Low-x and forward physics at HERA and the LHC

Workshop on High-energy QCD and nucleon structure

7 March 2014 @ KEK Tokai campus

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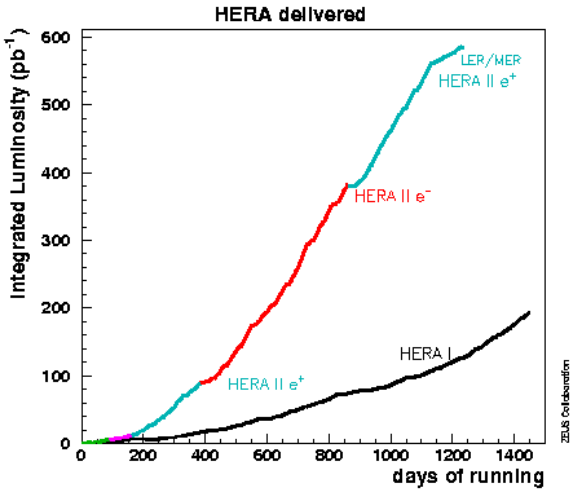
Today's subjects

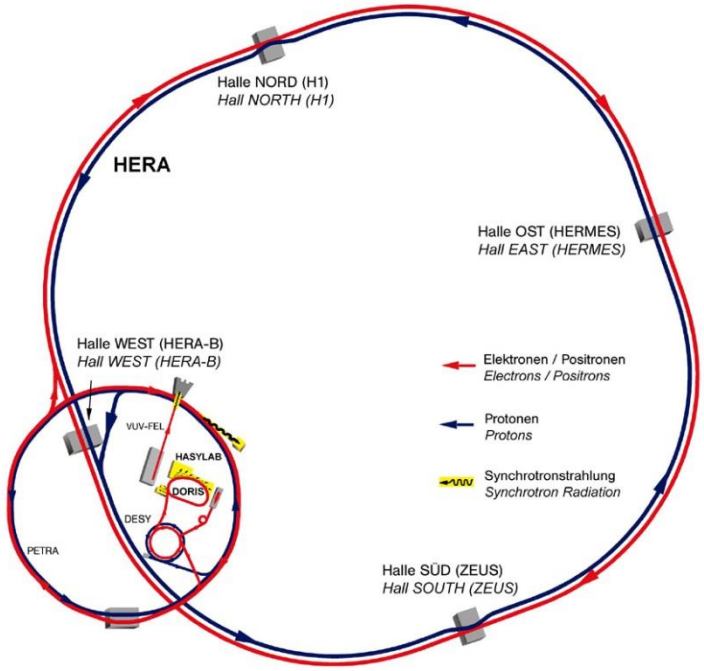
Low-x: high-density quark matter
(multi-)partons interact coherently/incoherently

1. Did we learn anything about unpolarised parton densities at the LHC?
2. Can we draw consistent picture on forward physics between HERA, Tevatron and the LHC?
   - Total cross sections
   - Diffractive scattering
   - Multi-parton interactions
3. Perturbative QCD at the LHC: personal selection
   - Multi-leg simulation, Fat jet
   - α_s at the TeV scale

HERA 1992-2007

- The only $e^{\pm}p$ collider, with the energy comparable to other pp and heavy ion colliders
  - 27.5 GeV e × 920 GeV p
  - Luminosity upgrade 2001-2003
  - 0.1fb^{-1}/experiment before upgrade
  - 0.5fb^{-1} when finished





The LHC

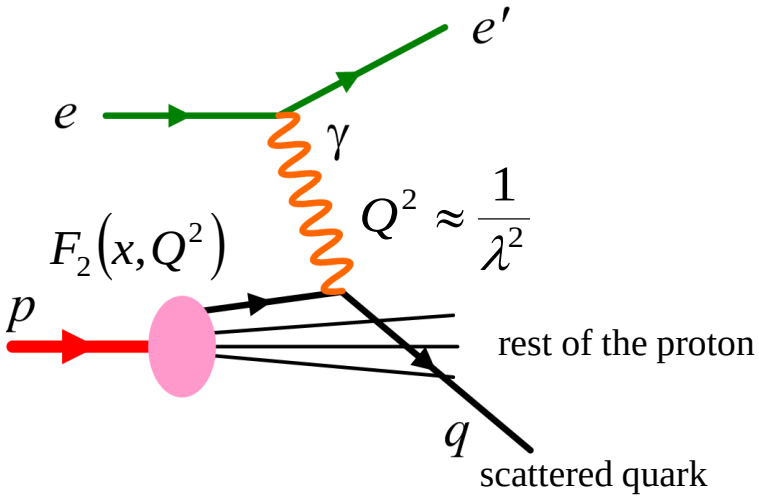
We are here

- Run-I finished
  - at 7/8 TeV with > 25 fb^{-1}
  - $L \gtrsim 7 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - small amount of data at 900 GeV, 2.76 TeV
  - Pb-Pb and p-Pb runs
- Restarting run-II in 2015
  - ~ 13 TeV CMS energy
  - $L > (1.x) \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - Further upgrade in 2019 and 2023 (SLHC) with $L \gtrsim 5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

2009	Startup	
2010		
2011	Run1	$25\mathrm{fb}^{-1}$
2012	$\sqrt{s} = 7-8\ \mathrm{TeV}, L = 7 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	
2013	Phase-0 upgrade	Muon: TGC inner stations
2014		
2015	$\sqrt{s} = 13\ -14\ \mathrm{TeV}, L = 1\sim2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	
2016	Run2	$100\mathrm{fb}^{-1}$
2017		
2018	Phase-1 upgrade	Muon: New Small Wheel
2019	$\sqrt{s} = 14\ \mathrm{TeV}, L \gtrsim 2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	
2020	Run3	$300\mathrm{fb}^{-1}$
2021		
2022	Phase-2 upgrade	
2023	$\sqrt{s} = 14\ \mathrm{TeV}, L \gtrsim 2 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	
~203x	Run3	$3000\mathrm{fb}^{-1}$

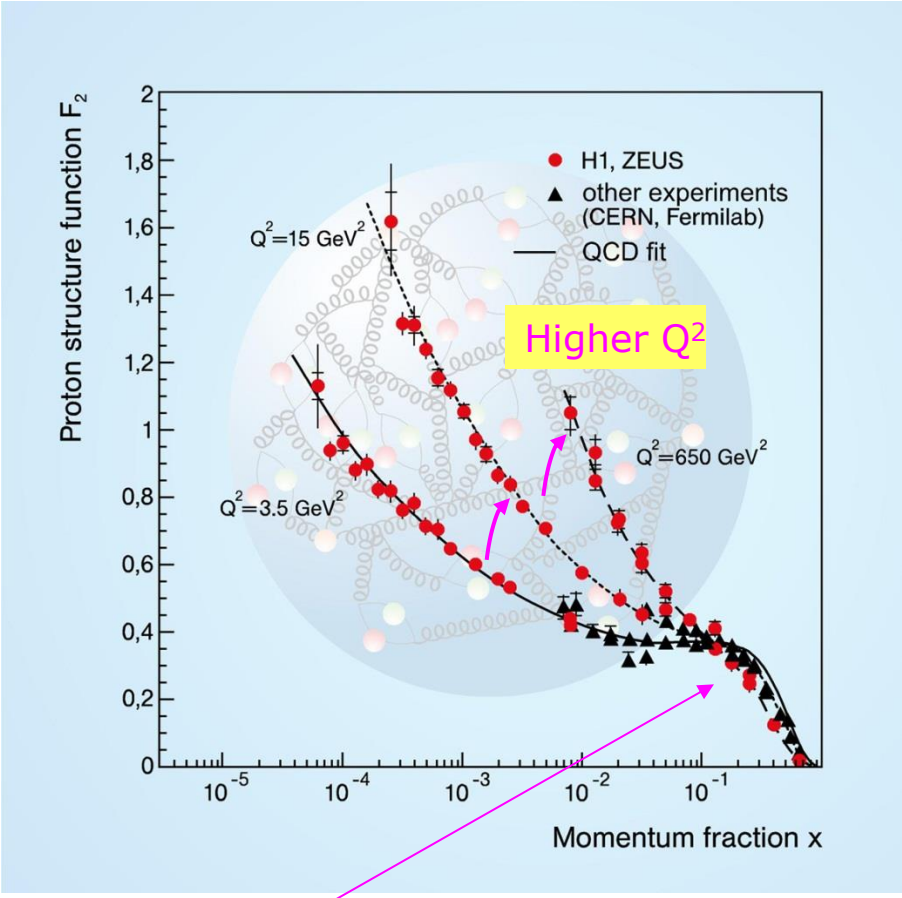
Parton densities at HERA and the LHC

Parton densities at low-x by ep collisions



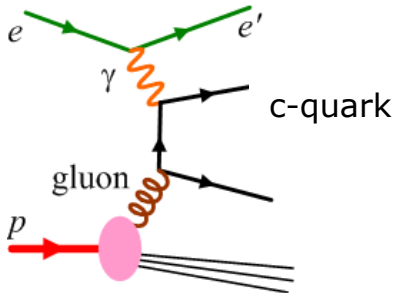
- Rapid increase in
  $F_2(x,Q^2) = e^2 x\big(q(x) + \bar{q}(x)\big)$
  towards low-x

$x \approx p_{parton}/p_{proton}$
$Q^2 = -(p'_e - p_e)^2$

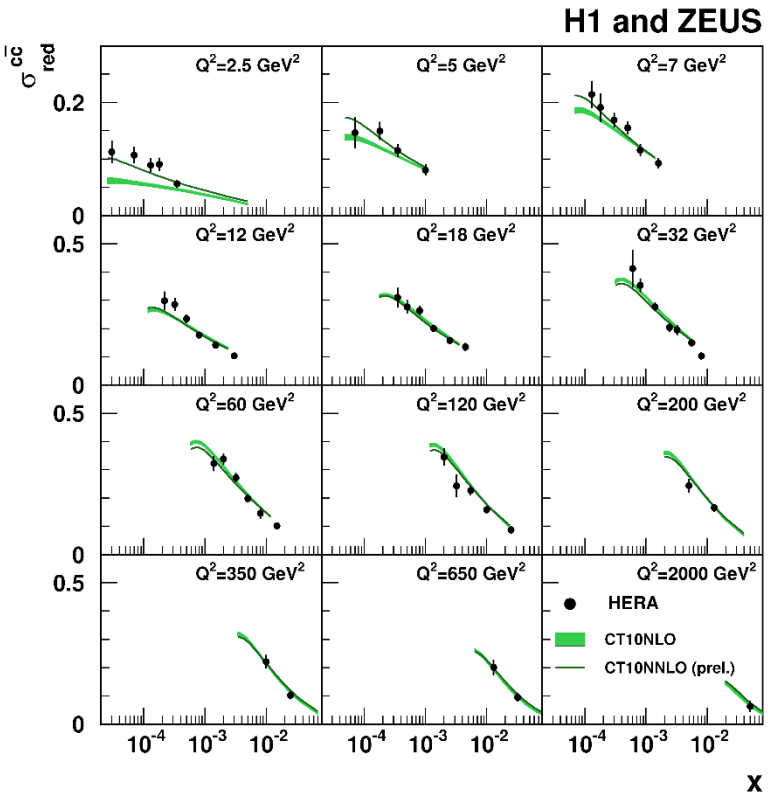


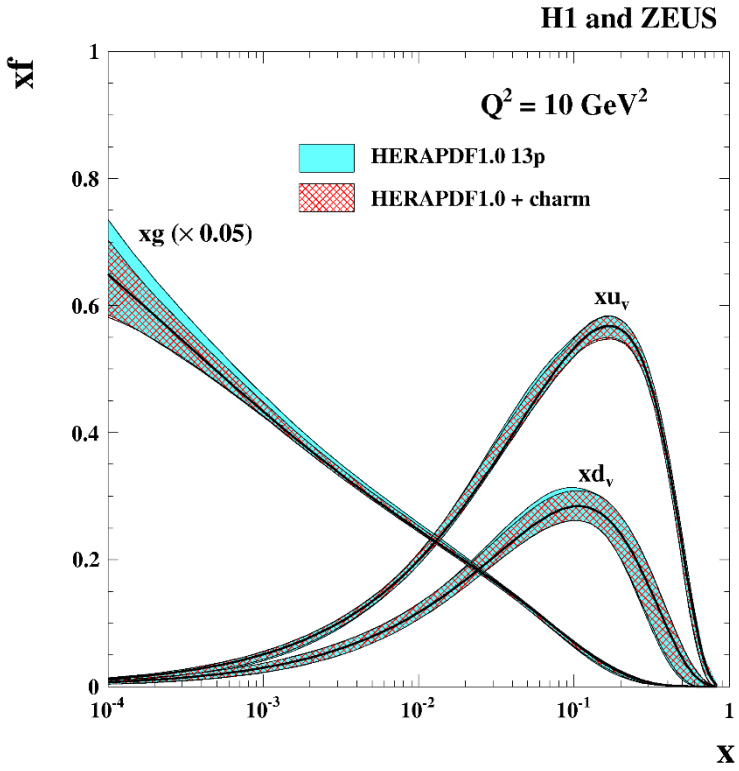
Quark density decreasing at high-x with Q^2

Improvement in low-x region



- With charm data $F_2^{cc}(x, Q^2)$
  - ➢ Charm quarks are mostly produced from gluons



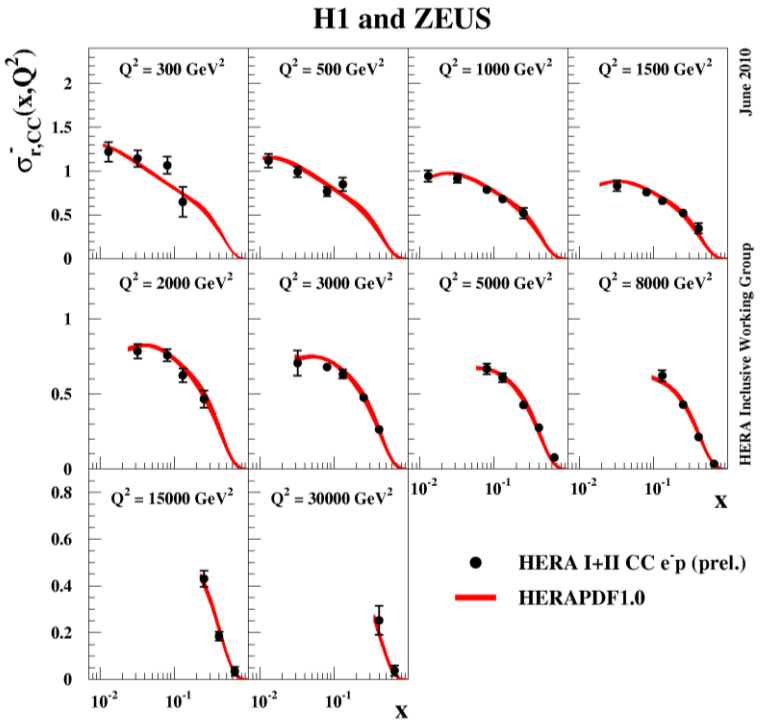


Gluons are better constrained at middle x ($10^{-3} < x < 10^{-1.5}$)

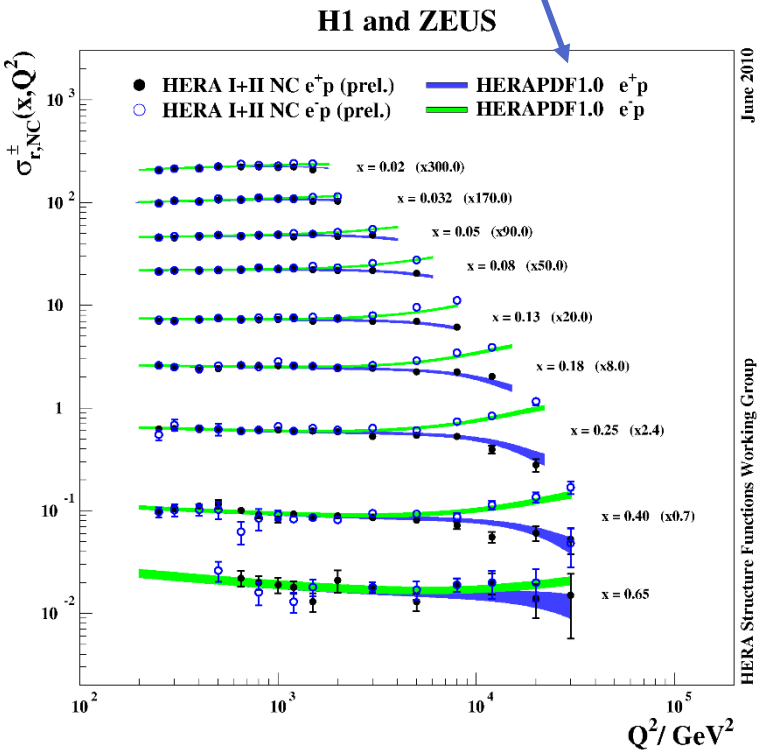
NC/CC data and high-x pdfs

- NC/CC high-Q^2 data analysis finalised
- Combination of H1 and ZEUS data

PDF from HERA (without fixed target) but without these data



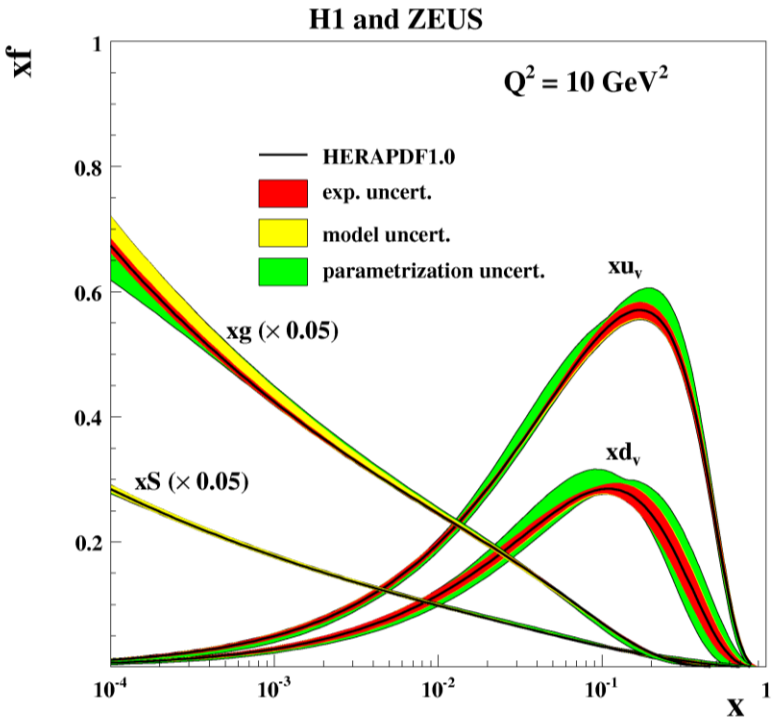
Charged current e^-p

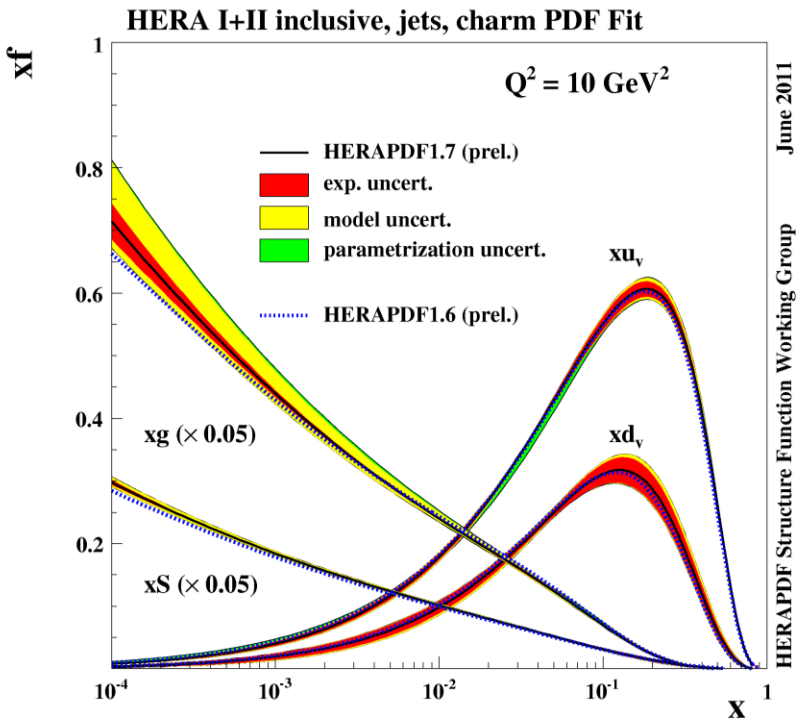


Neutral current $e^\pm p$

Give constraint also to valence quarks

Improvement in high-x regime

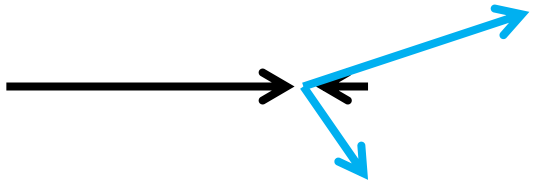


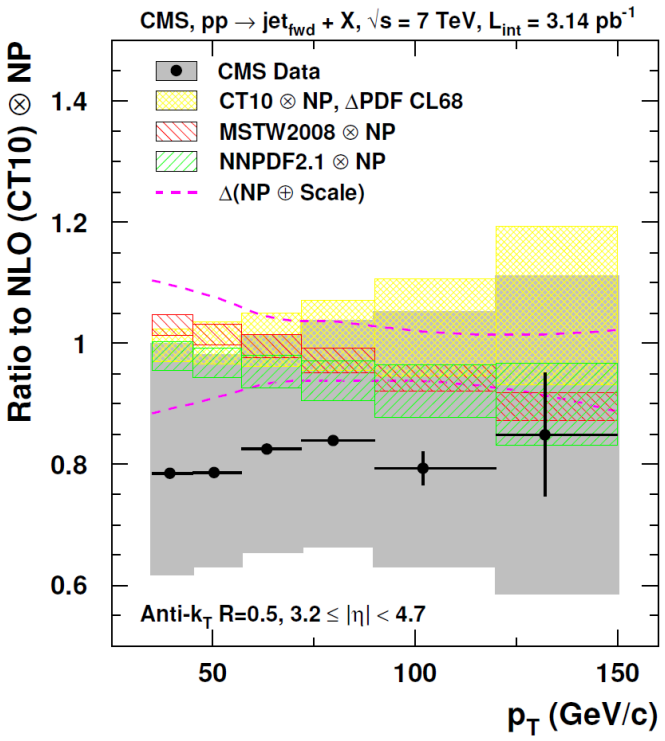


- Valence: better constrained, especially the shape
  - N.B. it does not use fixed target data
- Glue larger uncertainty
  - 10 vs 14 parameter fit

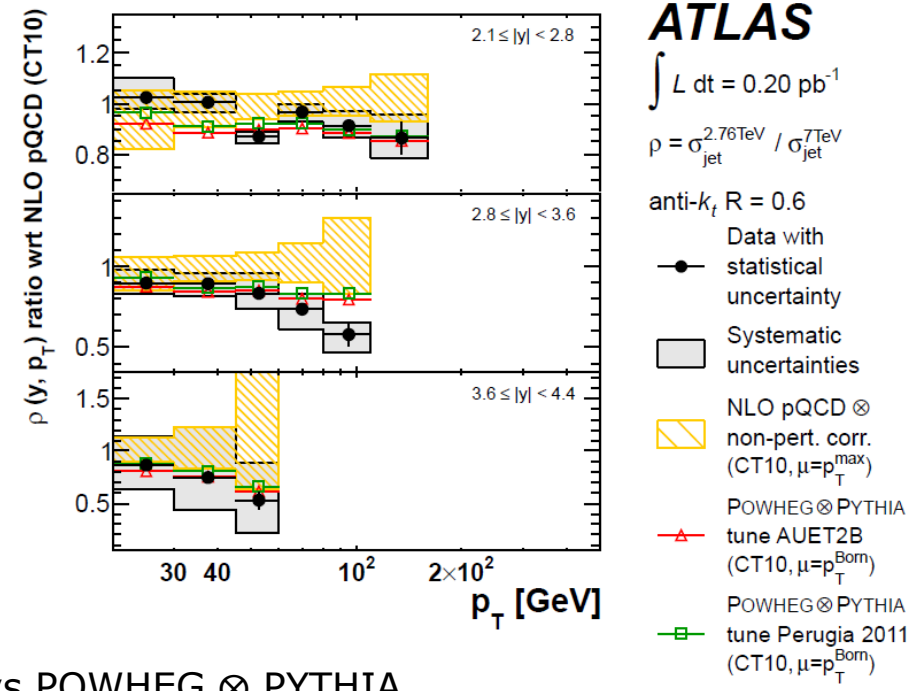
LHC forward jets

- Jet production is sensitive to parton densities
  - Forward jet: low-x gluons





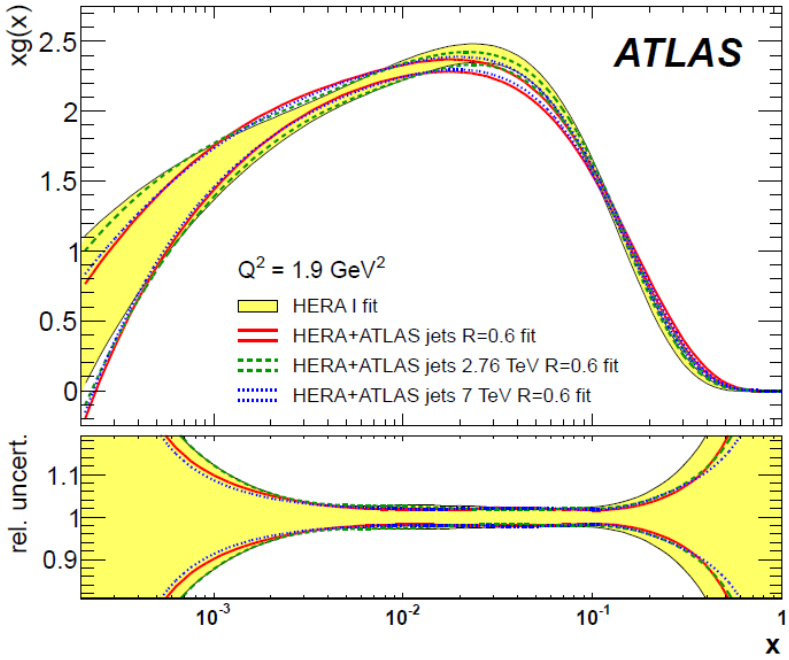
Jets in $3.2 \leq |\eta| < 4.7$, vs NLO



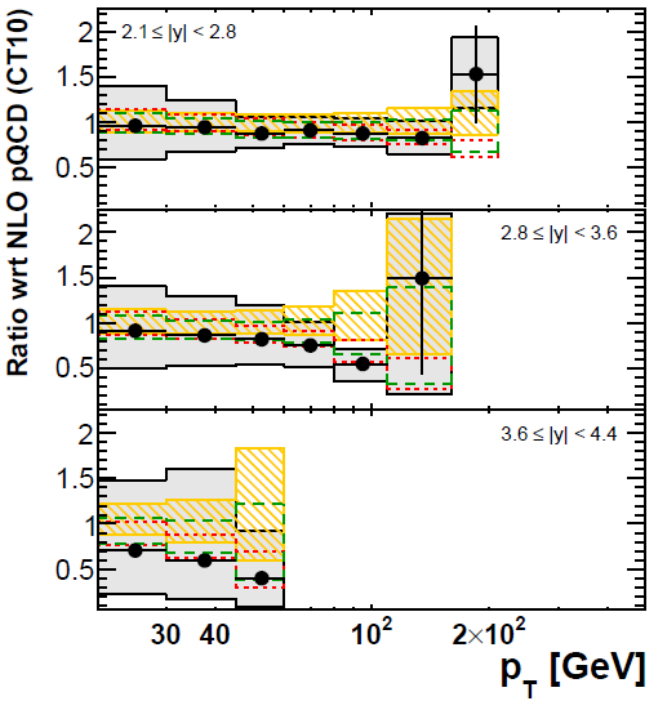
vs POWHEG ⊗ PYTHIA
(NLO interfaced to parton shower)

Forward cross sections are slightly lower than NLO

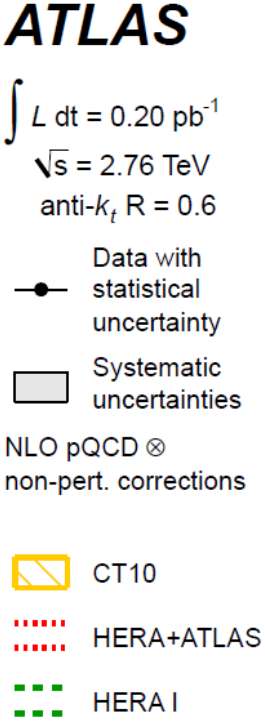
Combined HERA+LHC fit on PDF



reducing mid – high-x gluons
also reducing low-x gluons



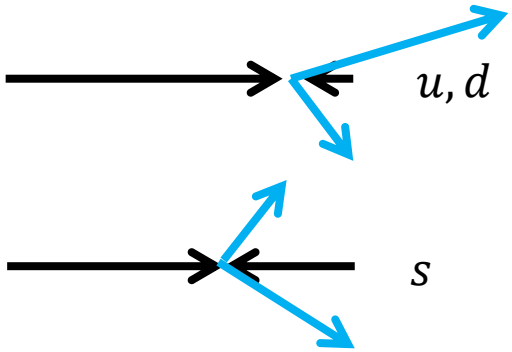
Improved description
on very forward jets

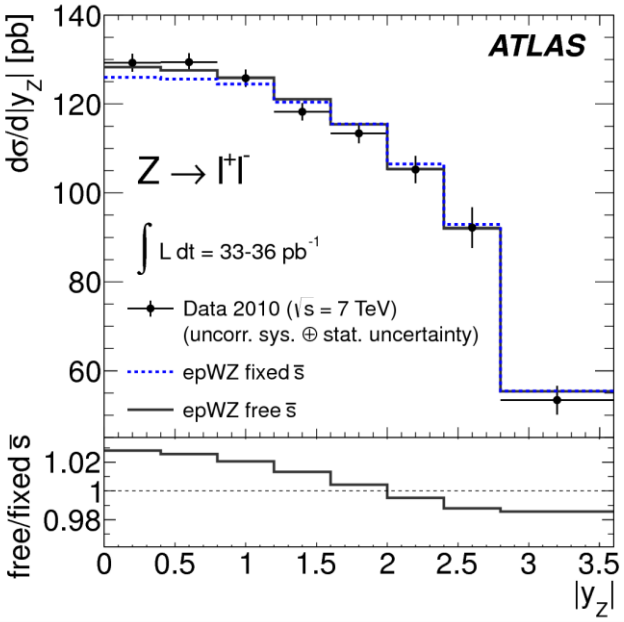


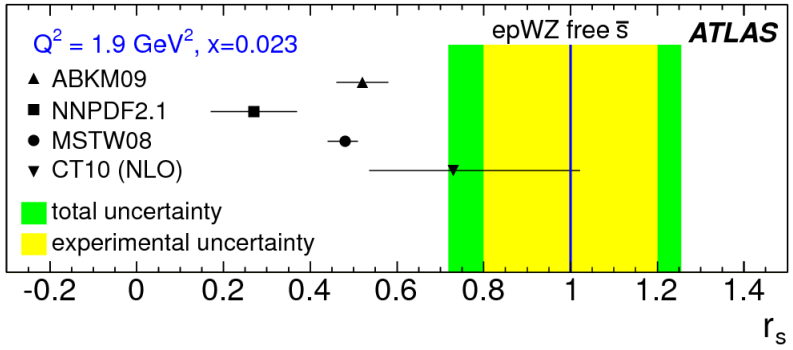
LHC data constrains gluon density!

Strange quark from W/Z at the LHC

- No valence contribution for strange quark (perhaps)
  - No largely asymmetric configuration
  - Z production through Drell-Yan (annihilation) occurs more in central rapidity if $s, \bar{s}(x)$ are larger







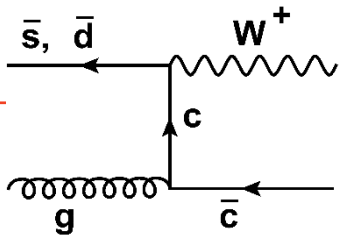
$$r_s \equiv \frac{0.5(s+\bar{s})}{\bar{d}} = 1.00 \pm 0.28\ (total)$$

Strange is not suppressed

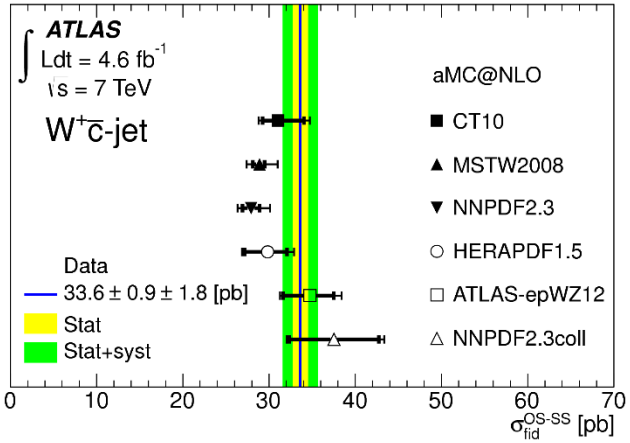
Data shows slight excess in central rapidity

Strange from W+charm production

- Sensitive to strange quarks
- Slight enhancement on c over $\bar{c}$



$$s \rightarrow W^- + c$$
$$d \rightarrow W^- + c$$
(Cabbibo-suppressed)
$$\bar{s} \rightarrow W^+ + \bar{c}$$

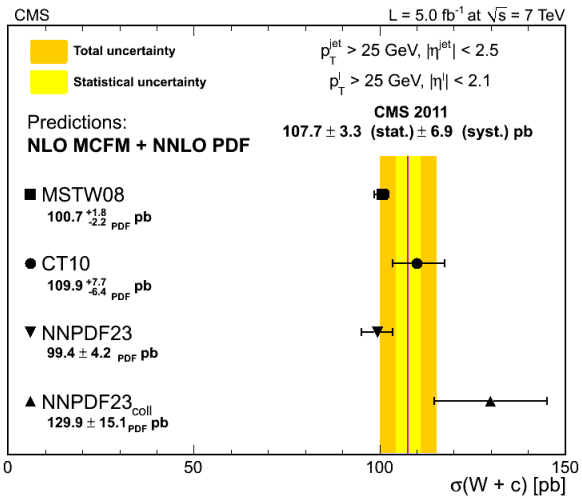


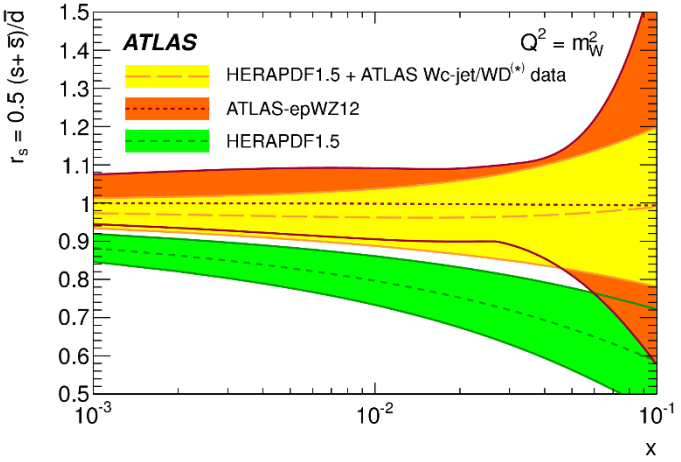
MSTW off (assuming $\bar{s}/\bar{d} \sim 0.5$)

CT10 ~ OK

NNPDF (collider only) overshoots

ATLAS WZ feedback: consistent!



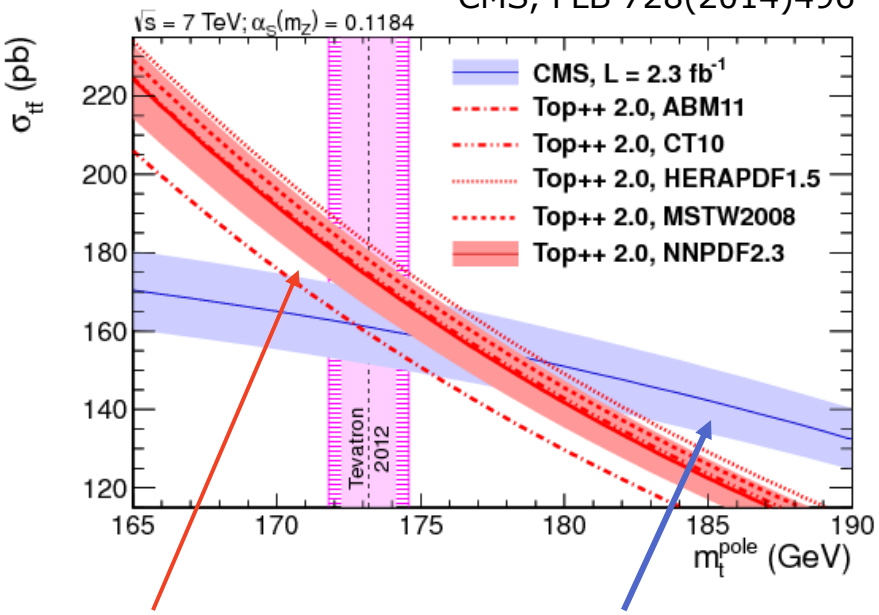


Another evidence: strange not suppressed

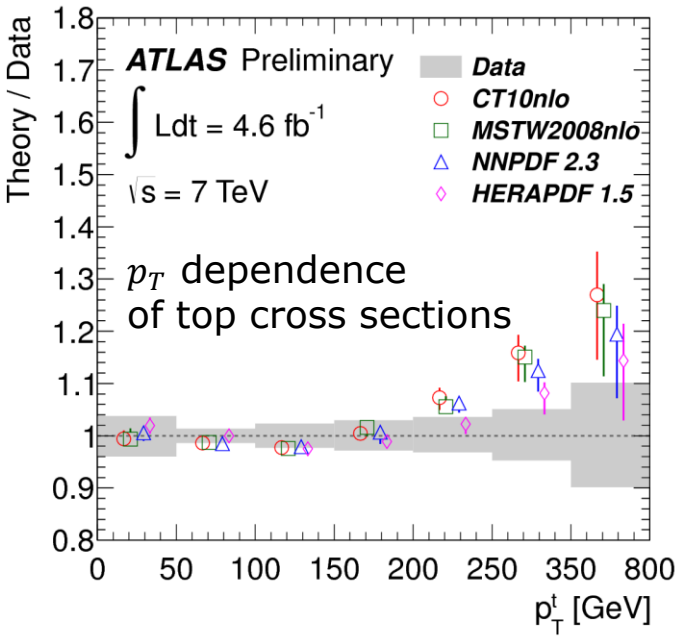
Top quark cross section and pdf

- Top mass is hard to define (pole, $\overline{MS}$ …) and measure
- An idea is to fix mass (or α_s) by measuring top cross section

CMS, PLB 728(2014)496



ATLAS-CONF-2013-099



NNLO cross section prediction with different PDFs

Cross section depends on m_t because of kinematics change in generators used for experimental correction

Top quark prediction: some uncertainty from PDF

Total cross sections

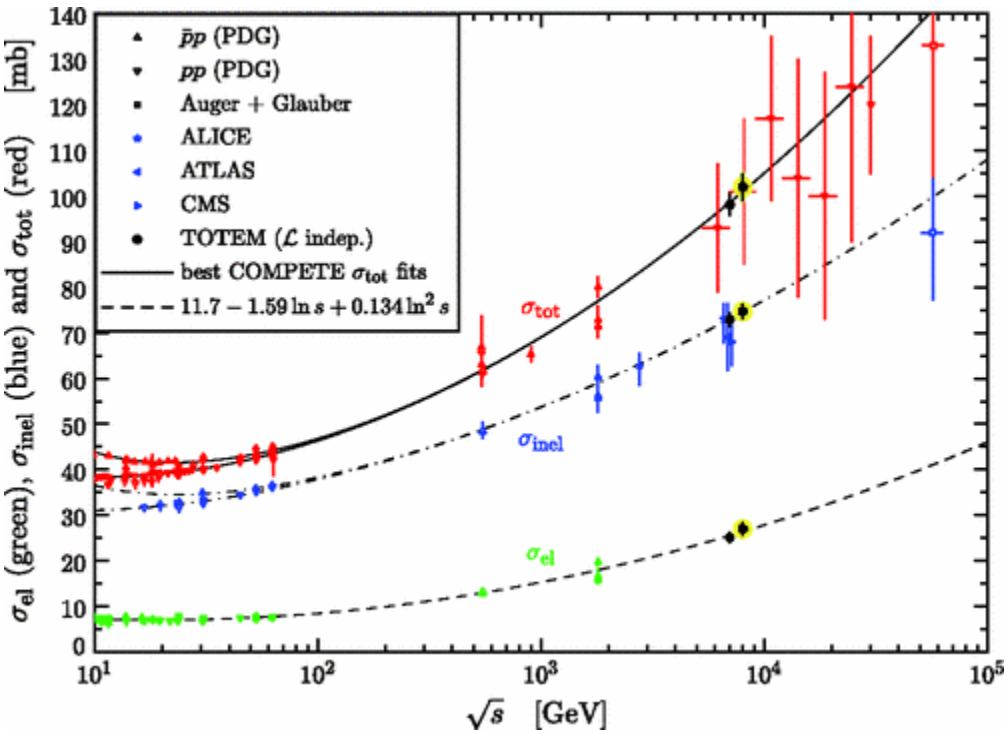
Diffraction

Other multi-parton phenomena

pp total cross sections

TOTEM collab., EPL, **101** (2013) 21004

- TOTEM is equipped with double-arm spectrometer (Roman Pot)
- Total cross section is derived from forward elastic scattering through optical theorem



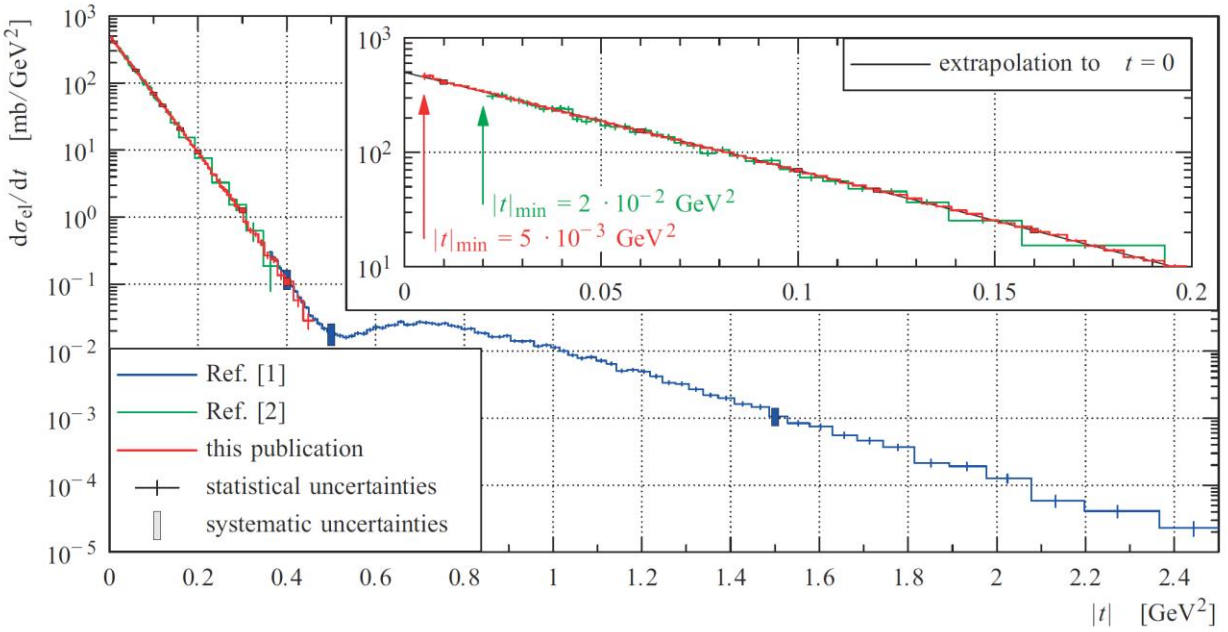
Rising slowly:

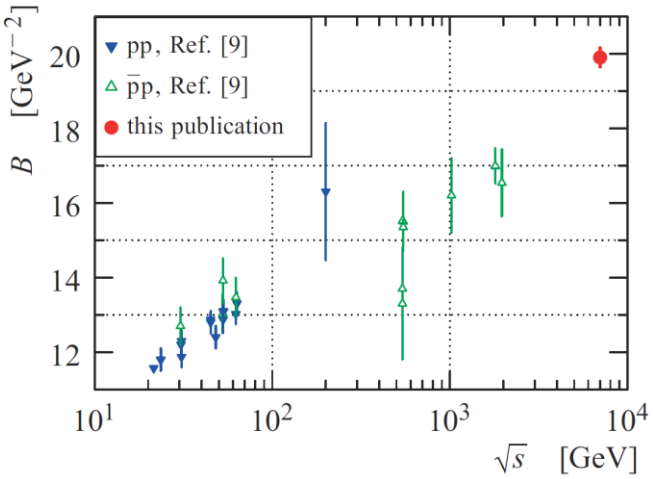
- No indication of saturation (unitarity)
- No indication of rapid increase (parton-like)

pp elastic cross sections

- Roman pot inserted very close to the beam, Reaching to $|t| = 5 \times 10^{-3}\ \mathrm{GeV}^2$
- $t \sim -p_T^2$ of recoil proton (for elastic)

TOTEM collaboration, EPL 101 (2013) 21002

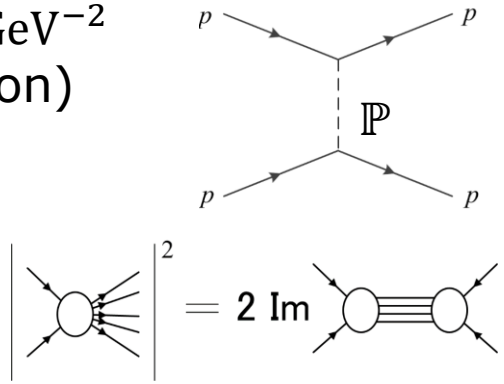


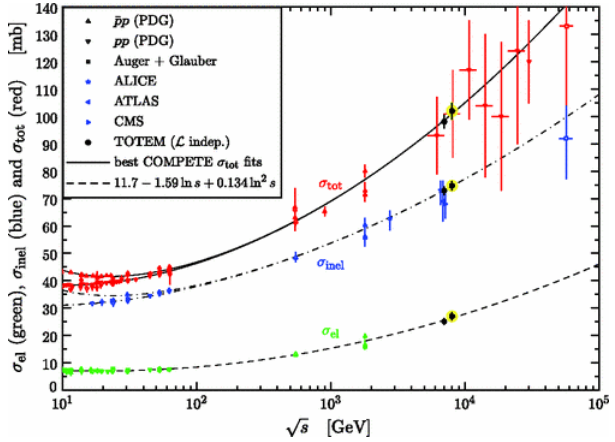


- Clear diffractive dip
- $e^{-B|t|}$ behaviour:
  - Large B value: very soft scattering
  - `Shrinkage' continues
    Hadrons becoming larger with $\sqrt{s}$

High-energy hadron collisions and the `Pomeron'

- The slow rise is often attributed to the Pomeron trajectory
  - $\alpha(t) = \alpha_0 - \alpha' t = 1 + \epsilon - \alpha' t$
    Often parameterised like: $\alpha_0 : \sim 1.08,\ \alpha' \sim 0.25\ \mathrm{GeV}^{-2}$
    (Donnachie and Landshoff's universal Pomeron)
  - Elastic cross section
    $\frac{d\sigma_{el}}{dt} \sim \frac{1}{s^2}\,|A|^2 \sim \left(\frac{s}{s_0}\right)^{2\alpha(t)-2}$
  - Total cross section through optical theorem:
    $\sigma_{tot}^2 \simeq 16\pi \left.\frac{d\sigma_{el}}{dt}\right|_{t=0} \rightarrow \sigma_{tot}(s) = \sigma_0 \left(\frac{s}{s_0}\right)^{\alpha_0 - 1}$

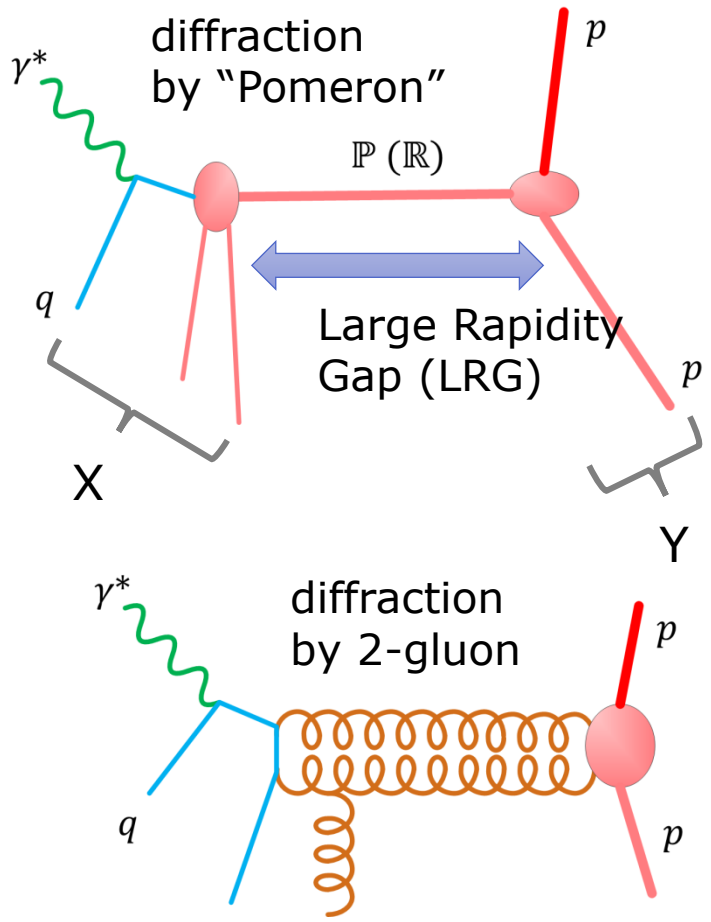




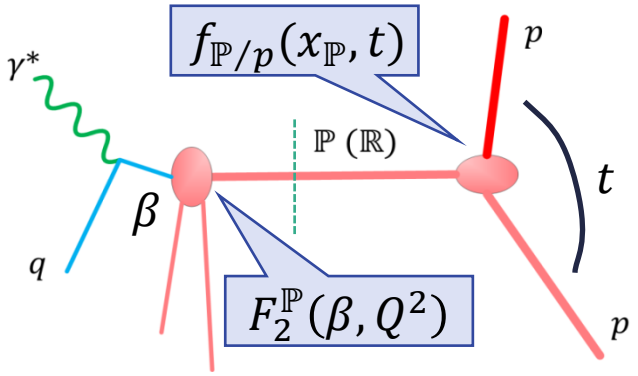
Does diffraction also be described by the Pomeron trajectory?

Diffraction in ep collisions: issues

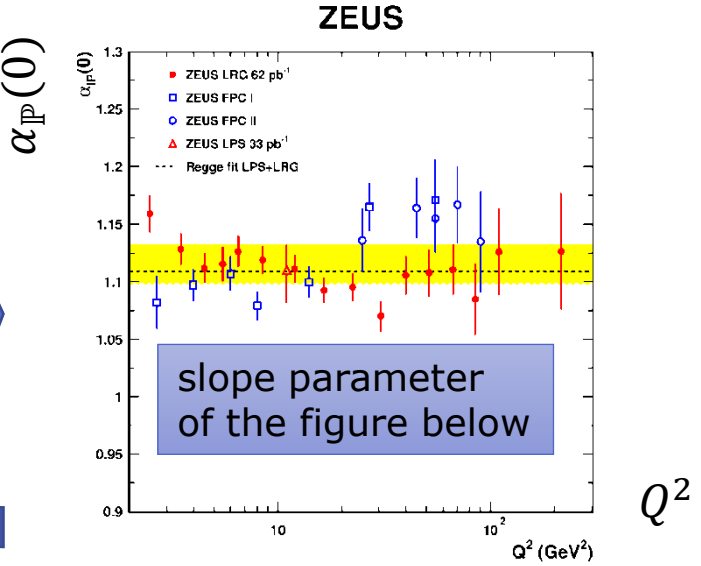
- Diffraction at HERA:
  - photon dissociates into small mass (X)
  - proton stays intact
    or proton dissociates into small mass (Y)
- Standard view:
  - Pomeron ($\mathbb{P}$) emitted from proton,
    which is scattered off by a photon
    DIS of the Pomeron
- Pomeron or 2-gluon ?
  - If 2 gluons, the exchanged intermediate state is no longer a particle:
    left and right vertices talks each other
    (factorisation breaking)

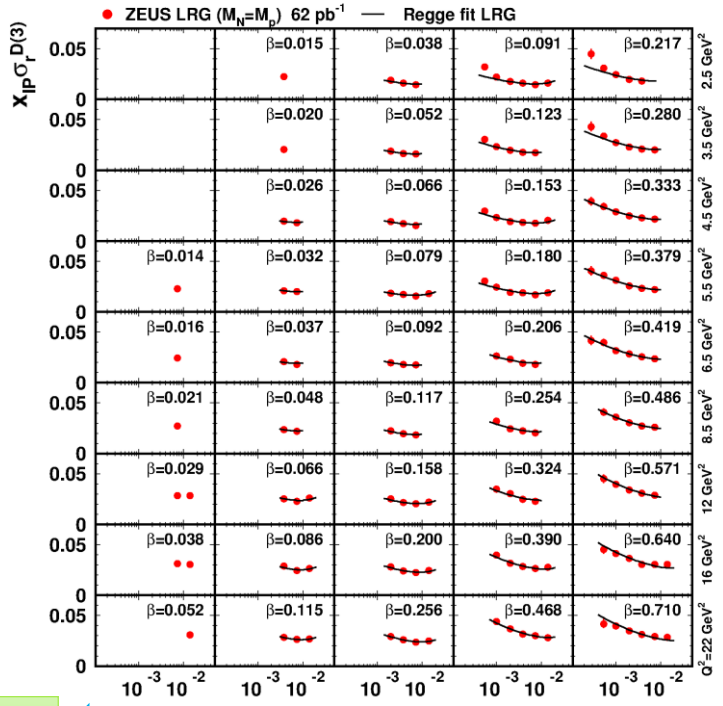


Is Pomeron a “particle” ?



Fit by $\frac{1}{x_P^{2\overline{\alpha_P}-1}}$



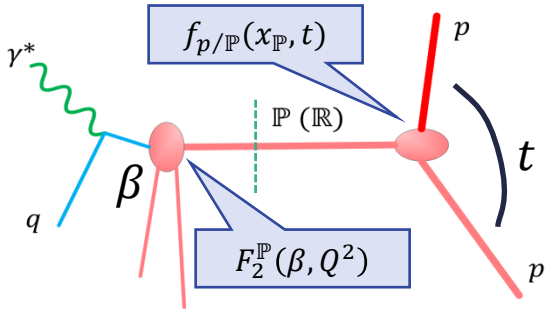


- Check if the cross section can be factorised into:
  - the Pomeron flux $f_{p/\mathbb{P}}(x_{\mathbb{P}}, t)$ and
  - the upper part $F_2^{\mathbb{P}}(\beta, Q^2)$
- This holds pretty well: cross section shape in x_P is independent of β and Q^2

Pomeron is not quite perturbative 2-gluon

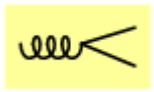
Slow rise towards low-x

Scaling violation analysis for $g(\beta, Q^2)$ in DPDF

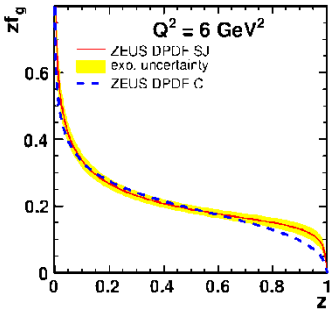


$$\beta = x/x_{\mathbb{P}}$$

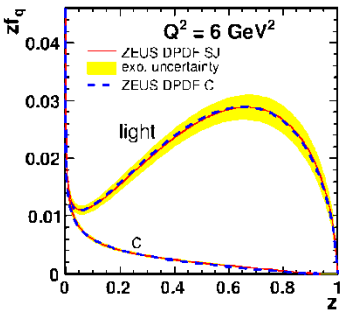
- Positive scaling violation in almost all β values
  - Quarks dynamically produced through gluons
  - **The exchanged object is still gluon-rich**



gluons

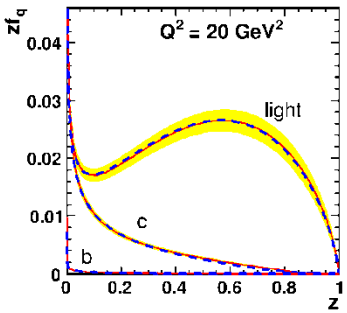


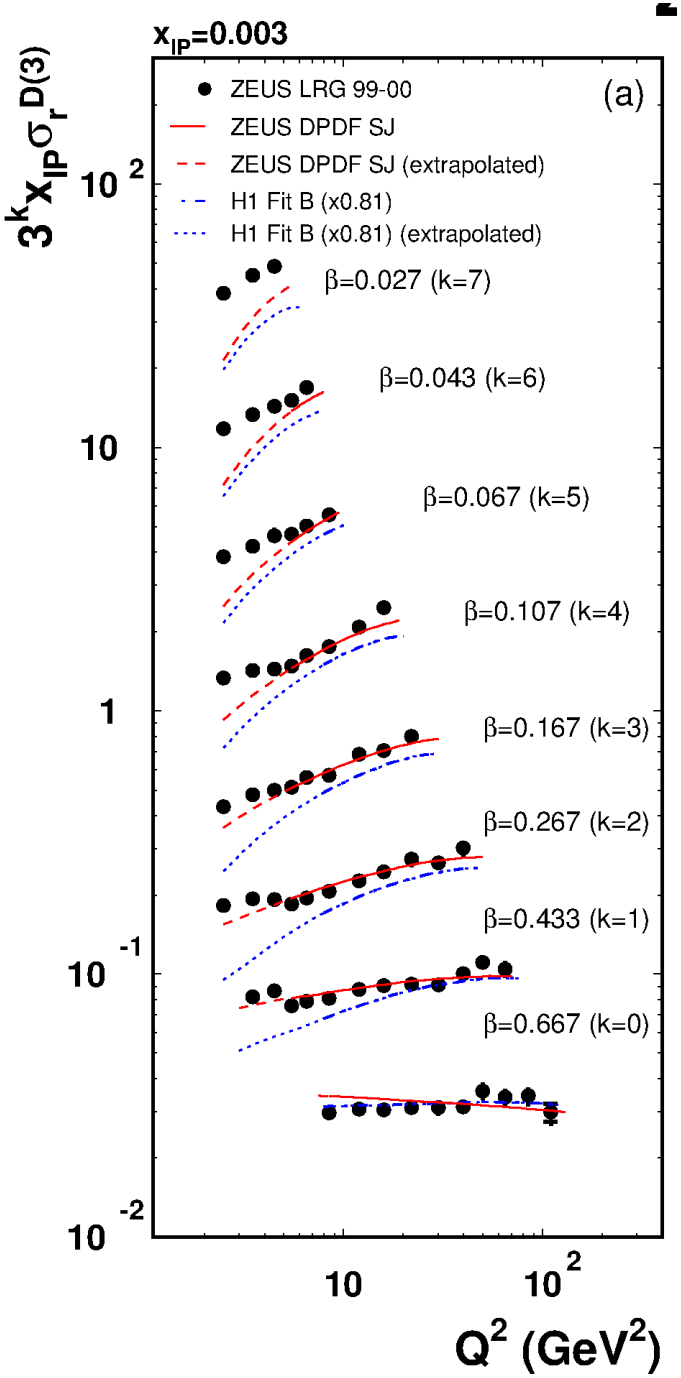
quarks



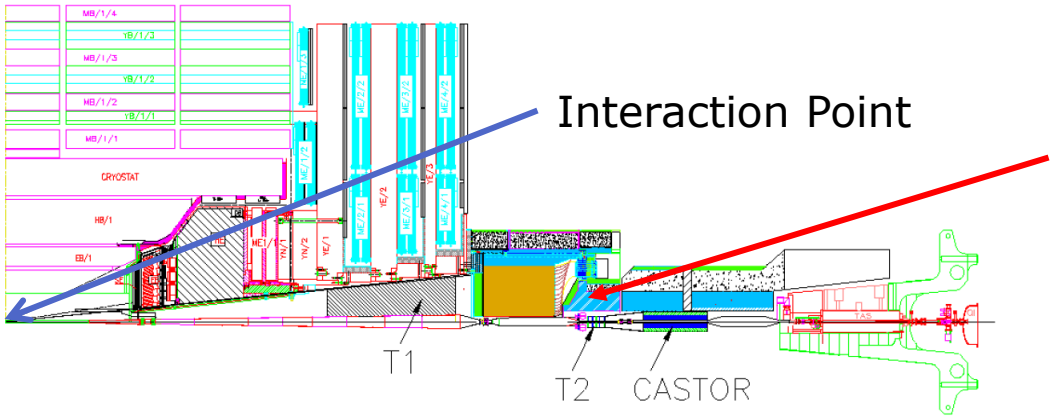
ZEUS

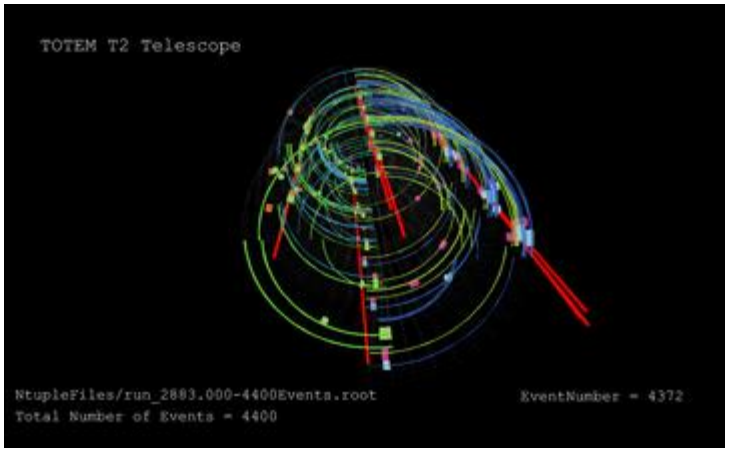
Quarks high Q^2





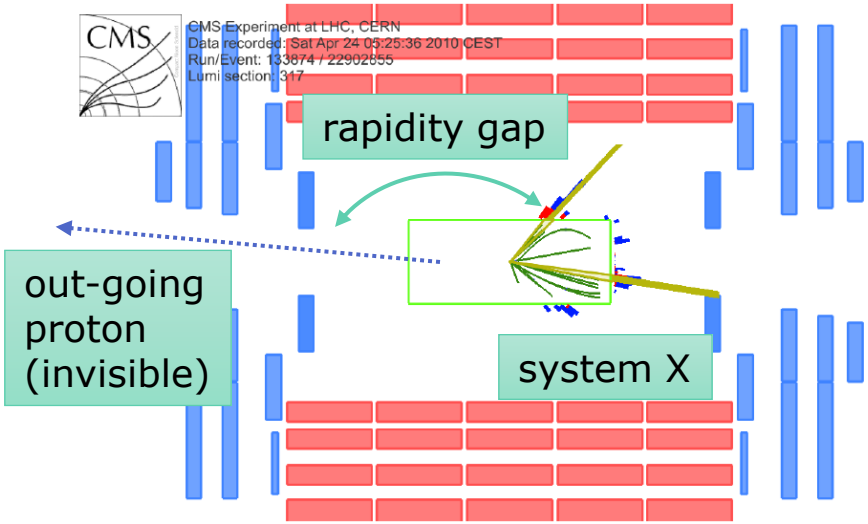
LRG events by detectors at the LHC

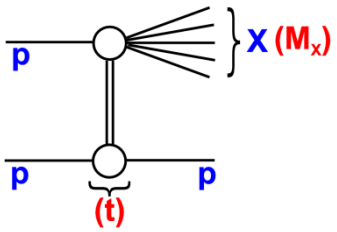




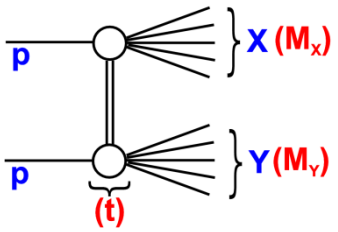
Diffractive dijet candidate at 7 TeV

`fragmented proton'





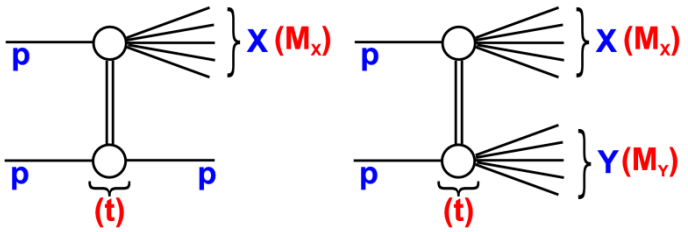
Single diffraction



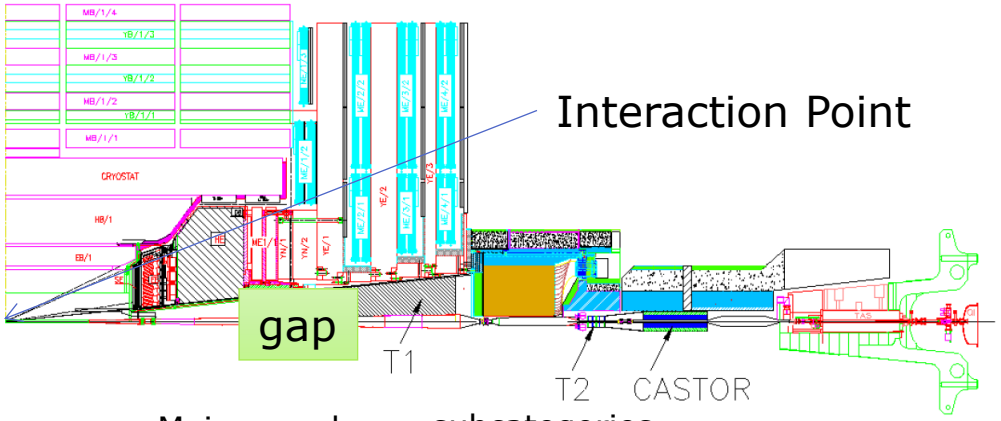
Double diffraction

Double diffraction by TOTEM

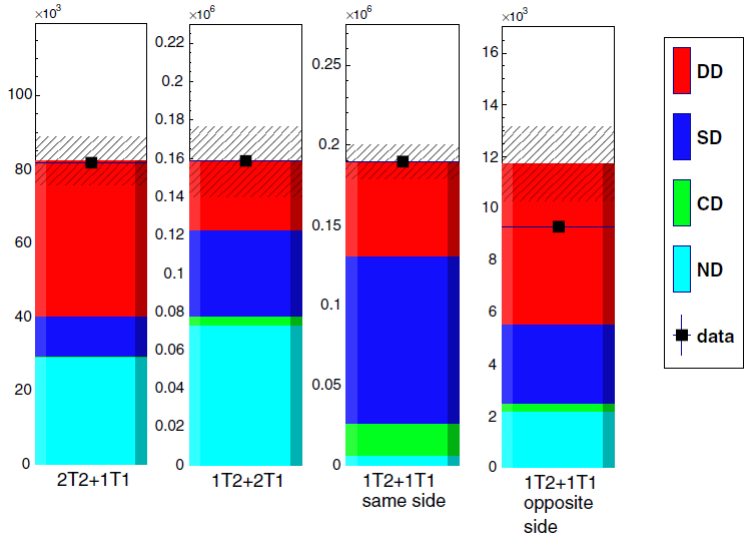
- T1 and T2 telescopes to tag proton dissociation system
  - T2 to tag the system X/Y
  - T1 veto for rapidity gap



Single diffraction Double diffraction



Main sample subcategories



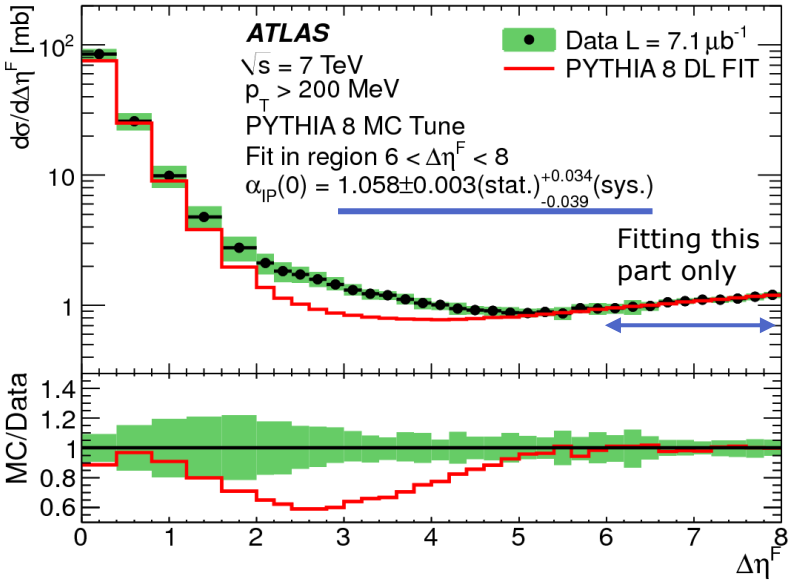
	I_{track}	$D11_{\text{track}}$	$D22_{\text{track}}$	$D12_{\text{track}}$	$D21_{\text{track}}$
Visible	131 ± 22	58 ± 14	20 ± 8	31 ± 5	34 ± 5
in μb	I	$D11$	$D22$	$D12$	$D21$
$\eta_{\min}$	116 ± 25	65 ± 20	12 ± 5	26 ± 5	27 ± 5
PYTHIA $\eta_{\min}$	159	70	17	36	36
PHOJET $\eta_{\min}$	101	44	12	23	23

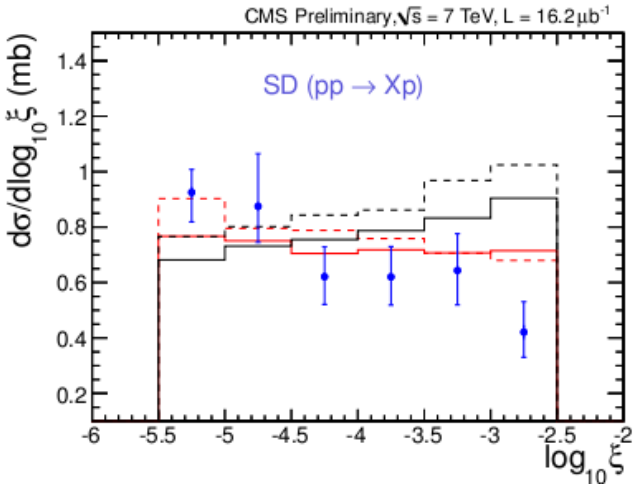
Somewhere between two models

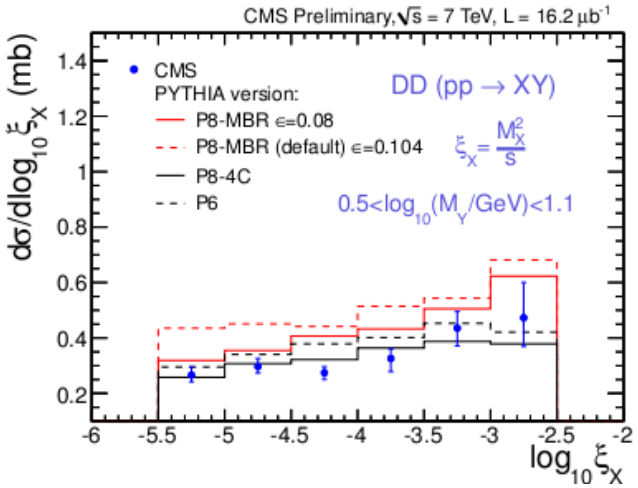
Next: t-dependence

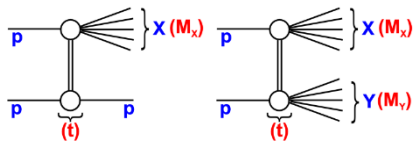
Events with LRG: ATLAS and CMS

- α_0 extracted from cross section dependence with rapidity gap $\Delta\eta$
  - triple-Pomeron formula:
    $\frac{d\sigma}{d\xi_X} \propto s^{-1+\epsilon}\xi_X^{-(1+\epsilon+2\alpha' t)}$
    $\xi_X = \frac{M_X^2}{s}$ (longitudinal momentum fraction of the diffractive exchange)
  - $\Delta\eta \simeq -\ln \xi_X$
    $\rightarrow$ cross section rise by $\sim (\Delta\eta)^{\epsilon}$
  - DL universal Poemron: $\alpha(0) = 1.08$





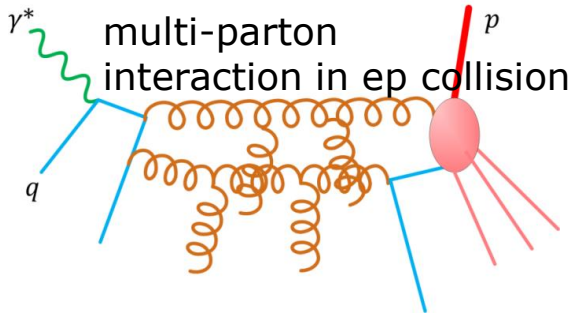




Single diffraction Double diffraction

MBR: Rockfeller saturation model on top of universal Pomeron
P8, P6: Schuler-Sjostrand Pomeron with partonic structure

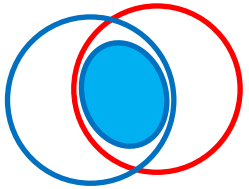
Multi-parton interaction at the LHC



- $\sigma_{parton} > \sigma_{inelastic}$
  at high $\sqrt{s}$ and low p_T
  - multiple parton collision in one crossing of nucleon is unavoidable
  - Observed in Tevatron, many evidences at HERA

- Double-parton interaction cross section is expressed as:

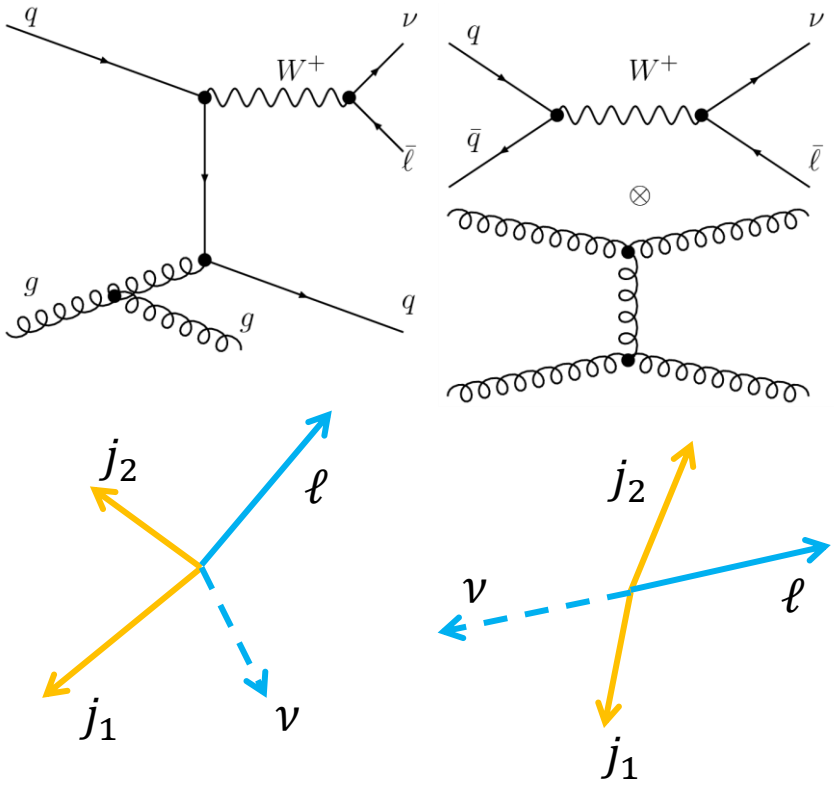
$$\sigma_{DPI}(A,B) = \frac{\sigma_A \cdot \sigma_B}{\sigma_{\text{eff}}}$$

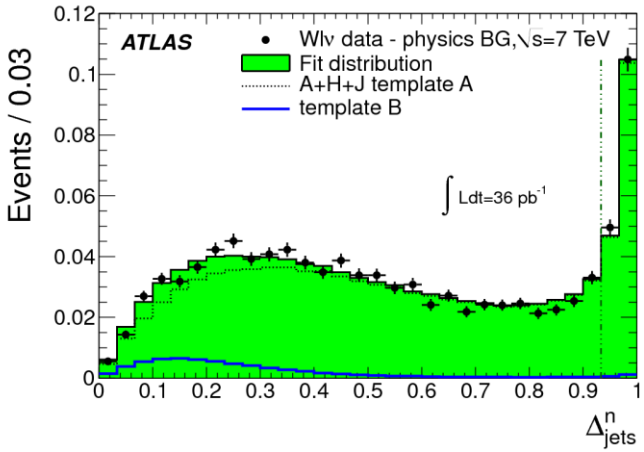


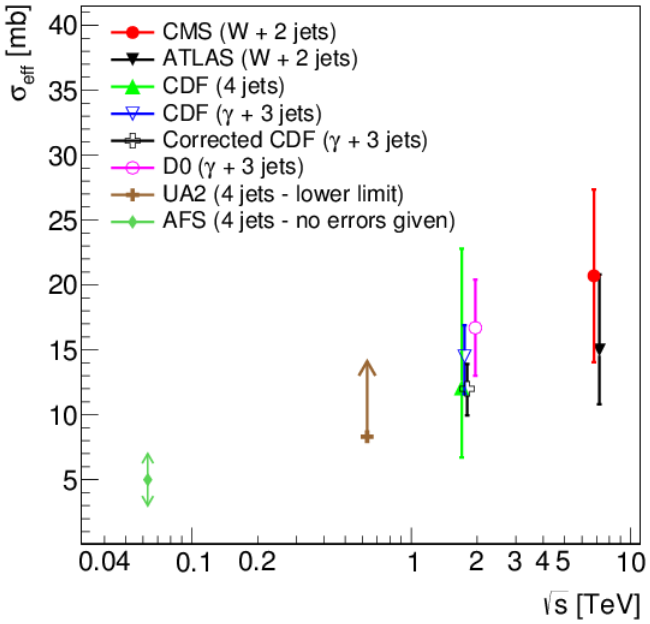
  - σ_A, σ_B : cross sections of the two interactions, which often increase with $\sqrt{s}$ because of increasing number of partons
  - σ_{eff} : effective overlapping area of partons from two nucleons in collision.
    Smaller the σ_{eff}, more squeezed the partons, thus higher σ_{DPI}

DPI in W + 2jets

- DPI dijet tend to be back-to-back
- Generic W+2jets: W balances to 2 jets







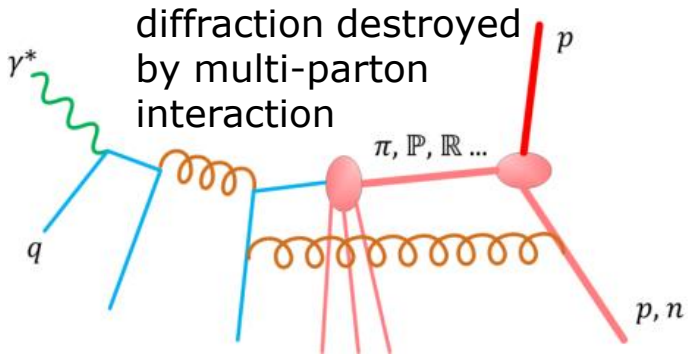
σ_{eff} rather flat with $\sqrt{s}$ or rising?

Diffraction and rescattering in pp

aka absorption, survival probability …

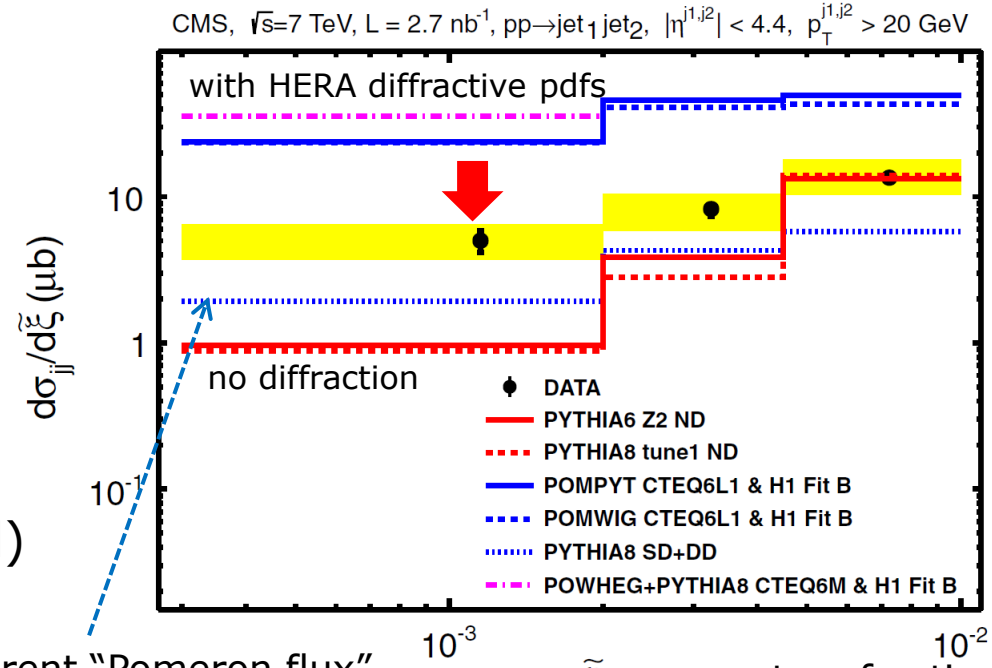
- Diffractive cross sections in pp can be calculated using factorisation assumption

$$\frac{d\sigma}{d\xi \mathrm{dt}} = \sum_i \int dx_1 dx_2 d\hat{t} f(\xi,t) f_P(x_1,\mu) f_p(x_2,\mu) \frac{d\hat{\sigma}(\hat{s},\hat{t})}{d\hat{t}}$$



- Rescattering may destroy diffractive condition (large rapidity gap)
  ⇒ suppression on diffraction

- CMS survival probability:
  $S = 0.08 \pm 0.04$
  (NLO rescaled, proton dissociation subtracted)

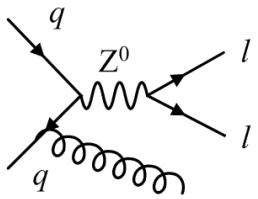


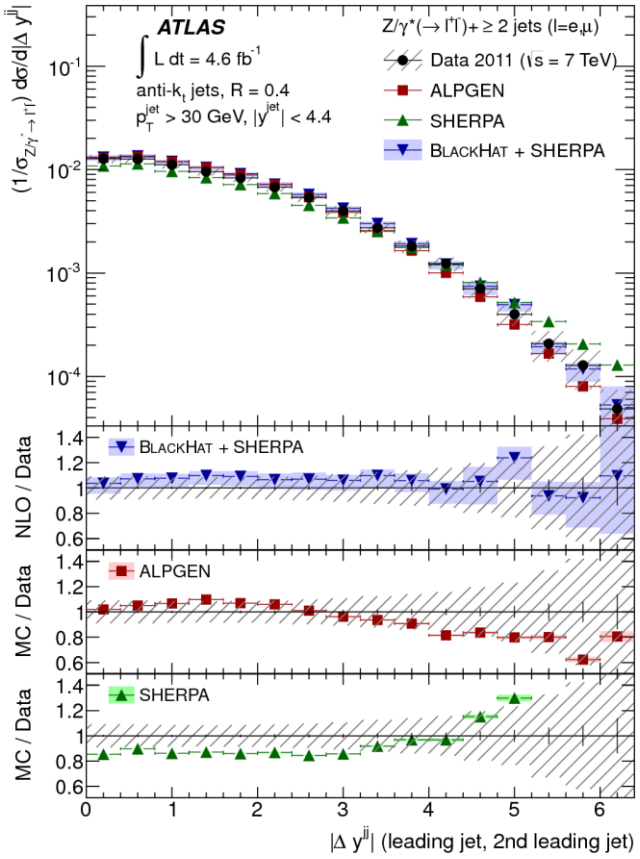
Diffraction, but different "Pomeron flux"

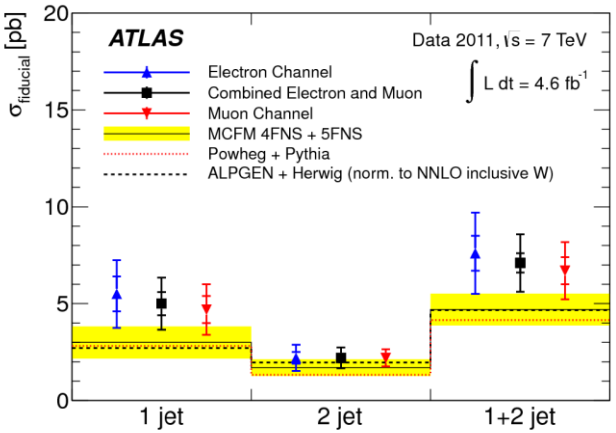
$\tilde{\xi}$ momentum fraction of the diff. exch (= x_P)

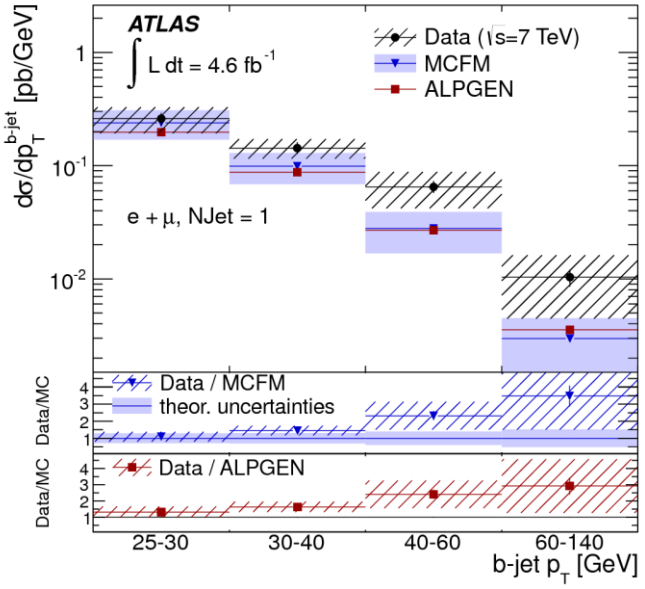
Selection from
Hard pQCD results at the LHC

Z+jets, W+b-jets





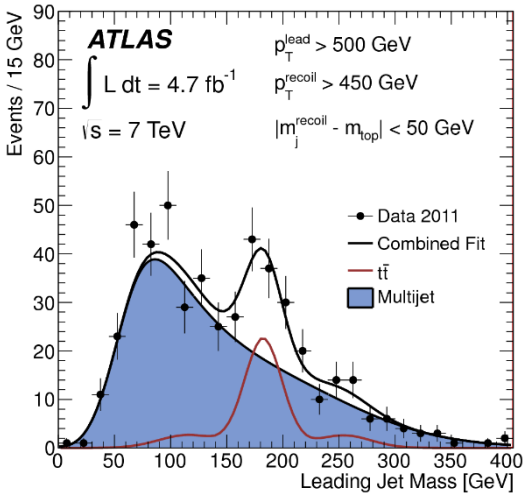




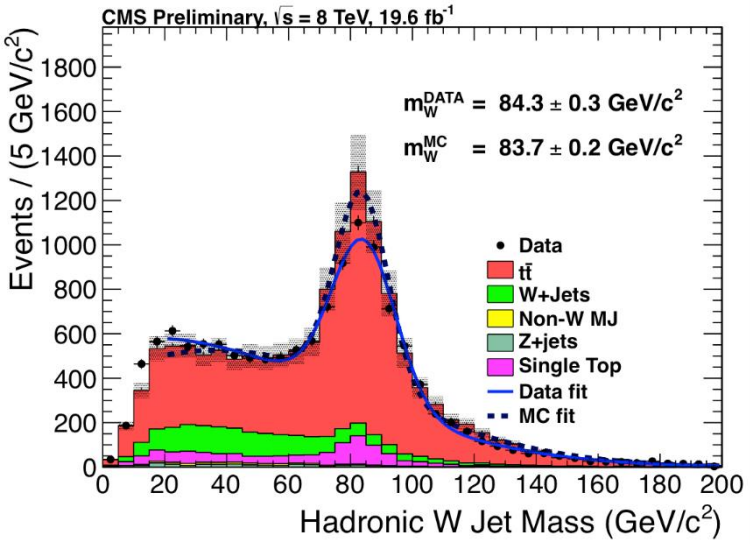
- Good agreement with NLO and multi-leg MCs for light jets, with some deviation
- b-quark: slight excess, but consistent with simulation

Boosted objects and subjets

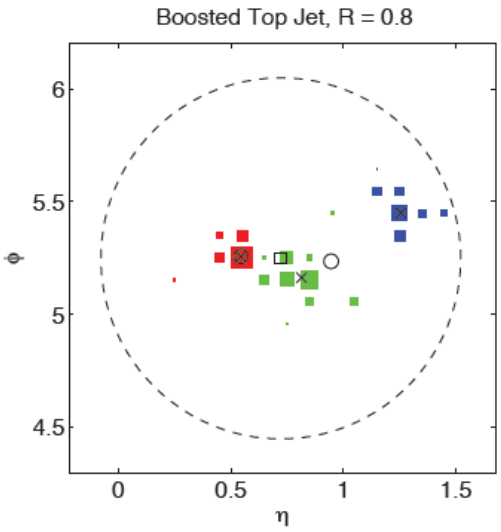
ATLAS, JHEP 1301 (2013) 116



CMS-PAS-B2G-13-001

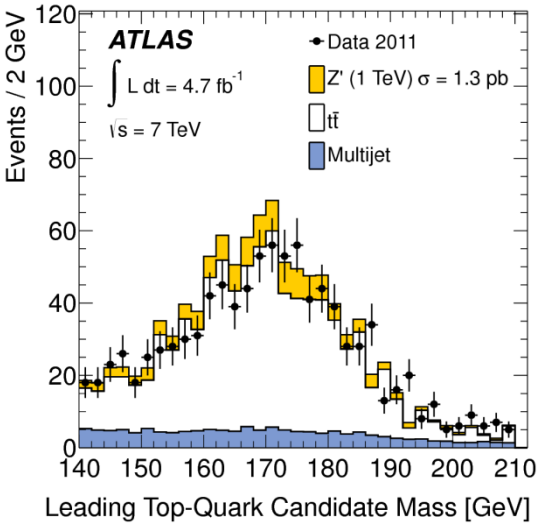


Nhan Tran, LP2013



Hadronic decay of a top quark

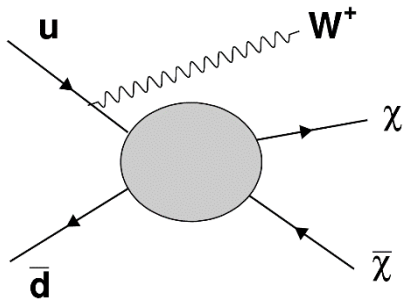
m_{jj} for $t \to Wb, W \to qq$



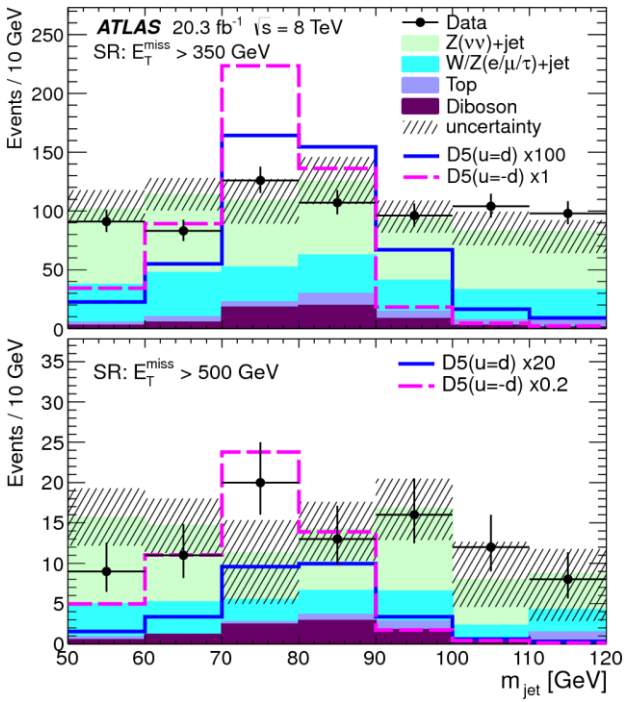
Top mass reconstruction for searching $t\bar{t}$ resonance

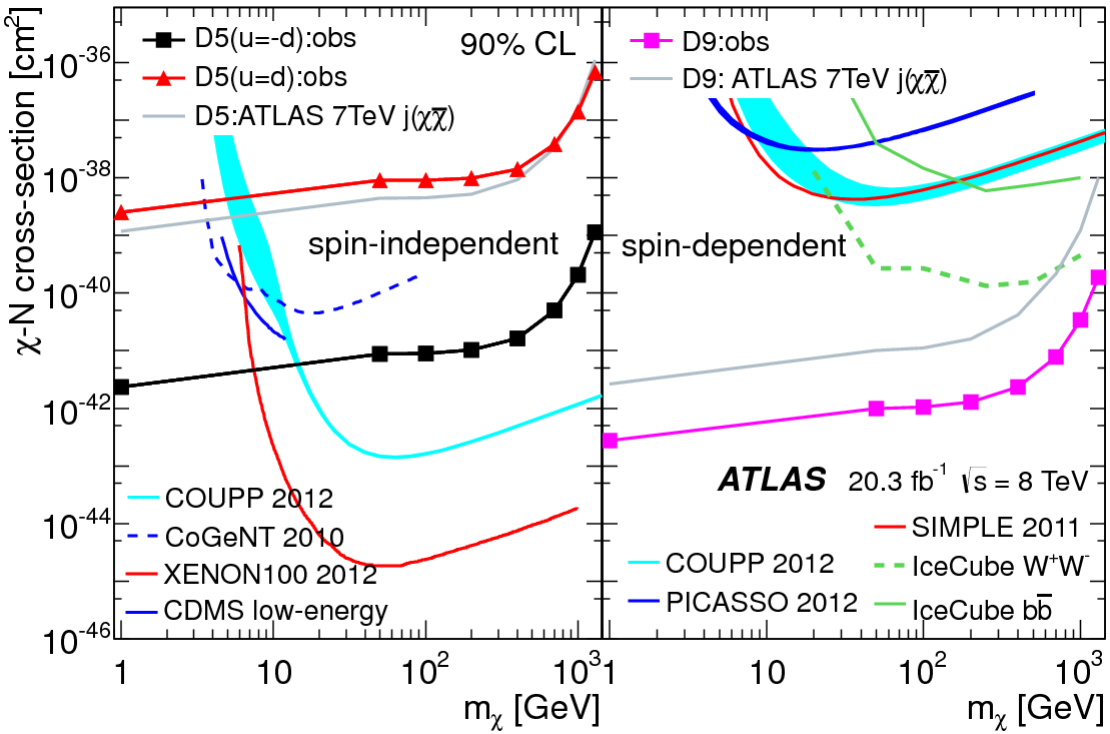
- Jet substructure adopted to tag heavy objects

Single W/Z + Etmiss Dark matter search



- Hadronic W/Z decay:
  Boosted object to reconstruct mass
- Sensitivity to:
  - D5 (vector)
    spin independent
  - D9 (tensor)
    spin dependent



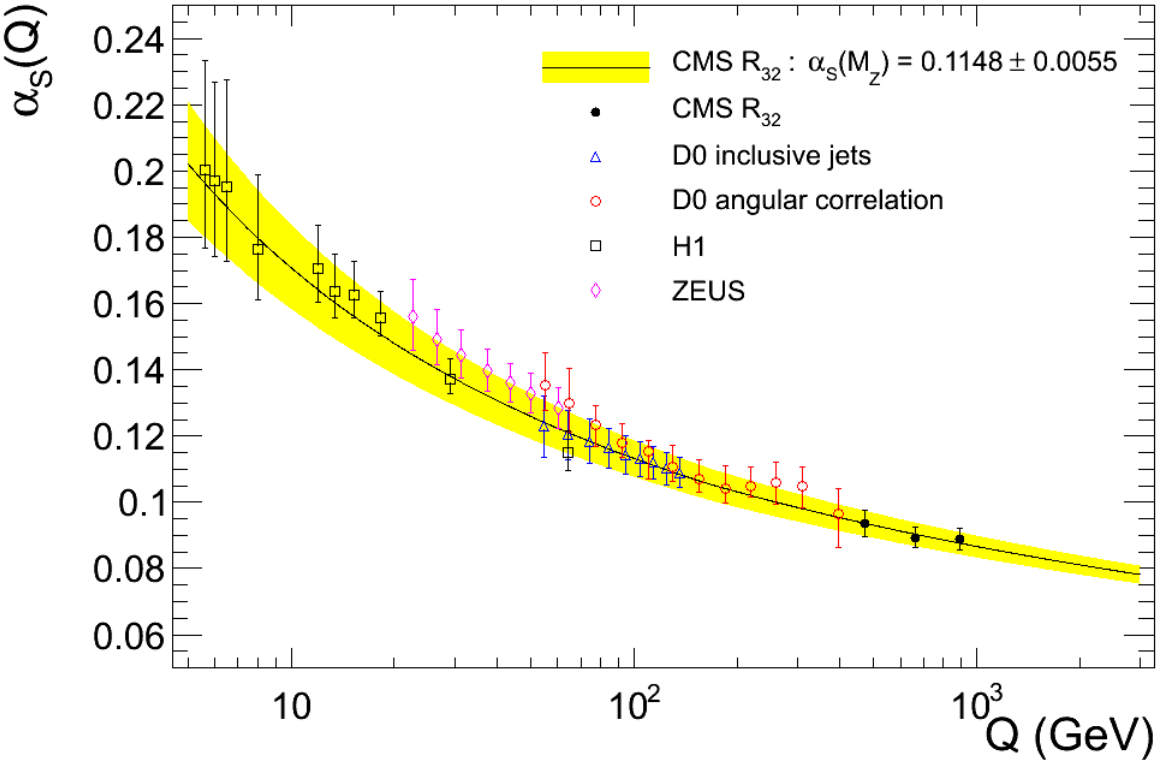


World best limit!!

α_s at TeV scale

- Renormalisation Group Equation may change the slope if there is new physics in the strong sector

CMS collab., Eur.Phys.J. C73 (2013) 2604



The data will be extended to higher Q in 14TeV run

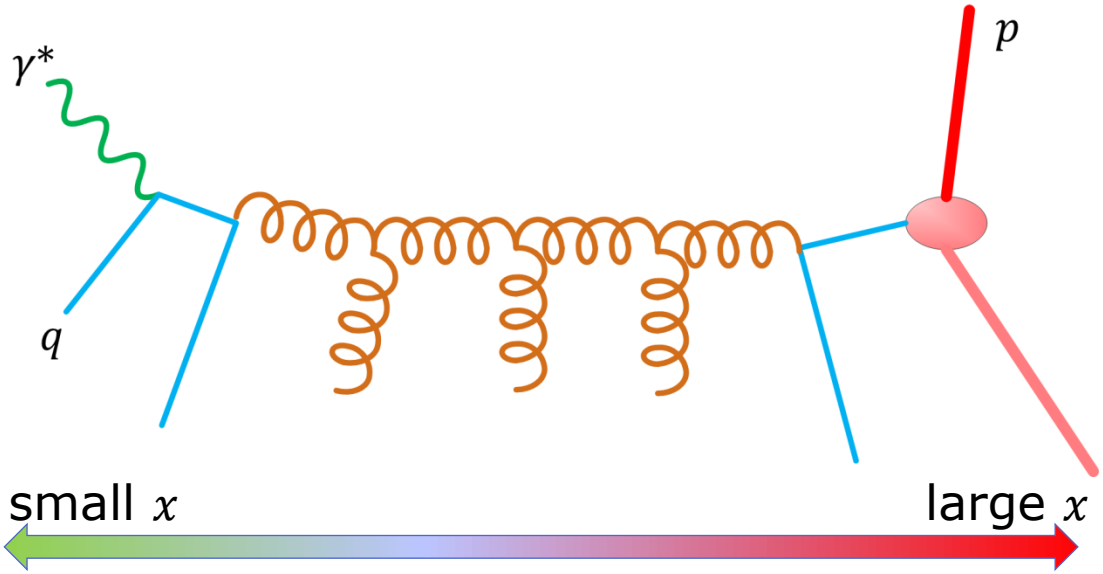
Summary

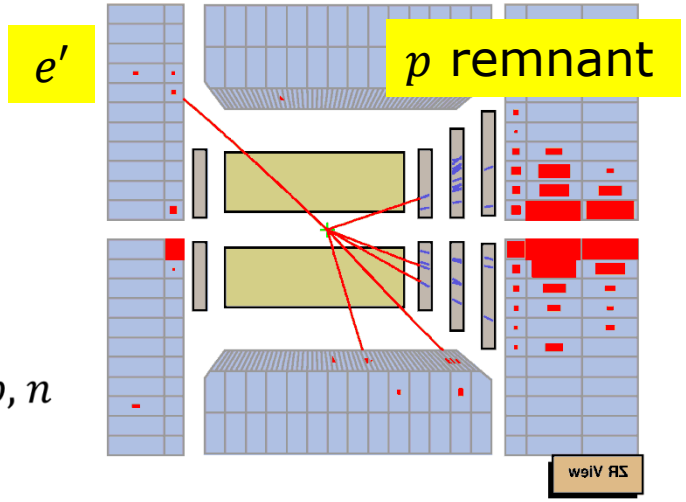
- LHC starts to constrain PDF
  - With interaction with HERA, where last piece of data are under careful analysis
  - Essential ingredients for discovery

- Investigating "Pomeron-related" phenomena at the LHC:
  - General feature can be understood in the framework of Pomeron exchange
  - Details are to be investigated

- pQCD quite advanced at the LHC
  - New tool: jet substructure
  - Indirect investigation of quark sector in very high-p_T regime by measuring α_s

Low-x ≃ forward





small x — large x

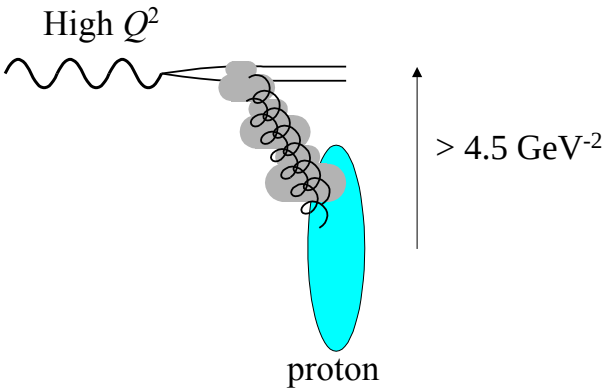
backward
$y \simeq -2$

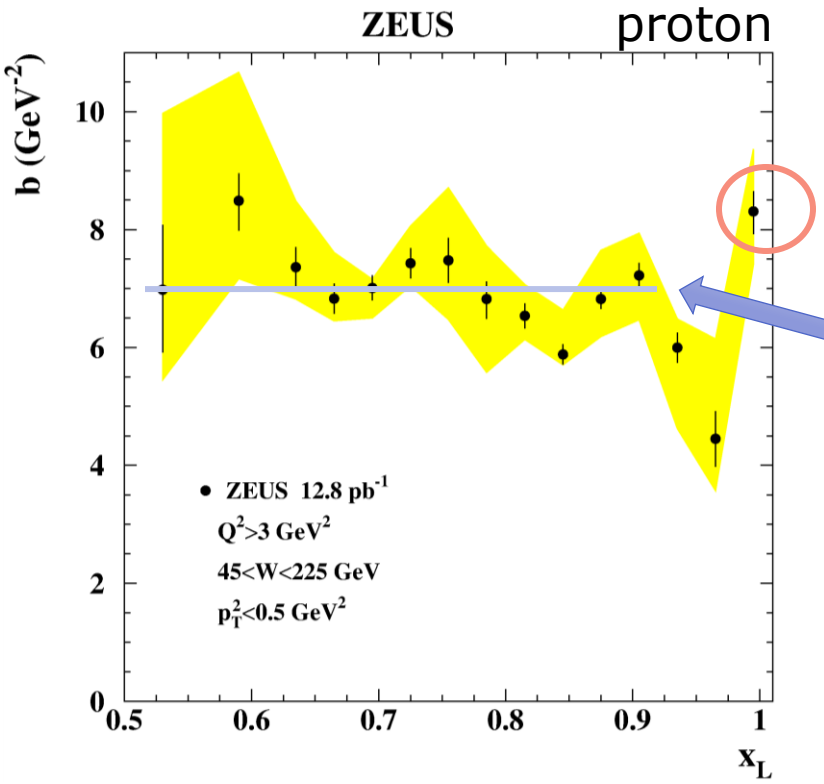
forward = 0 degree
$y \simeq 7$

- Protons almost unperturbed after small-x partons taken out
- Small-x partons are pretty "backward"
  - **Large rapidity gap (LRG)**
    between the small-x parton and most forward particle

B-slope of leading baryons at HERA

- Proton: flat at $b \sim 7\ \mathrm{GeV}^{-2}$ ($\sigma \propto e^{-bp_T^2}$)
  - Larger than the proton size
  - The vertex is somewhat soft = peripheral but not too soft either (unlike elastic pp)





Diffractive peak

Protons from inelastic scattering with $x_L = \frac{p_L}{p}$

p_L: proton longitudinal momentum in the final state

p: incoming proton's momentum