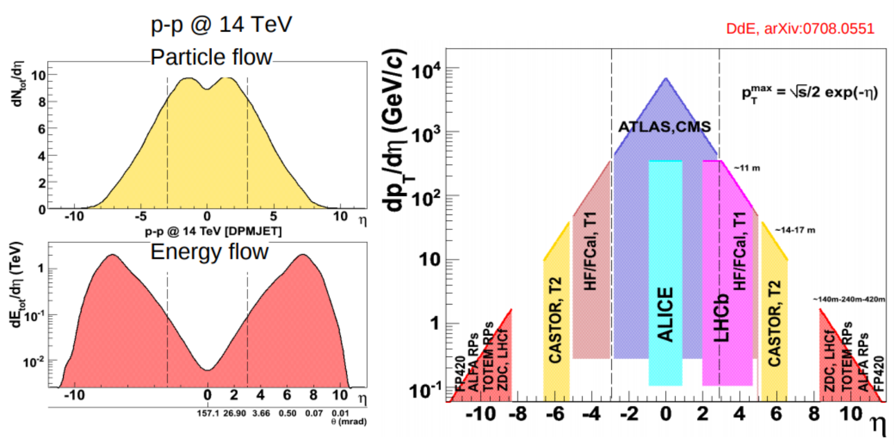
Particle Physics for Specialists

Forward Physics

Rafał Staszewski

23 January 2025

Introduction



David d'Enterria, arXiv:0708.0551

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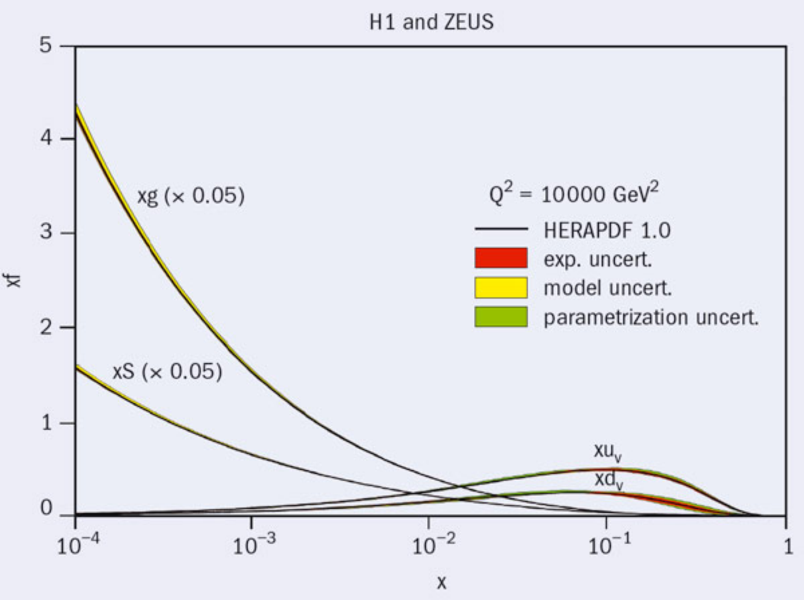
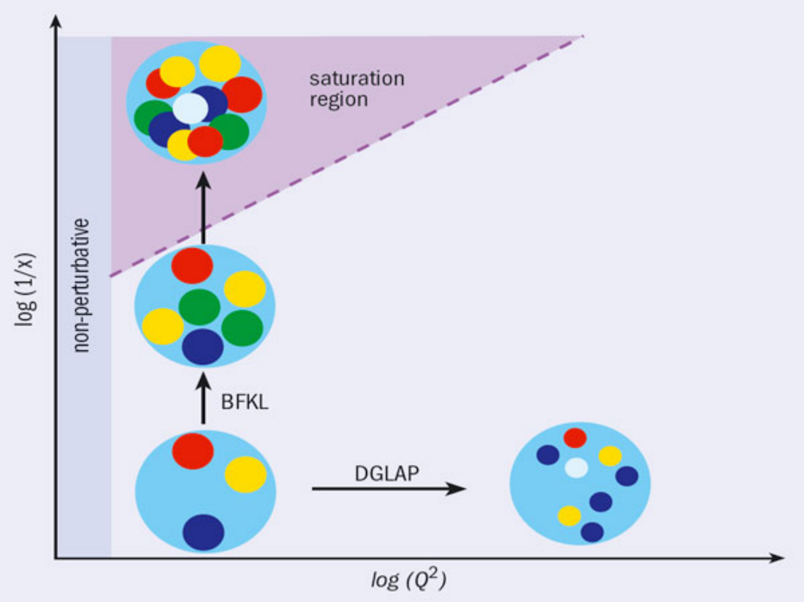
Gluons at low x



Saturation



saturation
region
non-perturbative
log (1/x)
BFKL
DGLAP
$log\ (Q^2)$

Underlying event

- Complex structure of hadron-hadron interaction
- Underlying event – activity in addition to the hard interaction:
  - initial state radiation
  - final state radiation
  - multiple parton interaction
  - colour reconnections with beam remnants
- Non-perturbative effects
- No clear soft/hard separation
- Phenomenological model in MC generators
- A need for tuning to experimental data

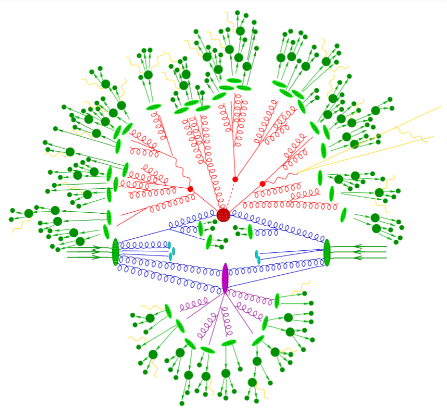
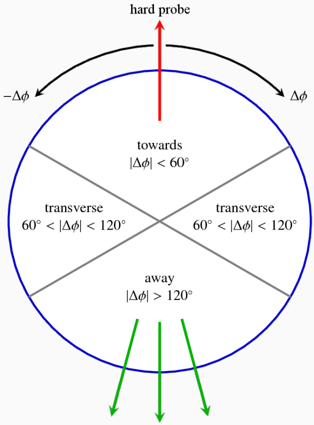


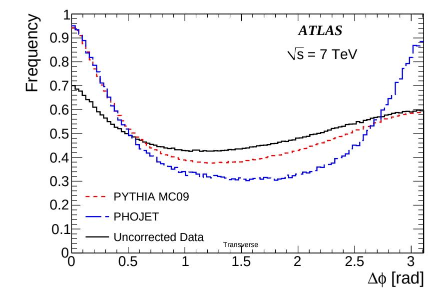
Figure from [arXiv:1411.4085]

Principle of the measurements

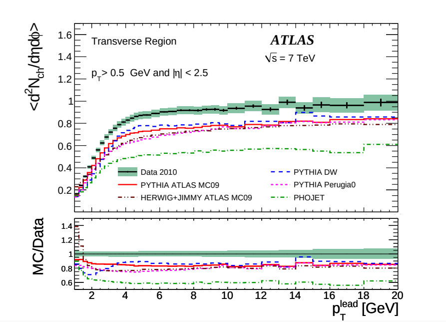
- Regions in ϕ defined w.r.t. the direction of the hard object
- Transverse region – sensitive to UE
- Two transverse regions $\rightarrow$ trans-min and trans-max (distinguished on the event-by-event basis according to $\sum p_T$)
- UE observables:
  - $N_{\mathrm{ch}}/\delta\eta\,\delta\phi$
  - $\sum p_T/\delta\eta\,\delta\phi$
  - Mean p_T



Results from inclusive pp interactions



- $\Delta\phi$ distribution initially not well described by MC
- Flattening of p_T dependence: entering dense region in proton



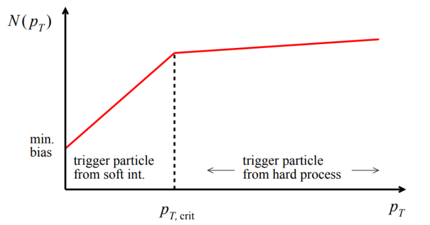
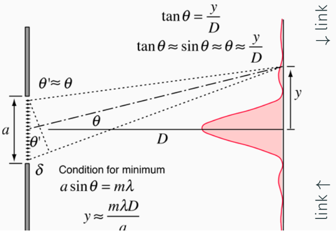


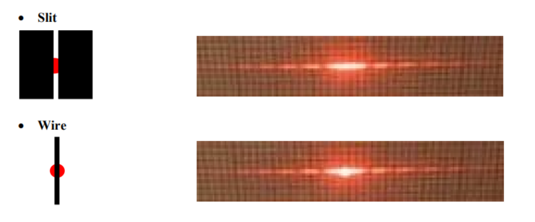
FIG. 6. Schematic illustration of the expected dependence of the transverse multiplicity, $N(p_T)$, on the p_T of the trigger.

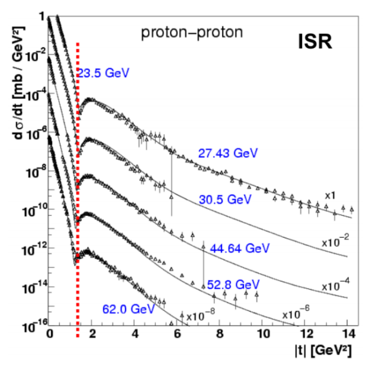
arXiv:1009.2559 [hep-ph]

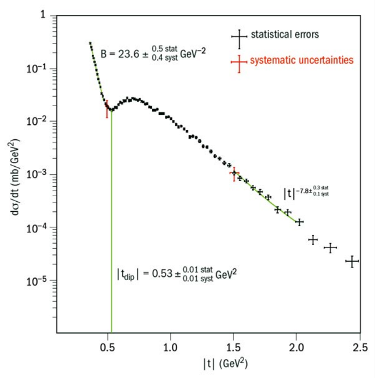
Contents

Diffraction in particle physics



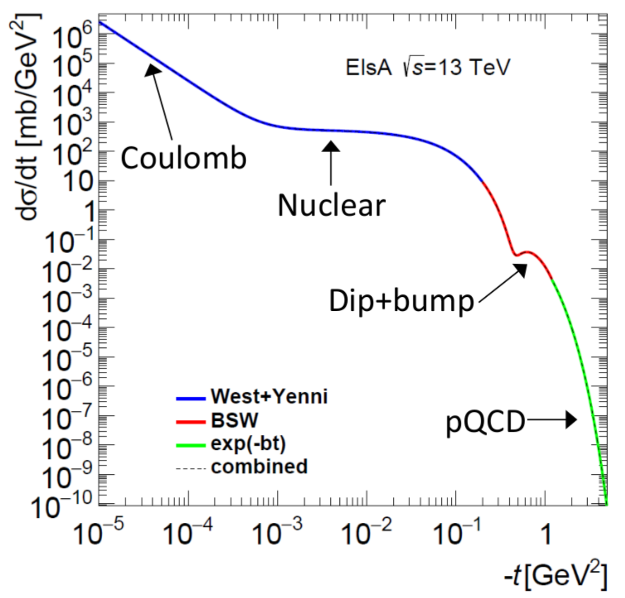






$$t \approx p^2\theta^2$$

Physics of elastic scattering



Scattering angle vs impact parameters

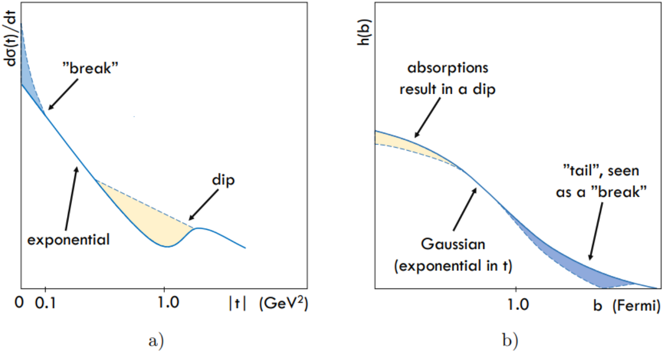


Figure 1: Schematic (qualitative) view of the "break", followed by the diffraction minimum ("dip"), shown both as function in t and its Fourier transform (impact parameter representation), in b. While the "break" reflects the presence of the pion "atmosphere" (clouding) around the nucleon at peripheral values of b, the dip results from absorption corrections, suppressing the impact parameter amplitude at small b.

István Szanyi, arXiv:1711.04743

Proton hollowness

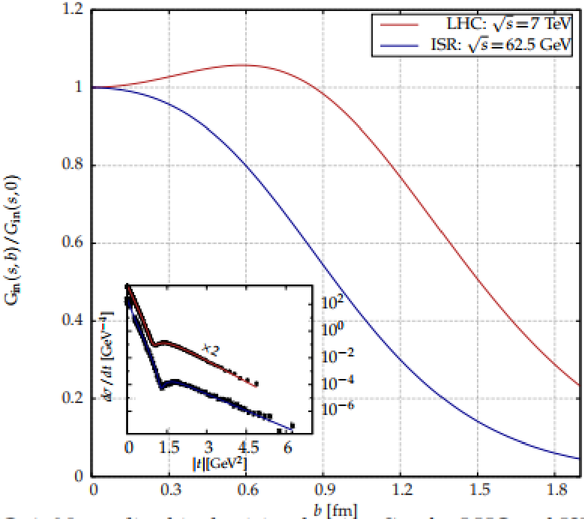


FIG. 1: Normalised inelasticity density, $G_{\rm in}$, for LHC and ISR energies as a function of the impact parameter. Sub-pannel: fits to $d\sigma_{\rm el}/dt$ data.

S matrix and the Optical Theorem

$$\sum_n P(i \to n) = 1 = \sum_n |\langle n|S|i\rangle|^2 = \sum_n \langle i|S^\dagger|n\rangle\langle n|S|i\rangle = \langle i|S^\dagger S|i\rangle = 1$$

true for any $|i\rangle$, so $\boxed{S^\dagger S = I.}$ Introduce trans matrix T: $\boxed{S = I + iT}$

$$(I - iT^\dagger)(I + iT) = I$$

$$i(T^\dagger - T) = T^\dagger T$$

$$i\langle f|T^\dagger - T|i\rangle = \sum_n \langle f|T^\dagger|n\rangle\langle n|T|i\rangle$$

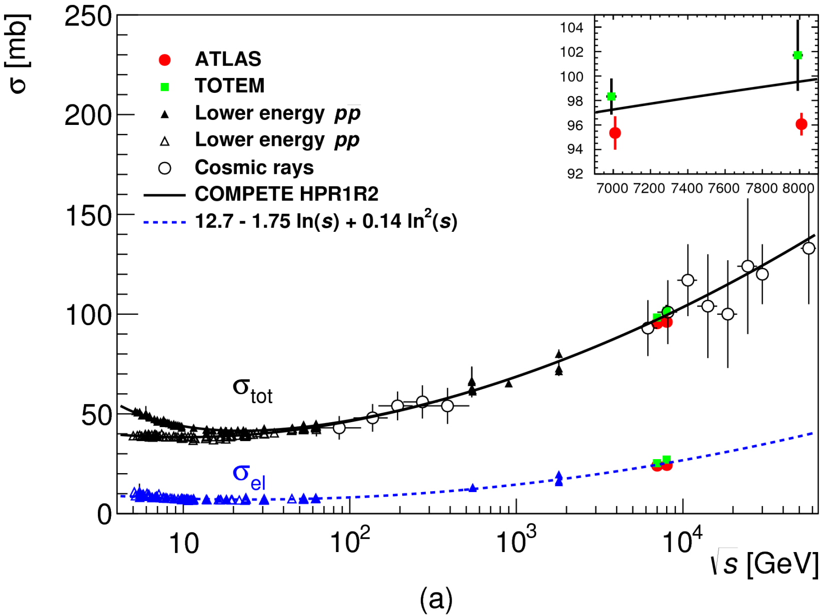
$$2\ \mathrm{Im}T(i \to f) = \sum_n \langle n|T^*|f\rangle\langle n|T|i\rangle$$

put $f = i$, forward elastic scatt. $\rightarrow$ Optical theorem

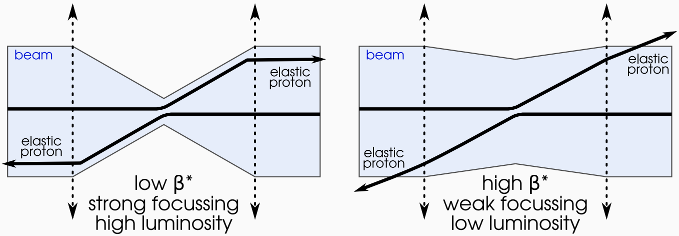
$$\boxed{2\ \mathrm{Im}T_{\mathrm{el}}(t=0) = \sum_n |T(i \to n)|^2 = \sigma_{\mathrm{tot}}}$$

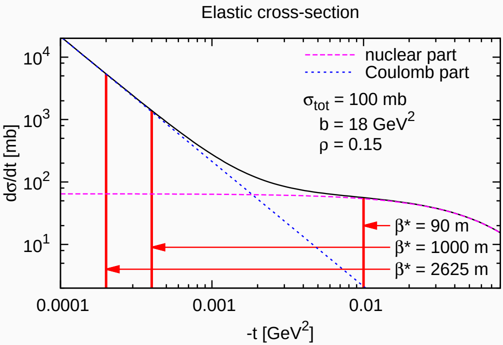
from prof. Alan Marin

Total cross section

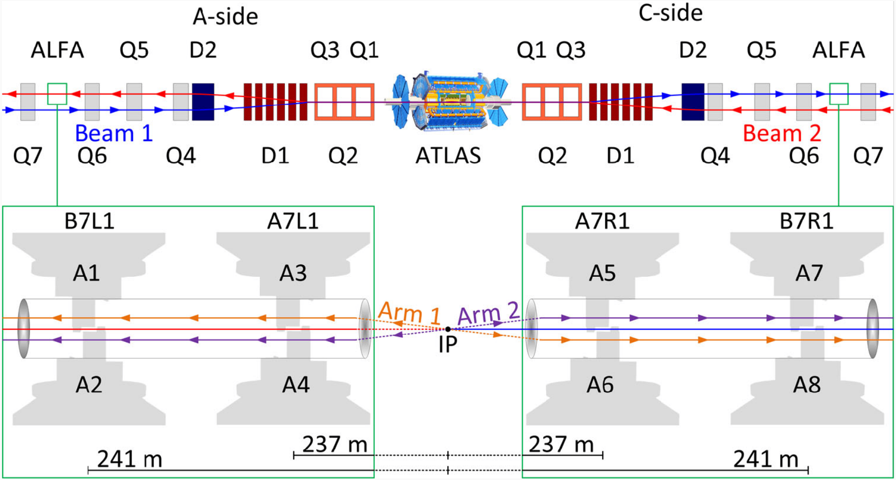


High-β optics

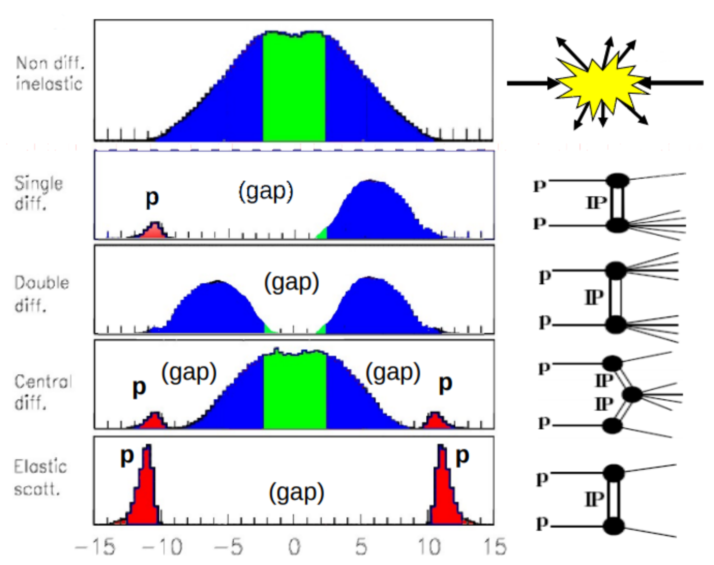




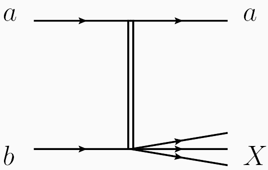
ALFA Detectors

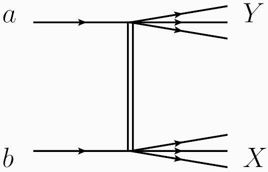


Diffractive processes



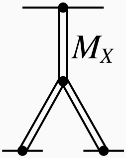
Modeling soft diffractive dissociation

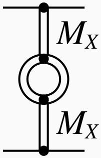




Regge theory

Triple pomeron vertex





$$d\sigma_{\mathrm{diff}}/d^2b = \langle T^2 \rangle$$

Good-Walker

Ψ_k – mass eigenstates

Φ_n – diffractive eigenstates

$$\Psi_k = \sum c_{kn} \Phi_n$$

$$\langle \Psi_1 | T | \Psi_1 \rangle = \langle T \rangle$$

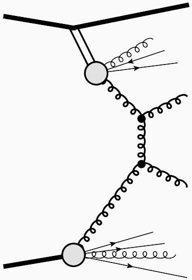
$$d\sigma_{\mathrm{el}}/d^2b = \langle T \rangle^2$$

$$d\sigma_{\mathrm{diss}}/d^2b = \langle T^2 \rangle - \langle T \rangle^2$$

Hard diffraction

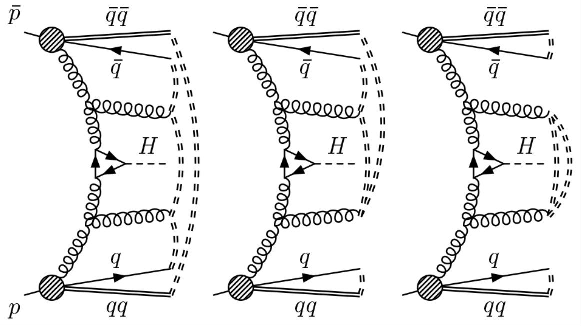
Resolved pomeron

- Ingelman-Schlein model
- pomeron has partonic structure

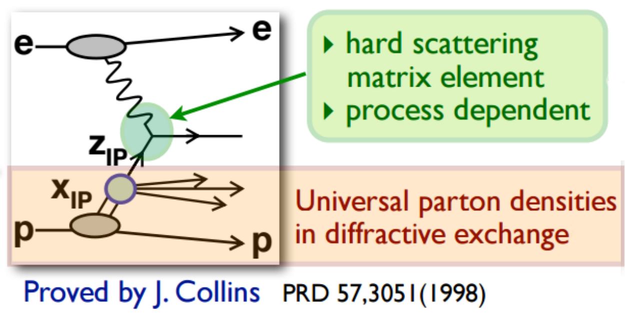


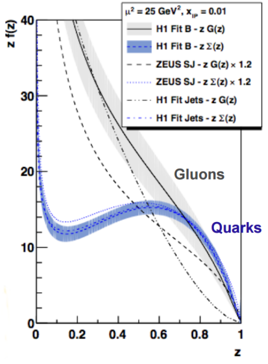
Soft colour interactions

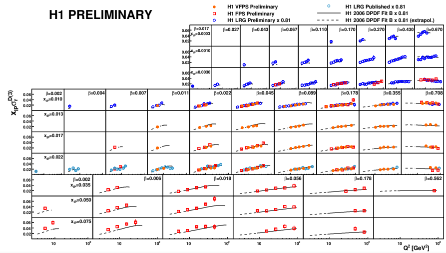
- QCD-inspired model
- additional gluon exchanges screen the color flow



HERA: Diffractive PDFs

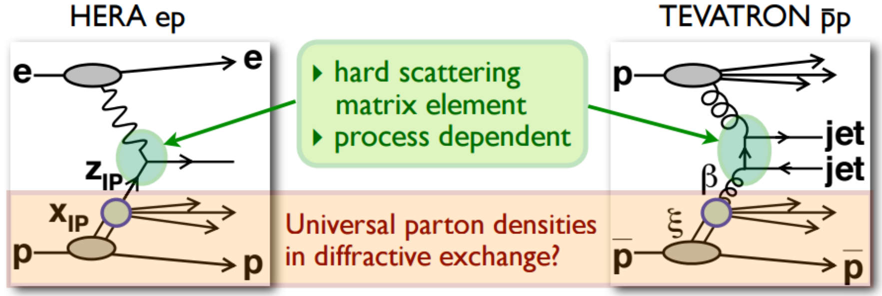


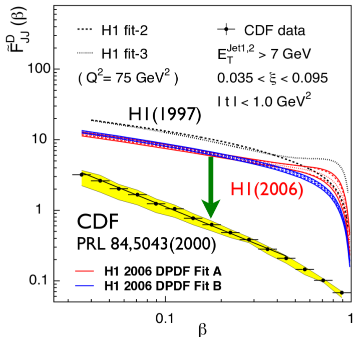




- QCD fits
- dominated by gluons

Factorisation breaking



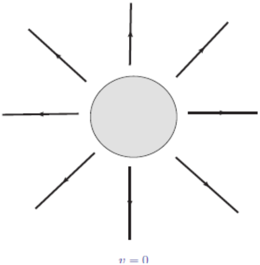


- Hard diffractive events rarer than naive extrapolations from HERA
- Suppression factor: gap survival probability
- Origin: additional interactions
- Confirmed in many processes

Contents

Equivalent photons

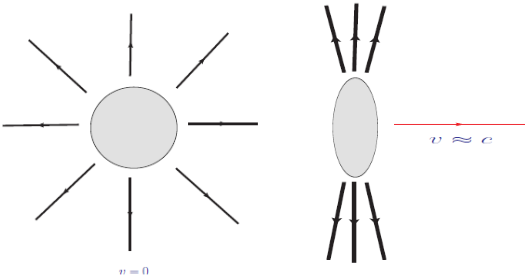
- Consider a charged nucleus at rest. The associated electromagnetic field can be represented by:



(slides from Victor Gonçalves)

Equivalent photons

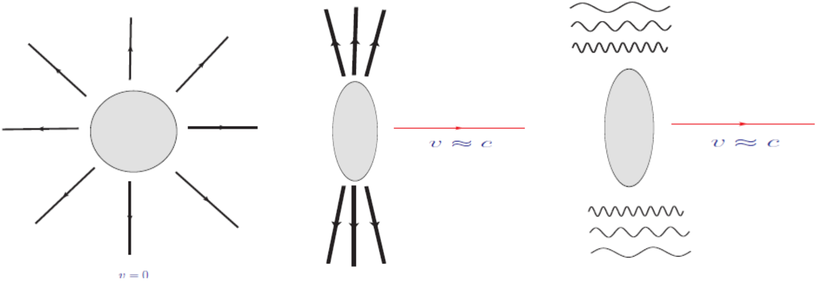
- As a charged nucleus moves with nearly the speed of light, the electromagnetic field becomes transverse to its velocity.



(slides from Victor Gonçalves)

Equivalent photons

- Since the electric and magnetic field associated to the nucleus take on the same absolute value, this transverse electromagnetic field can be simulated by an equivalent swarm of photons [a].

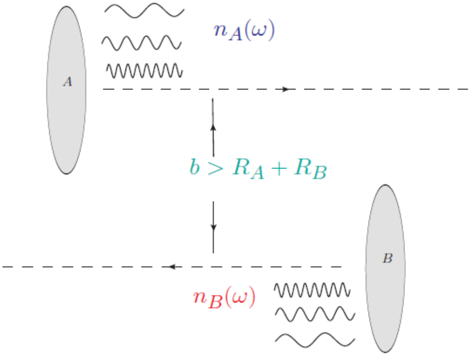


[a] E. Fermi (1924), E. J. Williams (1933), C. F. Von Weizacker (1934)

(slides from Victor Gonçalves)

Equivalent photons

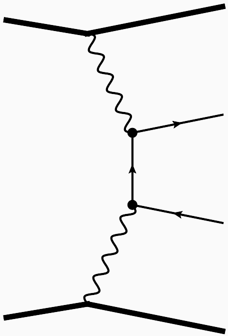
- Thus the collision of two charged nuclei at large impact parameter can be described as the collision of two equivalent swarms of photons.



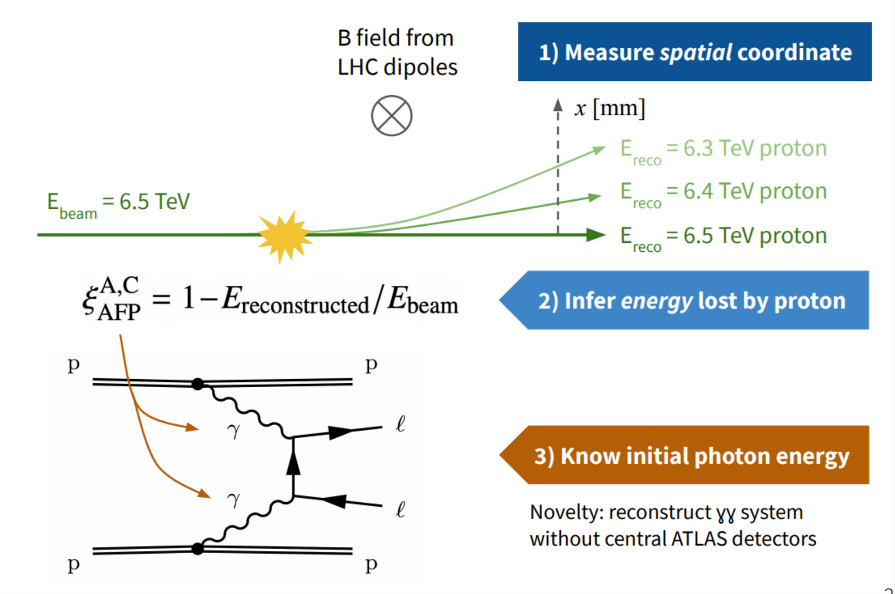
(slides from Victor Gonçalves)

Two-photon processes

- Two-photon processes can be computed within QED
- Exclusive $\gamma\gamma \to ll$
  - Standard candle for photon-induced physics
  - Non-negligible background to Drell-Yan like reactions
- Test of SM γWW and $\gamma\gamma WW$ couplings

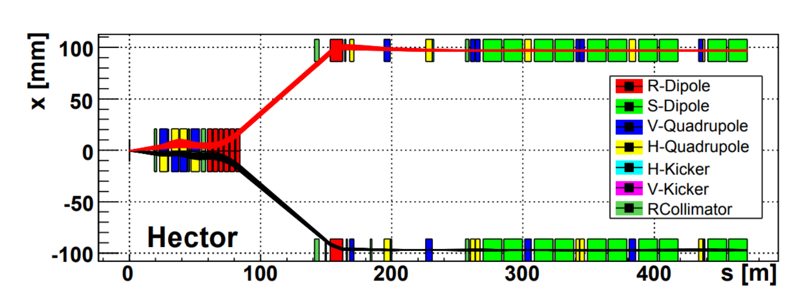


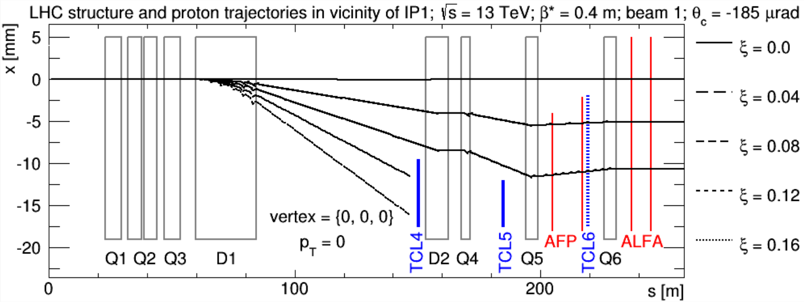
Forward proton spectrometer



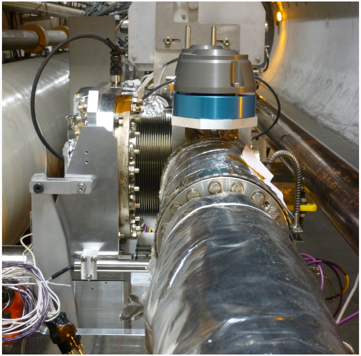
(drawing from Jesse Liu)

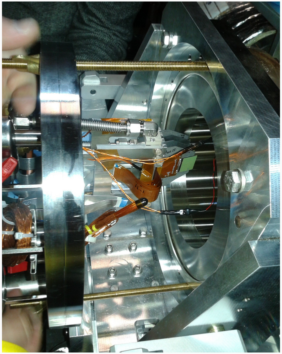
Trajectories of forward protons

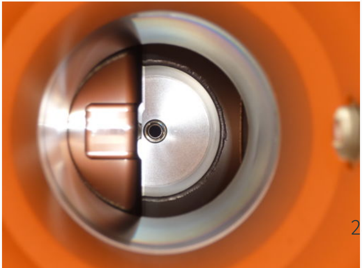




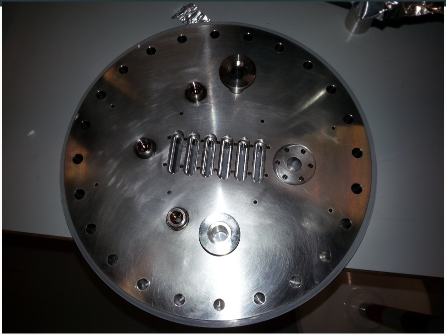
Roman pots

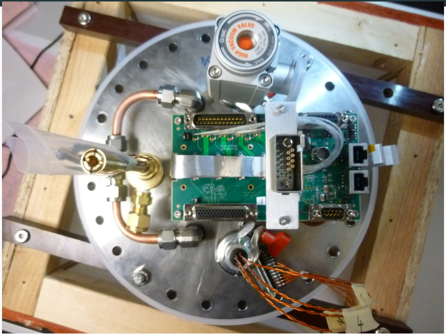


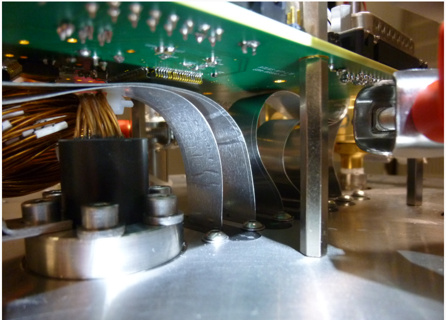


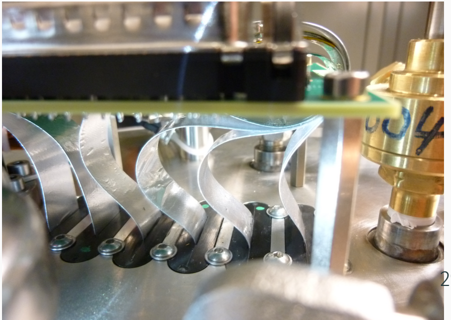


Feedthrough flange

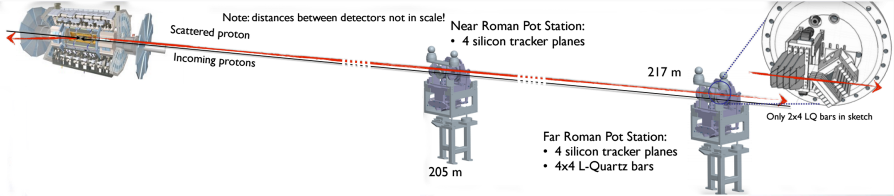


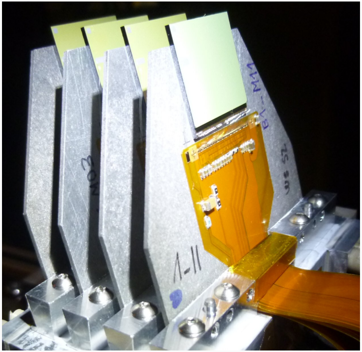


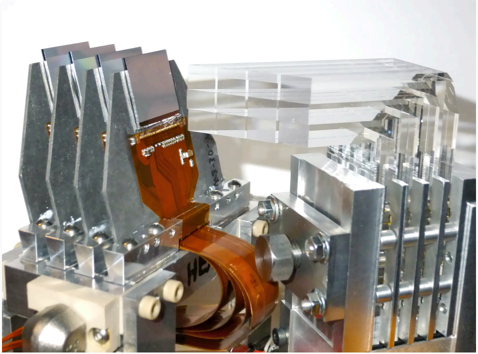




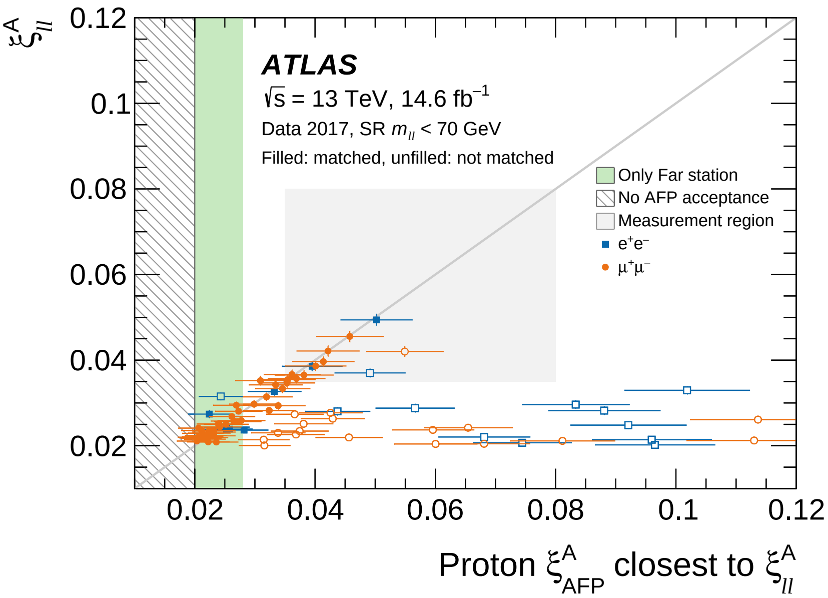
ATLAS Forward Proton detectors – one arm



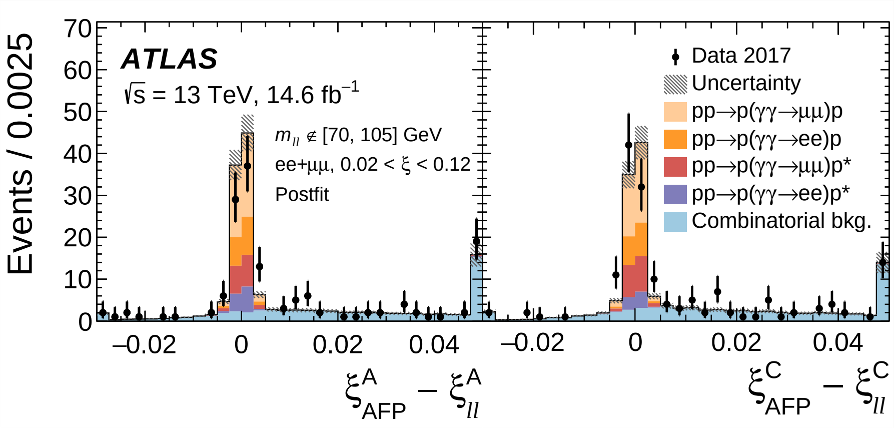




Kinematic matching



Signal evidence



Summary

Forward physics

- physics between perturbative and non-perturbative QCD
- wide range of different topics
- standard and dedicated experimental methods