Diffractive pp scattering at the LHC

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Standard Model @ LHC
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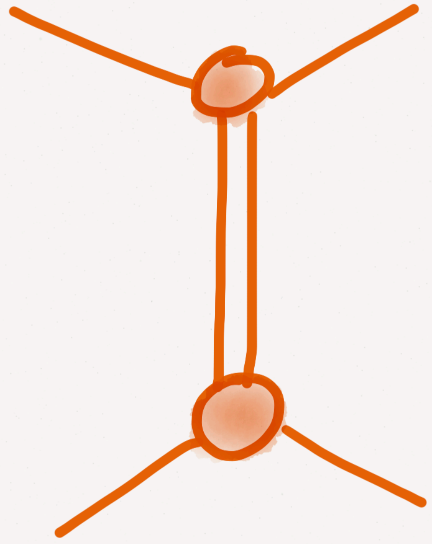
What is diffraction?

- **Proton excitation via quasi-elastic scattering, followed by dissociation**

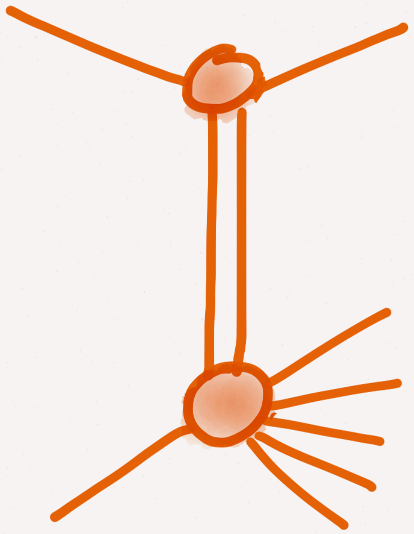
Classification

elastic

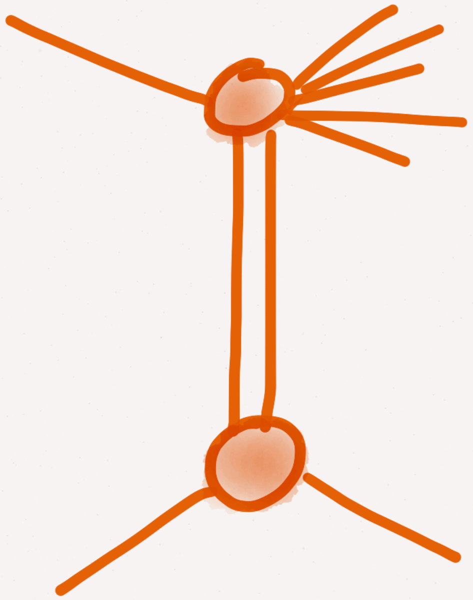


pp → pp

single-diffractive

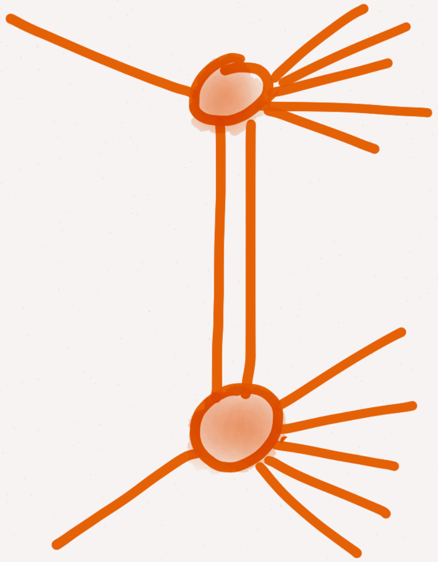


pp → pY



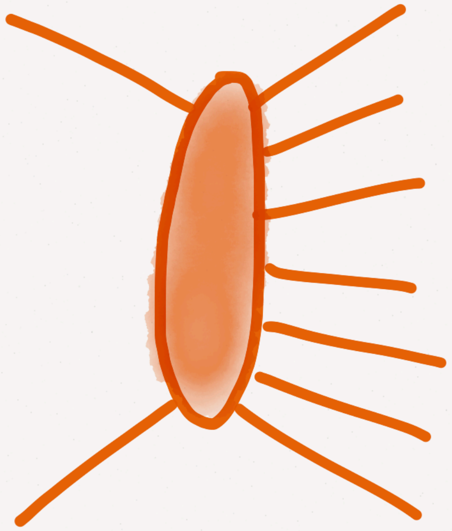
pp → Xp

double-diffractive



pp → XY

non-diffractive



pp → X

What is diffraction?

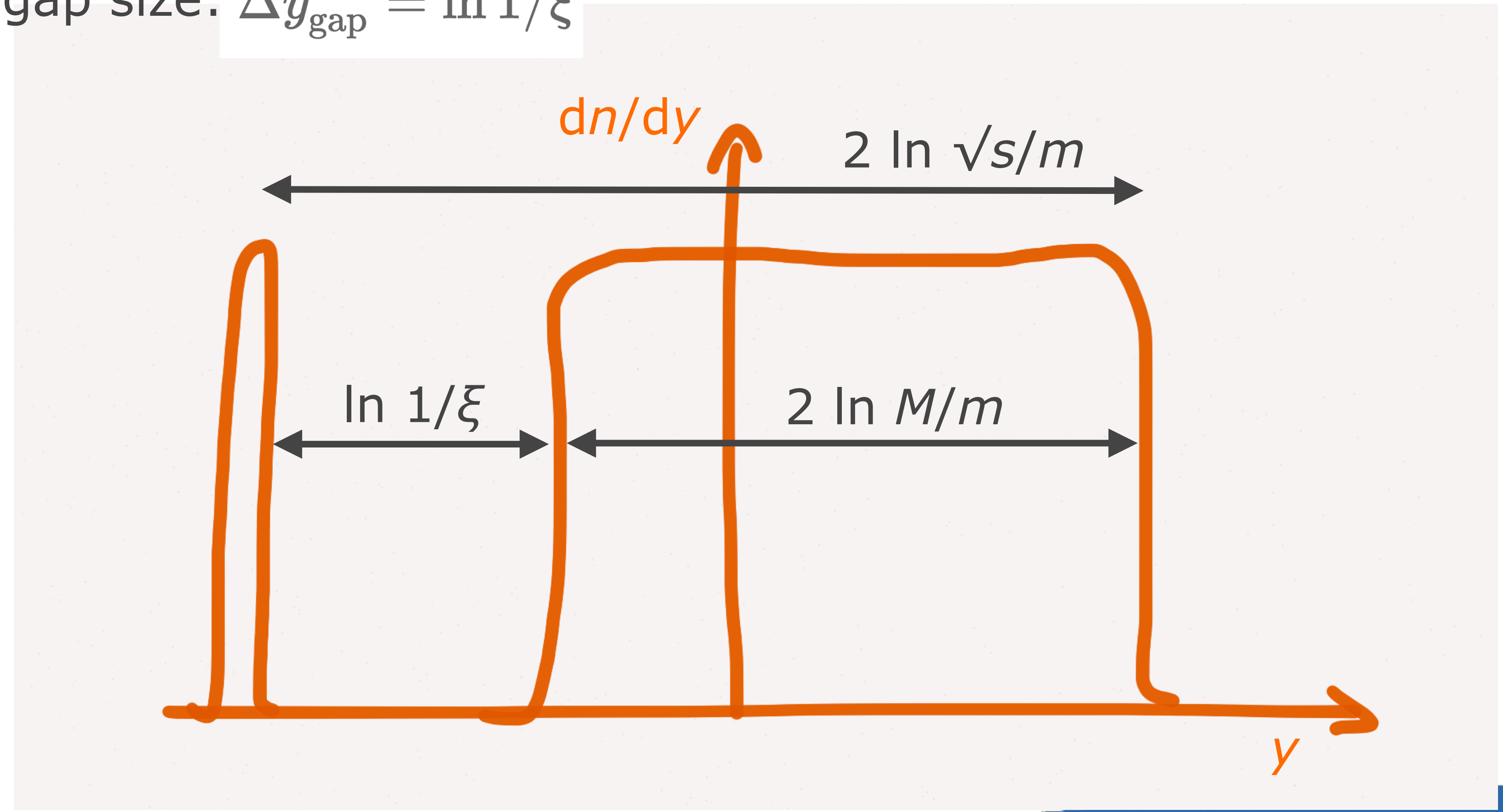
Proton excitation via quasi-elastic scattering, followed by dissociation

Kinematics

- proton energy loss ξ → diffractive mass M:

$$M^2 = \xi\, s \qquad \Rightarrow \qquad 2\ln\sqrt{s}/m = 2\ln M/m + \ln 1/\xi$$

  with m = hadronic mass scale (e.g. proton mass)
- rapidity span of soft hadronic system with mass M: $\Delta y = 2\ln M/m$
- rapidity gap size: $\Delta y_{\text{gap}} = \ln 1/\xi$



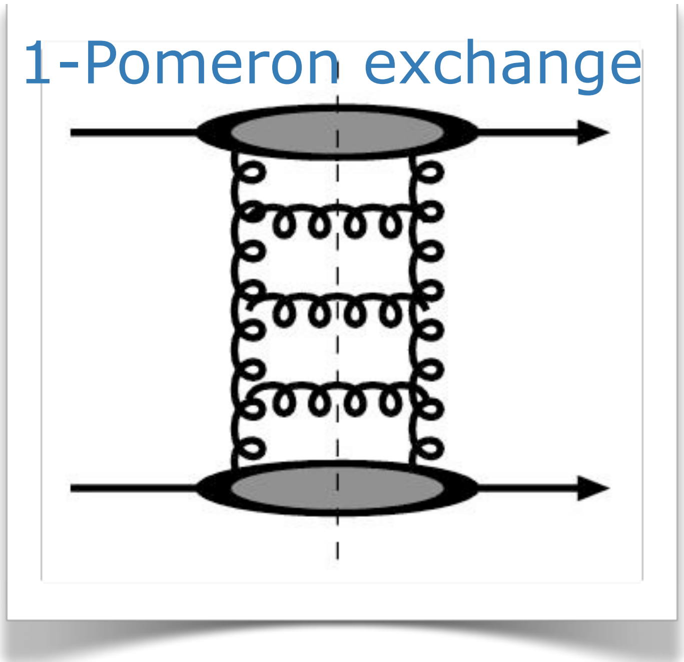
Why measure diffraction?

Diffraction accounts for 25-30% of the total cross section at the LHC

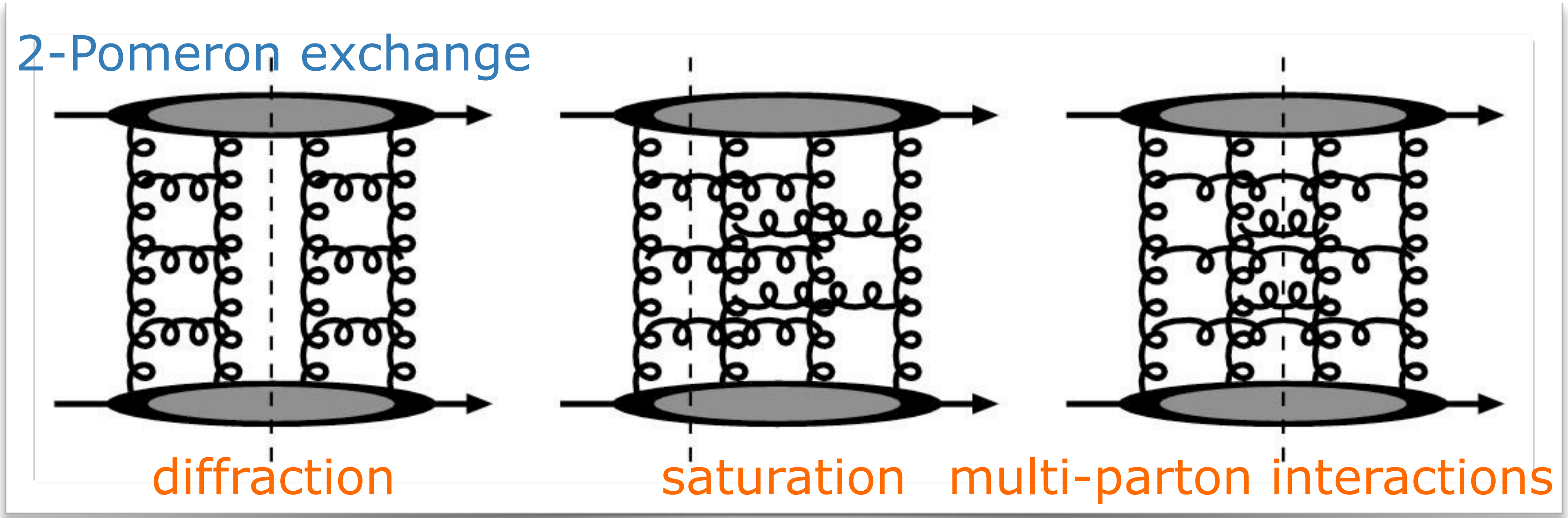
- diffractive dissociation must be well understood for a good description of the additional inelastic pp interactions (pile-up) which accompany most events

Diffraction is also interesting in its own right!

- diffraction goes beyond simplistic factorization and a probabilistic approach of parton densities
- diffraction is inherently linked to collective behavior of partons
- AGK rules: same physics plays in
  - multi-parton interactions
  - saturation of parton densities
  - diffractive scattering



1-Pomeron exchange



2-Pomeron exchange

diffraction

saturation

multi-parton interactions

Soft diffraction

Good and Walker formalism for low mass diffraction

- proton is superposition of diffractive eigenstates that are absorbed differentially by the target

$$|p\rangle = \sum_k |\psi_k\rangle = |p_0\rangle + |p^*\rangle + \ldots \qquad \mathrm{Im}\,T|p\rangle = \mathrm{Im}\,T\sum_k |\psi_k\rangle = \sum_k t_k|\psi_k\rangle \neq |p\rangle$$

$$\sigma_{\mathrm{el}} = |\langle p|\,\mathrm{Im}\,T\,|p\rangle|^2 = \langle t\rangle^2 \qquad \sigma_{\mathrm{diff}} = \sum_k |\langle\psi_k|\,\mathrm{Im}\,T\,|p\rangle|^2 - \sigma_{\mathrm{el}} = \langle t^2\rangle - \langle t\rangle^2$$

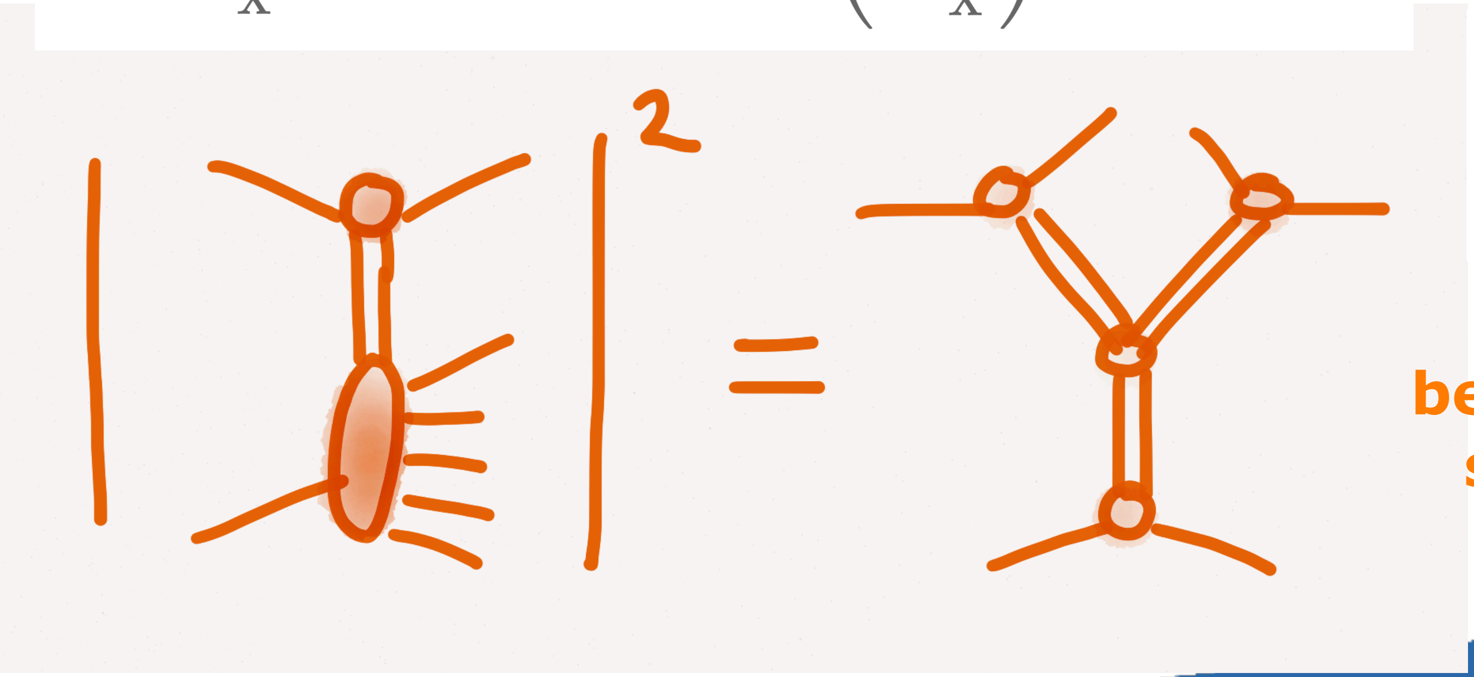
Triple-Regge formalism for high mass diffraction

- at large √s, Pomeron exchange is expected to dominate

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t\,\mathrm{d}M_{\mathrm{X}}^2} = G_{3\mathbb{P}}(0)\, s^{2\alpha_{\mathbb{P}}(t)-2}\left(\frac{1}{M_{\mathrm{X}}^2}\right)^{\alpha_{\mathbb{P}}(0)+2\alpha'_{\mathbb{P}}t} \mathrm{e}^{Bt}$$

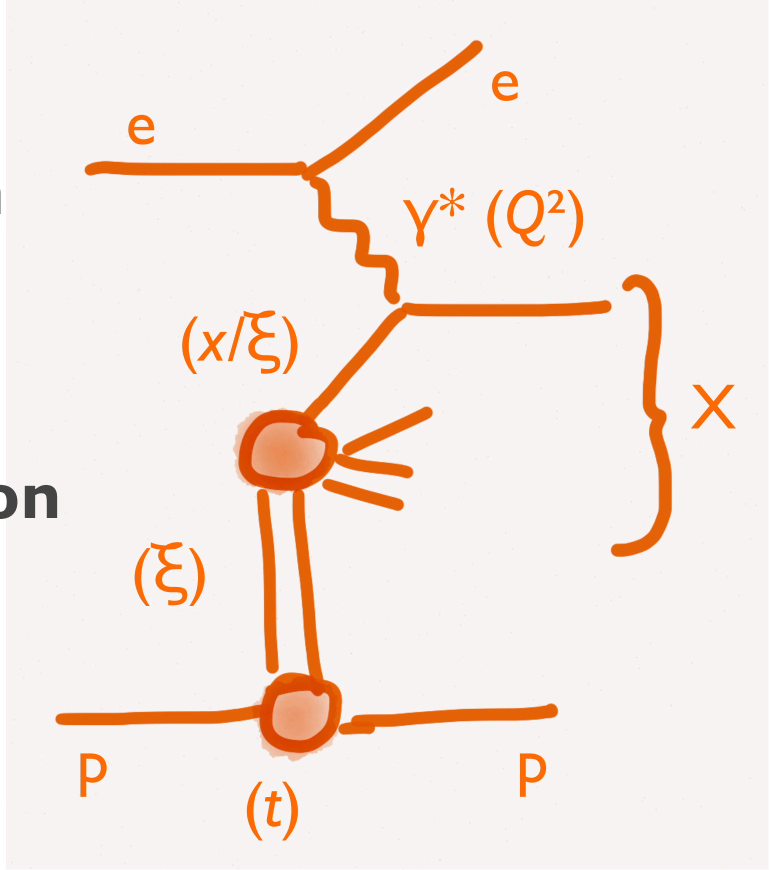
- $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}t, \quad \alpha_{\mathbb{P}}(0) = 1+\epsilon$
- at small *t*: $\sigma(s) \sim s^{2\epsilon}$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M_{\mathrm{X}}^2} \sim \left(\frac{1}{M_{\mathrm{X}}^2}\right)^{1+\epsilon}, \qquad \frac{\mathrm{d}\sigma}{\mathrm{d}\Delta y_{\mathrm{gap}}} \sim \mathrm{e}^{\epsilon\Delta y_{\mathrm{gap}}}$$



➧ diffraction is due to collective behavior of partons → orthogonal to standard, leading twist, collinear approach to pp interactions

Hard diffraction



Diffractive parton densities

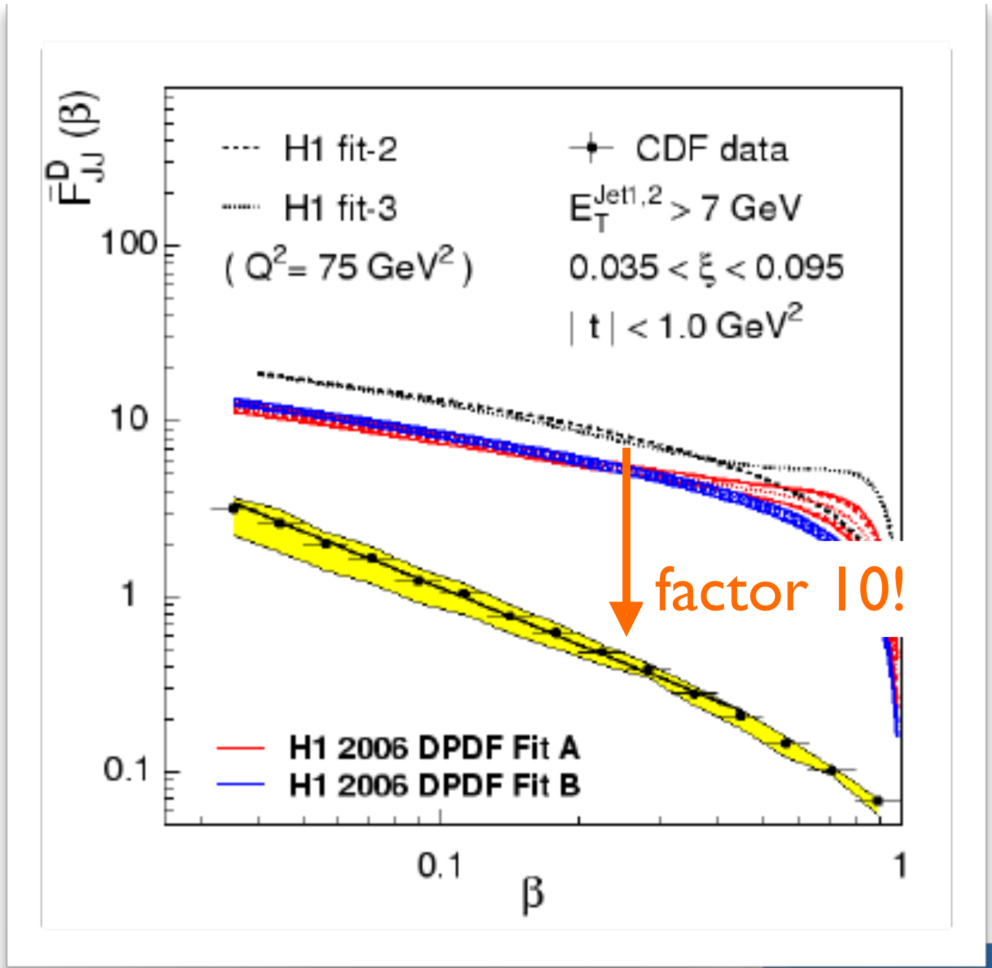
- J. Collins [hep-ph/9709499]: proof of QCD factorization in DDIS

$$\sigma(\mathrm{ep} \to \mathrm{epX}) = f^{\mathrm{D}}(x, Q^2, \xi, t) \otimes \hat{\sigma}(\mathrm{eq} \to \mathrm{eX})$$

Parameterization of diffractive *F*₂ with Regge factorization

- Pomeron flux + DGLAP-evolved parton densities

$$F_2^{\mathrm{D}}(x, Q^2, \xi, t) = f_{\mathbb{P}/\mathrm{p}}(\xi, t) \cdot F_2^{\mathbb{P}}(x/\xi, Q^2)$$



Application to hadron-hadron scattering?

- factorization is broken in hadron scattering due to soft re-scatterings (a.k.a. unitarity corrections, higher twist, saturation, ...)
- rapidity gap survival factor estimate from comparison between HERA and TEVATRON: factor 10!
- Can this be modeled with multi-parton interactions?

Observable definition of diffraction

Properties of diffractive events

- forward going proton (but how forward?)
- large rapidity gap (but how large?)
- low proton energy loss (but how low?)

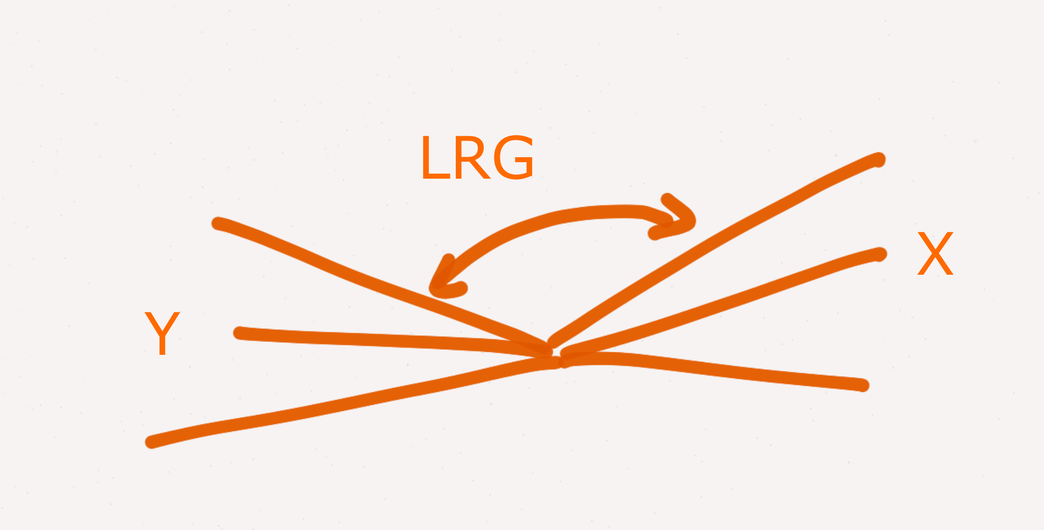
How can diffraction be defined from the observable final state?

- ND with large gaps is in principle identical to DD
- in many measurements, the outgoing proton is not detected and an event sample of SD+DD is obtained

➧ Not obvious how to disentangle SD, DD and ND from final state particles

➧ Need to avoid large model-dependent corrections

➧ A precise, particle-level definition of the cross section is needed!



Largest Rapidity Gap algorithm

(1) Consider all final state particles and their four-momenta

(2) Order particles with increasing rapidity

(3) Find largest rapidity gap between any two neighboring particles

(4) Largest gap defines the separation between hadronic final state systems X and Y

(5) Calculate invariant mass of X and Y: M_X and M_Y; take $M_X > M_Y$

(6) $\xi = M_X^2/s$

Total inelastic cross section

“Visible” cross section measured by ALICE, ATLAS and CMS

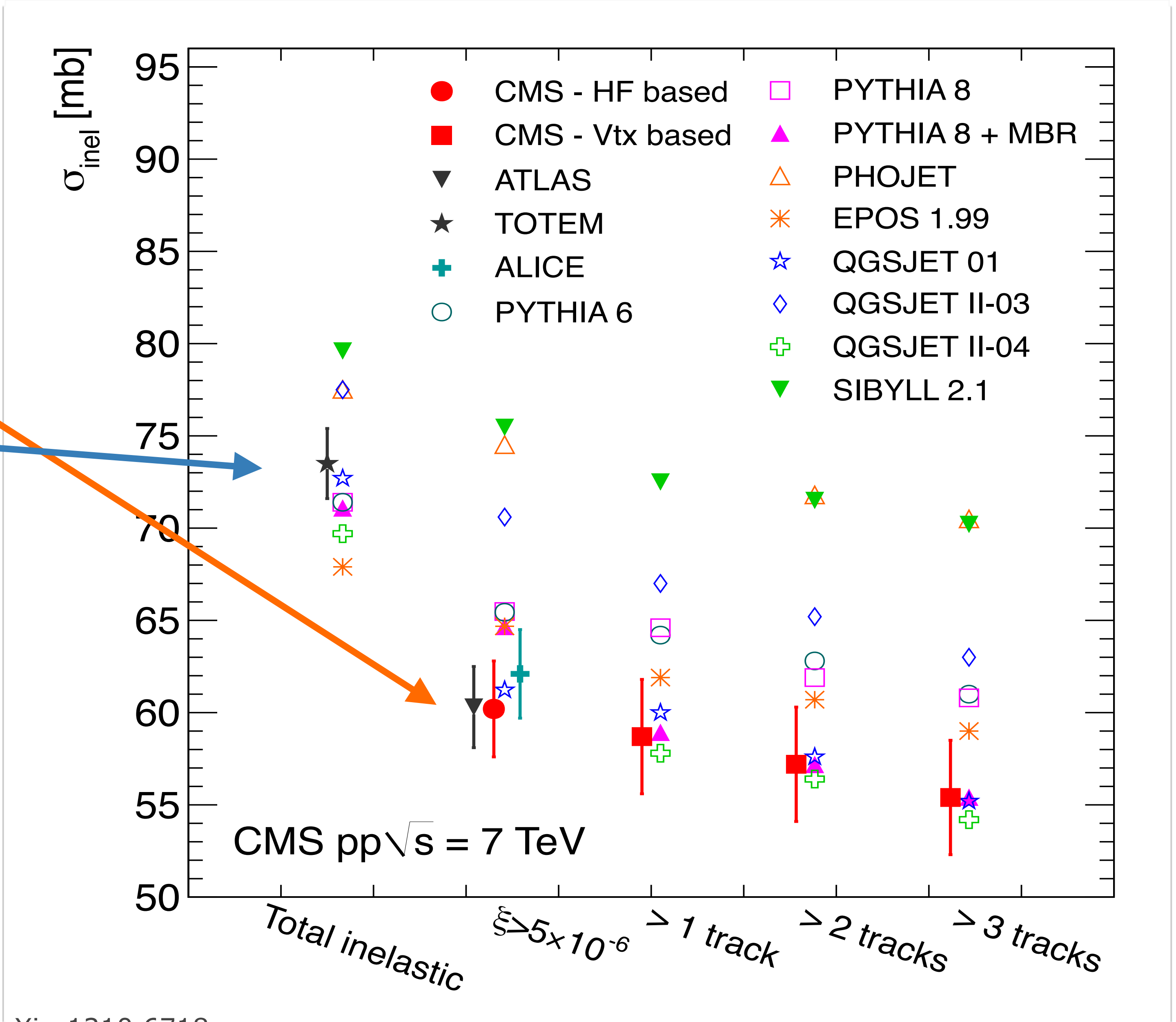
- includes all inelastic processes, except low mass (M < 15 GeV) diffraction
- $\sigma_{\text{inel}}(\xi > 5 \times 10^{-6}) \sim 60$ mb

Total inelastic cross section measured by TOTEM

- $\sigma_{\text{inel}} \sim 73$ mb

Relative amount of low-mass diffraction underestimated by all models

- PYTHIA (typical) predicts 6 mb low-mass diffraction (factor 2 lower than data)
- QGSJETII-01 remarkably close to data!
- may be explained by contributions from sub-leading Reggeon terms in 3IR approach

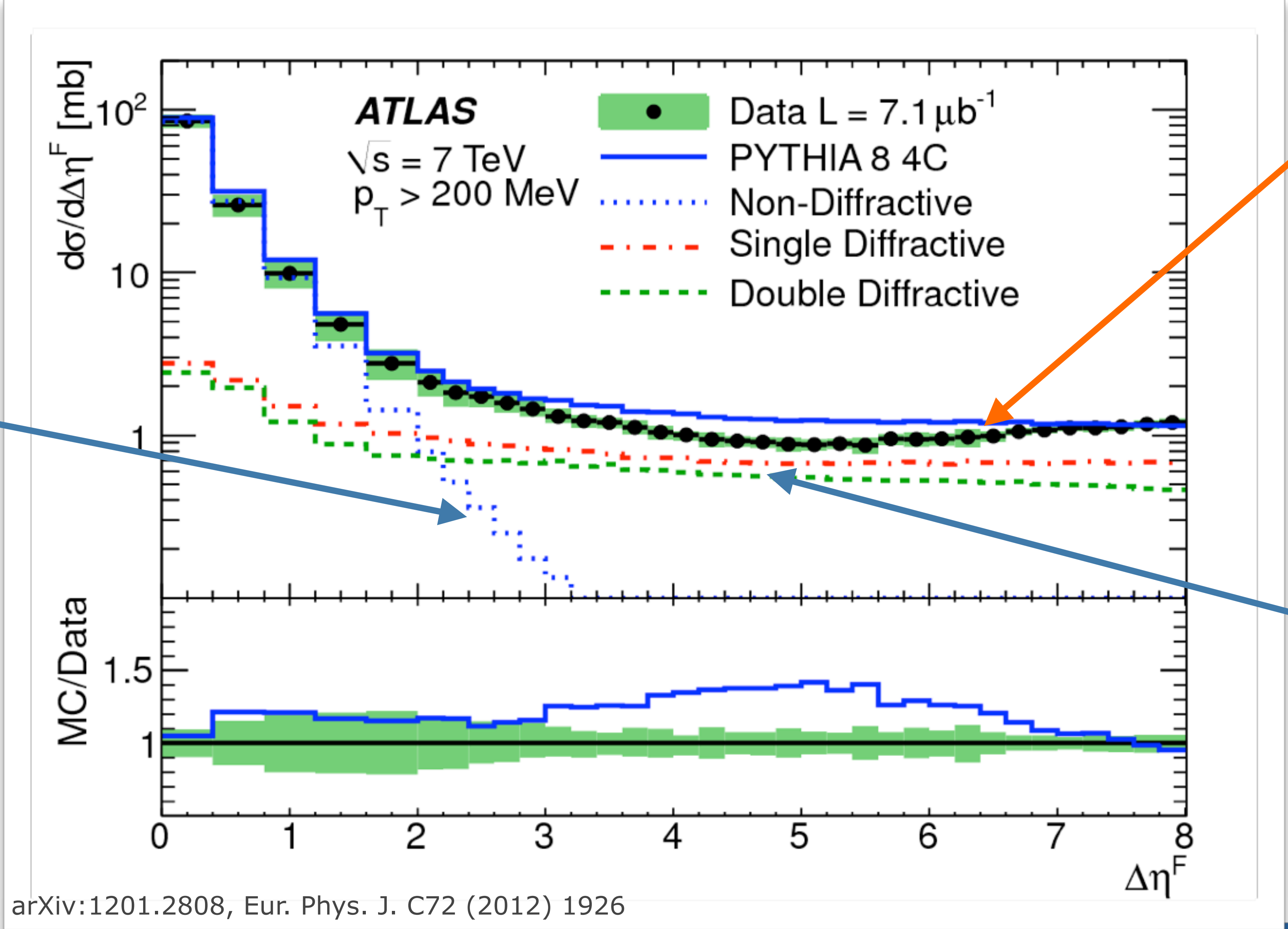


arXiv:1210.6718

Rapidity gap cross section

ATLAS result

- $\Delta\eta_F$ defined as the larger of the two empty η regions extending from edges of detector acceptance (η=+4.9 or η=-4.9) to nearest track or calorimeter cluster
- threshold on track p_T and cluster E_T > 200 MeV
- gap cross section fully corrected for detector effects



arXiv:1201.2808, Eur. Phys. J. C72 (2012) 1926

non-diffractive contribution is exponentially suppressed at large $\Delta\eta_F$

diffractive plateau: 1 mb/ unit gap size

single- and double-diffractive (M_Y < 7 GeV) dissociation present in almost equal amounts

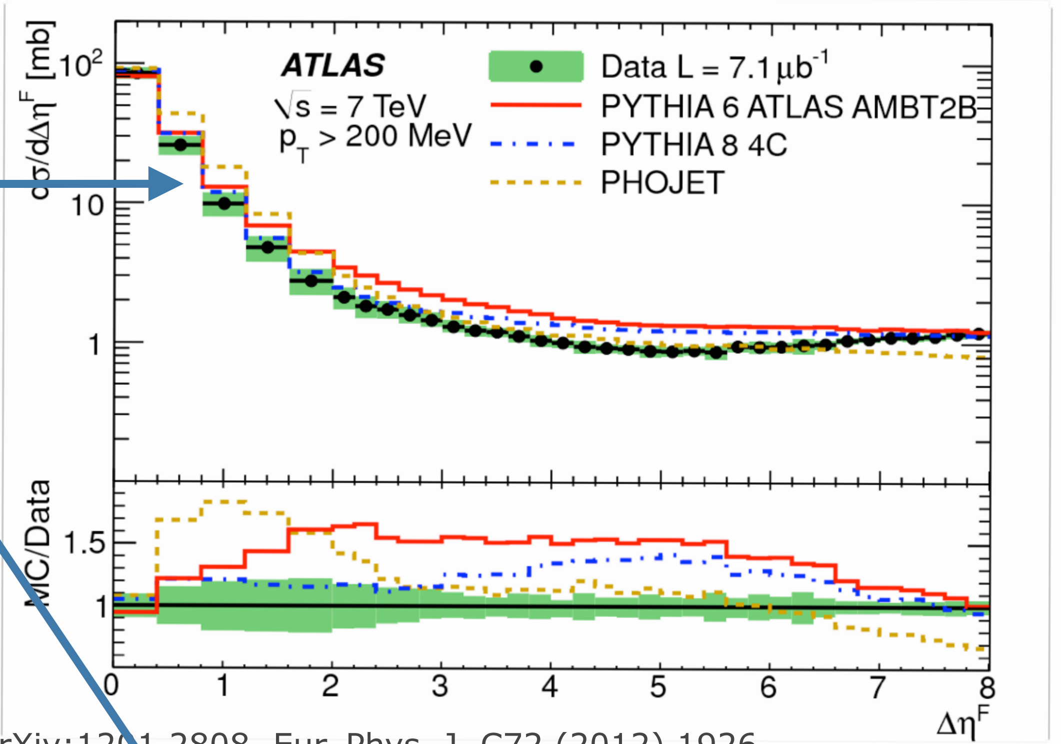
Rapidity gap cross section

Small $\Delta\eta_F$

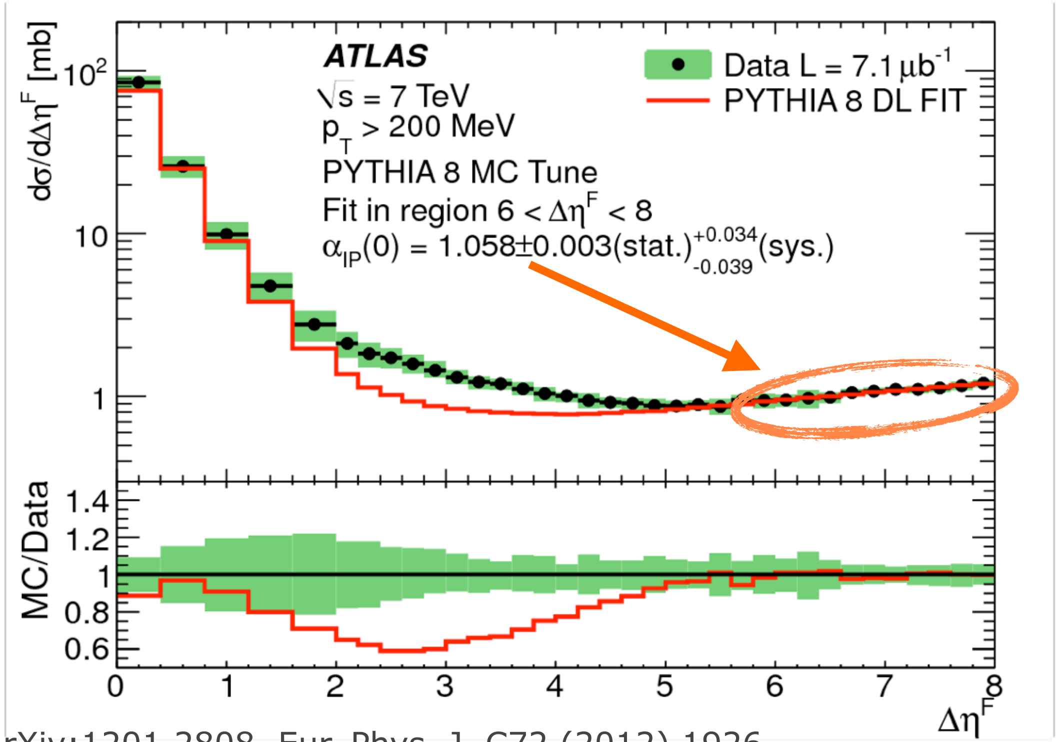
- sensitive to soft particle hadronization fluctuations: PYTHIA & PHOJET
- HERWIG++ generates large gaps even with no diffractive model included

Large $\Delta\eta_F$

- increase of cross section indicates $\alpha_{IP}(0) > 1$
- fit yields ~1.058 (compatible with soft DL pomeron with intercept = 1.085)



arXiv:1201.2808, Eur. Phys. J. C72 (2012) 1926



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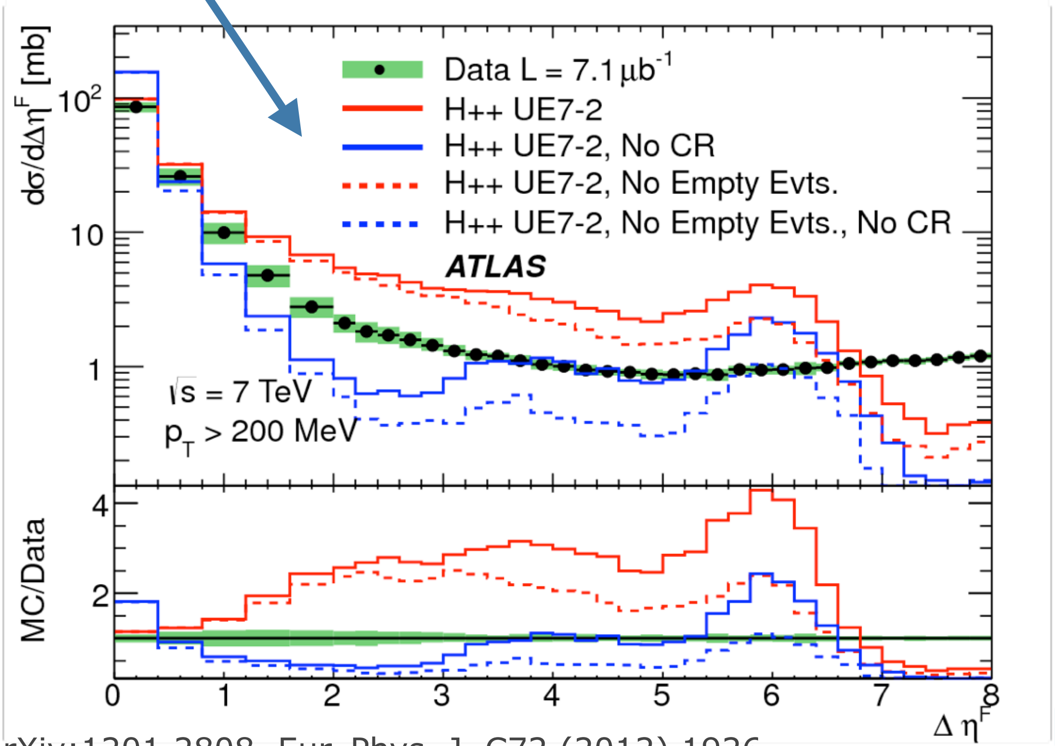
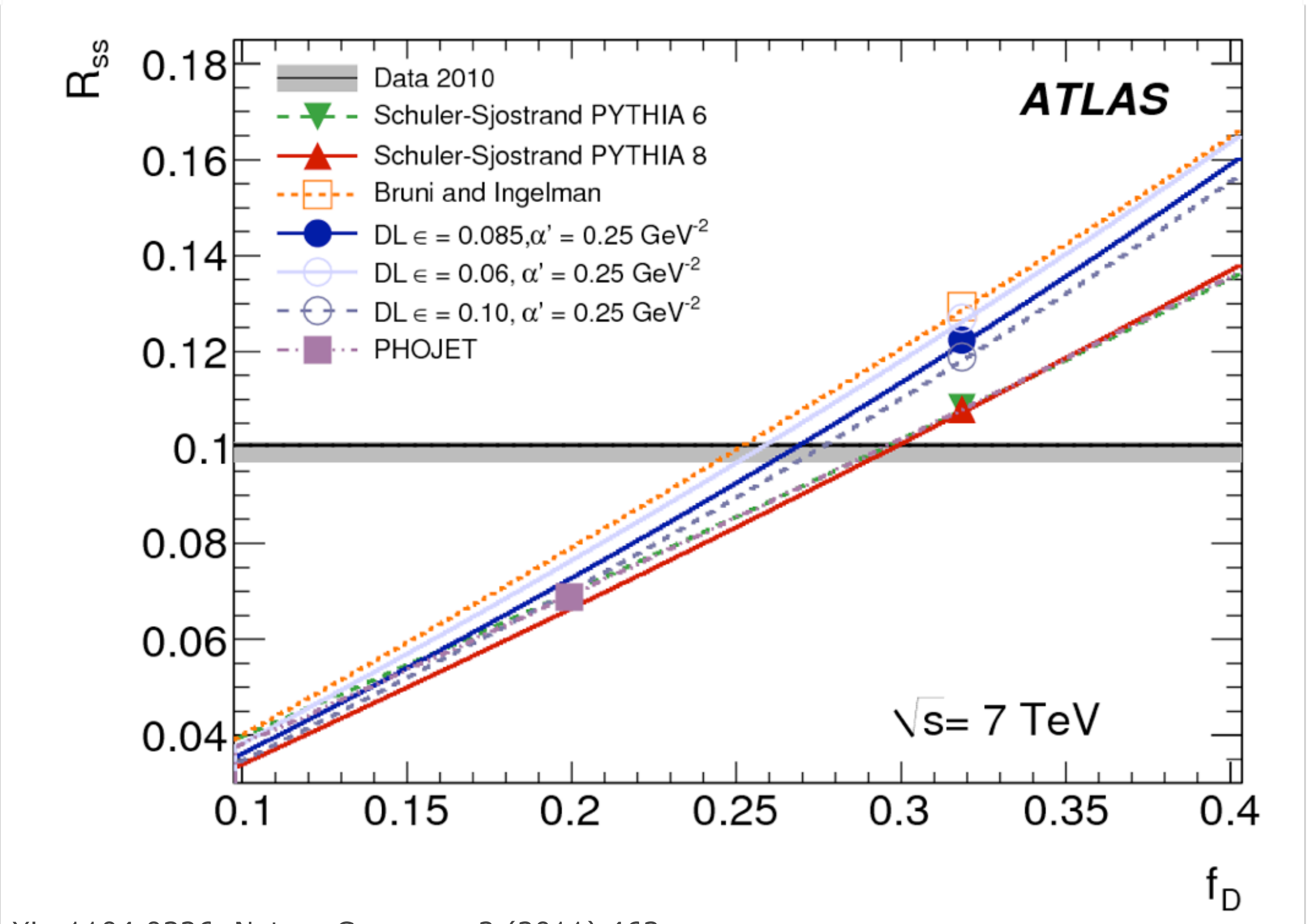


arXiv:1201.2808, Eur. Phys. J. C72 (2012) 1926

SD and DD cross sections measurements

ATLAS result

- using ratio of Single-Sided to Double-Sided triggered events to extract fraction of diffractive processes in total inelastic cross section
- default DL-model with $\alpha_{IP}(0) = 1.085$ yields f_D = (SD+DD)/(SD+DD+ND) ~ 27%

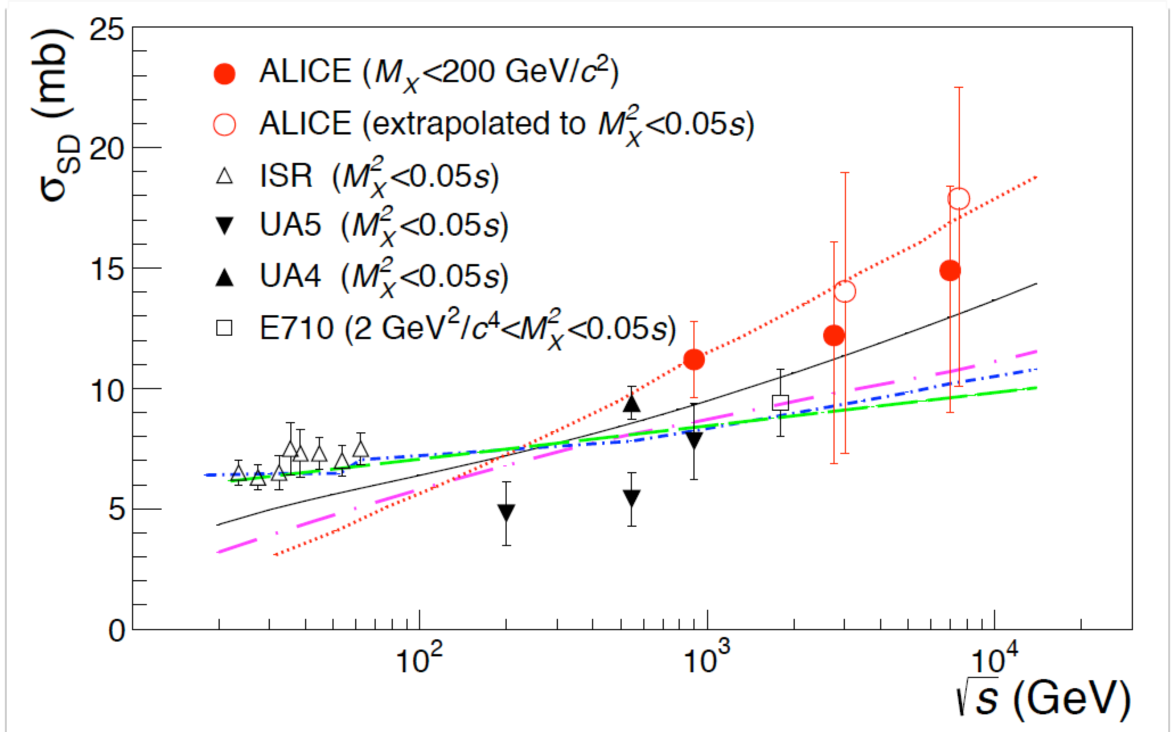


arXiv:1104.0326, Nature Commun. 2 (2011) 463

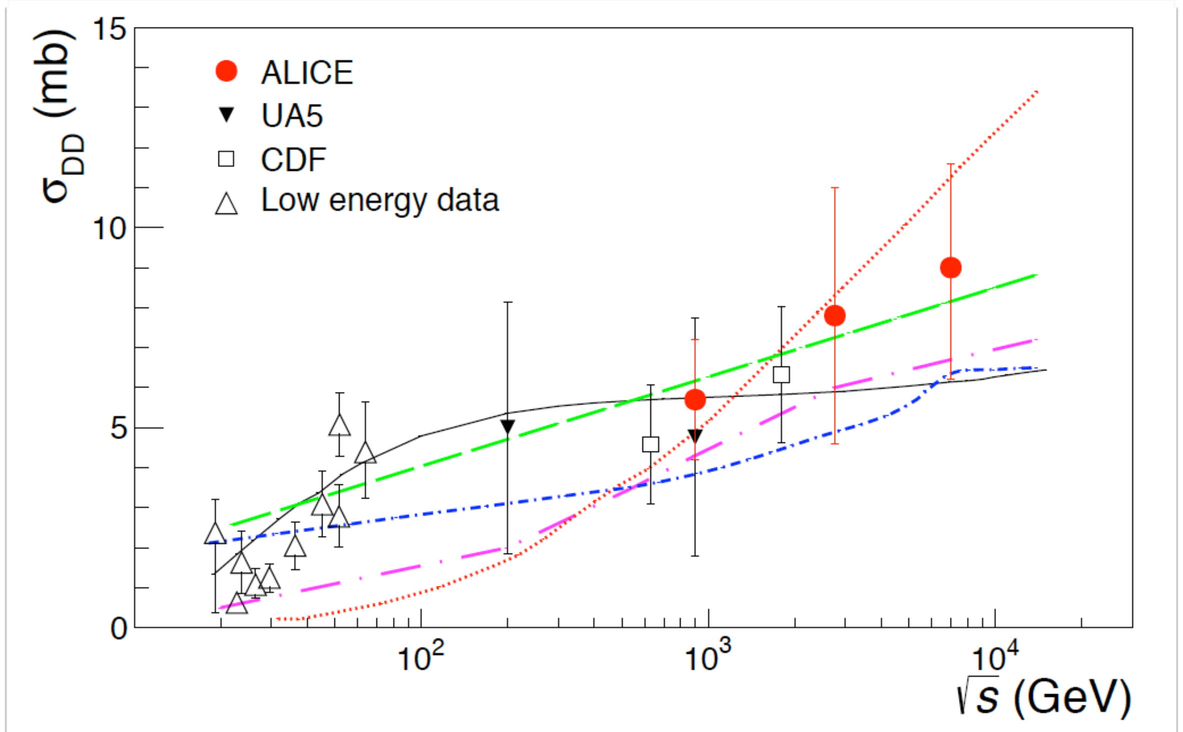
SD and DD cross sections measurements

ALICE result

- using ratio of 1-arm to 2-arm selected events to extract fraction SD/(DD+ND) ~ 20% (approx. equal at √s = 0.9, 2.76, and 7 TeV)
- fraction of 2-arm events with gaps yield DD/(SD+DD+ND) ~ 12%
- absolute cross sections obtained after multiplying with measured σ_{inel}
- caveats:
  - large extrapolation (and uncertainty) for unseen low-mass diffraction
  - σ_{DD} contains ND with $\Delta\eta_{\mathrm{gap}} > 3$



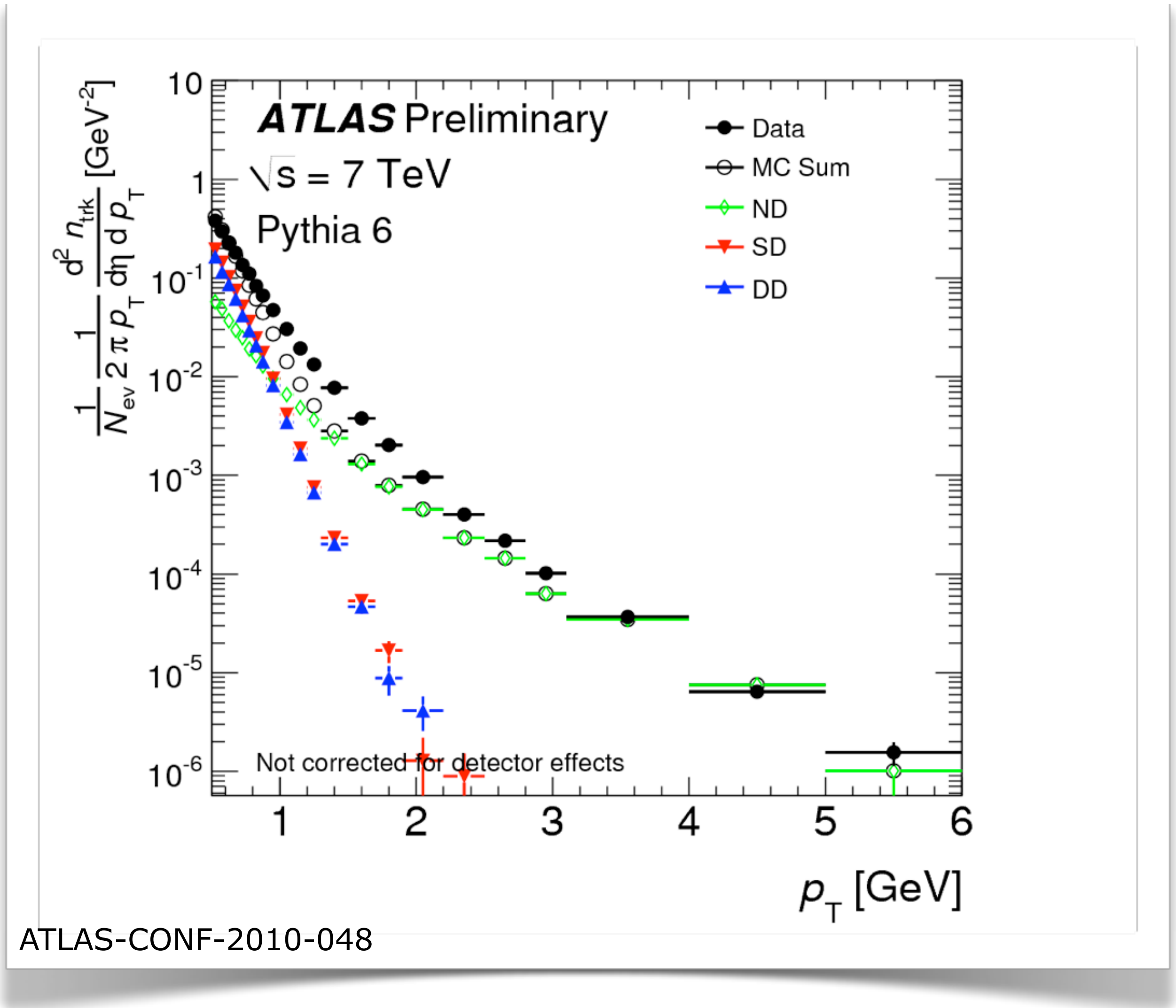
arXiv:1208.4968



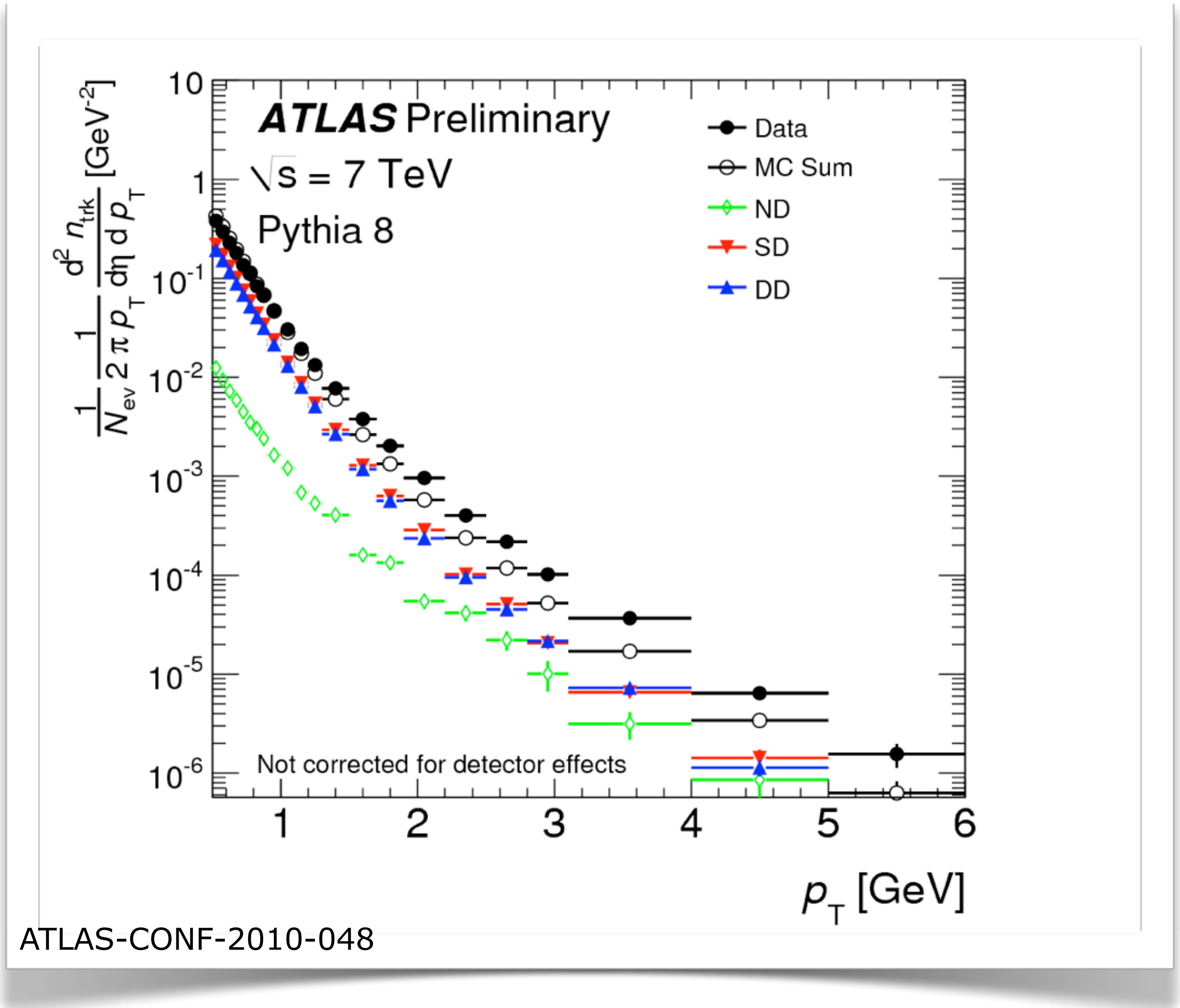
arXiv:1208.4968

Particle p_T spectra

Uncorrected p_T spectra from ATLAS Single-Sided event sample (i.e. dominated by SD+DD)



ATLAS-CONF-2010-048



ATLAS-CONF-2010-048

- PYTHIA6 (no hard diffraction):
  - needs ND to explain high-p_T tail
- PYTHIA8 (with diffractive pdfs and hard diffractive scattering):
  - large p_T particles produced by SD+DD
  - ND contribution much reduced

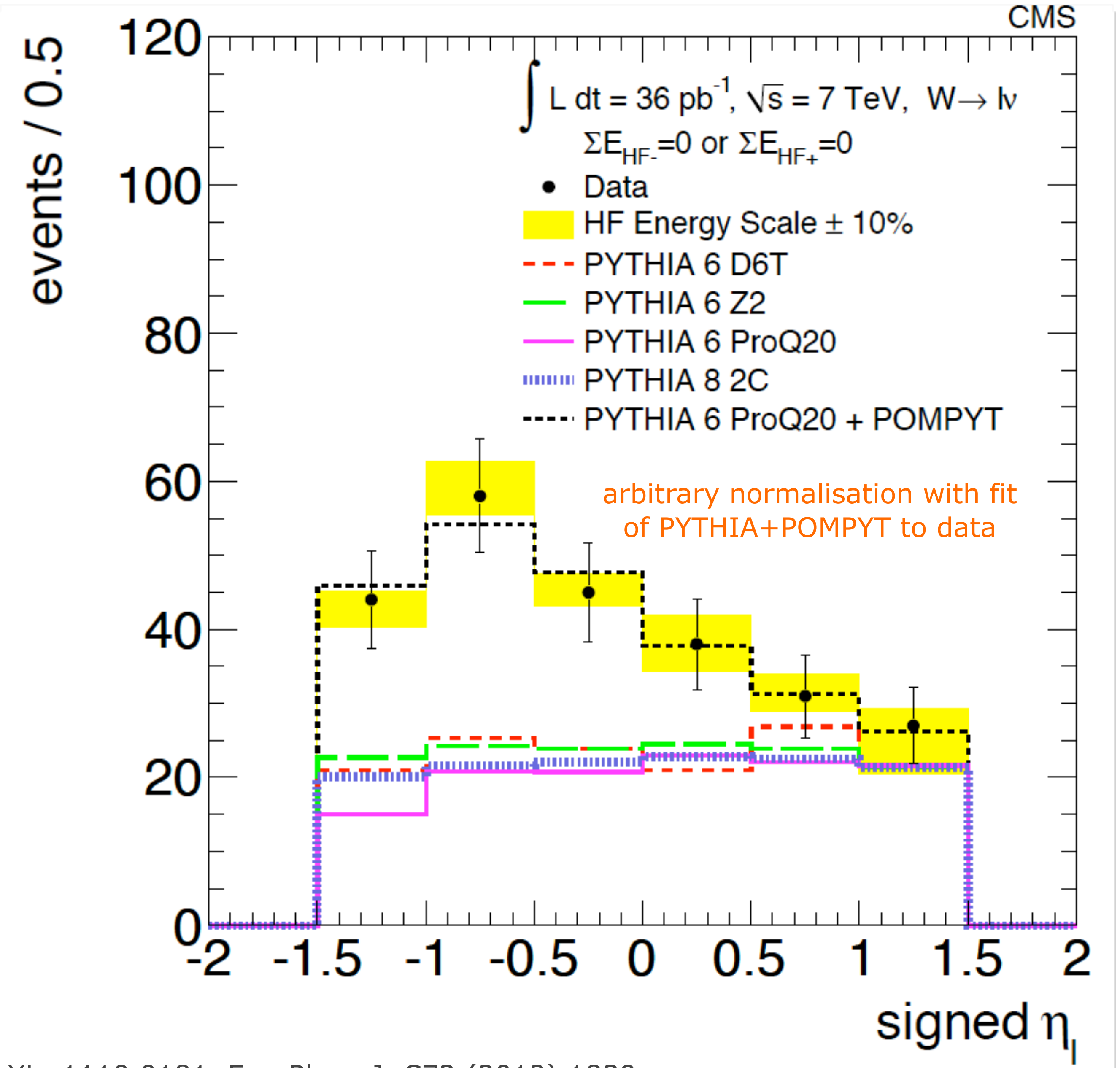
Hard diffractive W production

CMS result

- selection of W → lν events
- detector-level gap requirement: no energy within $3 < |\eta| < 4.9$ (caveat forward energy flow very badly modeled by MC)
- signed η_{lepton} distribution: $\eta_{\text{lepton}} < 0$ when e, μ opposite to the pseudorapidity gap

Comparison of data to MC

- ND models yield flat η_{lepton} distribution, regardless of UE tune
- POMPYT predict preference to to have lepton in the hemisphere opposite to the gap
- evidence for contribution of ~50% diffractive W production in event sample



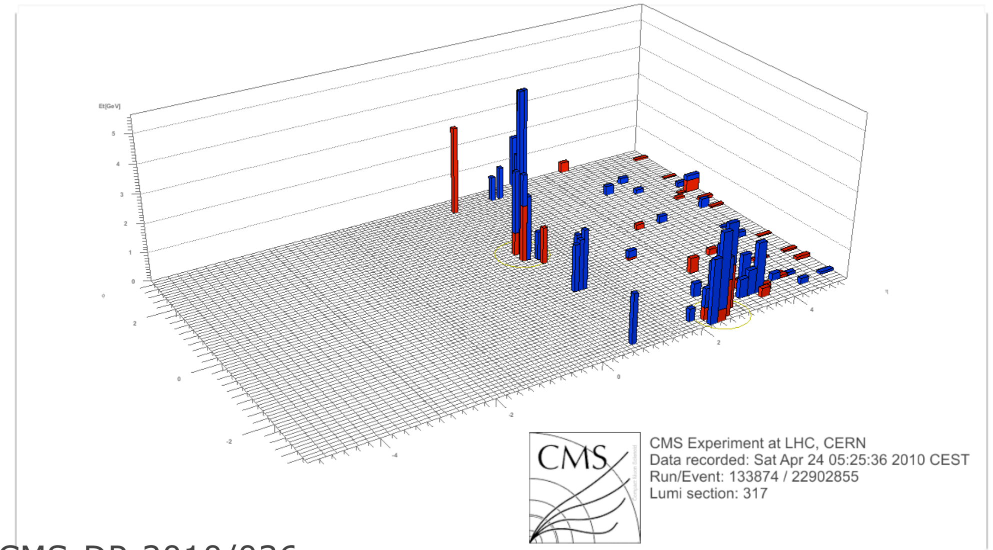
arbitrary normalisation with fit of PYTHIA+POMPYT to data

arXiv:1110.0181, Eur. Phys. J. C72 (2012) 1839

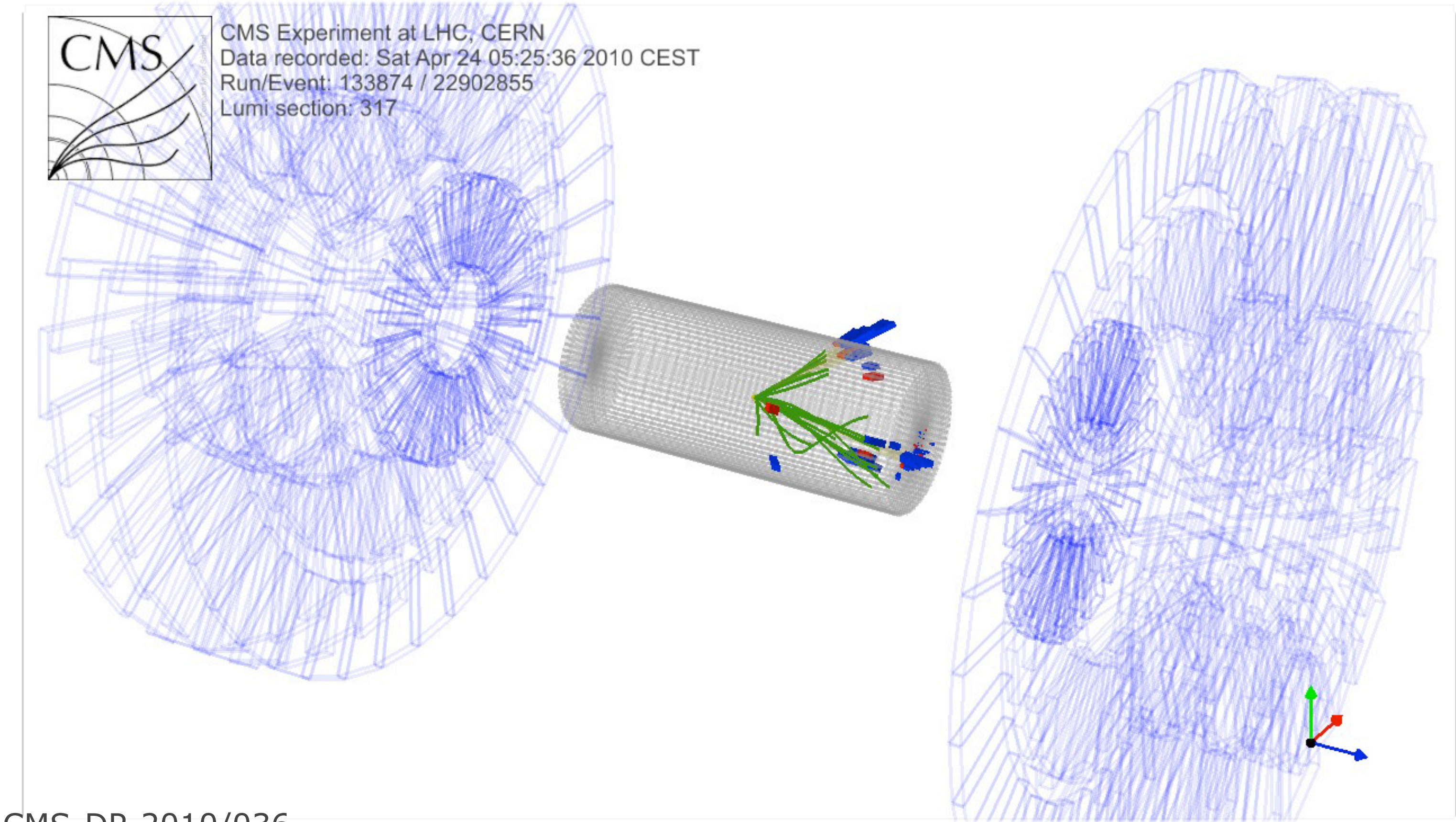
Hard diffractive dijets

CMS result

- inclusive di-jets with
  - $|\eta| < 4.4$
  - $p_T > 20$ GeV



CMS-DP-2010/036



CMS-DP-2010/036

- particle-level definition of ξ: sum over final state particles within acceptance

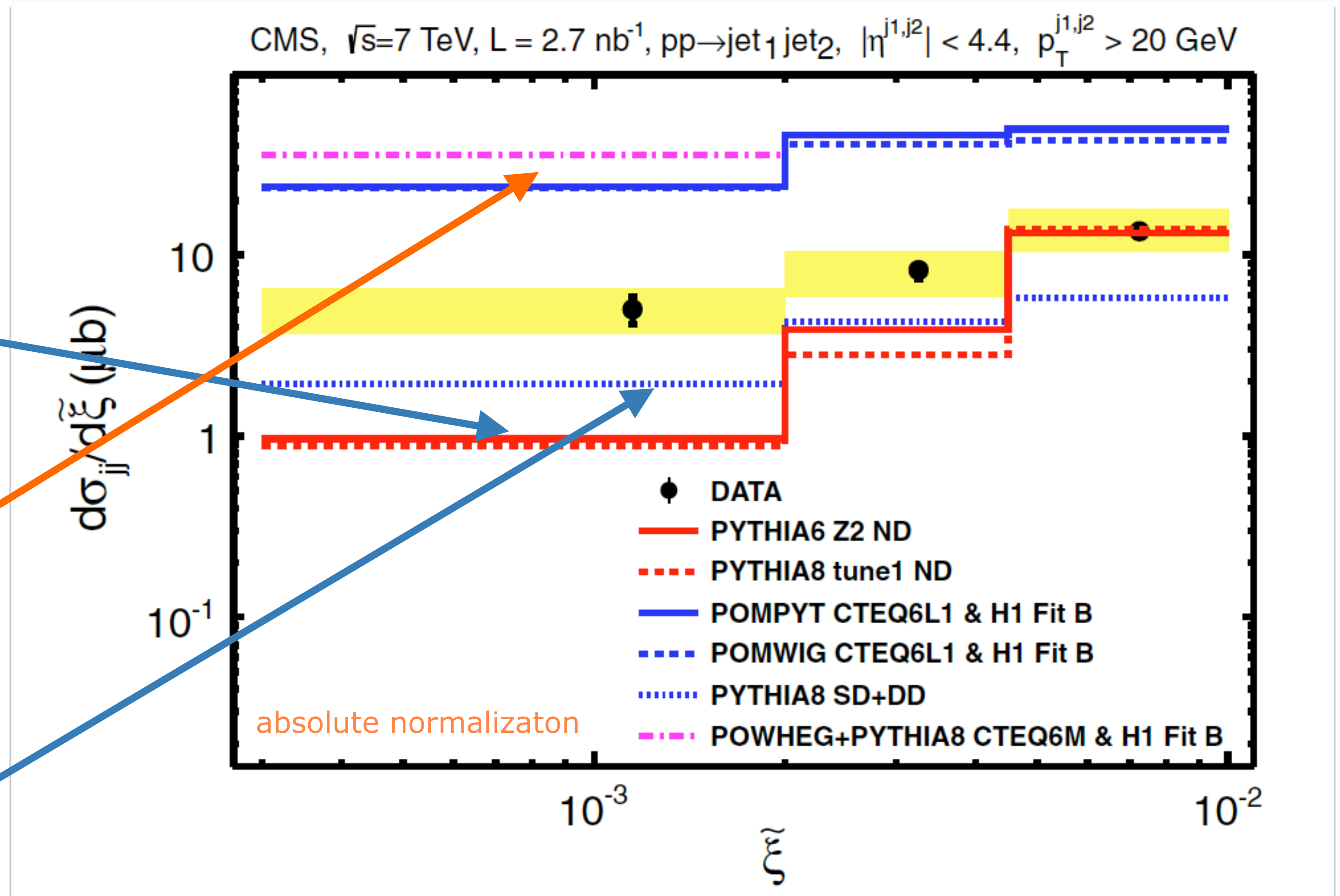
$$\tilde{\xi}^{+} = \frac{1}{\sqrt{s}} \sum_{\eta<4.9} E^i + p_z^i, \qquad \tilde{\xi}^{-} = \frac{1}{\sqrt{s}} \sum_{-4.9<\eta} E^i - p_z^i$$

  - good approximation of the true ξ in SD events at low ξ
  - no explicit rapidity gap selection, but low ξ implies a large gap

Hard diffractive dijets

CMS result

- inclusive dijet cross section as function of ξ
  - fully corrected for detector effects
  - excess observed at low ξ w.r.t. non-diffractive models PYTHIA6 and PYTHIA8
  - POMPYT and POMWIG (LO) diffractive MC's and NLO calculation from POWHEG, are a factor ~5 above the data in lowest ξ bin
  - PYTHIA8 diffractive cross sections are considerably lower due to different Pomeron flux parametrization



absolute normalizaton

arXiv:1209.1805, Phys. Rev. D87 (2013) 012006

- Normalization discrepancies give upper limit predictions (corrected for DD) to rapidity gap survival probability:
  - $\langle S^2 \rangle_{\text{data/MC}} = 0.12 \pm 0.05$ (LO MC)
  - $\langle S^2 \rangle_{\text{data/MC}} = 0.08 \pm 0.04$ (NLO MC)

Summary

Soft and hard diffraction has been established at the LHC

- rapidity gap cross section
- total, single- and double-diffractive inelastic cross sections
- hard diffractive dijet and W production

➧ **MC models in general should be improved to be able to describe diffractive interactions in detail**

Some open questions/next steps:

- What is the link between rapidity gap survival and multi-parton interactions?
  Can this be used to describe gap survival in MC models?
- Search for central exclusive production (double Pomeron exchange) at the LHC
- Use of proton taggers in diffractive studies

Further reading

- *"Measurements of inelastic, single- and double-diffraction cross sections in pp collisions at the LHC with ALICE"*, Eur. Phys. J. C (arXiv:1208.4968)
- *"Rapidity gap cross sections measured with the ATLAS detector in pp collisions at √s = 7 TeV"*, Eur. Phys. J. C 72 (2012) 1926 (arXiv:1201.2808)
- *"Measurement of the Inelastic Proton-Proton Cross-Section at √s=7 TeV with the ATLAS Detector"*, Nature Commun. 2 (2011) 463 (arXiv:1104.0326)
- *"Observation of a diffractive contribution to dijet production in proton-proton collisions at √s=7 TeV"*, Phys. Rev. D 87 (2013) 012006 (arXiv:1209.1805)
- *"Forward Energy Flow, Central Charged-Particle Multiplicities, and Pseudorapidity Gaps in W and Z Boson Events from pp Collisions at √s= 7 TeV"*, Eur. Phys. J. C 72 (2012) 1839 (arXiv:1110.0181)