Forward Physics: An Experimental Perspective

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H1, ATLAS, LHeC, ePIC experiments

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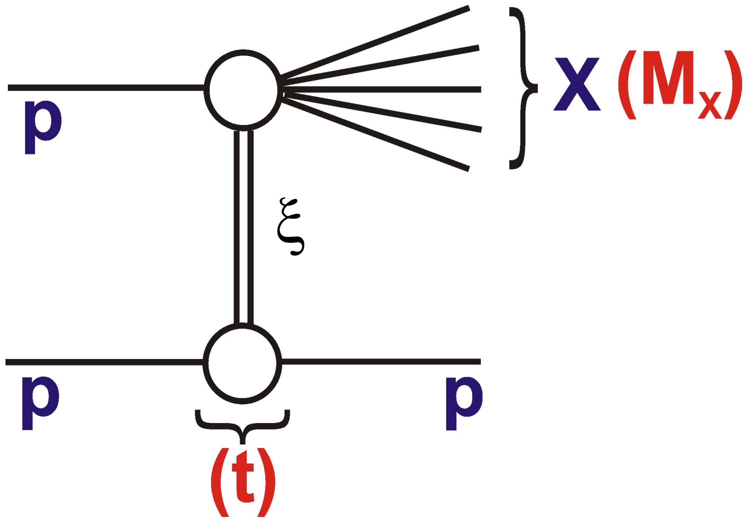
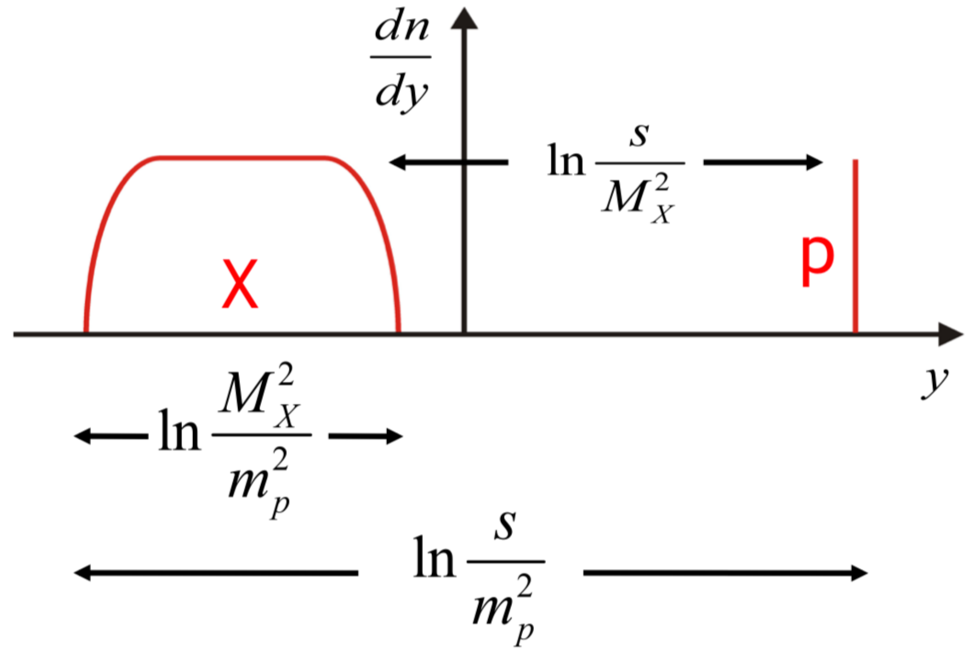
Lecture 3: Diffraction at the Parton Level

Lecture 3

- Wrapping up Single Diffractive Dissociation at the LHC
- Exclusive Vector Meson production in ep Physics
- Diffractive Deep Inelastic Scattering
- Factorisation breaking between ep and pp
- Future ep Experimental Facilities

Diffractive Channels:
& Rapidity Gap Kinematics





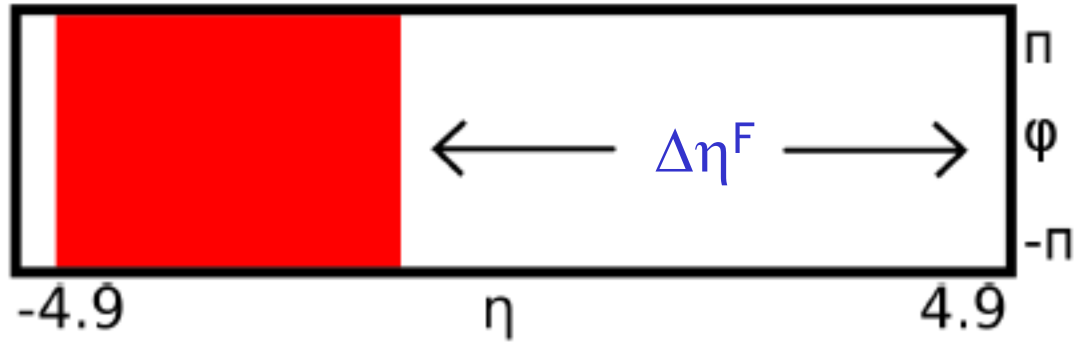
- $\xi = {M_X^2}/{s}$ is strongly correlated with $\Delta\eta \approx -\ln\xi$ empty rapidity regions

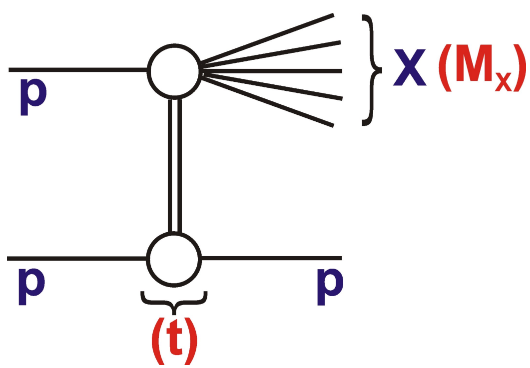
… exploited in SD measurements

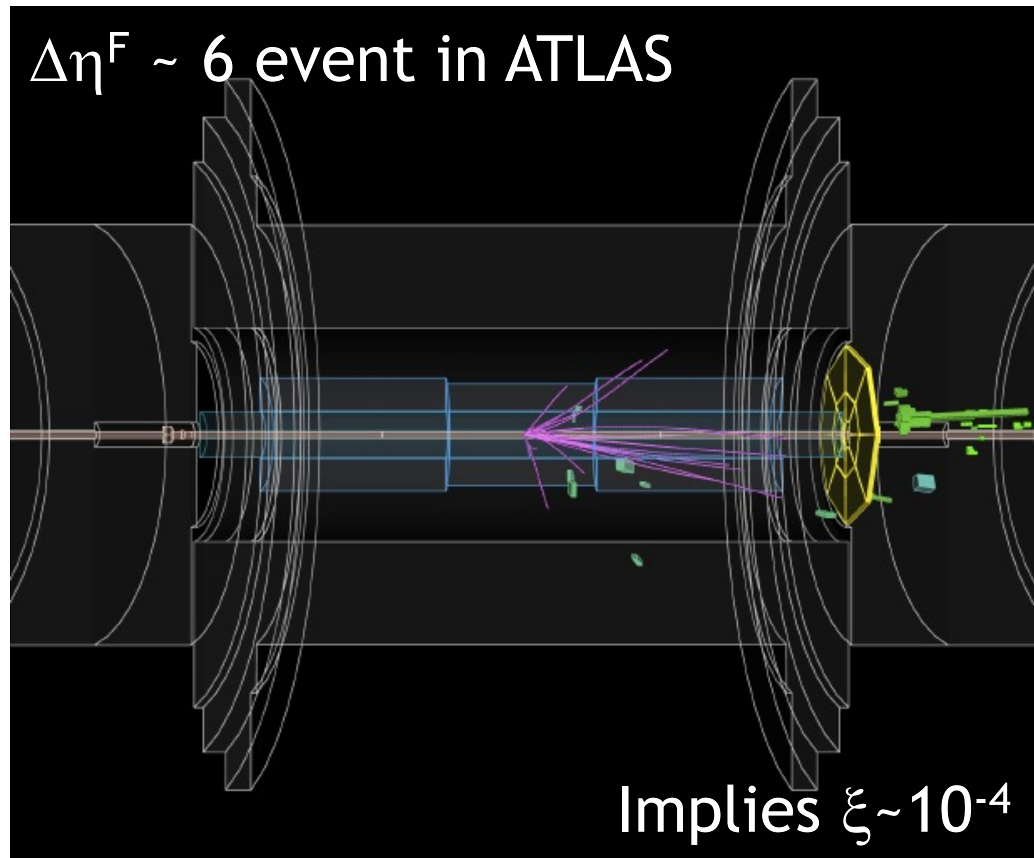
[Correlation limited by hadronisation fluctuations]

Rapidity gap cross-sections

Method developed by ATLAS to measure hadron level cross section as a function of $\Delta\eta^F$: forward rapidity gap extending to limit of instrumented range: i.e. including $\eta = \pm 4.9$







… no statement on $|\eta| > 4.9$

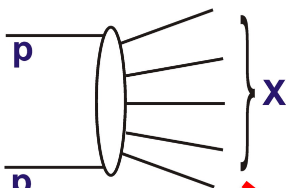
… large $\Delta\eta^F$ sensitive to SD + low M_Y DD

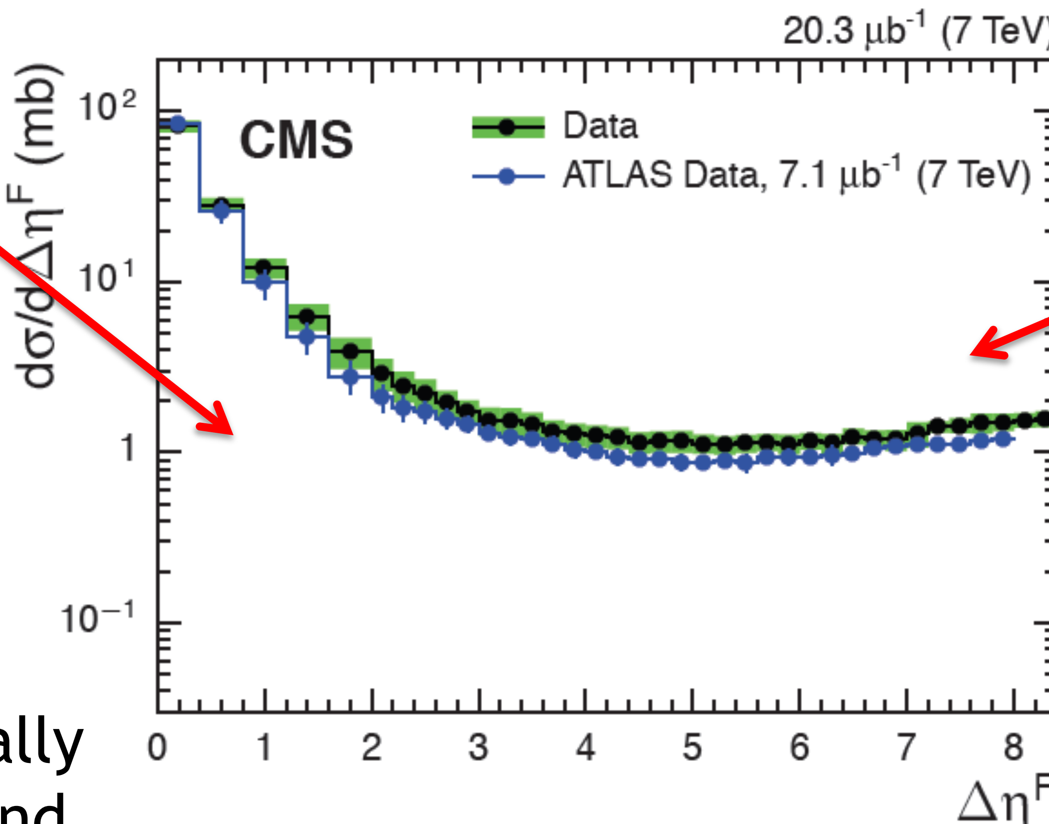
CMS and ATLAS Rapidity Gap Data

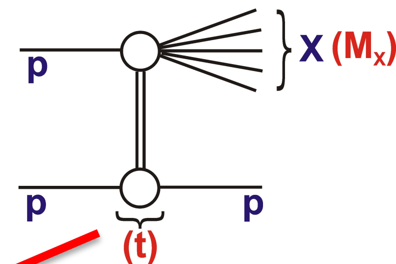
- Using very early LHC runs at 7 TeV (avoiding pile-up) …

ATLAS: $\Delta\eta^F$ extends from $\eta = \pm 4.9$ to 1st particle with $p_t > 200$ MeV

- CMS: $\Delta\eta^F$ extends from $\eta = \pm 4.7$ to 1st particle with $p_t > 200$ MeV







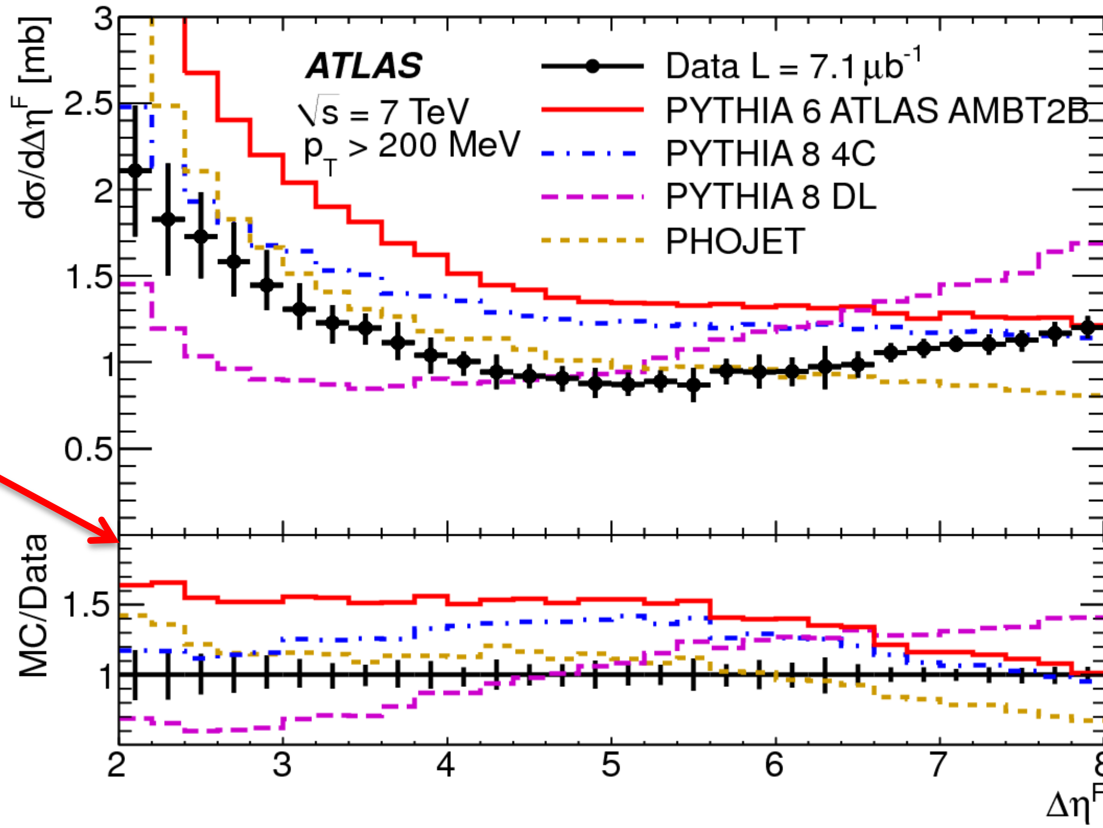
Small gaps dominated by non-diffractive processes … exponentially suppressed and sensitive to hadronisation fluctuations / underlying event

Large gaps dominated by diffractive processes … characteristic plateau

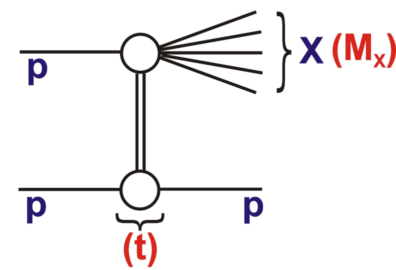
Roughly 1mb per unit gap size

Large Gap Region compared with Models

$\xi \sim 10^{-2.5}$



$\xi \sim 10^{-5}$



- Large differences between Monte Carlo models due to assumptions on total diffractive cross sections, $\alpha(t)$ and fragmentation modelling.

- Fit to large $\Delta\eta^F$ data using $\Delta\eta \sim -\ln\xi$ relation and $\alpha_{IP}(0) = 1.058 \pm 0.003\ (\text{stat}) \pm 0.036\ (\text{syst})$

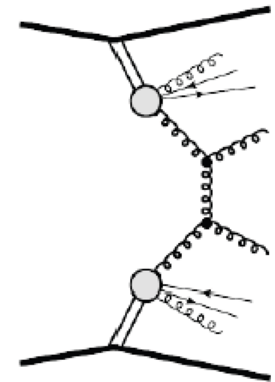
$$\frac{d\sigma}{d\xi\, dt} \propto \left(\frac{1}{\xi}\right)^{2\alpha(t)-\alpha(0)} e^{bt}$$

… still consistent with soft pomeron …

Current and Future Diffraction at LHC

- Most of the ongoing diffractive programme involves Roman Pot tagging in normal high luminosity running conditions

→ Studies with double proton tags (pp→ppX)

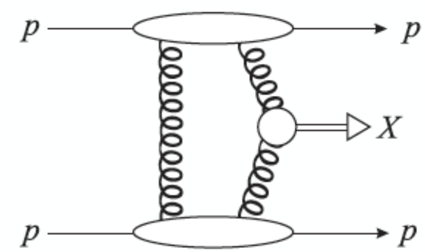


- **Inclusive central production**

pomeron-pomeron hard scattering with jets, HF, W, Z signatures

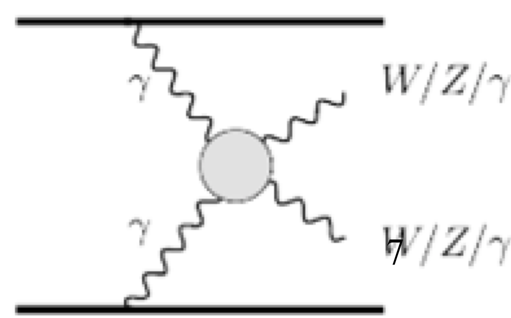
- **Central Exclusive QCD Production**

of dijets, γ-jet and other strongly produced high mass systems … Higgs?...



- **Two photon physics** → exclusive dileptons, dibosons & anomalous multiple gauge couplings …

[Dominates at large masses]



→ See Valery and Christophe's lectures

Summary of Minimum Bias LHC Physics

- Bulk data at LHC is a laboratory for soft strong interactions

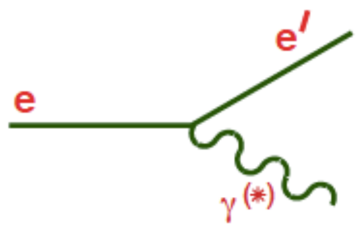
  - Rich phenomenology of non-diffractive processes, but hard to extract underlying dynamics

  - Gaps between jets provide some evidence for BFKL

  - Elastic and diffractive data broadly as expected from soft-Pomeron Regge predictions, but with need for multi-pomeron exchanges.

  - σ_{EL}/σ_{TOT} ~0.25 is close to black disk limit

Diffractive Lepton-Hadron Scattering



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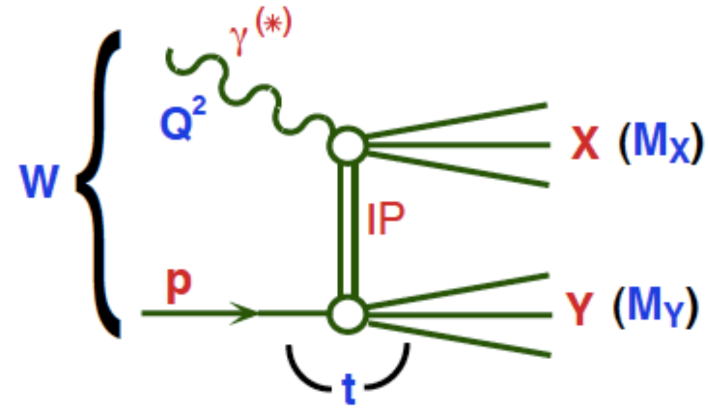


Diffractive γ(*)p scattering …

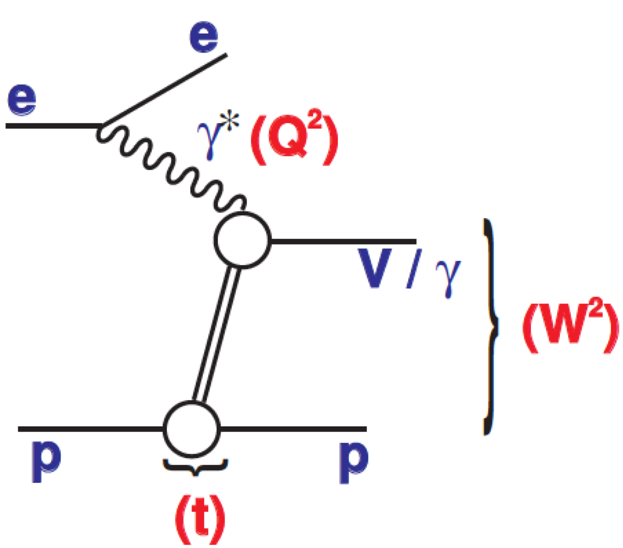
- HERA (and EIC) have favourable kinematics to study X system (photon dissociation)

- Rapidity gap method yields cases where proton remains intact (or dissociates to a very low mass excitation $M_Y < \sim 1.6$ GeV): **γ(*)p→Xp**

- By varying Q^2, the process can be smoothly changed
… from a soft process (real photon, $Q^2 \rightarrow 0$)
… to a deep inelastic process (highly virtual photon, large Q^2, resolving partons and probing QCD structure)

→ Huge topic at HERA (>50 publications each for H1 and ZEUS)

Exclusive Vector Meson Production

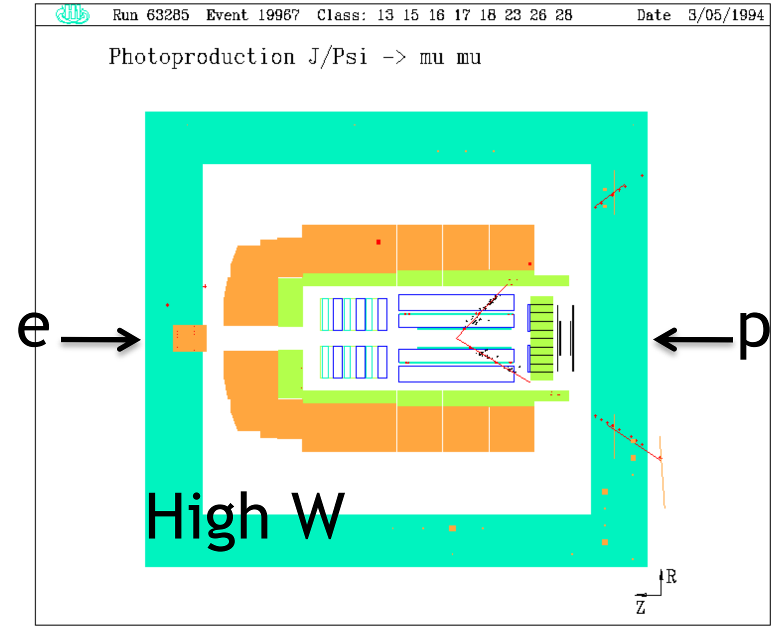


Relation to low x Physics:

$$x = \frac{Q^2}{W^2 + Q^2 + m_p^2}$$

i.e. $W^2 \approx \frac{Q^2}{x}$

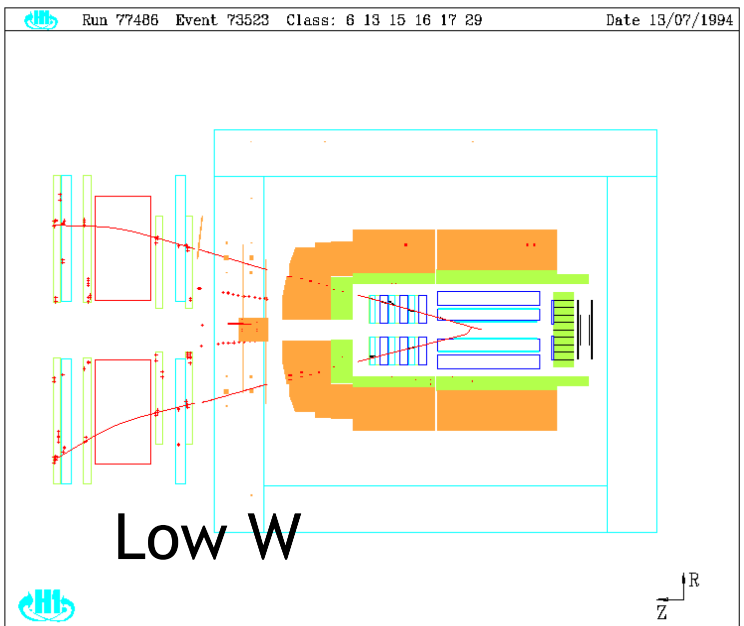
Experimental Selection (examples from H1 - Elastic J/Ψ → μμ)



2-prong decays give beautifully clean events.

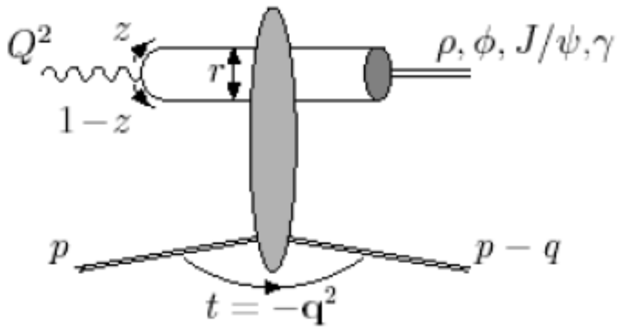
→ Select by requiring otherwise empty detector

→ Decay muon direction is determined by $W = \sqrt{s_{\gamma p}}$



Describing Vector Mesons in terms of Partons

Factorisation theorem



Dipole Models

step 1. γ fluctuation into $q\bar{q}$ dipole

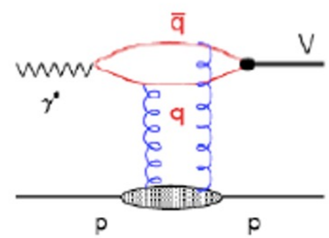
step 2. dipole – proton interaction $A = \int dr^2\, dz\, \Psi_\gamma\, \sigma(dip-p)\, \Psi_V$

step 3. pair recombination into VM

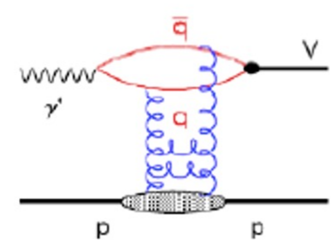
- Elastic scattering of $q\bar{q}$ dipole from proton via dipole cross section

- In t-channel picture, exchange is a pomeron

- Where hard scales present, dipole size r→0 and partonic interpretation of exchange possible

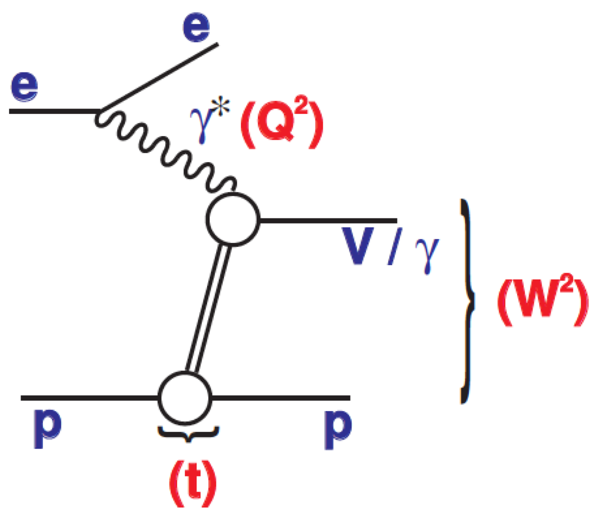


LO 2 gluons



LL1/x ladder

Vector Mesons & the Soft → Hard Transition



Behaviour usually parameterised in Regge form based on γ(*)p elastic scsttering

$$\frac{d\sigma_{el}}{dt} \sim \left(\frac{W^2}{W_0^2}\right)^{2\alpha(t)-2} e^{bt}$$

- Recall $\alpha(t)=\alpha(0)+\alpha' t$ is the 'effective pomeron trajectory'
    - 'Universal' description of soft physics: $\alpha(t)=\alpha(0)+\alpha' t \sim 1.08 + 0.25t$
    - 'Hard' pomeron (e.g. from BFKL) increases $\alpha(0)$

- e^{bt} empirically motivated – Fourier transform of spatial distribution of interaction
  $b = b_{dipole} + b_{proton} \rightarrow b_{proton}$ as dipole size → 0

- Signatures for 'hard' behaviour include increase in $\alpha(0)$
  and decrease in b

Photoproduction of Light v Heavy VM

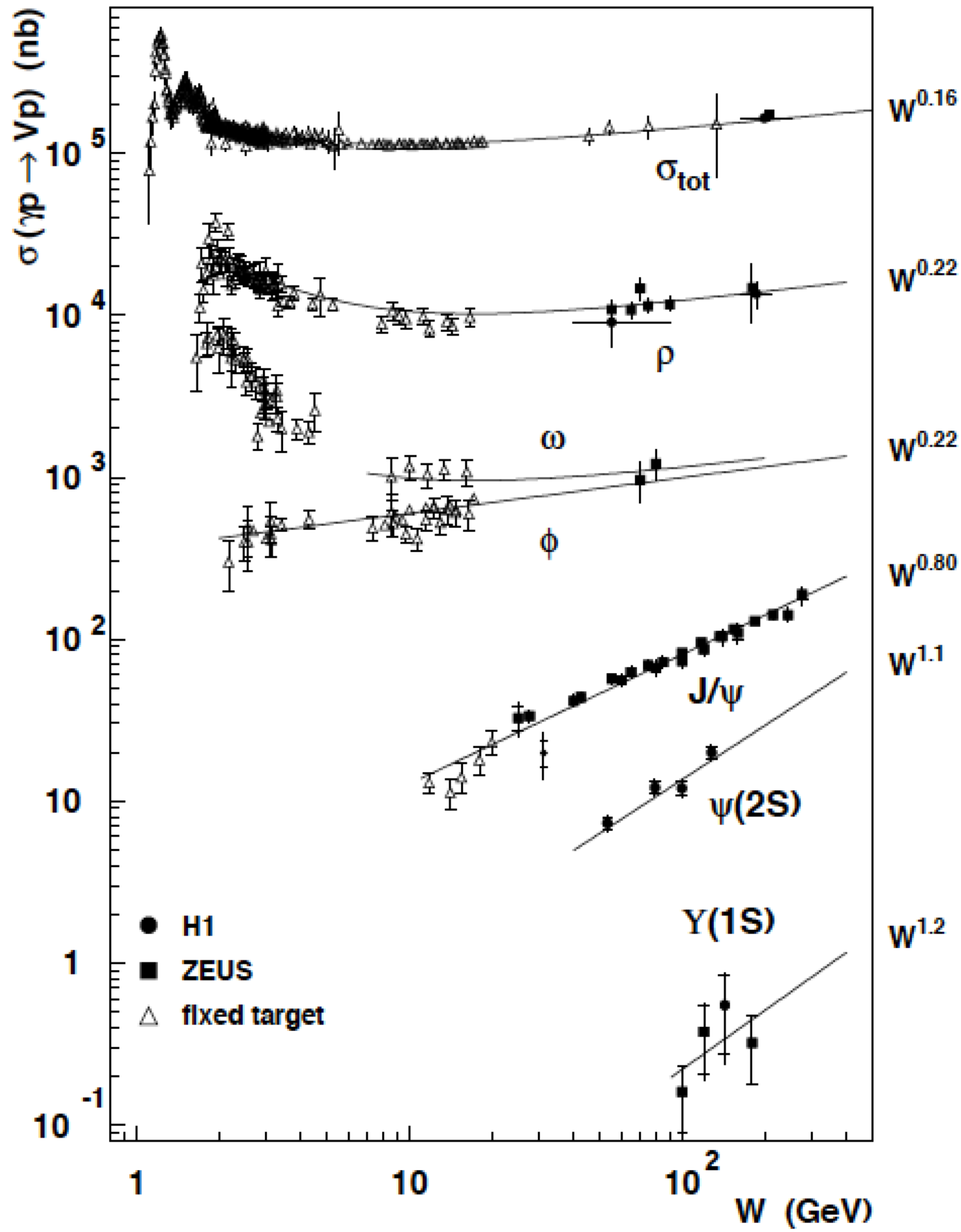
Increasing M_V leads to harder energy dependences

$\sigma \propto W^{\delta}$ with $\delta = 4\alpha(\langle t \rangle) - 4$

- Consistent with soft pomeron for light vector mesons

- For J/Ψ, effective
$\alpha(t) \sim 1.20 + 0.13t$

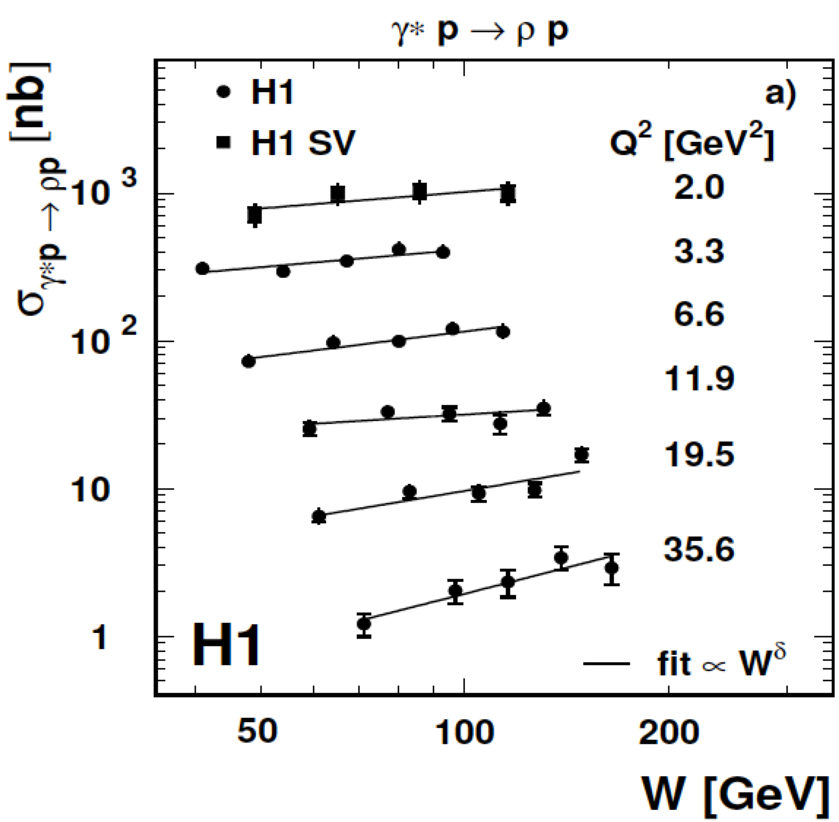
… c, b mass implies pQCD already valid for J/Ψ, Υ at $Q^2 = 0$

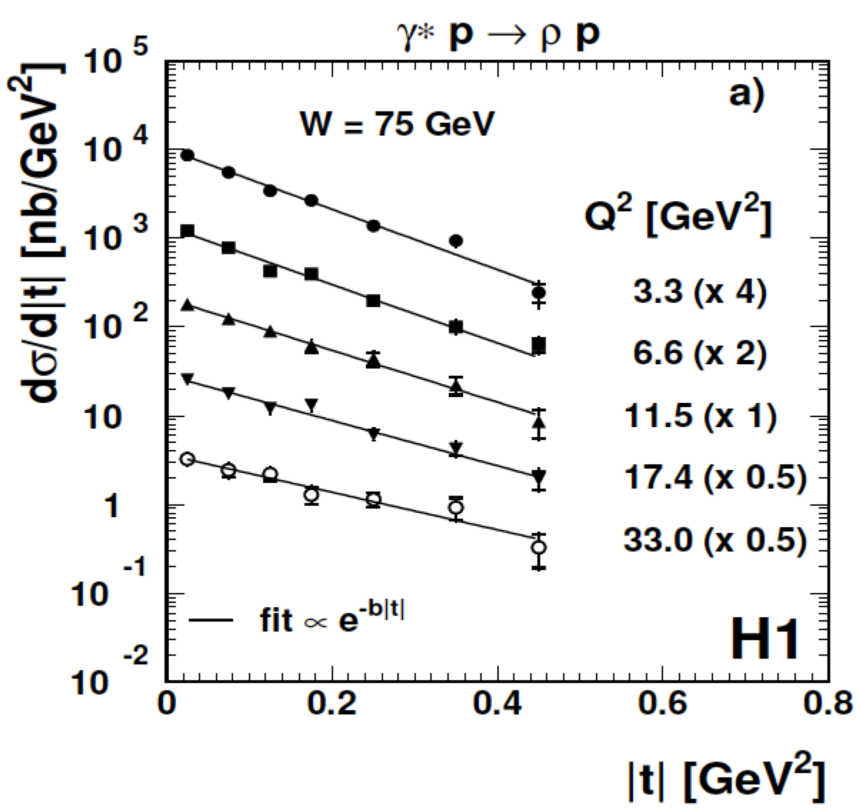


Turning the Q^2 Handle

- J/Ψ: W & t dependences ~ unchanged - already hard at $Q^2=0$

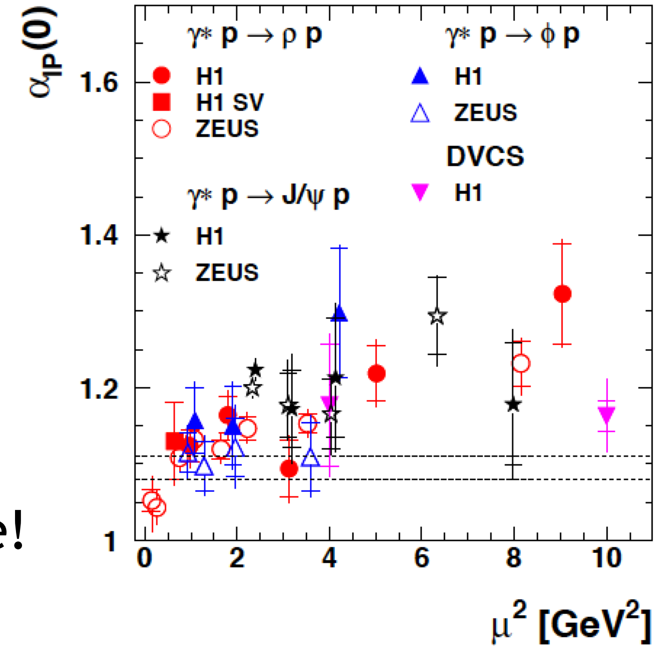
- Light vector meson behaviour evolves from soft to hard (eg ρ^0)





VM Overall Characterisation Summary

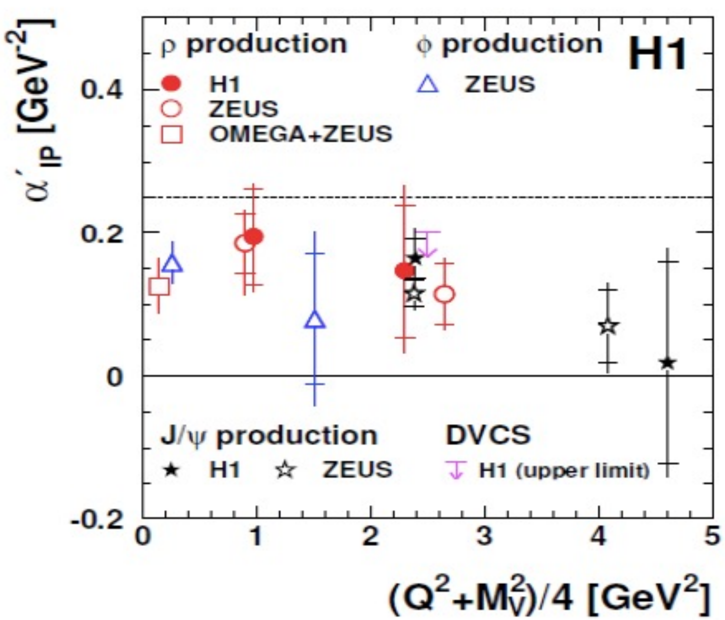
- Approximate scaling between different vector meson species in $\mu^2 = (Q^2 + M_V^2)/4$

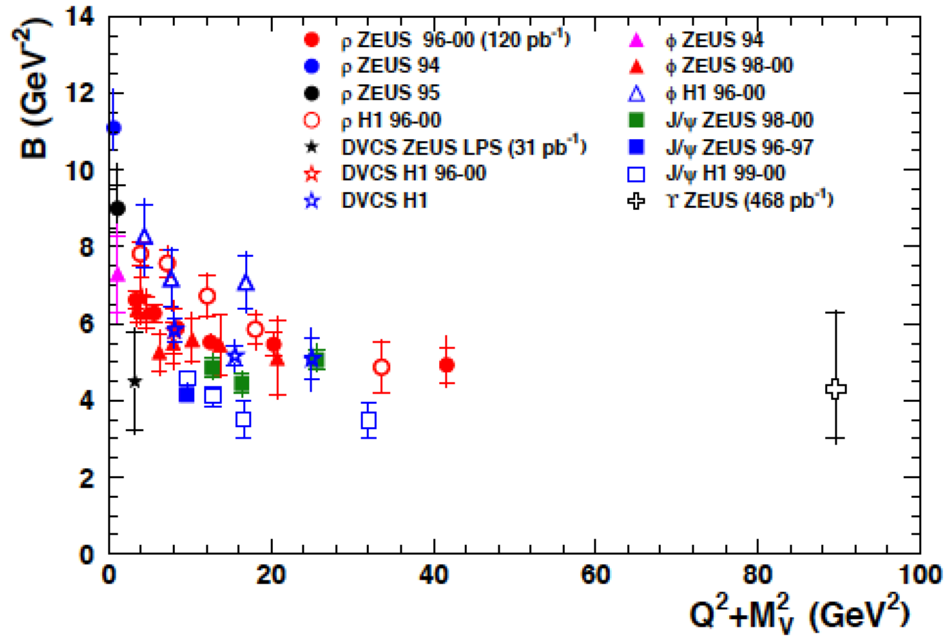


- t-slope approaches B~ 4-5 GeV^{-2} ~ 0.6fm

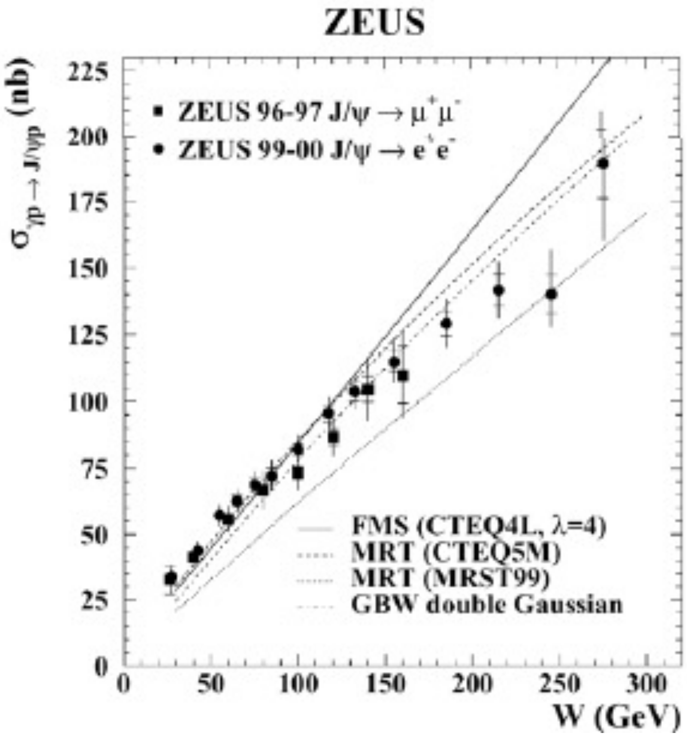
… strong interaction measures slightly smaller proton radius than EM size → hints at 3D structure!

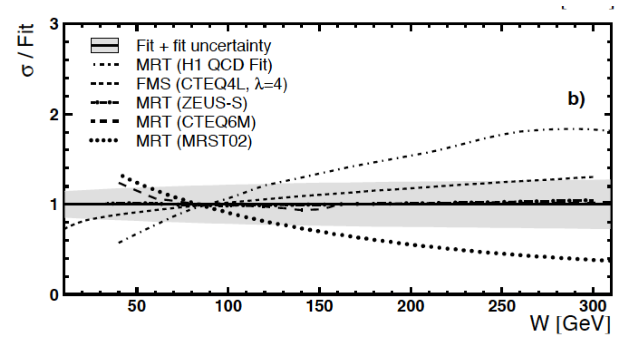
- α' shows no significant variation with any scale, but is smaller than expected for pure soft-pomeron exchange

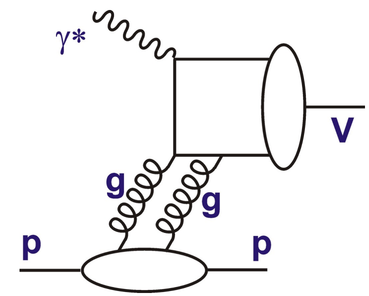




HERA Photoproduction of J/Ψ and the Gluon



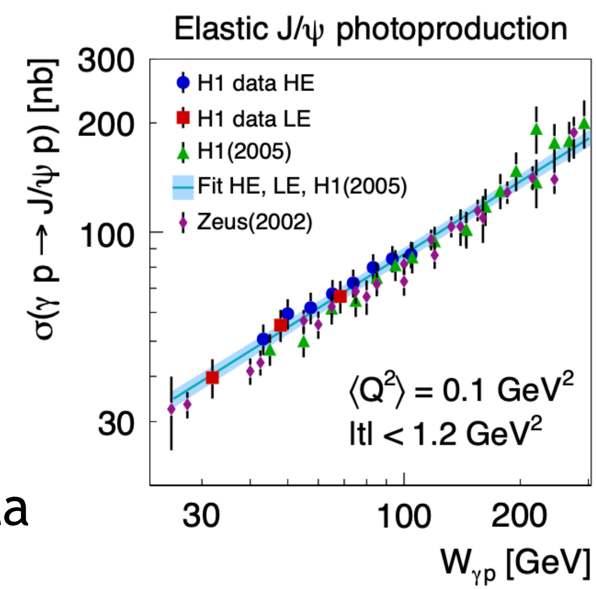




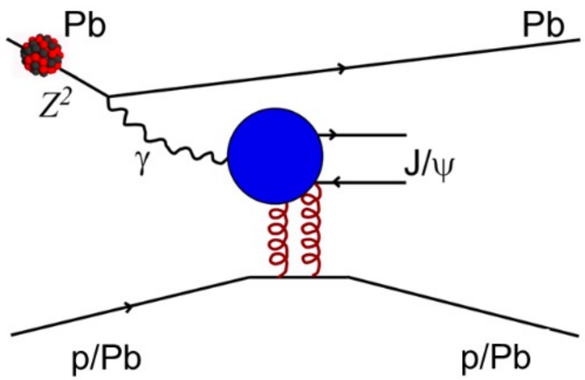
- QCD models based on 2-gluon exchange describe HERA data well & suggest power to discriminate between gluon PDFs

- Sensitivity limited by large scale uncertainties (NLO-LO convergence)

→ No evidence for saturation phenomena in HERA data (single power law dependence persists to highest W)



Relation to LHC: Ultra-peripheral Collisions



Using an LHC proton or (better!) Pb ion as a source of photons allows for photoproduction studies, γp or γPb

Thriving activity, not limited to vector mesons ... sufficient for an entire conference series!

UPC2025: The second international workshop on the physics of Ultra Peripheral Collisions

9–13 Jun 2025
Saariselkä, Finland
Europe/Helsinki timezone

Enter your search term

- Overview
- Call for Abstracts
- Participant List
- Important dates
- Travel and accommondation
- Venue
- Local organizing committee
- Previous UPC workshop

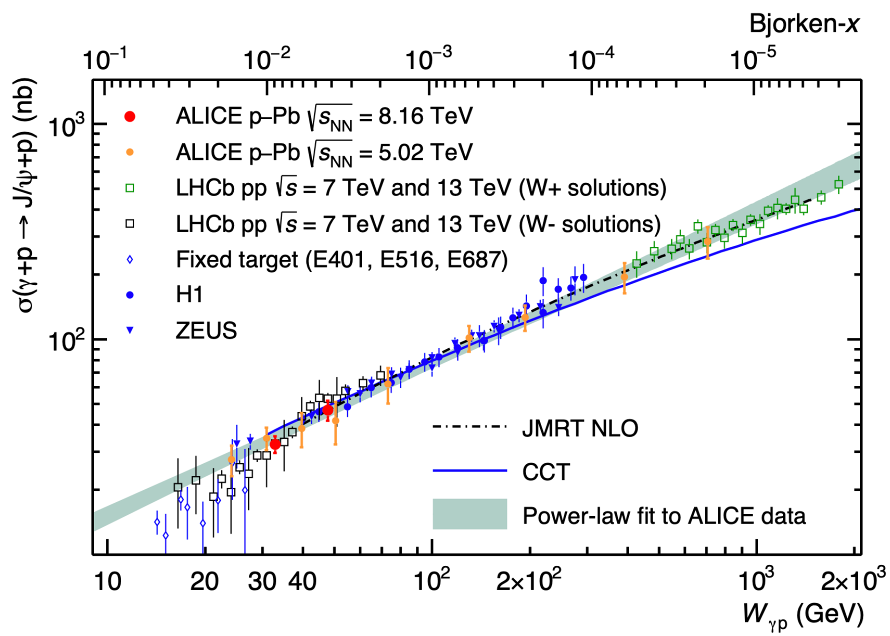
The second international workshop on the physics of Ultra Peripheral Collisions will be organized in Finland in June 2025. More information willbe provided here later.

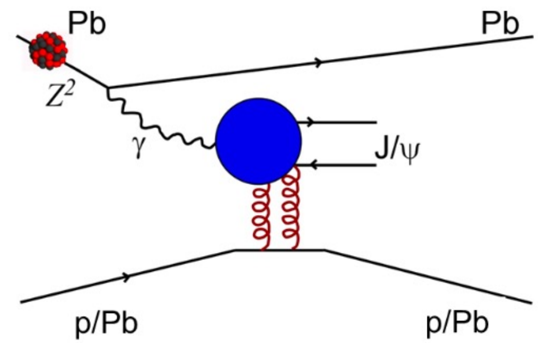
This is an in-person only event.

The following research topics will be discussed:

- Recent experimental results at HERA, RHIC and LHC
- Theoretical description of exclusive photon-proton and photon-nucleus scattering
- Nuclear PDFs developments using photon-induced data
- Nonlinear and gluon saturation effects in photon-nucleus scattering
- Hadronization in exclusive processes
- Soft nucleon and nucleus interactions
- Photoproduction in events with nuclear overlap
- Photon-photon physics
- UPCs related to future electron-ion colliders

Ultra-peripheral J/Ψ Photoproduction



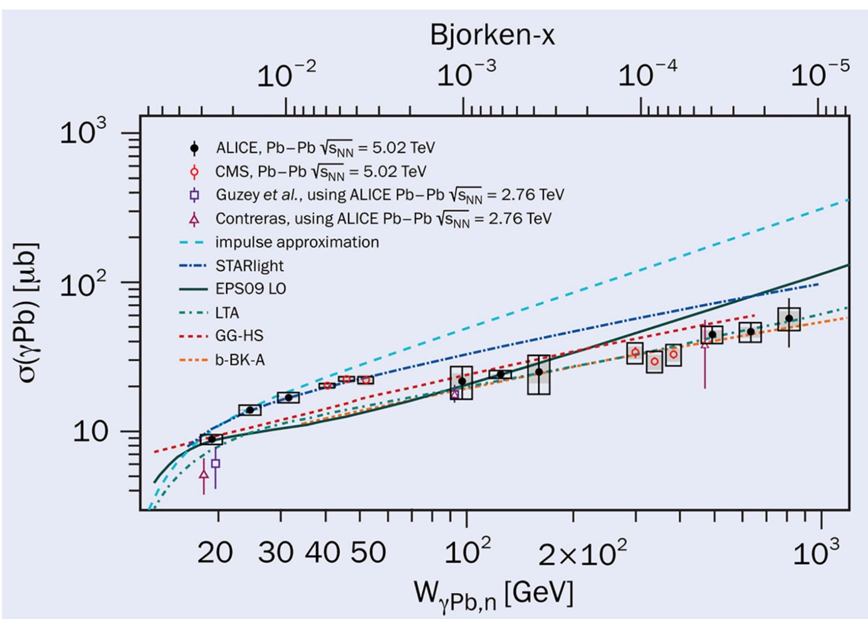


γp → J/Ψ Pb

- Continuation of HERA data into TeV range of W: ALICE, CMS, LHCb
- Simple power law remains adequate

→ Still no evidence for saturation

→ Double differential data in (W,t) would be interesting.



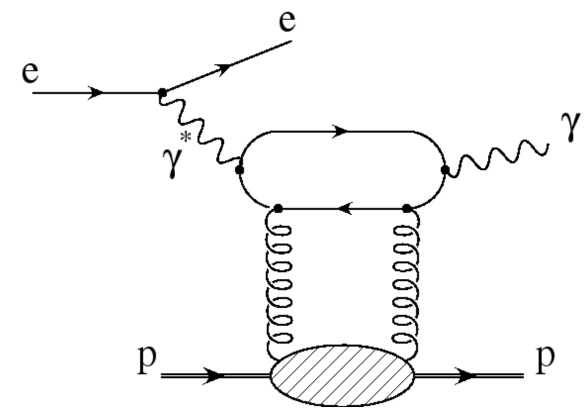
γA → J/Ψ A cross-sections

- Clear suppressions relative to simply scaled protons, extending to x~10^{-5}

→ Sensitivity to nuclear PDFs

→ Enhanced sensitivity to saturation

Deeply Virtual Compton Scattering (ep → eγp)

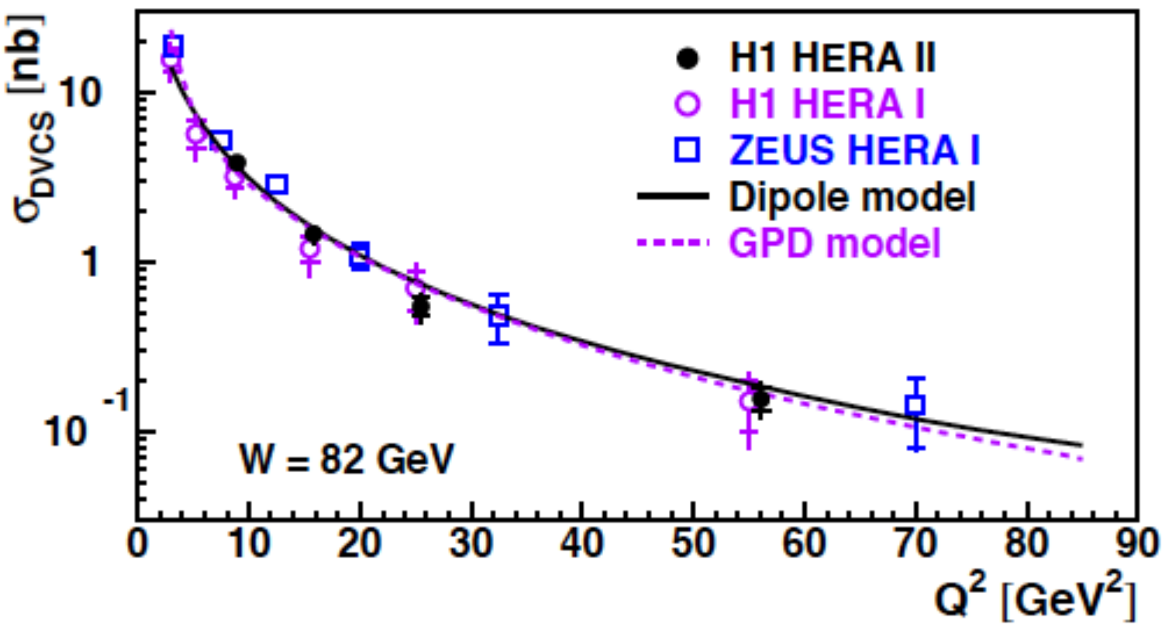


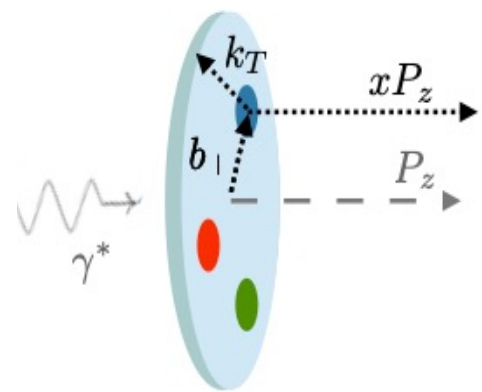
DVCS is the classic exclusive process to investigate hadron transverse degrees of freedom and correlations via Generalised Parton Densities

… BUT …

- HERA measurements were luminosity-limited and cross sections are small (extra γ coupling)
- HERA did not have polarised proton beams

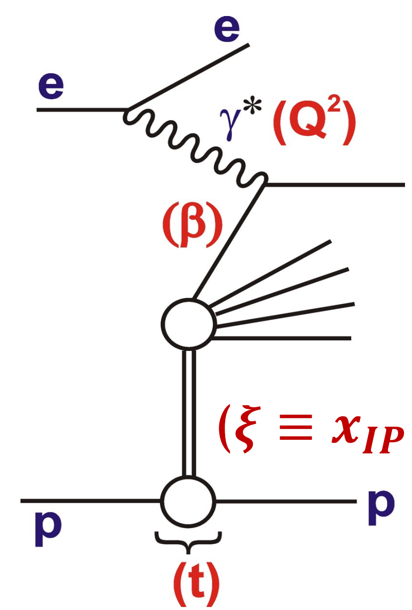
→ Major topic for the Electron Ion Collider





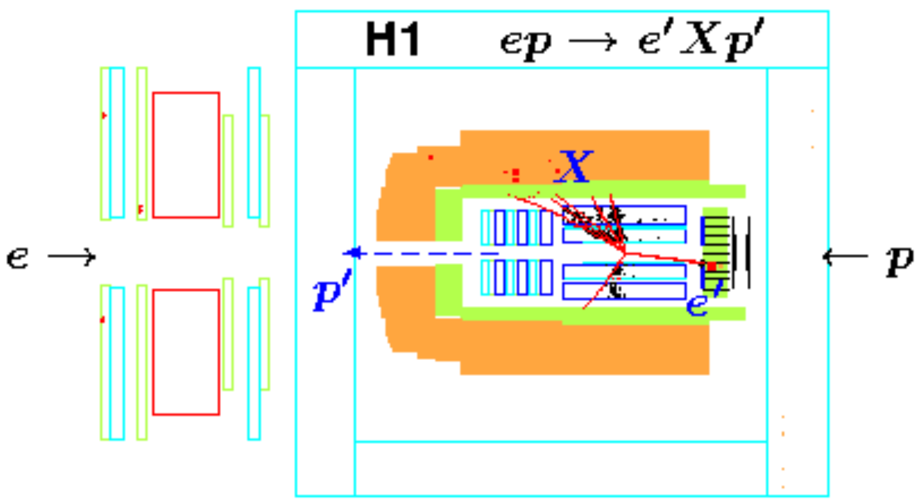
Inclusive Diffraction in Deep Inelastic Scattering

Vector meson production is a 'higher twist' (Q^2 suppressed) process



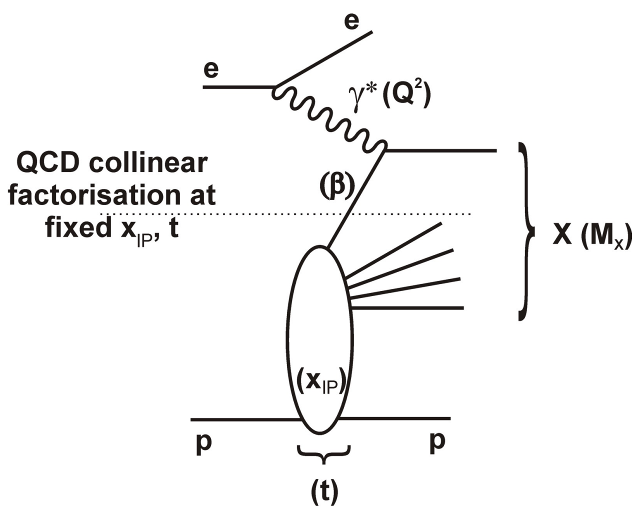
There are also 'leading twist' diffractive processes with same Q^2 dependence as bulk DIS cross section

~10% of DIS events have no forward energy flow



Interpreted as DIS from the (soft) Pomeron … with potential to measure its partonic structure as a function of $\beta = \frac{x}{\xi}$ and Q^2

Semi-Inclusive QCD Factorisation (Proven for DIS)



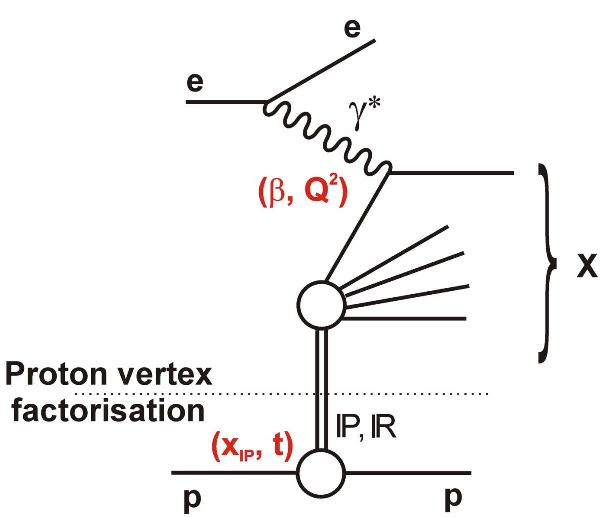
Can define

diffractive PDFs (DPDFs), f_i^D

$$\boxed{d\sigma_{\text{parton } i}(ep \to eXY) = f_i^D(x, Q^2, x_{IP}, t) \otimes d\hat{\sigma}^{ei}(x, Q^2)}$$

At fixed (x_{IP} , t), DPDF Q^2 evolution obeys DGLAP in same way as proton PDFs

'Proton Vertex Factorisation' (Phenomenological)

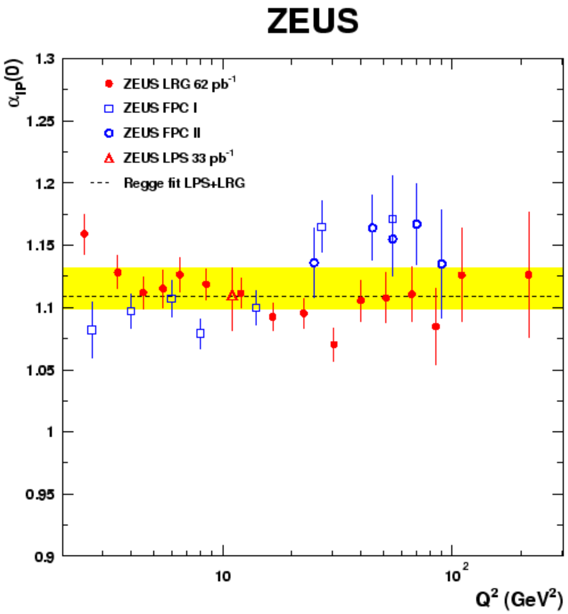


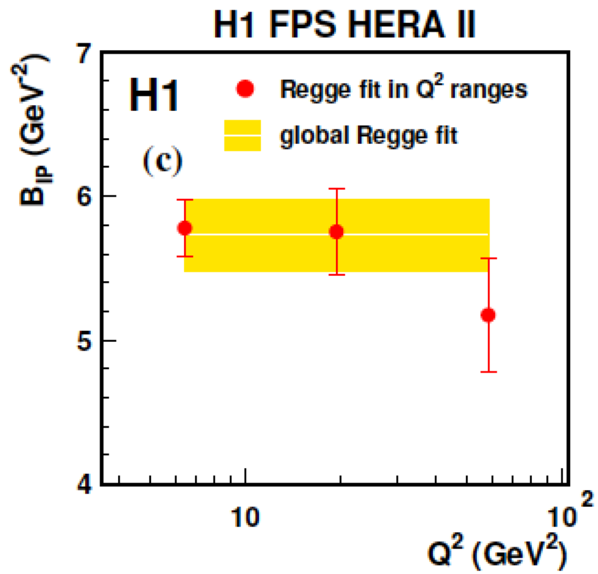
… completely separate (x_{IP} , t) from (β, Q^2) dependences ('Ingelman-Schlein model')

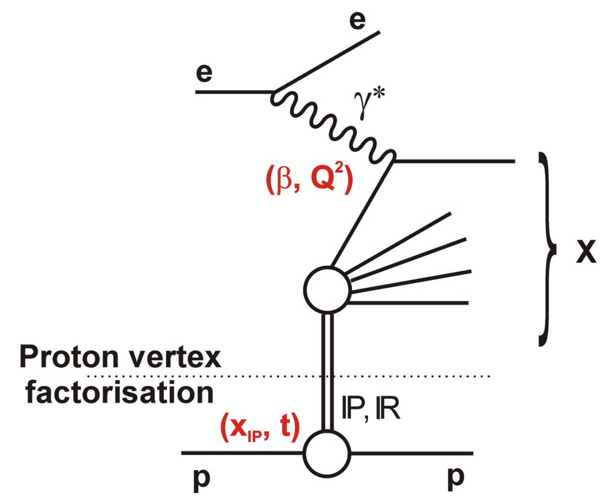
$$\boxed{f_i^D(x, Q^2, x_{IP}, t) = f_{IP/p}(x_{IP}, t) \cdot f_i^{IP}(\beta = x / x_{IP}, Q^2)}$$

DPDFs f_i^{IP} then measure partonic structure of the exchanged system (IP)

Proton Vertex Factorisation & the Effective Pomeron of Diffractive DIS







- x_{IP} (via $\alpha_{IP}(0)$) and t (via b slope) dependence invariant with Q^2 and β

e.g. From H1 FPS data:

$$\alpha_{IP}(0) = 1.10 \pm 0.02\,(\text{exp.}) \pm 0.03\,(\text{model})$$

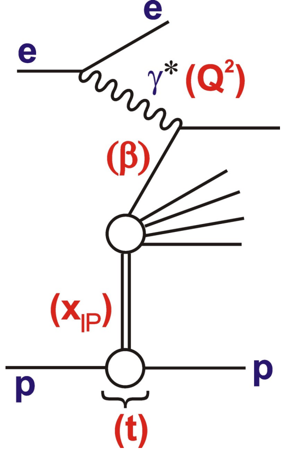
$$\alpha'_{IP} = 0.04 \pm 0.02\,(\text{exp.}) \pm 0.07\,(\text{model})\ \text{GeV}^{-2}$$

$$B_{IP} = 5.7 \pm 0.3\,(\text{exp.}) \pm 0.9\,(\text{model})\ \text{GeV}^{-2}$$

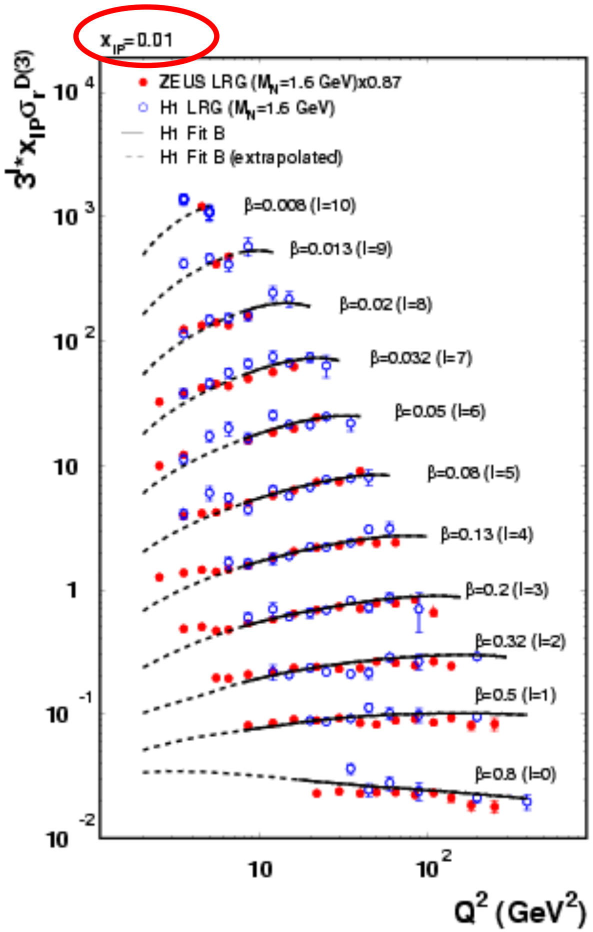
$\alpha_{IP}(0)$ consistent with soft IP → Dominantly soft exchange

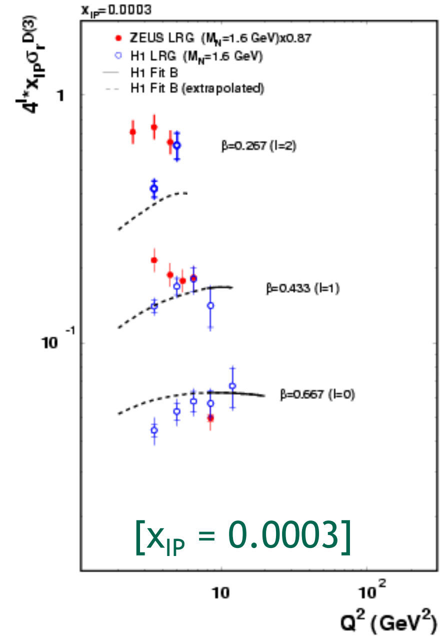
α_{IP}' smaller than soft IP → Absorptive effects?

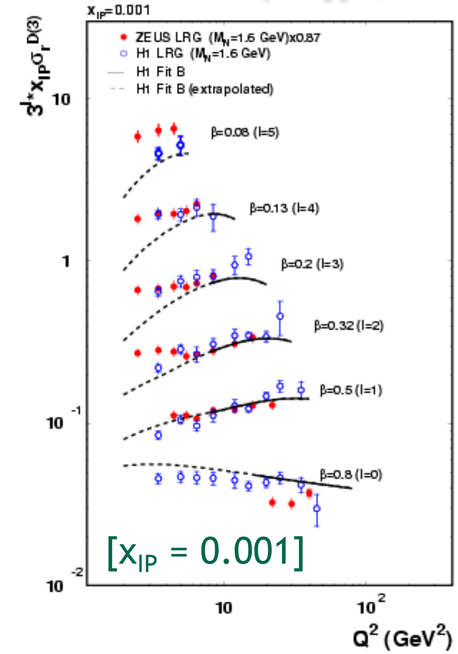
(β, Q^2) Dependences at fixed (x_{IP}, t)

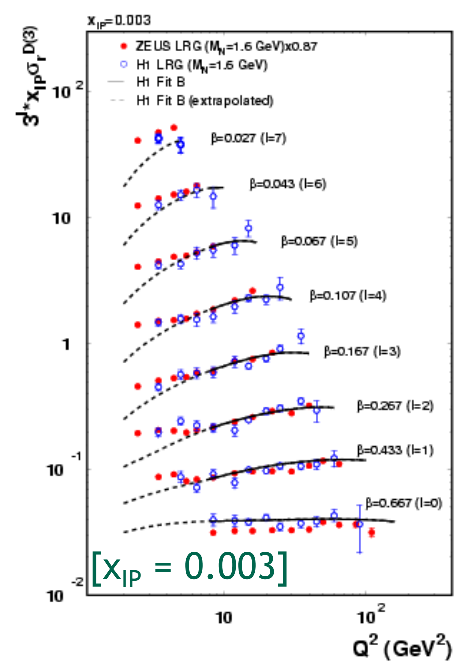


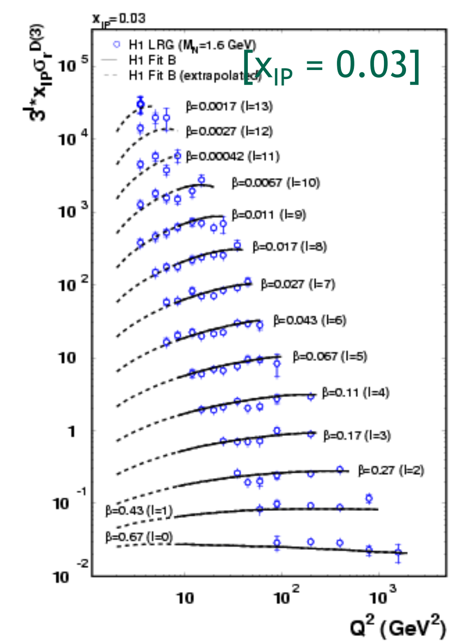
Leading twist and ~10% of total x-sec



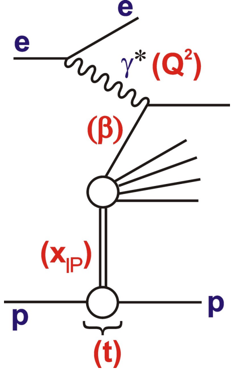




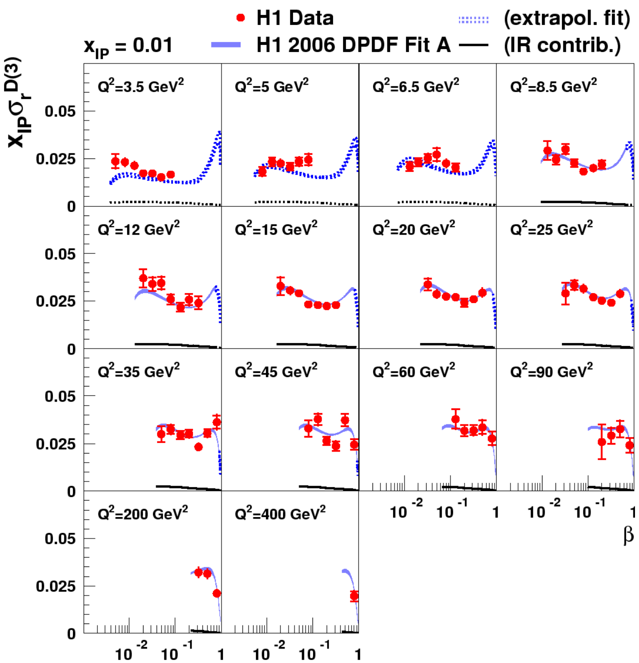




Sensitivity to Diffractive Quarks & Gluons

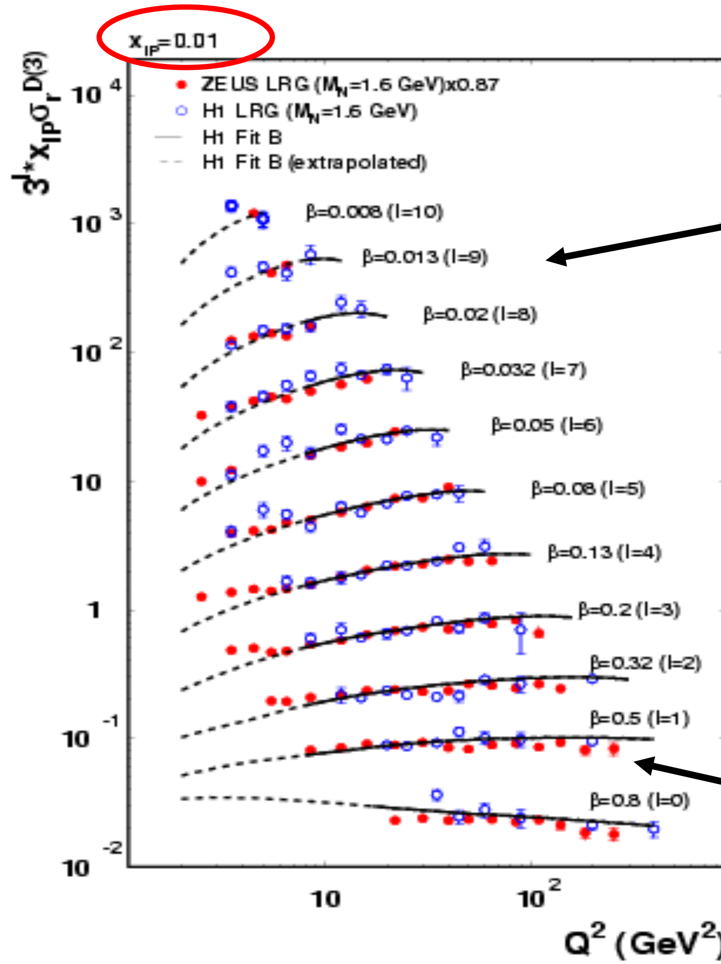


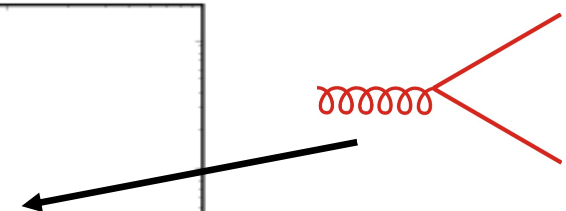
Similarly to
Inclusive DIS ...



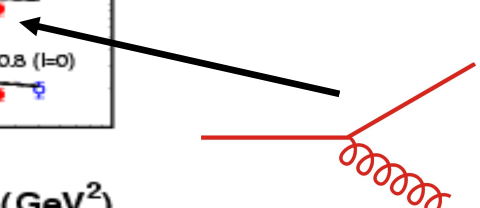
Diffractive cross section
measures quark density

$$F_2^D = \sum_q e_q^2 \, \beta \, (q+\bar{q})$$



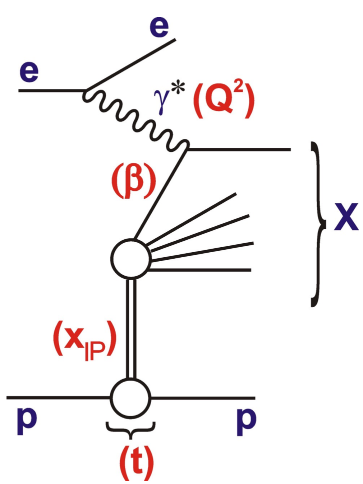


Q² dependence
tells us gluon
density via
DGLAP eqns
...
except at
highest β



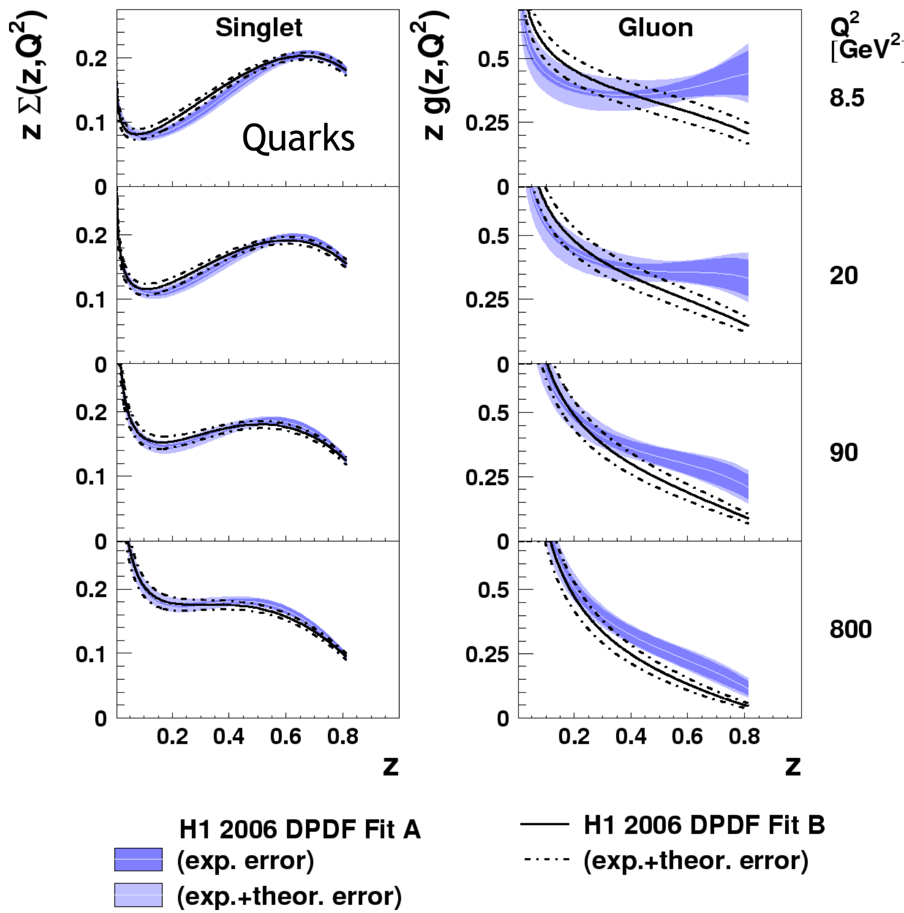
$$\frac{d\sigma_r^D}{d\ln Q^2} \sim \frac{\alpha_s}{2\pi}\left[P_{qg}\otimes g + P_{qq}\otimes q\right]$$

Diffractive Parton Densities (DPDFs)



DPDFs extracted through fits to inclusive (& jet) data, assuming NLO/NNLO DGLAP evolution, similarly to inclusive DIS

e.g. H1



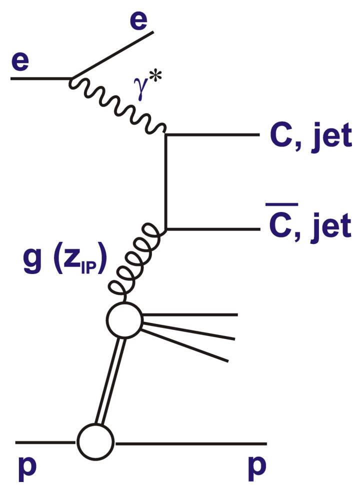
… dominated by gluon density extending to large momentum fractions, z

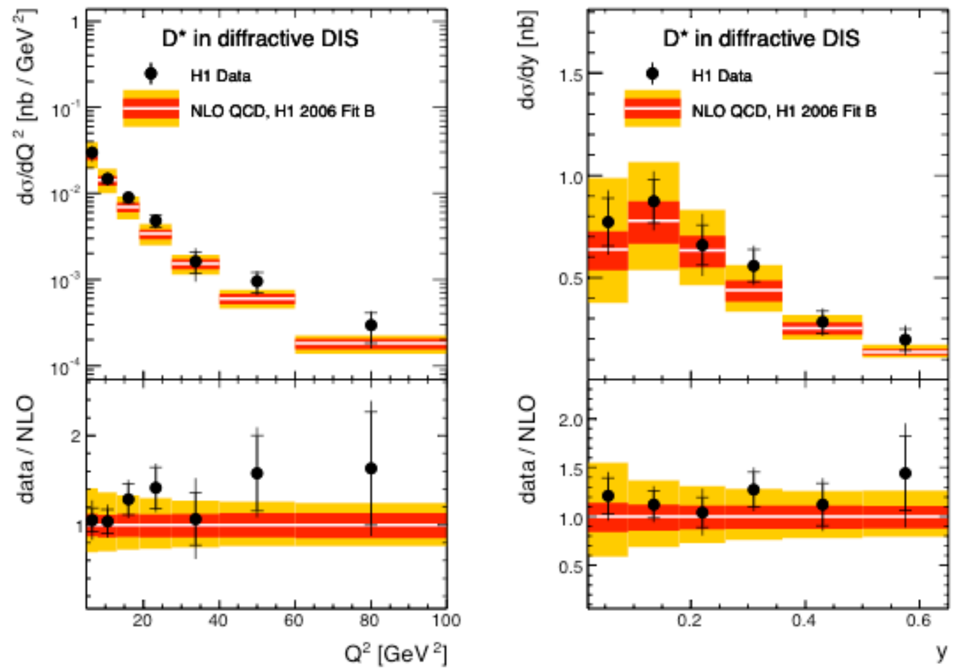
(as might be expected for object with gg-like 'valence' structure)

→ Widely used in model-building for LHC and beyond

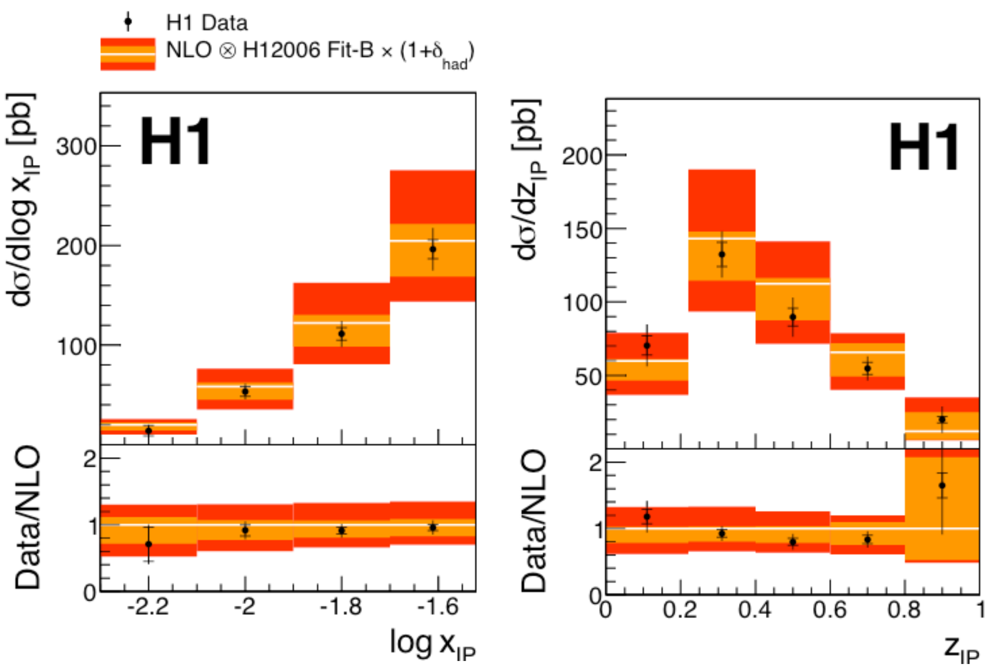
Testing Factorisation; eg HERA Jets & Charm

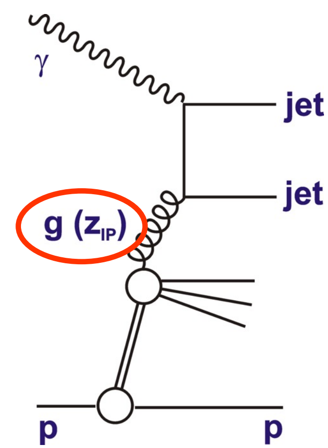
Remarkably good description of all variables in Diffractive DIS over a wide kinematic range





Charm in DIS

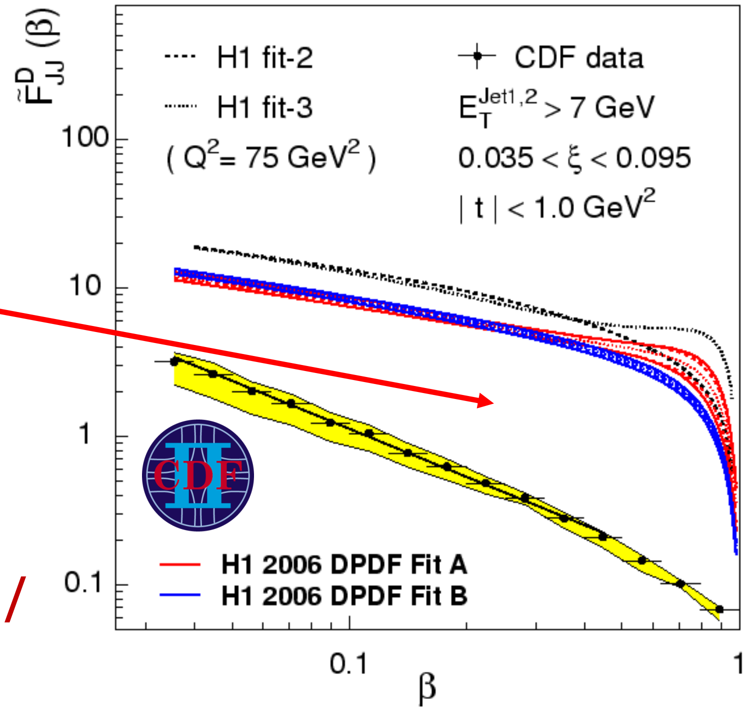




Dijets in DIS

… but in pp(bar)

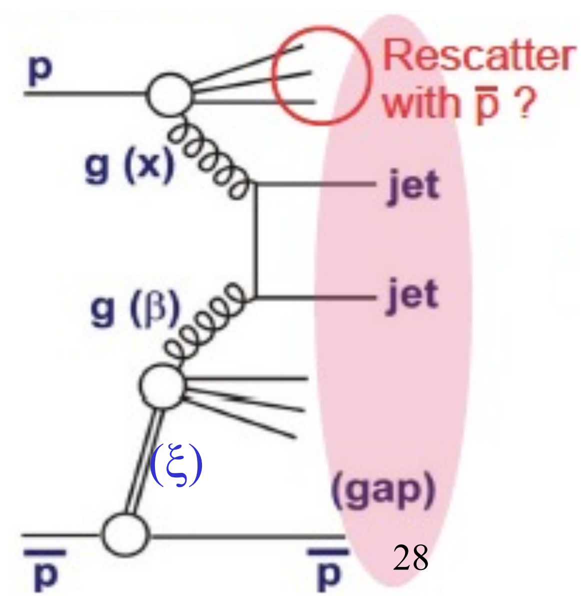
Spectacular failure in comparison of Tevatron proton-tagged diffractive dijets with HERA DPDFs [PRL 84 (2000) 5043]



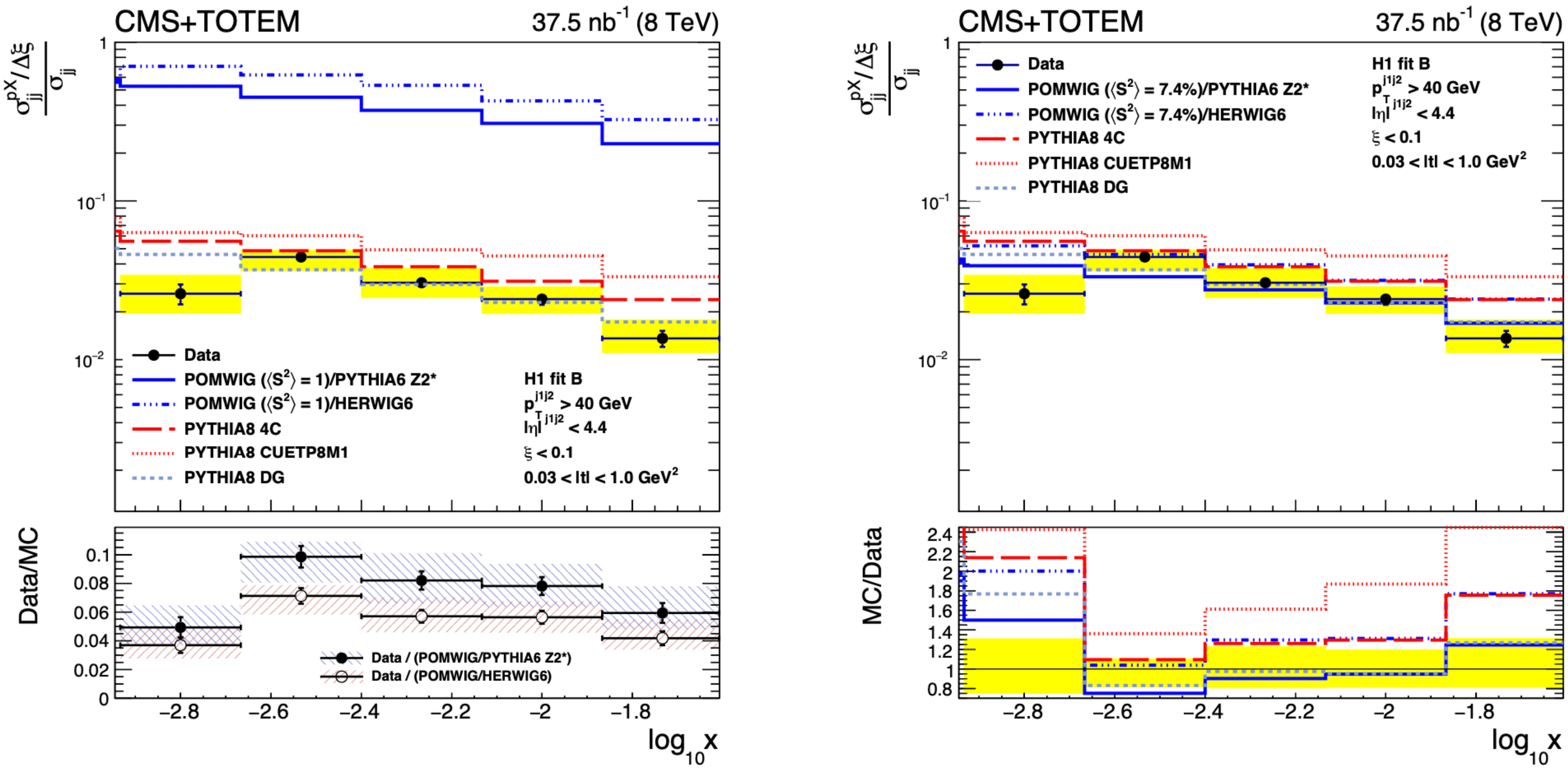
… rescattering (absorptive corrections / related to Multi Parton Interactions …) breaks factorisation …

`*rapidity gap survival probability*' ~ 0.1

Gap survival probability needs to be understood to interpret all LHC hard diffraction data.



Proton-tagged LHC Diffractive Jets



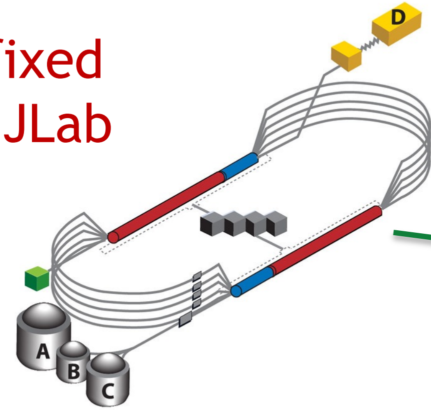
- Predictions based on HERA DPDFs require Gap Survival probability
$\langle S^2 \rangle = 9 \pm 2$ %

- Dynamic Gap Survival Model in PYTHIA (Simultaneous description of gap survival and Multi-Parton Interactions) also reproduces data

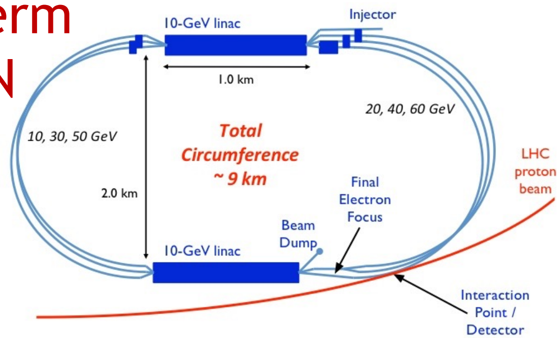
- Huge potential for further exploration

Current and Future ep Colliders

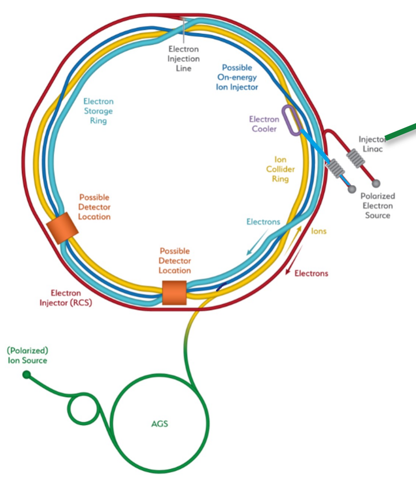
Ongoing fixed target @ JLab

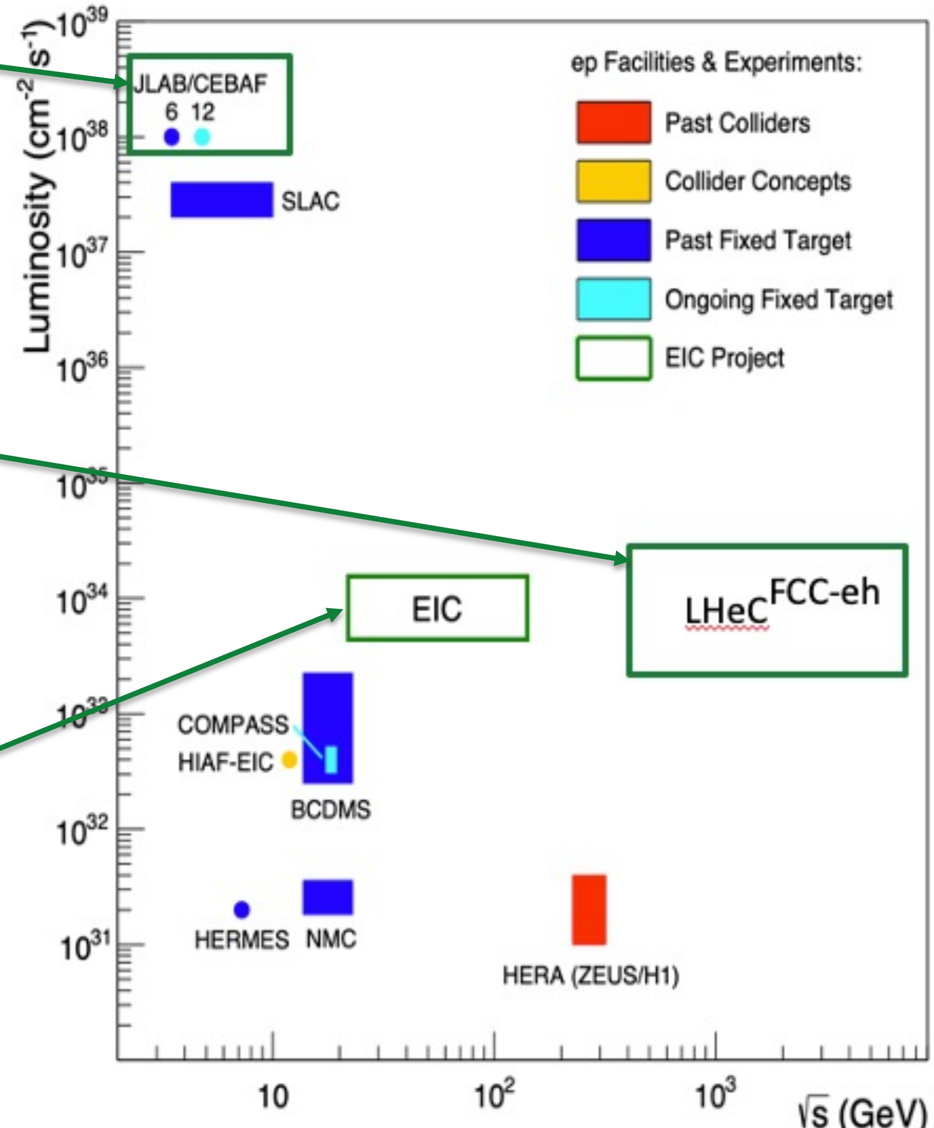


Longer-term @ CERN



On-target for early 2030s @ BNL





Crude Mapping Between Physics & Facilities

Partons with decreasing x

[Kong Tu]

High x (fixed Target)
Basic Structure

Intemediate x (EIC)
Emergent properties

Low x (HERA / LHeC)
QCD radiation
dynamics

Summary of Hard Diffraction

- Vector mesons map transition from soft to hard pomeron as hard scales turn on

- J/Ψ photoproduction as 'golden channel' linking HERA and UPCs at LHC, with sensitivity to gluon density and dynamics
  → No evidence for saturation yet

- Leading Twist inclusive diffractive DIS sensitive to partonic structure of object broadly consistent with soft pomeron
  → Dominated by gluons with high momentum fractions
  → Factorisation works beautifully within DIS
  → Gap survival probability of ~10% at Tevatron and LHC

- Much higher luminosities at EIC (and LHeC) can unlock a whole new era of diffractive physics