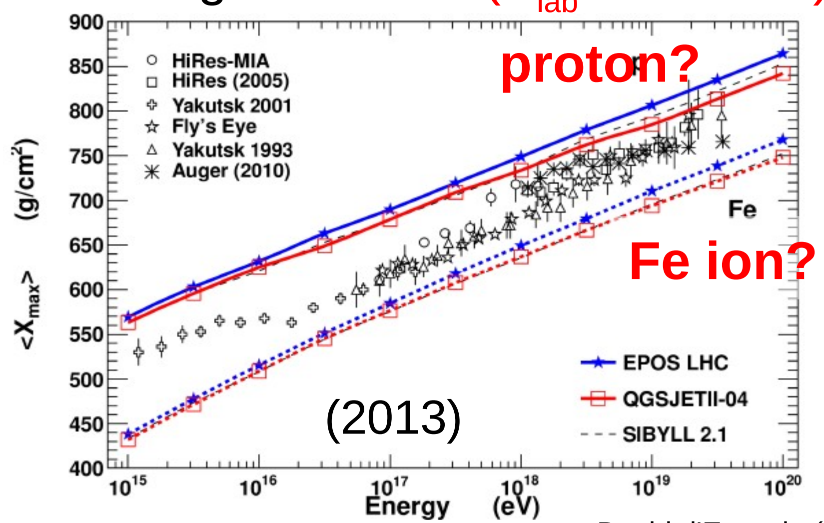
- CR energy & identity above 10^{15} GeV via comparison of air-showers with hadronic MCs (Regge-Gribov FT extended to pQCD via “cut Pomerons”).





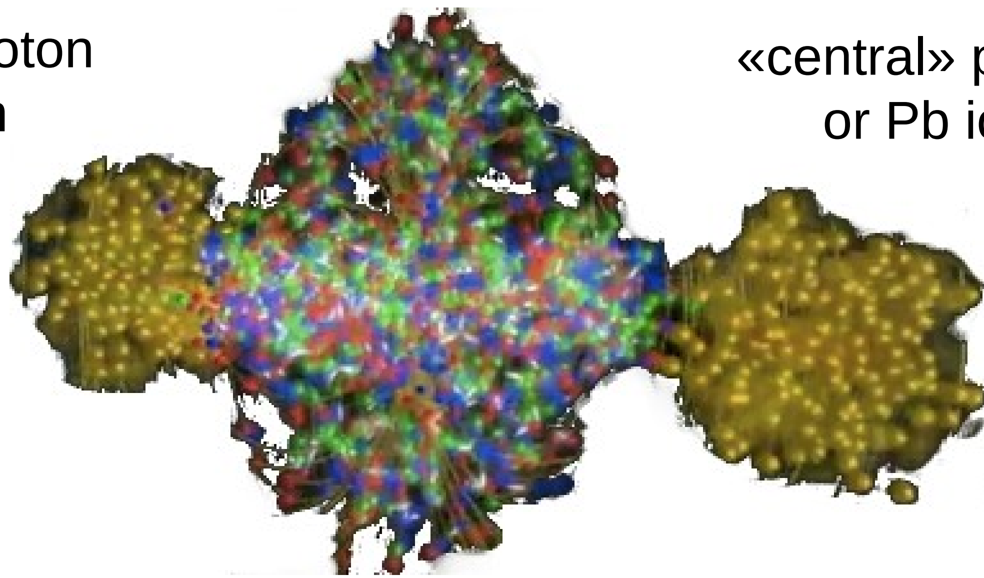
- MC retuned to LHC data: e.g. reduced σ(p-p) ⇒ deeper shower X_{max}
- Mixed p-Fe UHECRs at GZK-cutoff after including LHC data (E_{lab} ~ 10^{17} eV):





“Many-body” QCD at the LHC

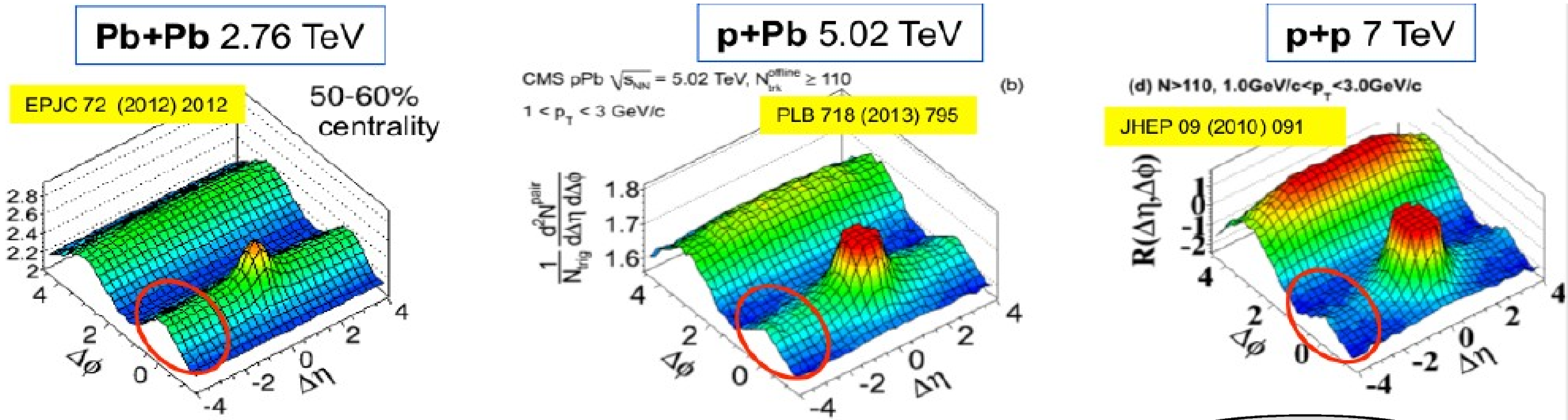
«central» proton
or Pb ion



«central» proton
or Pb ion

"Ridge" of correlated hadron production

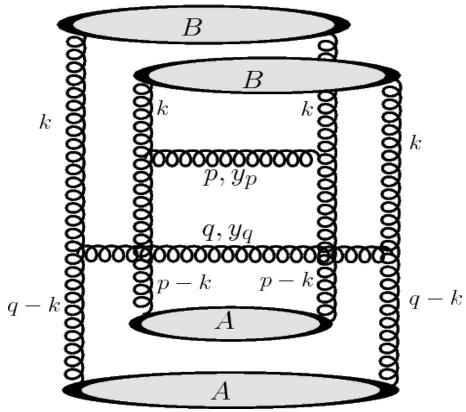
- Observation of long-range (over $\Delta\eta$~8 !) near-side hadron correlations "ridge" in "central" (high multiplicity) collisions:



- Initial-state ? Correlated gluons around Q_{sat} ?

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

Multiparton interactions enhance the near-side diagrams

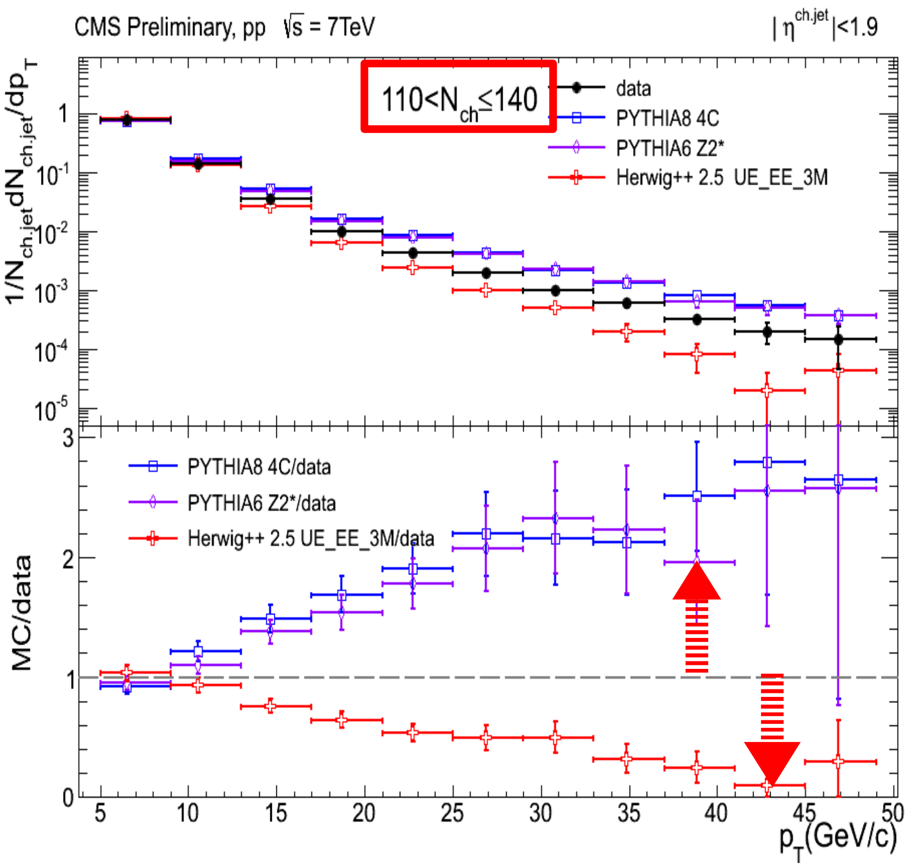


- Final-state ? Collective parton-flow ? PYTHIA(pp) + β_T ~ 0.5 generates such structure too

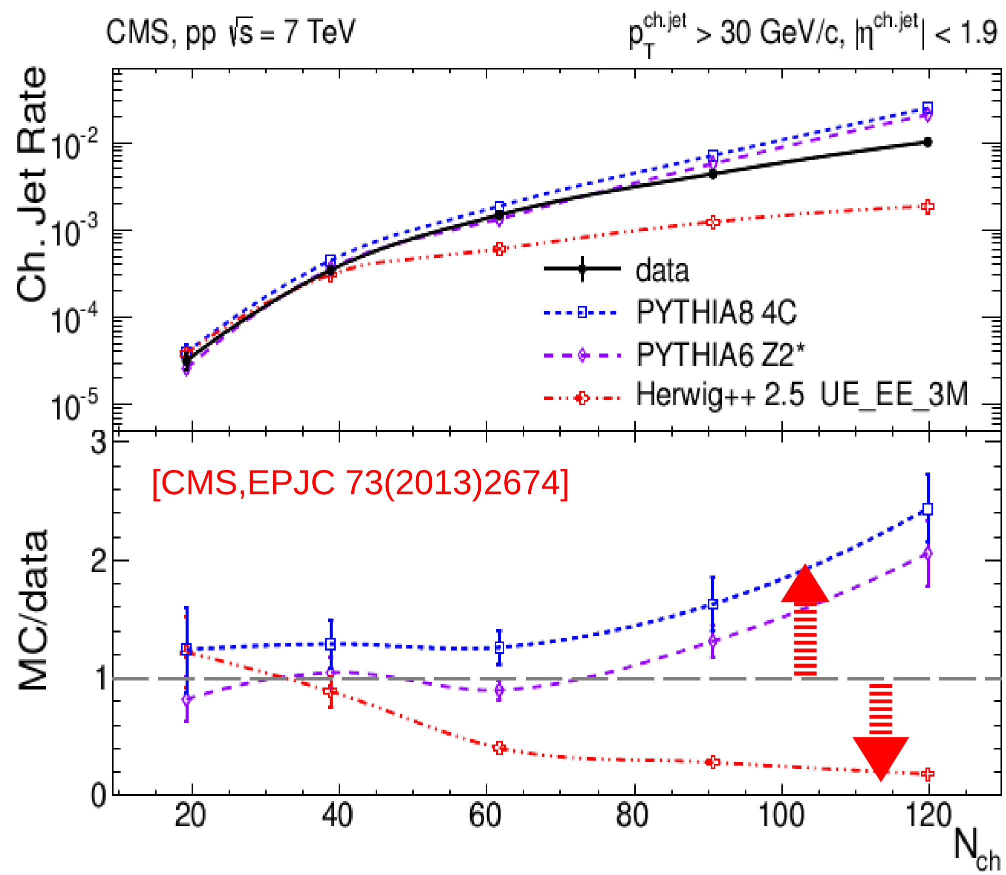
Jet production in “central” p-p collisions

- Are jets modified in central p-p at 7 TeV (as seen in Pb-Pb) ?

Jet spectra in most central p-p:



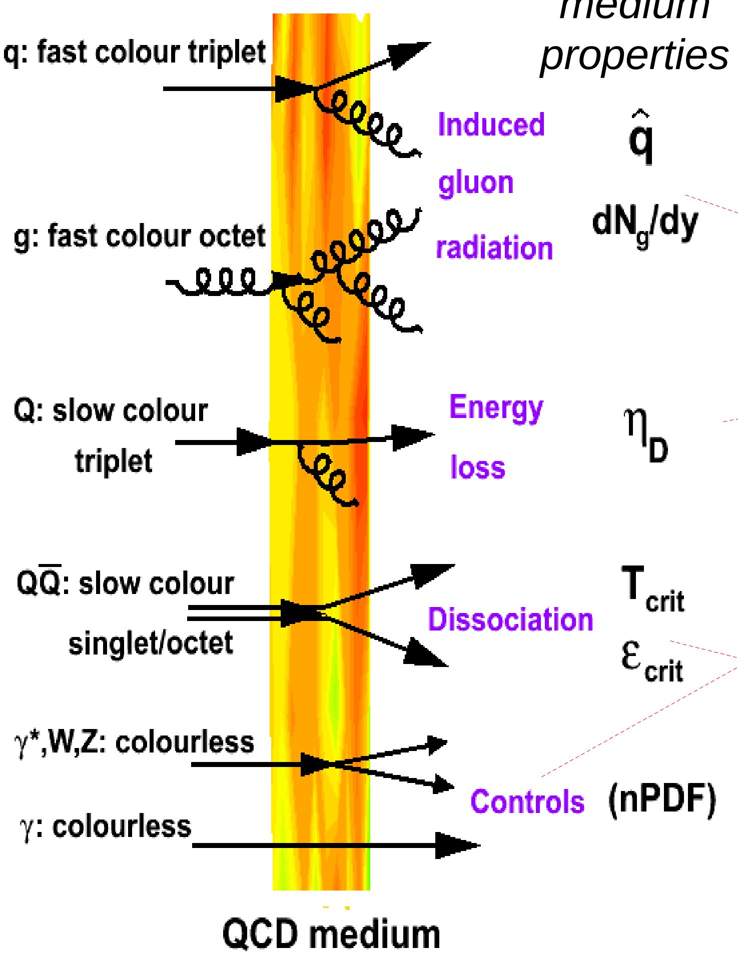
Jet rates versus particle multiplicity:



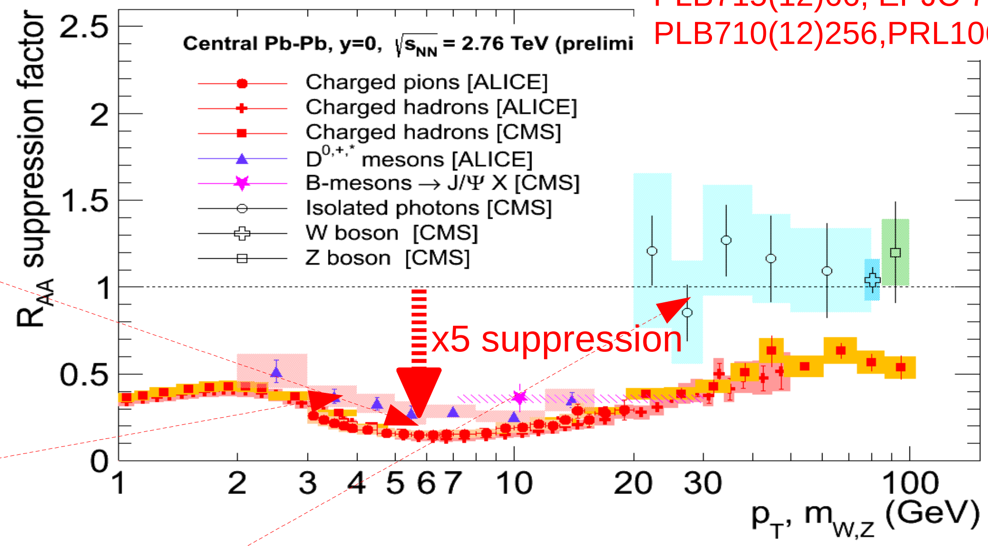
- PYTHIA (HERWIG) over(under)predicts jet hardness & rates at the highest multiplicities: Retuning and/or new model ingredients needed

QCD plasma: q,g,$Q\bar{Q}$ suppression in Pb-Pb

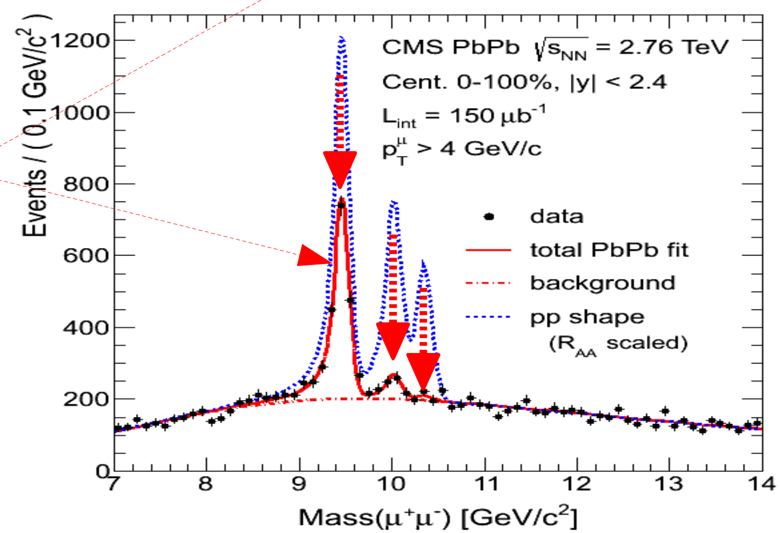
- Yields of strongly-interacting particles suppressed in Pb-Pb compared to p-p. Weakly probes (γ,W,Z) unmodified by medium:



PLB715(12)66, EPJC 72(12)1945
PLB710(12)256,PRL106(11) 212301



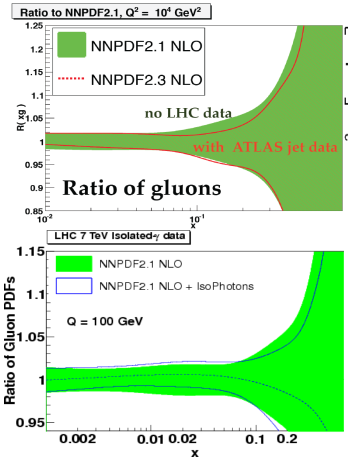
PRL109(12)222301

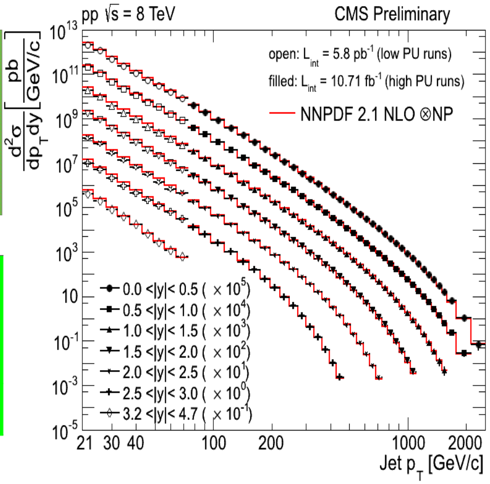


Υ(1S,2S,3S) yields suppressed as expected by seq. «melting» of b-bbar resonances in QGP

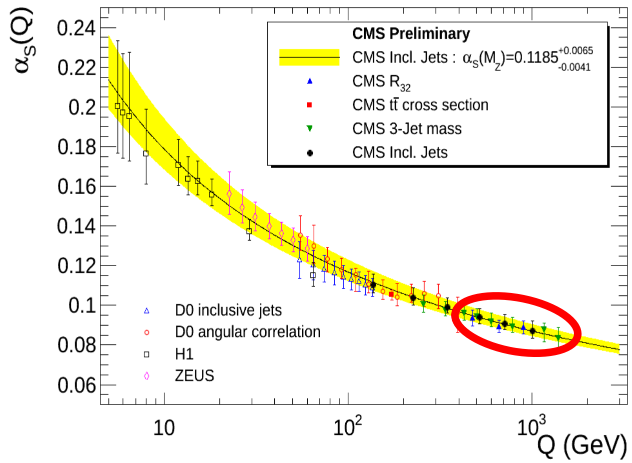
Summary: 3 years of QCD at the LHC

- Precision (N)NLO PDFs via jets, isolated-γ, W,Z, top

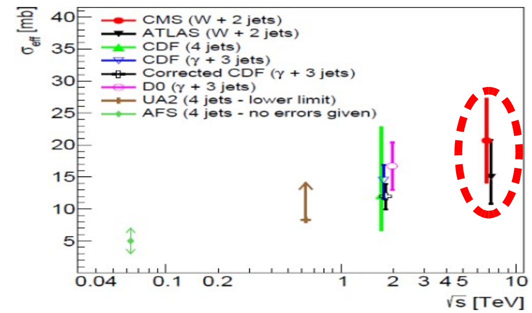




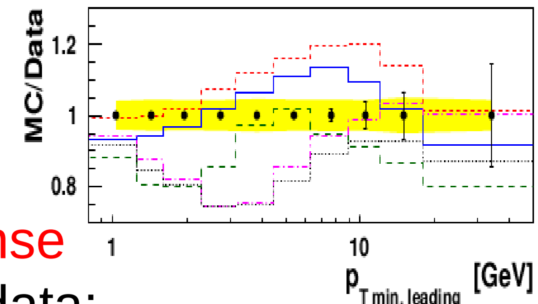
- Test of fundamental SM parameters: α_s



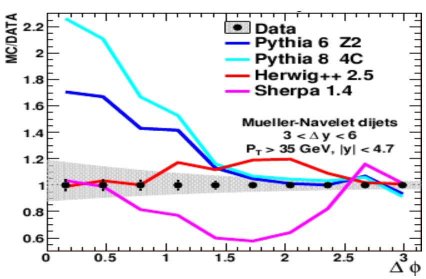
- Generalized PDFs via MPI & DPS



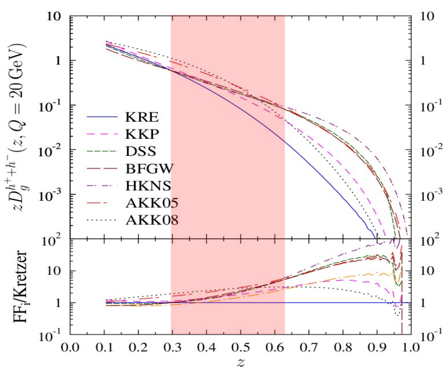
- Minijets at Q_{sat}



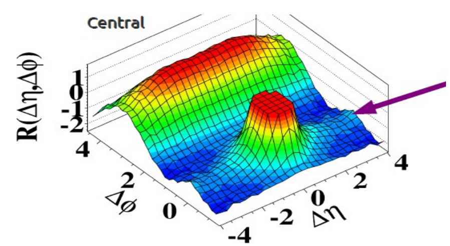
- «Beyond DGLAP» searches

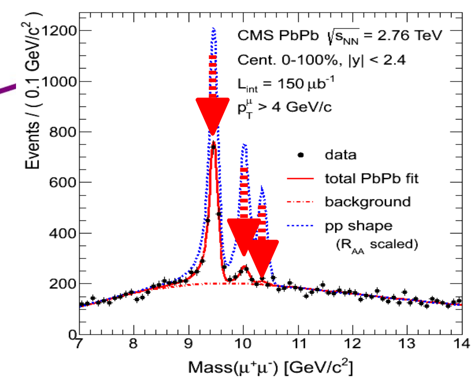


- Parton FFs problems



- Intriguing dense QCD-matter data:





- Exciting QCD results in Run-1 p-p, p-Pb, Pb-Pb !
- Data (up to 14 TeV) back in April 2015 !

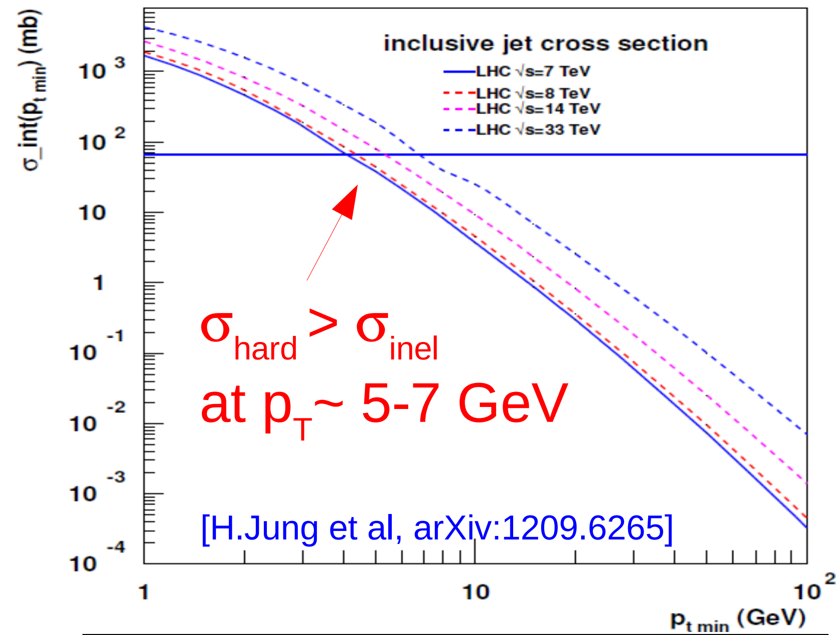
Back up slides

Unitarity of pQCD x-sections: saturation scale

- 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 ?

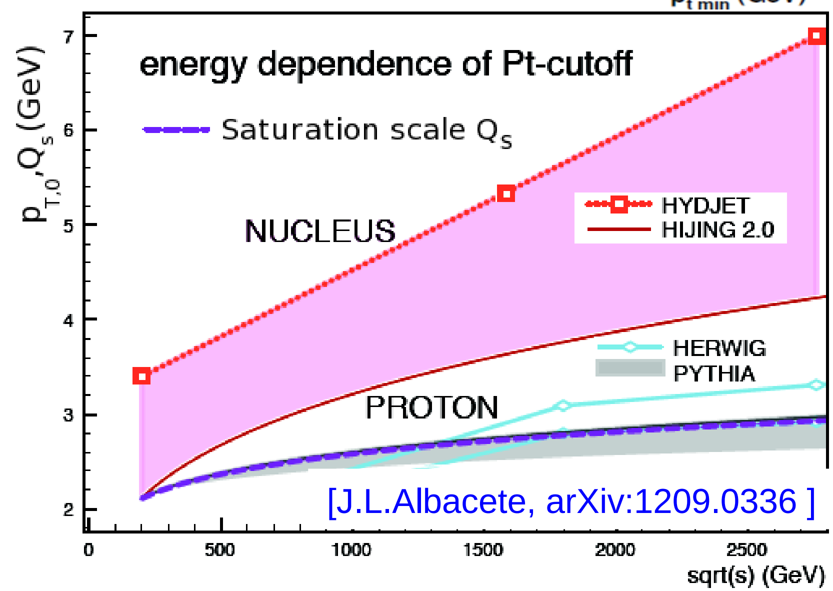


- Very high gluon densities at small-x
- Solution (1): Gluon saturation around perturbative "saturation scale" Q_s:

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

- Enhanced in nuclei (larger g density):

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



Double Parton Scattering x-sections

- pQCD factorized expression for DPS x-section:

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

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

- Assumption 1: factorization of transverse & longitudinal components

$$\Gamma_h^{ij}(x_1,x_2;\mathbf{b_1},\mathbf{b_2};Q_1^2,Q_2^2) = D_h^{ij}(x_1,x_2;Q_1^2,Q_2^2)\,f(\mathbf{b_1})f(\mathbf{b_2})$$

p-p overlap function:

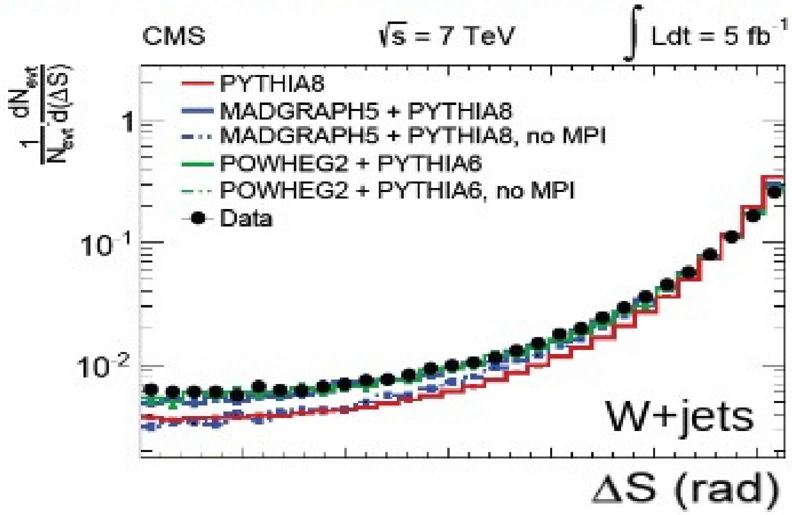
$$t(\mathbf{b}) = \int f(\mathbf{b_1})f(\mathbf{b_1}-\mathbf{b})d^2b_1$$

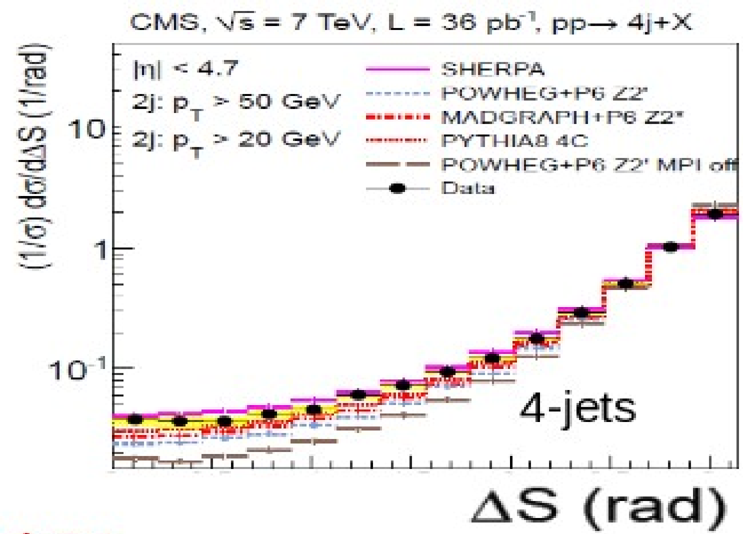
- Assumption 2: double-PDF= product of 2 single PDF (no correlations)

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

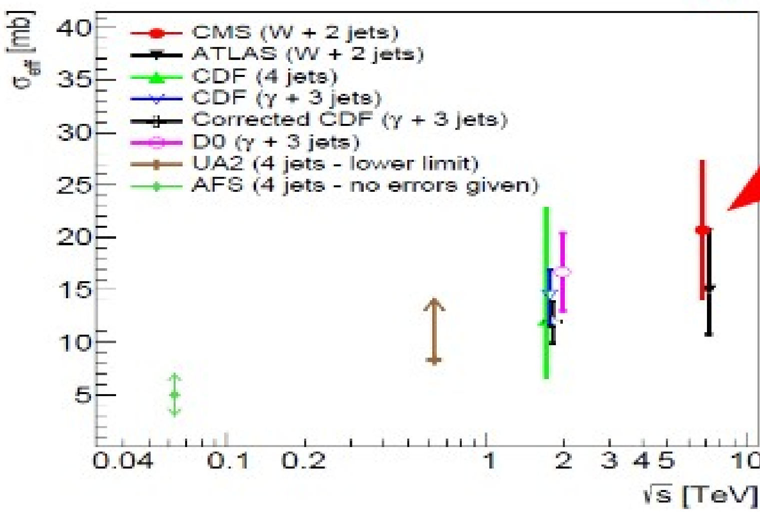
Double Parton Scattering at the LHC

- DPS-sensitive differential x-sections (fully unfolded) in W+jets, 4-jets:





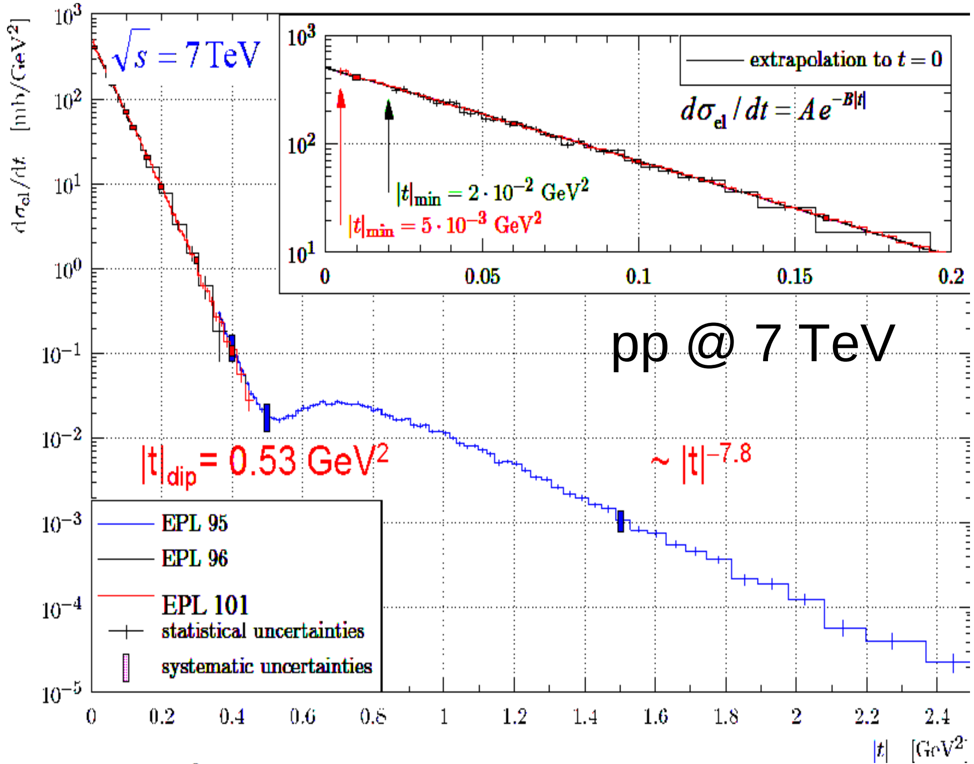
- Measurement of the DPS σ_{eff} in W+jets:

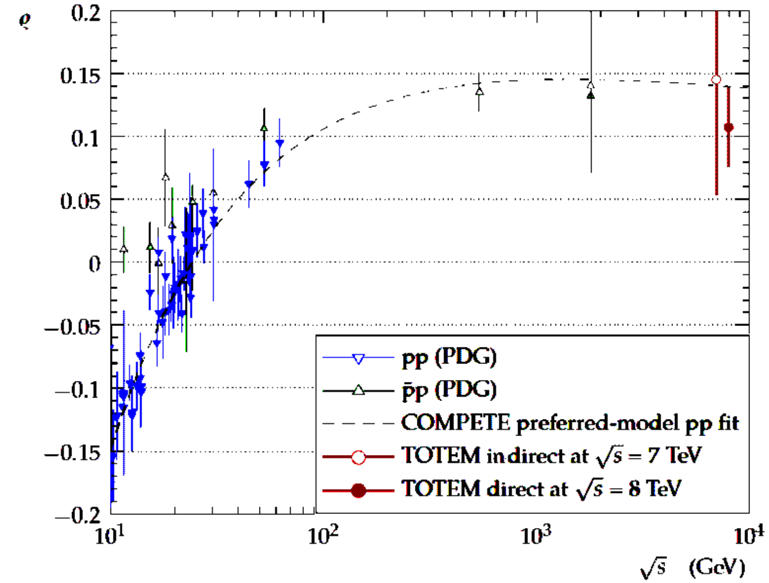


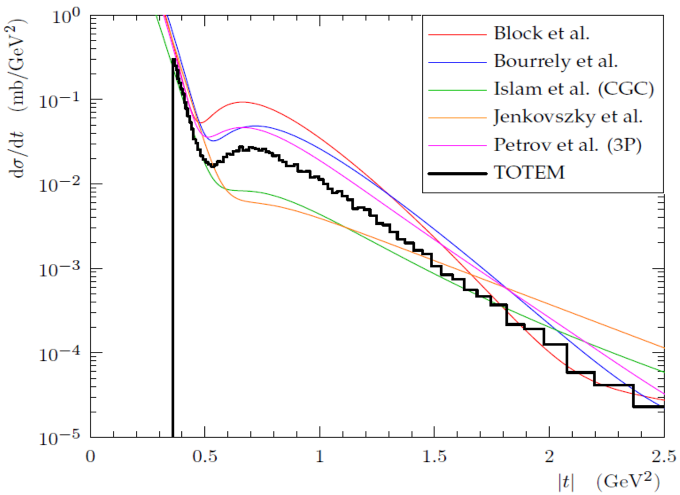
σ_{eff} = 20.7 ± 0.8 ± 6.5 mb

- Between latest Tevatron average (13.9±1.5 mb) & value preferred by LHC UE tunes (20-35 mb), but still compatible with both

Differential elastic p-p cross sections (Totem)



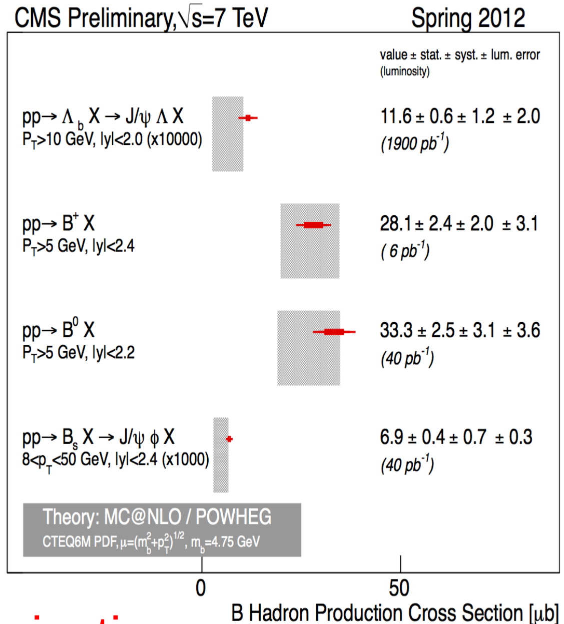


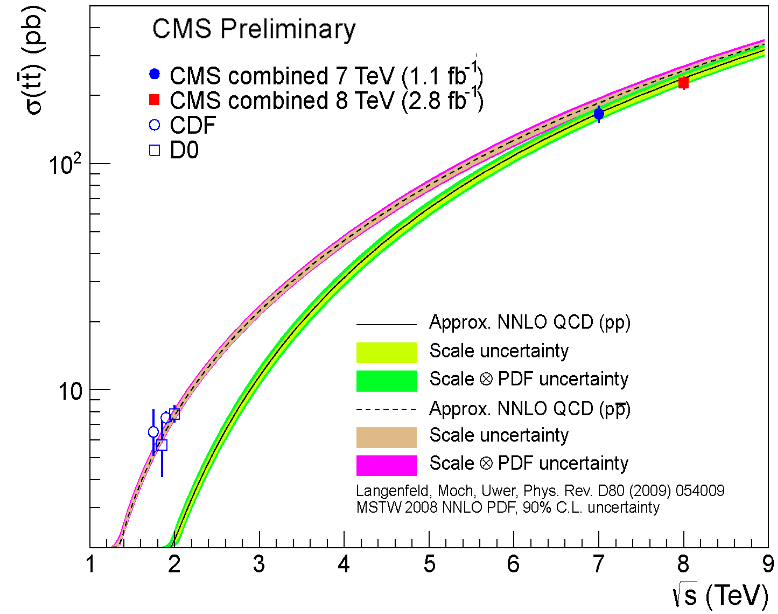


- TOTEM has confirmed :
  - Increase of σ_{el}/σ_{tot}
  - Decrease of inverse expo slope
  - Shrinkage of diffraction peak
  - Decrease of dip t-position
- But so far only partial quantitative agreement with model predictions.

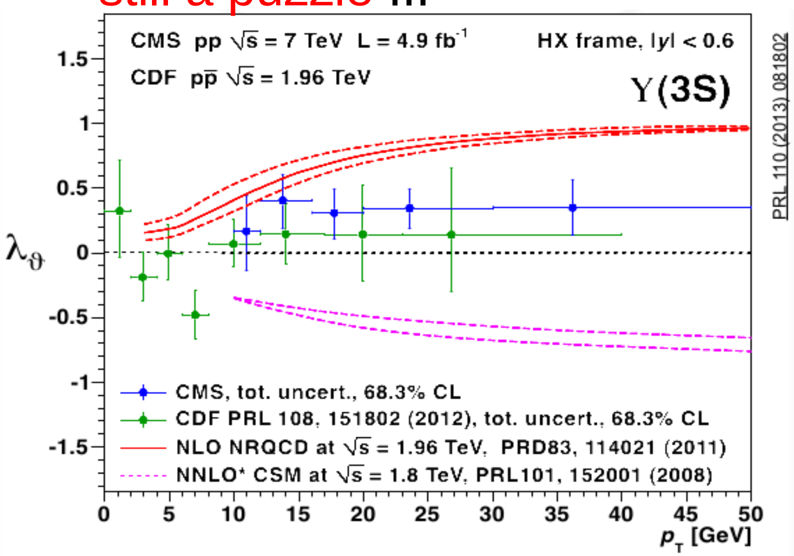
Heavy-Q cross-sections & $Q\bar{Q}$ polarization

- Bottom & top x-sections in good agreement with NLO (approx. NNLO) predictions:





- Although quarkonia polarization still a puzzle ...



- Quality of differential top x-sections can constrain gluon (N)NLO PDF: