# forward particle physics – past, present and future

Tomáš Sýkora

Institute of Particle and Nuclear Physics

Faculty of Mathematics and Physics

what are relevant (= meaningful) question [what is (the definition of) art? – the sculpture in Troja…]

what are (really!) relevant problems? [nothing(?) in particle physics…] (Veltman and non-commutative field theory)

how the answers to these questions depend on time? [a new discovery opens new gates…]

is there some set of "invariants"?

probably these questions themselves belong to such set…

from my perspective a man should never stop to ask such questions but, sure…
we should try to formulate questions more concretely (="usefully", ;-)) set

| | | |
|---|---|---|
| Vítkovice | | Pardubice |
| 3:3 | | 3:3 |
| Hradec Králové | | Třinec |

https://en.wikipedia.org/wiki/List_of_unsolved_problems_in_physics

## High-energy physics/particle physics [ edit ]

*See also: Beyond the Standard Model*

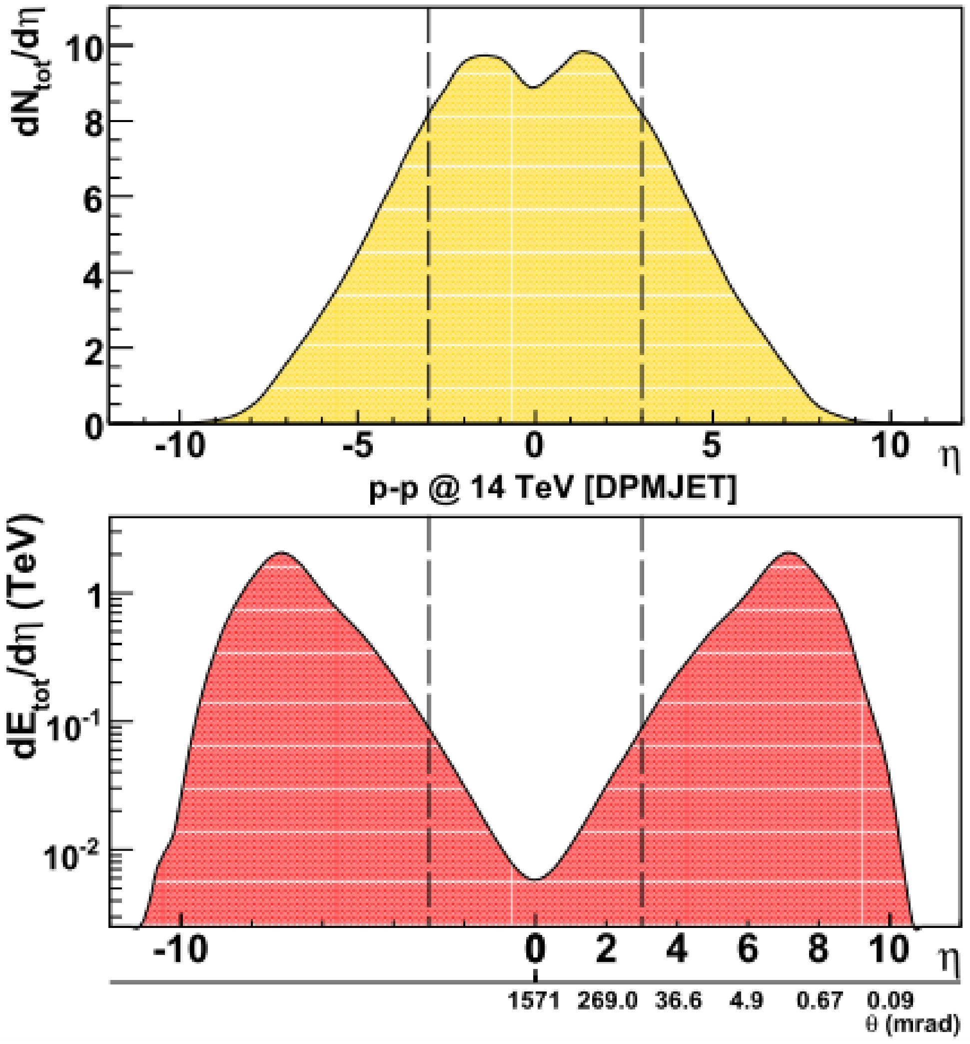
- Hierarchy problem: Why is gravity such a weak force? It becomes strong for particles only at the Planck scale, around $10^{19}$ GeV, much above the electroweak scale (100 GeV, the energy scale dominating physics at low energies). Why are these scales so different from each other? What prevents quantities at the electroweak scale, such as the Higgs boson mass, from getting quantum corrections on the order of the Planck scale? Is the solution supersymmetry, extra dimensions, or just anthropic fine-tuning?
- Magnetic monopoles: Did particles that carry "magnetic charge" exist in some past, higher-energy epoch? If so, do any remain today? (Paul Dirac showed the existence of some types of magnetic monopoles would explain charge quantization.)[27]
- Neutron lifetime puzzle: While the neutron lifetime has been studied for decades, there currently exists a lack of consilience on its exact value, due to different results from two experimental methods ("bottle" versus "beam").[28][b]
- Proton decay and spin crisis: Is the proton fundamentally stable? Or does it decay with a finite lifetime as predicted by some extensions to the standard model?[29] How do the quarks and gluons carry the spin of protons?[30]
- Supersymmetry: Is spacetime supersymmetry realized at TeV scale? If so, what is the mechanism of supersymmetry breaking? Does supersymmetry stabilize the electroweak scale, preventing high quantum corrections? Does the lightest supersymmetric particle (LSP) comprise dark matter?
- Color confinement: The quantum chromodynamics (QCD) color confinement conjecture is that color-charged particles (such as quarks and gluons) cannot be separated from their parent hadron without producing new hadrons.[31] Is it possible to provide an analytic proof of color confinement in any non-abelian gauge theory?
- Generations of matter: Why are there three generations of quarks and leptons? Is there a theory that can explain the masses of particular quarks and leptons in particular generations from first principles (a theory of Yukawa couplings)?[32]
- Neutrino mass: What is the mass of neutrinos, whether they follow Dirac or Majorana statistics? Is the mass hierarchy normal or inverted? Is the CP violating phase equal to 0?[33][34]
- Reactor antineutrino anomaly: There is an anomaly in the existing body of data regarding the antineutrino flux from nuclear reactors around the world. Measured values of this flux appears to be only 94% of the value expected from theory.[35] It is unknown whether this is due to unknown physics (such as sterile neutrinos), experimental error in the measurements, or errors in the theoretical flux calculations.[36]
- Strong CP problem and axions: Why is the strong nuclear interaction invariant to parity and charge conjugation? Is Peccei–Quinn theory the solution to this problem? Could axions be the main component of dark matter?
- Anomalous magnetic dipole moment: Why is the experimentally measured value of the muon's anomalous magnetic dipole moment ("muon $g-2$") significantly different from the theoretically predicted value of that physical constant?[37]
- Proton radius puzzle: What is the electric charge radius of the proton? How does it differ from a gluonic charge?
- Pentaquarks and other exotic hadrons: What combinations of quarks are possible? Why were pentaquarks so difficult to discover?[38] Are they a tightly-bound system of five elementary particles, or a more weakly-bound pairing of a baryon and a meson?[39]
- Mu problem: A problem in supersymmetric theories, concerned with understanding the reasons for parameter values of the theory.
- Koide formula: An aspect of the problem of particle generations. The sum of the masses of the three charged leptons, divided by the square of the sum of the roots of these masses, to within one standard deviation of observations, is $Q = \frac{2}{3}$ . It is unknown how such a simple value comes about, and why it is the exact arithmetic average of the possible extreme values of $\frac{1}{3}$ (equal masses) and 1 (one mass dominates).

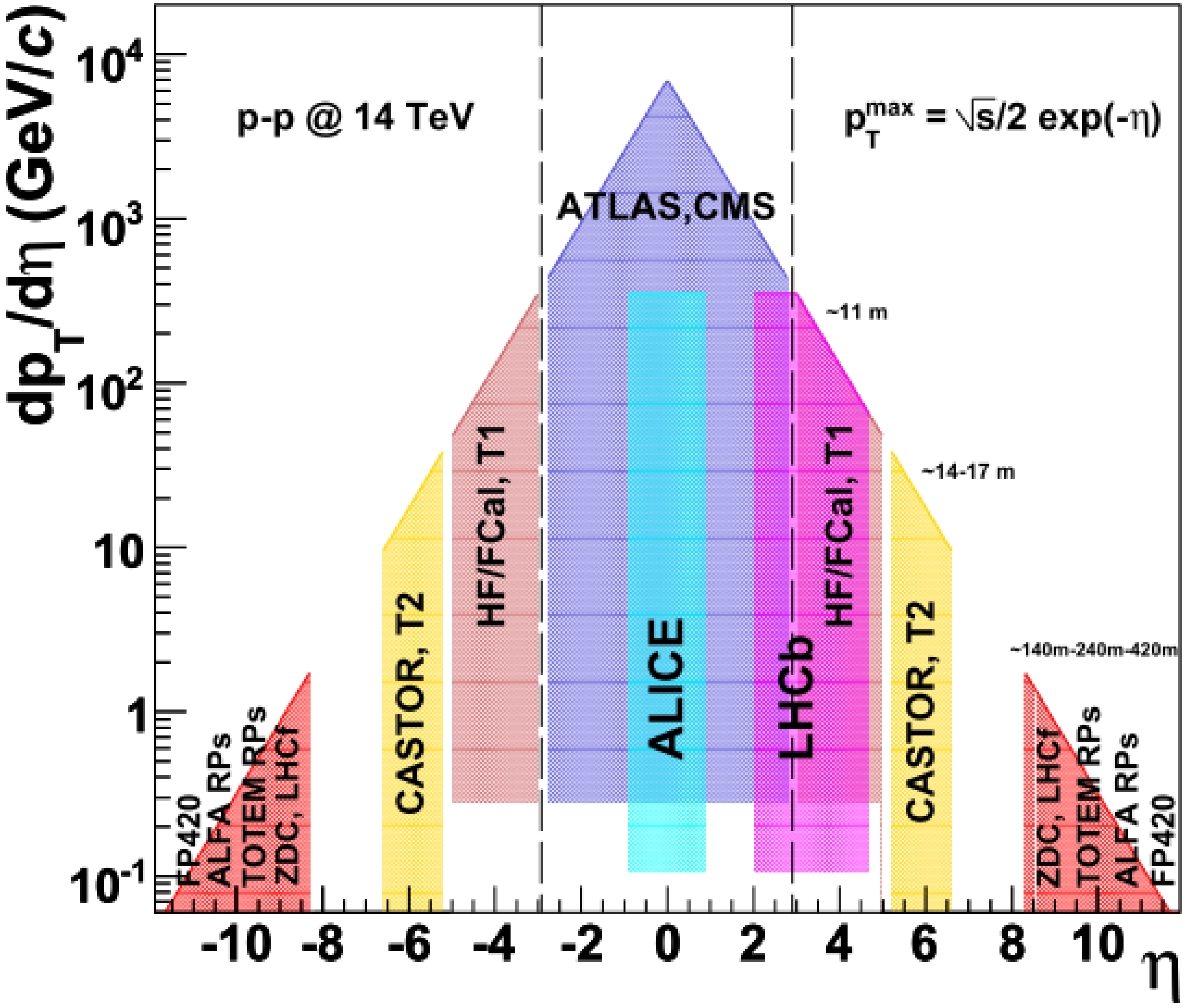
many of these problems are subjects of work of our department

I will talk only about the work related(!) to problems in red

# flows (p-p)

https://doi.org/10.48550/arXiv.0806.0883




$$\eta = -\ln \tan(\theta/2)$$

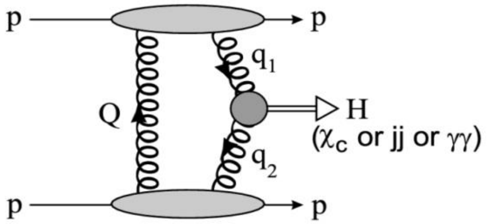
## what can we learn from forward region?

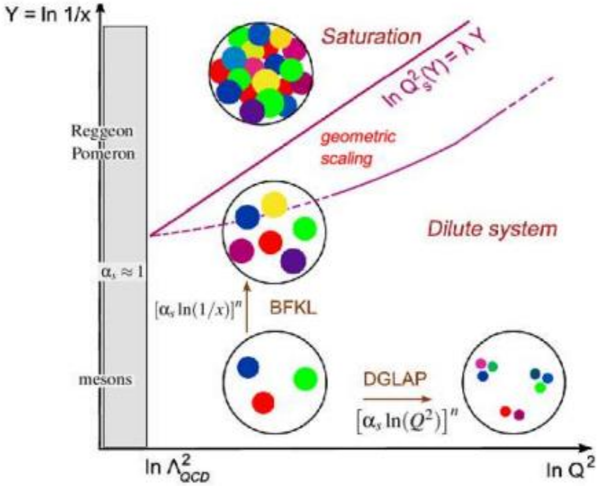
For a successful run of the LHC it is essential to have a full understanding of the complete final states. This includes, besides the central region, also the kinematic region as close as possible to the forward direction. New physics is mainly searched for in the central region where factorization theorems for inclusive cross sections allow the use of parton densities and hard subprocesses whose cross sections can be calculated by using perturbative theory. However, there is a rich physics content outside this kinematic region, in particular close to the forward directions. Prominent examples include the final states with high forward multiplicities, as well as those with rapidity gaps, notably in elastic, diffractive, and central exclusive processes. Some of these configurations originate from purely nonperturbative reactions, while others can be explained in terms of multiparton chains or other extensions of the perturbative QCD parton picture. Future progress in this field requires the combination of thorough experimental measurements and extensive theoretical work.

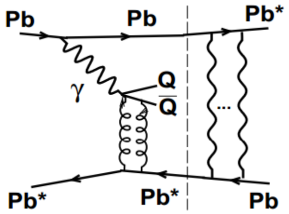
1611.05079.pdf (arxiv.org)

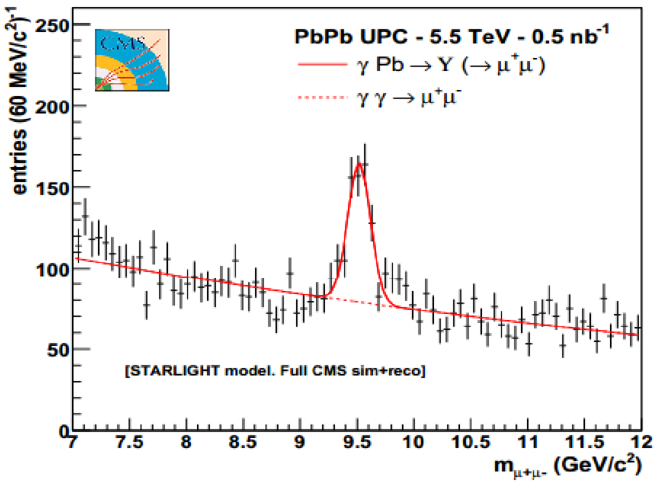
## hm, could you be more specific? (2008!)

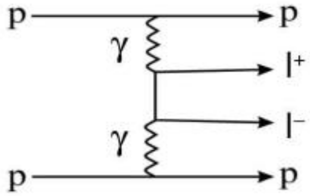
- elastic and diffractive collisions
  - central exclusive production [l.i.t.] (heavy particles & resonances) pp → p ⊕ X ⊕ p where X stands for a fully measured system like jet-jet, $l^+l^-$, γγ, H, $W^+W^-$, … and '⊕' represents Large Rap-Gap (Δη ≥ 4)
  - low-x QCD
    structure functions, factorization violation, parton saturation, non-linear QCD evolution, small-x PDFs, multi-parton scattering
  - models of hadron interactions for high energies – cosmic showers, measurement of dE/dη, dN/dη for p-p, p-A and A-A interactions,
    ultra peripheral collisions
- electroweak interactions
  anomalous coupling constants

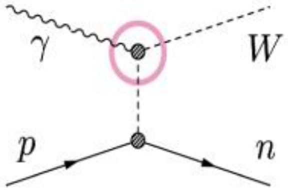


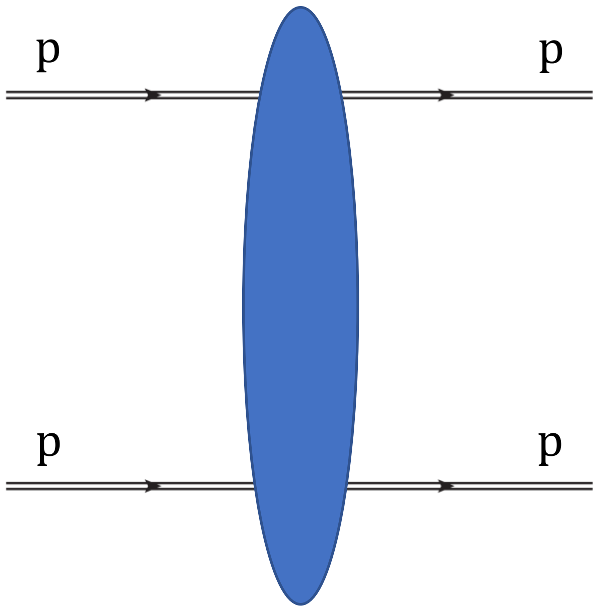



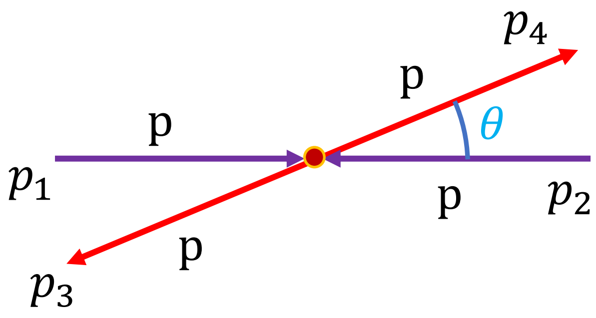



# kinematics




Mandelstam variables, invariants

$$s = (p_1 + p_2)^2$$

$$t = (p_1 - p_4)^2 \cong -(p_0 \theta)^2,\ |\vec{p_1}| = |\vec{p_2}| = |\vec{p_4}| = p_0$$

## proton structure (low x)

total cross section $\sigma_{tot}$ of proton-proton interaction

# total cross section $\sigma_{tot}$ of proton-proton interaction

- $\sigma_{tot}$ of p-p interaction is a fundamental quantity giving the upper bound on probability (cross section) of any process in p-p collisions
- $\sigma_{tot}$ is not calculable in the framework of perturbative QCD; Regge model is used in HEP generators to describe kinematic area where perturbative QCD cannot be applied
- optical theorem

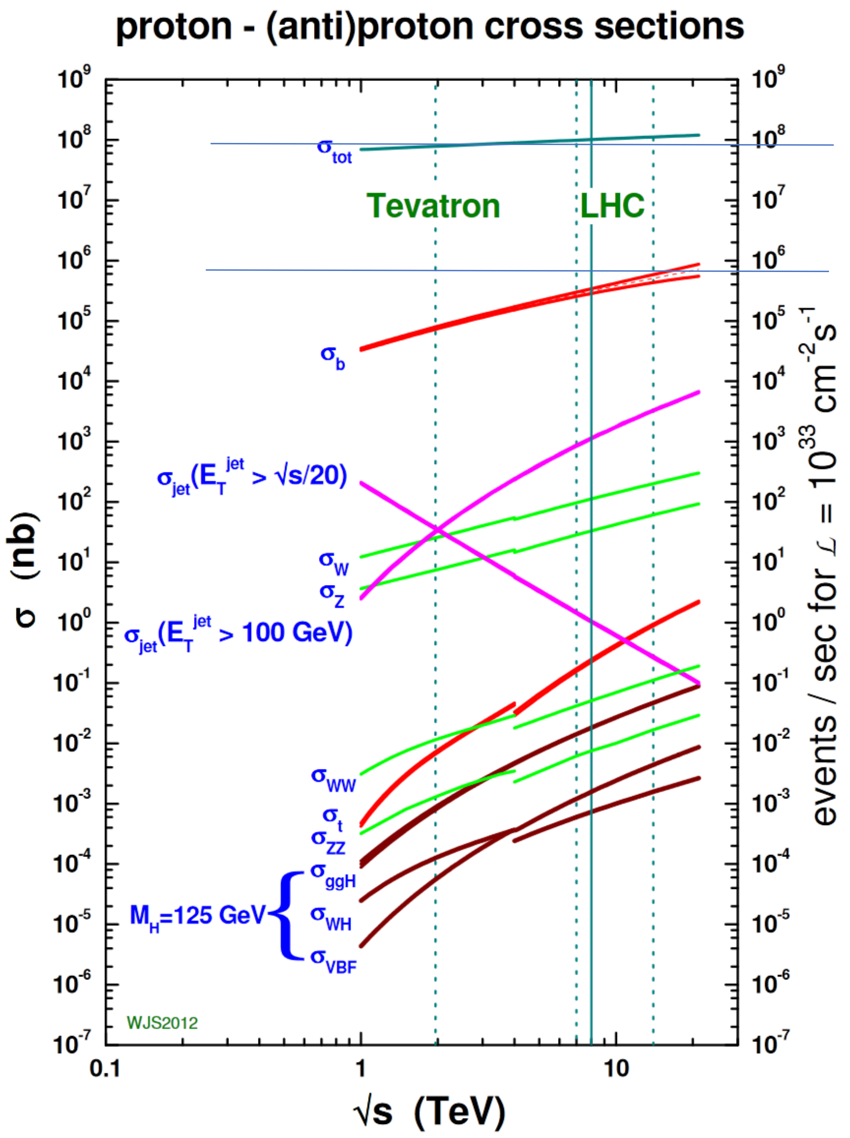
$$\sigma_{\text{tot}} \propto 4\pi \cdot \text{Im}\left(f_{\text{el}}\right)_{t\to 0}$$

- black disk limit

$$\left.\frac{\sigma_{\text{el}}}{\sigma_{\text{tot}}} = \frac{1}{2}\right|_{s\to\infty}$$

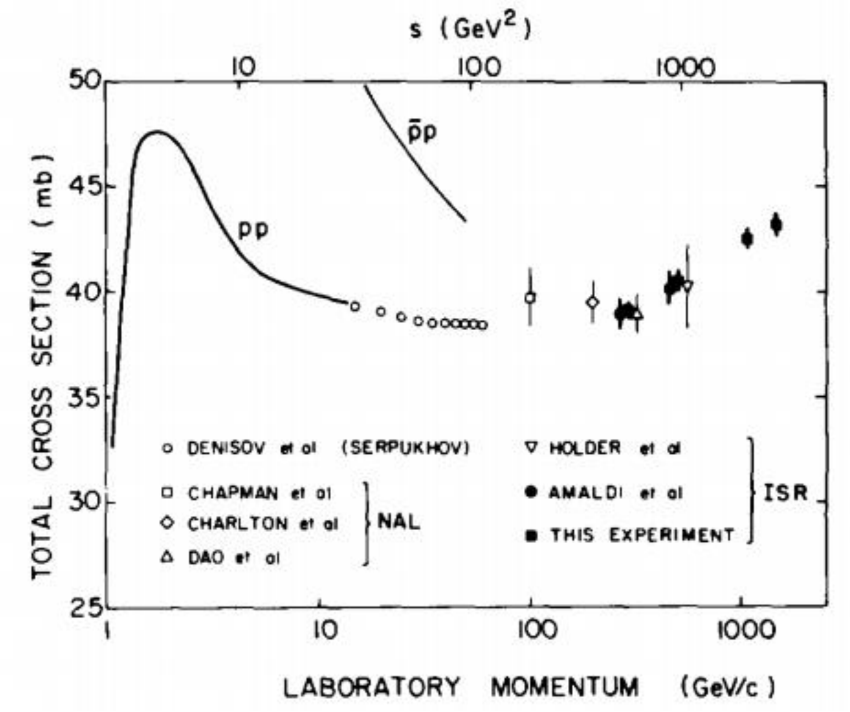
- Pomeranchuk theorem

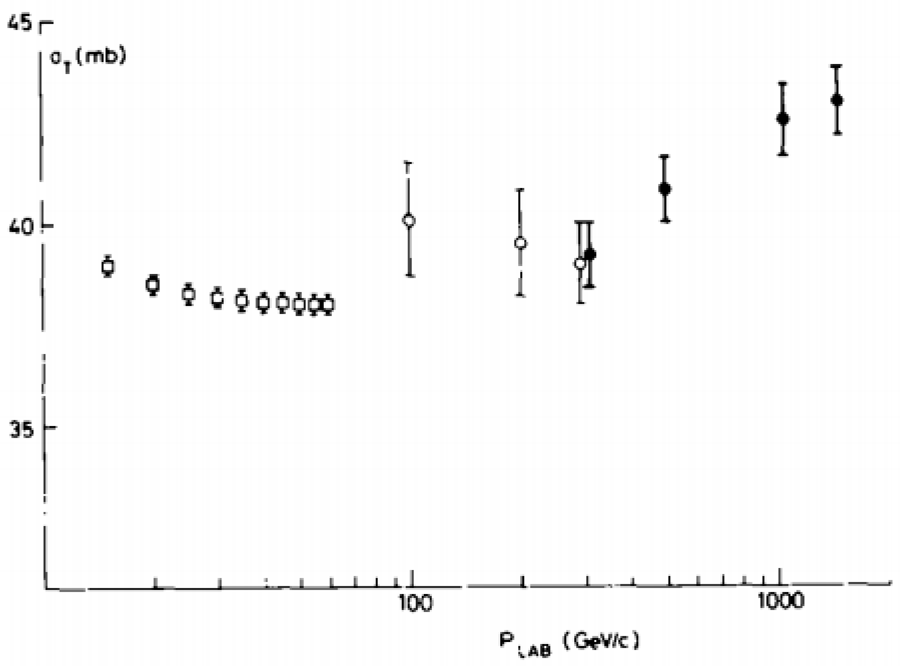
$$\sigma_{\text{pp}} = \left.\sigma_{\text{p}\bar{\text{p}}}\right|_{s\to\infty}$$



# ISR (past)

ISR – rise of $\sigma_{tot}$ was observed first time




U. Amaldi et al., Phys. Lett. B 44 (1973) 192 S.R. Amendolia et al., Phys. Lett. B 44 (1973) 119

would the total cross section continue to rise with ln(s) or rather $\ln^2(s)$?

# $\sigma_{tot}$ and $\sigma_{el}$ – optical theorem

direct ($\rho$-independent; see below) measurement of $\sigma_{tot} = N_{tot}/L$,
where $N_{tot}$ is total number of events with interaction, $L$ is luminosity, is nontrivial; (due to the limited acceptance, model dependence)

$\sigma_{tot} = \sigma_{el} + \sigma_{inel}$

$\sigma_{inel} = \sigma_{inel\ diffractive} (\sigma_{SD} + \sigma_{DD} + \ldots) + \sigma_{non\ diffractive}$

traditional way (ISR) of $\sigma_{tot}$ measurement – via elastic cross section measurement and the use of optical theorem

$$\sigma_{tot} = 4\pi\,\mathrm{Im}[f_{el}(t=0)]$$

where $f_{el}$ is elastic amplitude

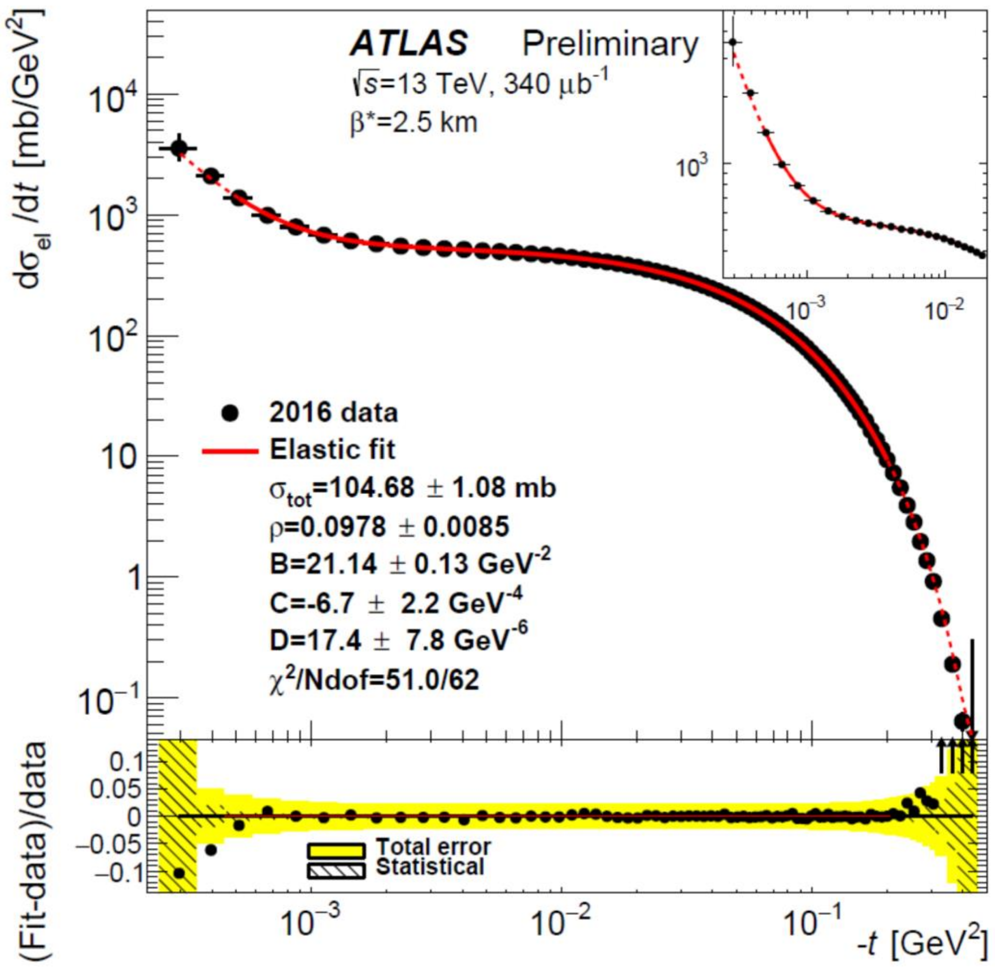
$$\sigma_{tot}^2 = \frac{16\pi}{1+\rho^2}\frac{1}{L}\left(\frac{dN_{el}}{dt}\right)_{t=0} \qquad \rho = \left.\frac{\mathrm{Re}[f_{el}(t)]}{\mathrm{Im}[f_{el}(t)]}\right|_{t\to 0}$$

luminosity dependent measurement,
$N_X$ - number of events of $X \in$ (el, tot, inel, …) type

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2}\frac{(dN_{el}/dt)_{t=0}}{N_{tot}}$$

luminosity independent measurement

# differential elastic cross section – results




$t \in [2.5 \cdot 10^{-4}, 4.6 \cdot 10^{-1}]$ GeV²

physics parameters are extracted from a profile fit
to the cross section including experimental systematic uncertainties

fit function – nuclear part depends on considered models (next slide)

$$f_N(t) = (\rho + i)\frac{\sigma_{tot}}{\hbar c} e^{\frac{-B|t|}{2}}$$

$$\phi(t) = -\ln\frac{B|t|}{2} - \phi_C$$

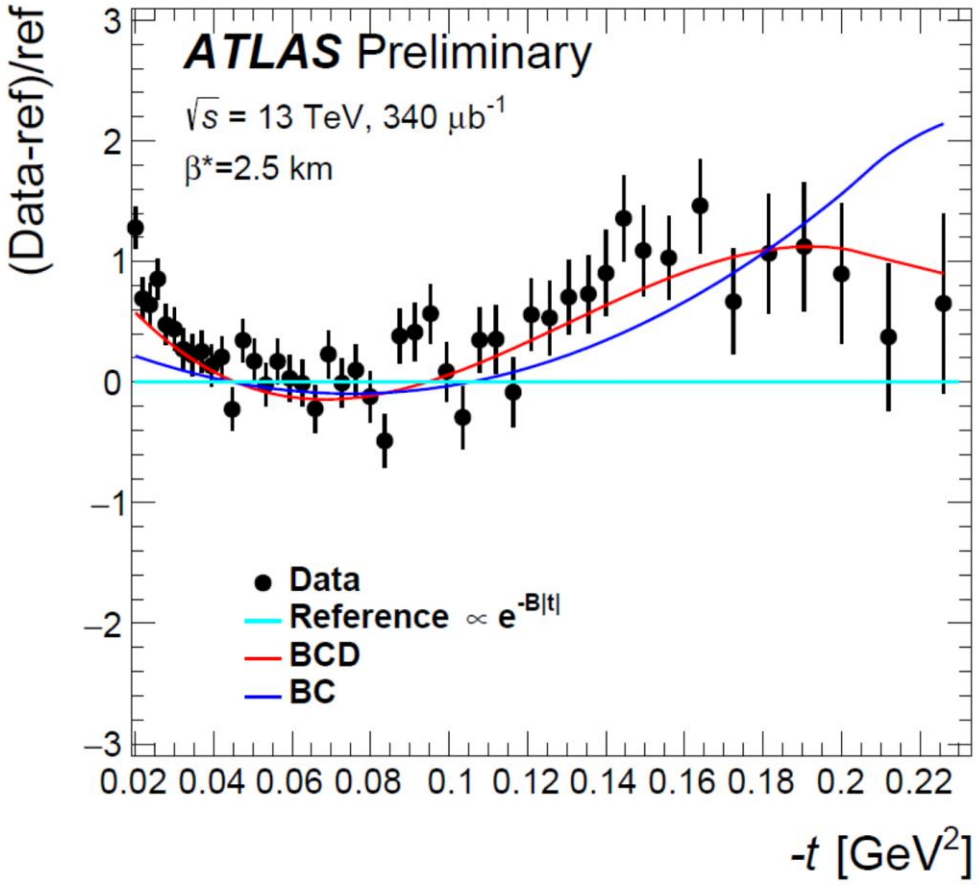
$$f_N(t) = (\rho + i)\frac{\sigma_{tot}}{\hbar c} e^{\frac{-B|t|-Ct^2-D|t|^3}{2}}$$

$$\phi(t) = -\left(\gamma_E + \ln\frac{B|t|}{2} + \ln\left(1 + \frac{8}{B\Lambda}\right)\right) + \frac{4|t|}{\Lambda}\cdot\ln\frac{\Lambda}{4|t|} - \frac{2|t|}{\Lambda}$$

| | |
|---|---|
| $\sigma_{tot}$ | 105 mb |
| $B$ | 21.13 GeV$^{-2}$ |
| $C$ | −6.5 GeV$^{-4}$ |
| $D$ | 17.4 GeV$^{-6}$ |
| $\rho$ | 0.096 |
| $\Lambda$ | 0.71 GeV$^2$ |
| $\phi_C$ | 0.577 |

the main uncertainties are related to the luminosity and to the alignment;
for $\rho$ also theoretical uncertainties are important

# theoretical (model) uncertainties




$$f_N(t) = (\rho + i)\frac{\sigma_{tot}}{\hbar c} e^{\frac{-B|t| - Ct^2 - D|t|^3}{2}}$$

| | $\sigma_{tot}$[mb] | $\rho$ | $B$[ GeV$^{-2}$] | $C$[GeV$^{-4}$] | $D$[GeV$^{-6}$] |
|---|---|---|---|---|---|
| Central value | 104.68 | 0.0978 | 21.14 | −6.7 | 17.4 |
| Statistical error | 0.22 | 0.0043 | 0.07 | 1.1 | 3.8 |
| Experimental error | 1.06 | 0.0073 | 0.11 | 1.9 | 6.8 |
| Theoretical error | 0.12 | 0.0064 | 0.01 | 0.04 | 0.15 |
| Total error | 1.09 | 0.0106 | 0.13 | 2.3 | 7.8 |

theoretical uncertainties:

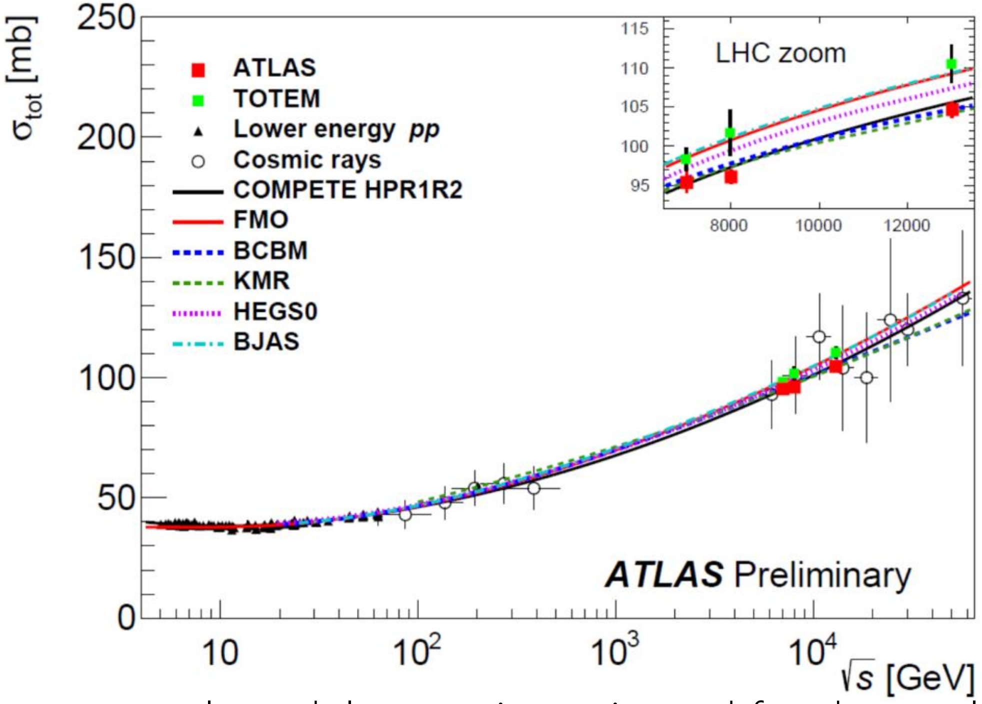
- parametrization of the strong amplitude
- Coulomb phase
- proton form factor
- nuclear phase important for $\rho$

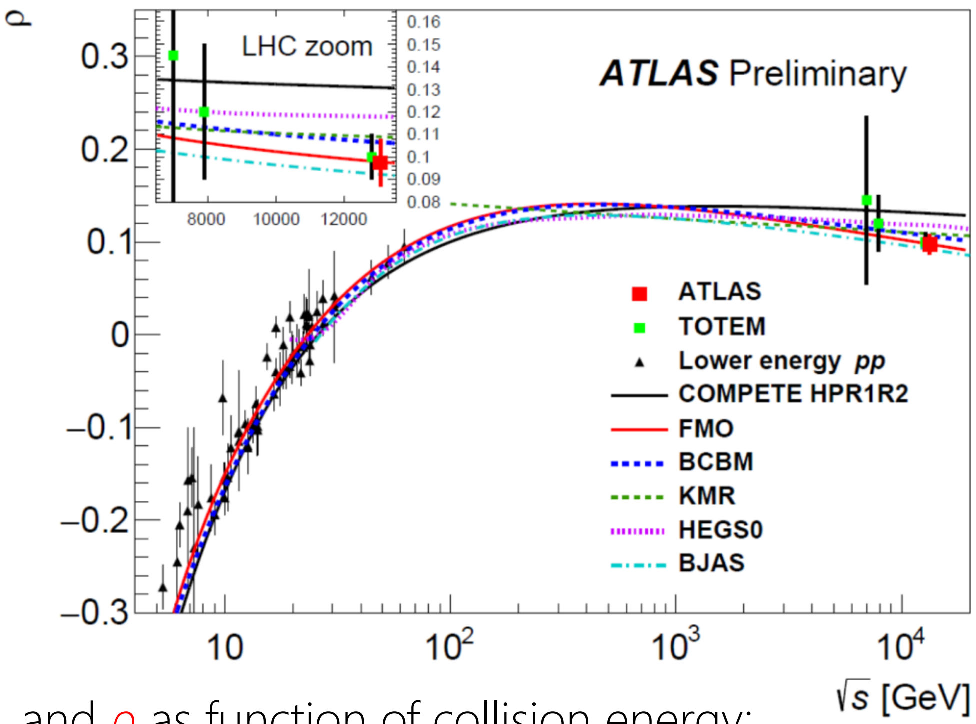
stability:

- time dependence
- fit range
- different $t$-reconstruction methods
- difference between arms

arXiv:2207.12246 [hep-ex], accepted for publication in EPJC

# behavior of $\sigma_{tot}$ and $\rho$ as function of collision energy (now)




- several models were investigated for the evolution of $\sigma_{tot}$ and $\rho$ as function of collision energy;
  $\sigma_{tot}$ and $\rho$ connected via dispersion relations
- the canonical evolution model, COMPETE, is disfavored as it predicts the value of $\rho \approx 0.13$
- the model with an Odderon and tuned to TOTEM data is not in a good agreement with corresponding ATLAS $\sigma_{tot}$ result
- the damped amplitude model is in the best agreement with ATLAS data
- ALFA and TOTEM difference in $\sigma_{tot}$ about 2.2 σ (similar trend seen at 7 and 8 TeV)

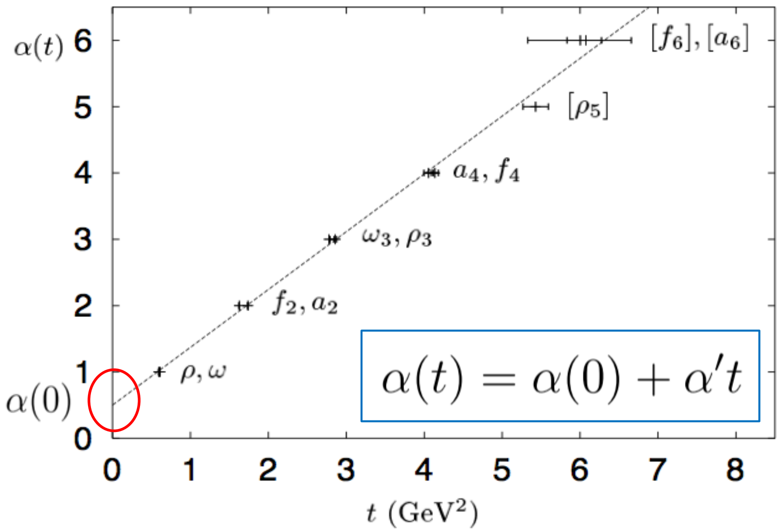
# evolution of B; $\sigma_{el}/\sigma_{tot}$ ratio

using optical theorem and Regge theory we can write

$$\sigma_{\text{tot}} \approx s^{\alpha(0)-1}$$

$$\frac{d\sigma_{\text{el}}}{dt} \approx s^{2(\alpha(0)-1)} e^{-B|t|} \qquad B = B_0 + 2\alpha' \ln s$$

where $\boldsymbol{\alpha}(0)$ is so-called intercept of a Regge trajectory

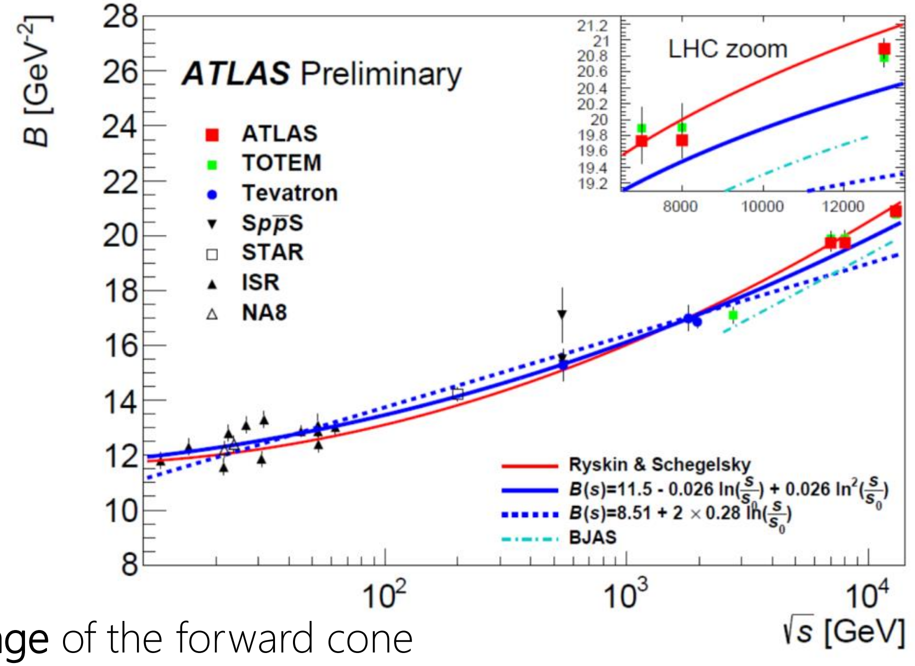



then:

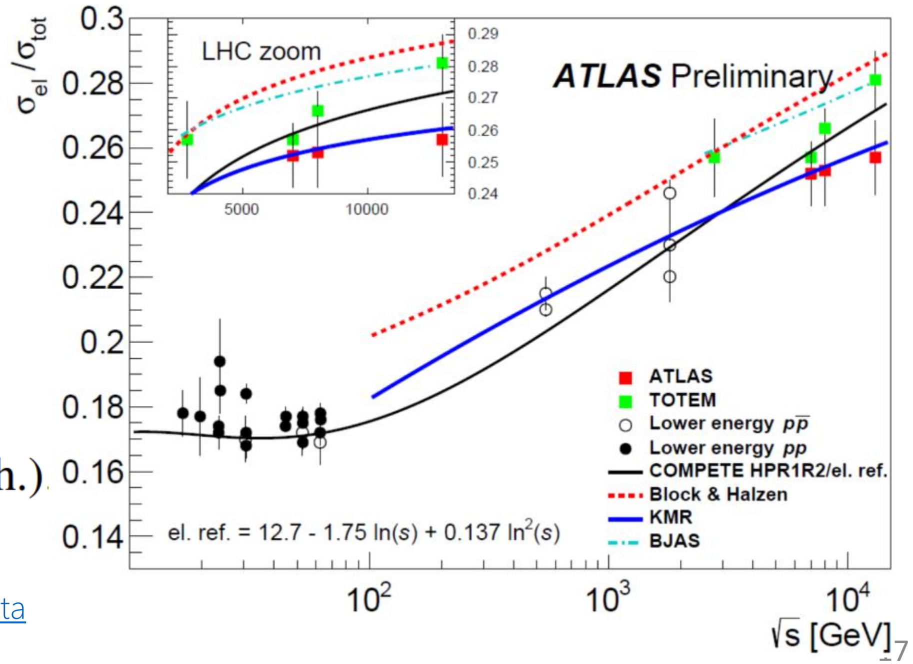
$$\frac{\sigma_{\text{el}}}{\sigma_{\text{tot}}} \approx s^{\alpha(0)-1}/(B_0 + \alpha' \ln s^2)$$

measurement at $\sqrt{s} = 13$ TeV gives:

$$\frac{\sigma_{\text{el}}}{\sigma_{\text{tot}}} = 0.257 \pm 0.008\ (\text{exp.}) \pm 0.009\ (\text{th.})$$

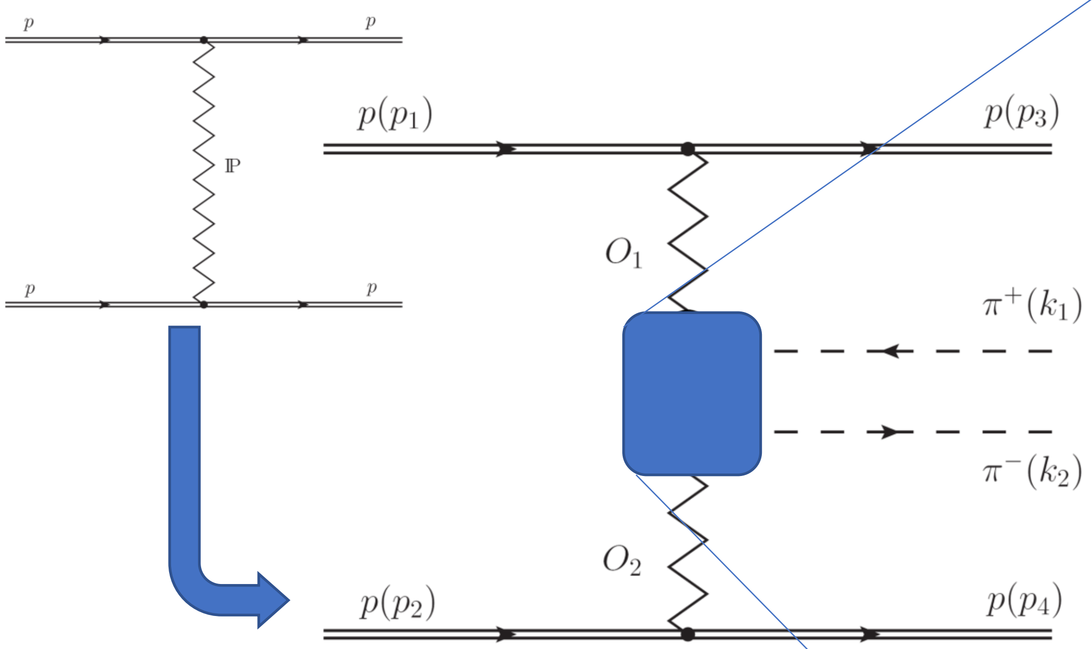


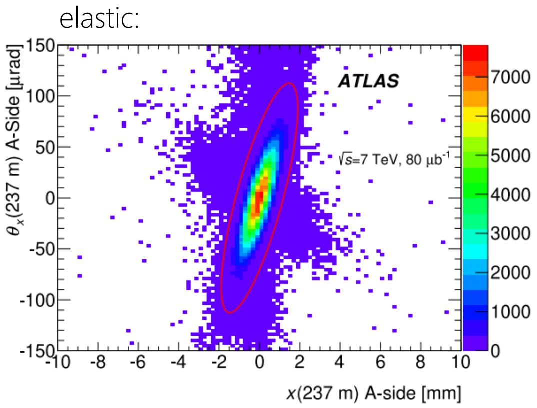

shrinkage of the forward cone

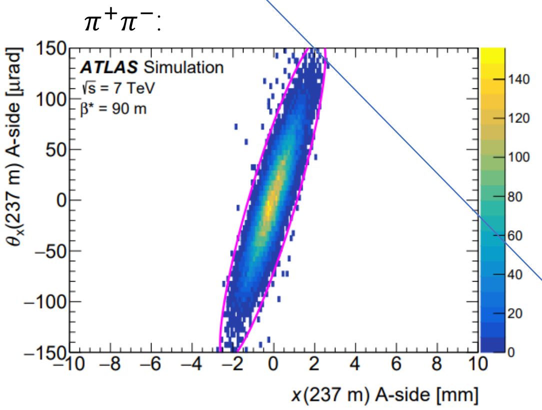


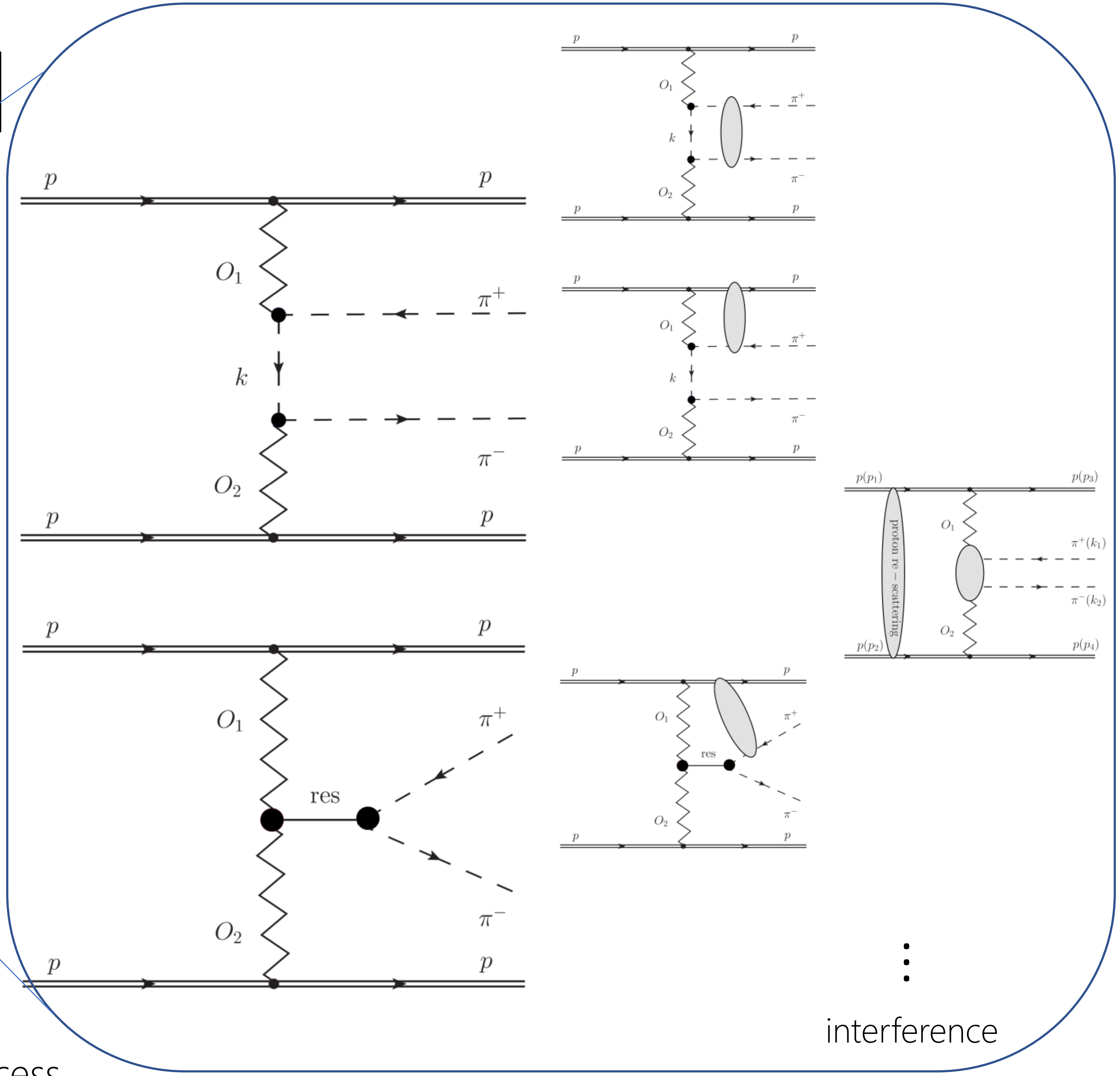

for some recent discussion see e.g. [Soft Pomeron in light of the LHC correlated data] a bit more…

# exclusive pion pair $\pi^+\pi^-$ production




very similar, very small $t$ and $\xi$ → non-perturbative process arXiv:2212.00664 [hep-ex], accepted for publication in EPJC

# data selection and cut flow

- data samples, the same as for ATLAS Collaboration, *Measurement of the total cross section from elastic scattering in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector*, Nucl. Phys. B 889 (2014) 486, arXiv: 1408.5778 [hep-ex]
- the present analysis used also the same proton reconstruction criteria – bunch group, data quality, selections on the reconstructed track and geometrical deflection, beam-screen and edge conditions (see Table 2) – together with the detector alignment

| Selection |
|---|
| Bunch selection |
| Lumi blocks selection |
| Trigger configuration |
| Pions: |
| number of tracks |
| primary vertex |
| ID track quality |
| MBTS veto |
| Protons: |
| ALFA track quality |
| ALFA $uv$-condition |
| ALFA clean track |
| ALFA geometry condition |
| Full system momentum balance in $p_x$ and $p_y$ |
| Fiducial region |

fiducial region:

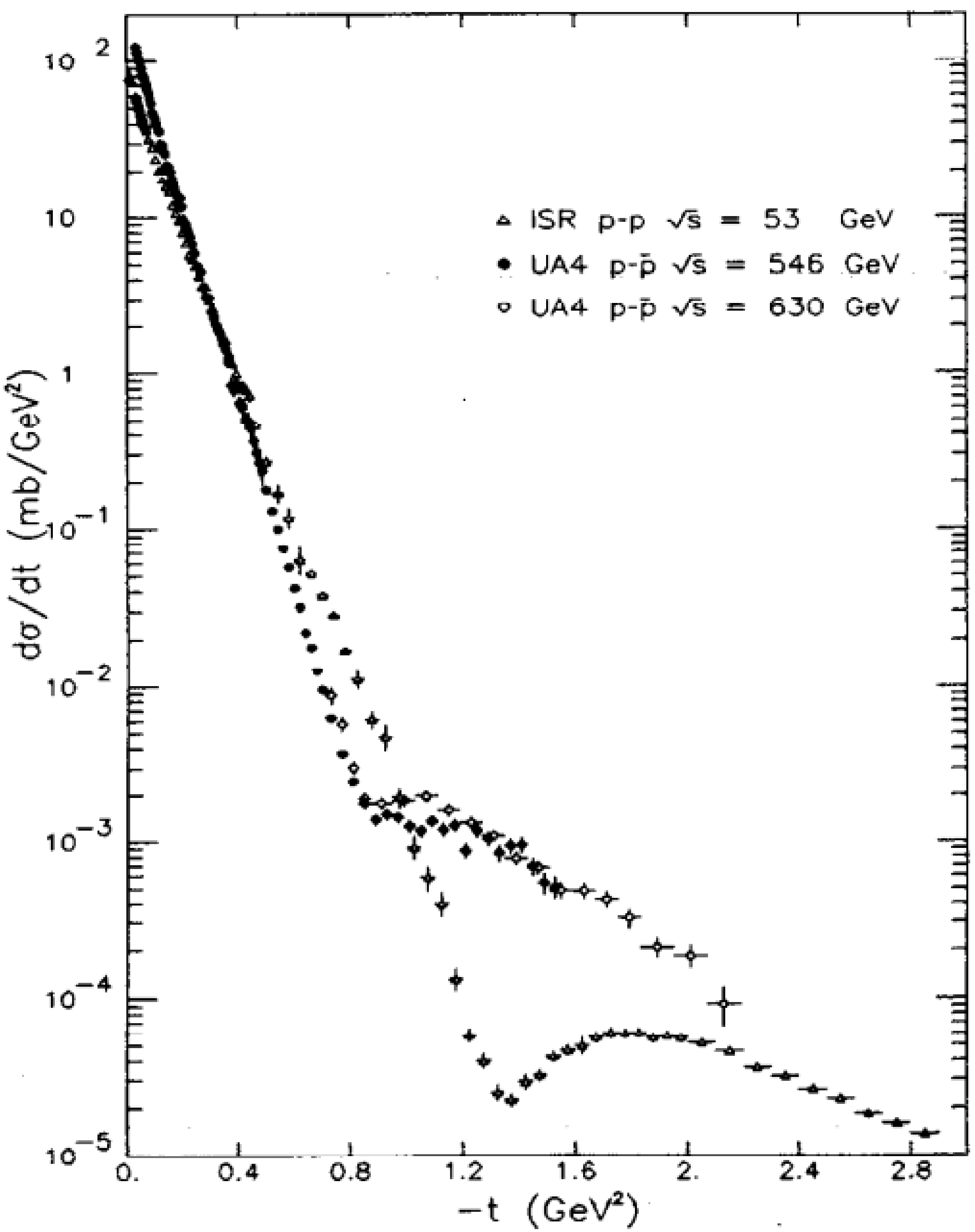
$$|\eta(\pi)| < 2.5,\ p_T(\pi) > 0.1\ \text{GeV},\ 2m_\pi < m_{\pi\pi} < 2.0\ \text{GeV}$$

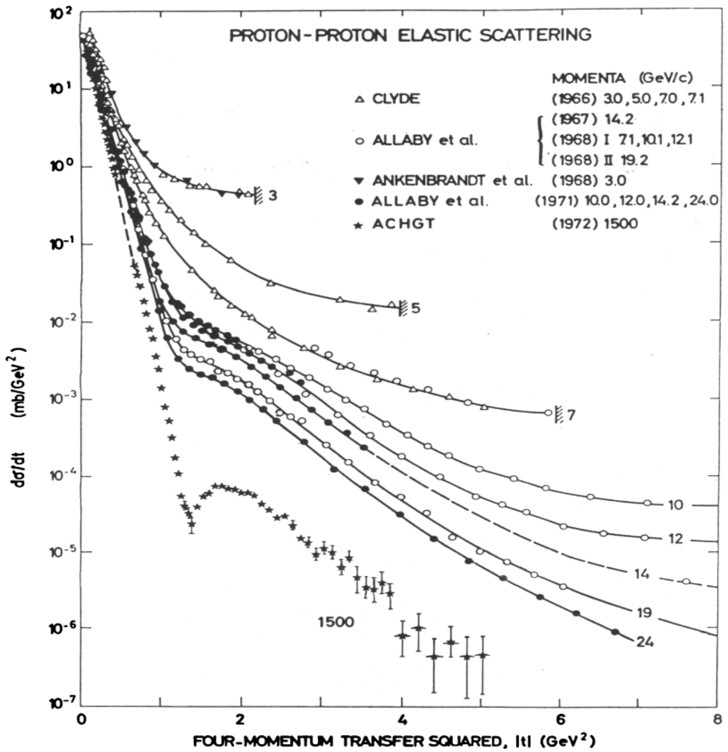
$$\text{armlet}_{ij}^{\text{low\_cut}} < p_y(A) < \text{armlet}_{ij}^{\text{up\_cut}} \quad \text{and} \quad \text{armlet}_{kl}^{\text{low\_cut}} < p_y(C) < \text{armlet}_{kl}^{\text{up\_cut}}$$

$$ijkl \in \{1368, 2457, 1357, 2468\}$$

| Selection | Configuration | |
|---|---|---|
| | elastic | anti-elastic |
| Recorded ATLAS events | 6 620 953 | |
| Data quality and trigger preselections | 1 106 855 | 397 683 |
| ID selection (pion pair) | 1 520 | 1 115 |
| ALFA track selection (incl. clean track and $uv$-condition) | 486 | 11 |
| MBTS veto | 136 | 5 |
| ALFA geometry condition | 96 | 5 |
| Full system momentum balance in $x$ and $y$ | 30 | 3 |
| Fiducial region | 28 | 3 |
| (arm 0 + arm 1) **Total selected** | (18+10) **28** | (2+1) **3** |

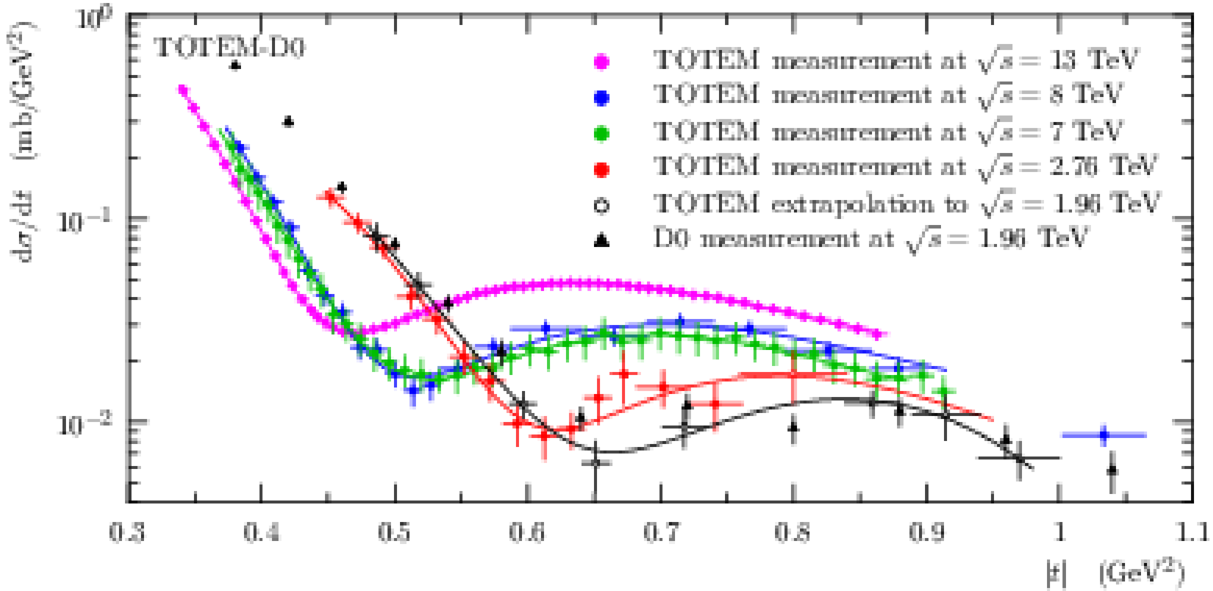
## diffraction



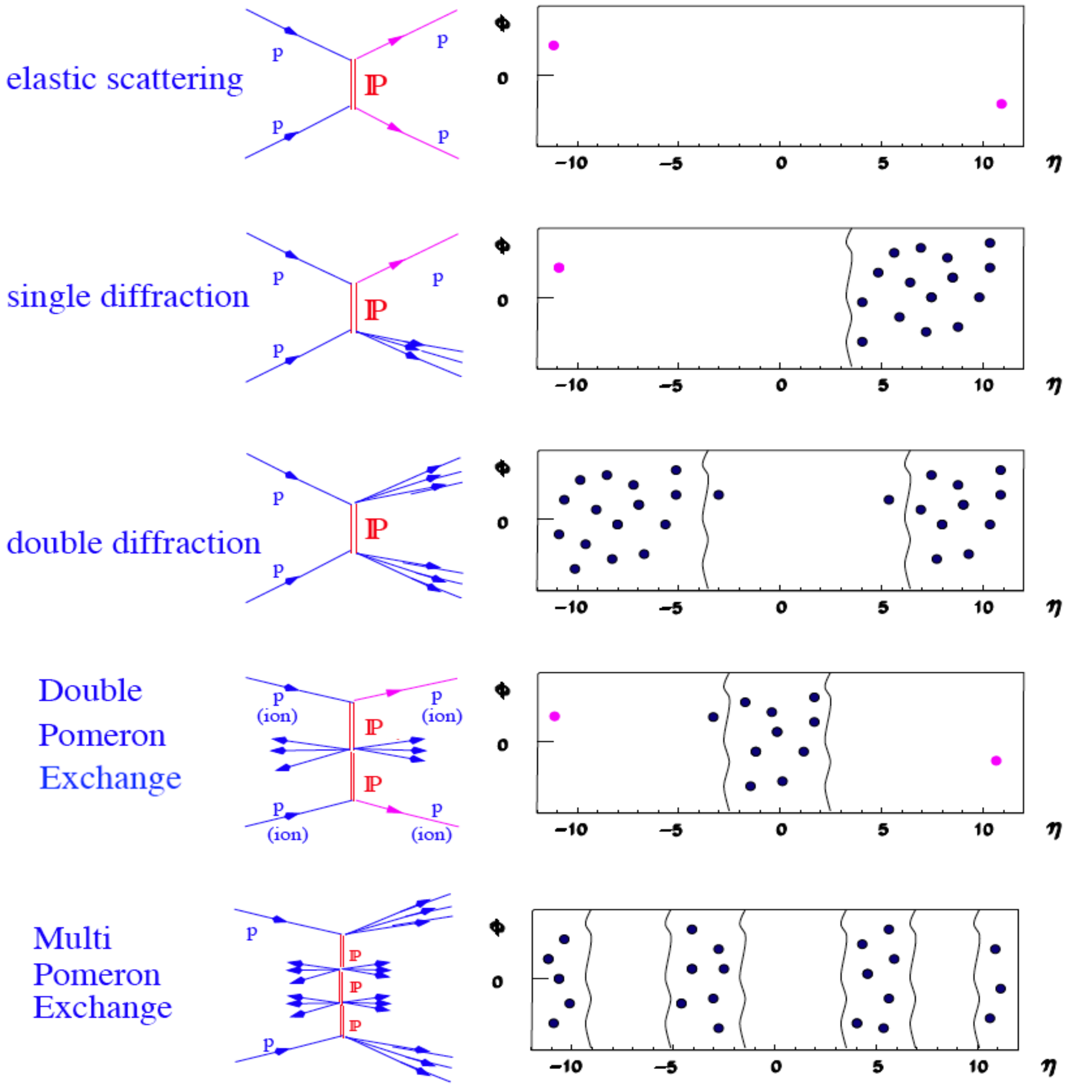




differential cross sections

observations



# event topologies

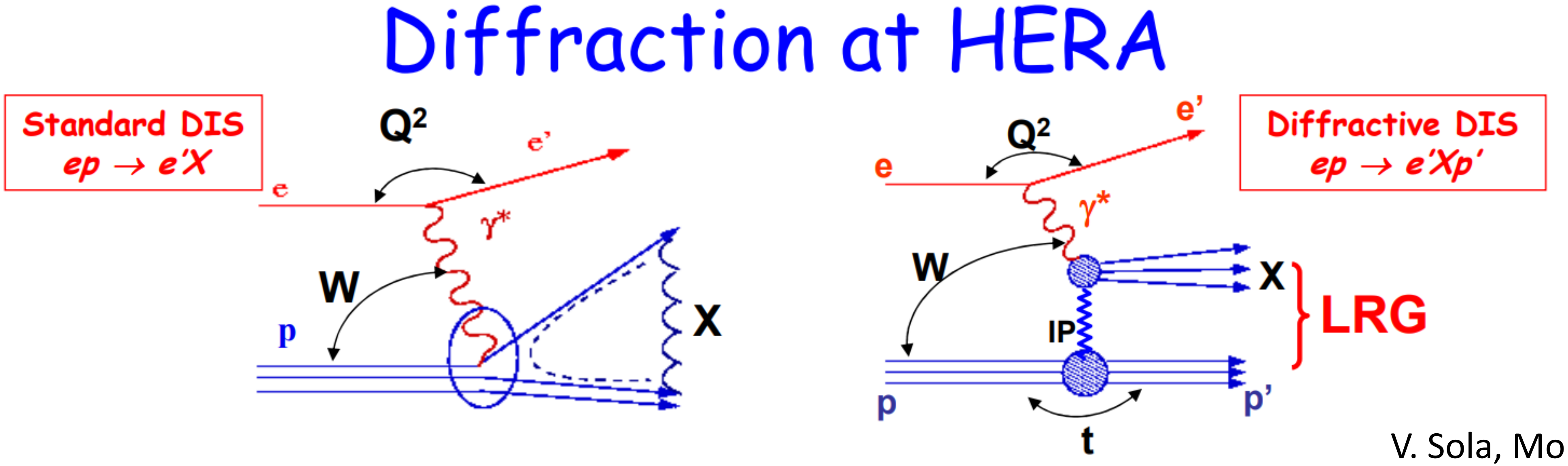



elastic events are the subset of diffractive events; diffractive like pattern was actually observed in elastic collisions

# HERA and diffraction

1992, H1, ZEUS, HERMES and HERA-B, $\sqrt{s}$ = 318 GeV

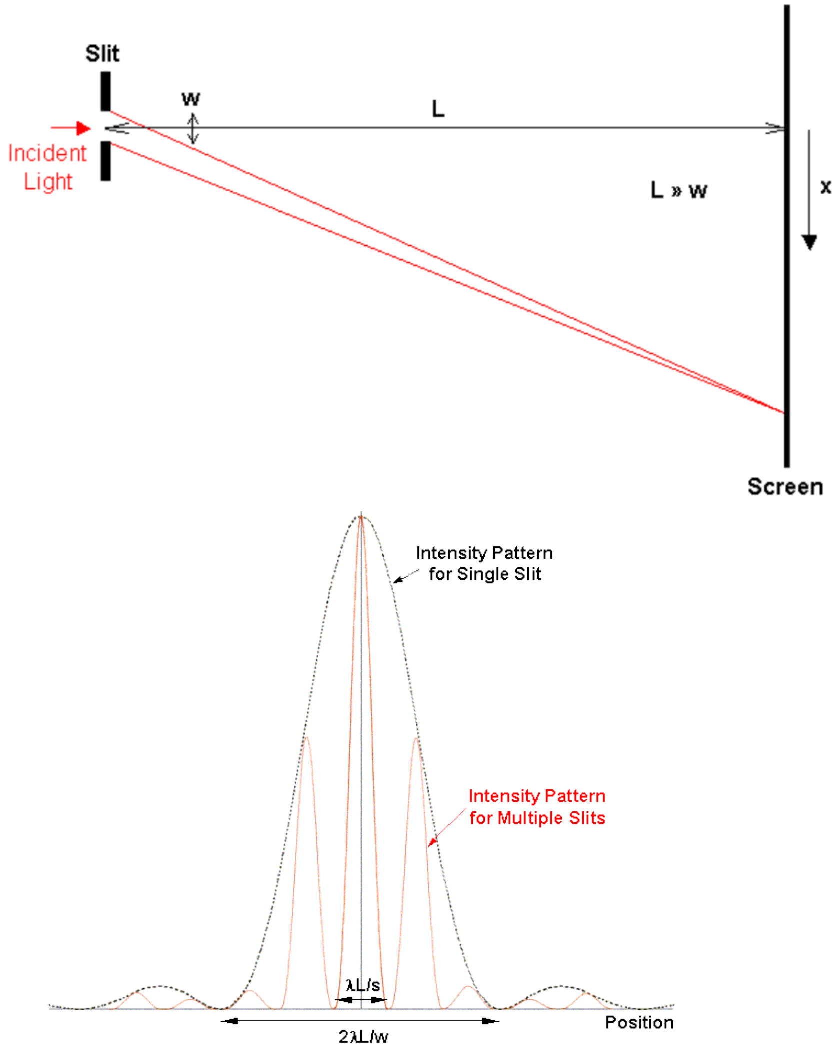
HARD diffraction!

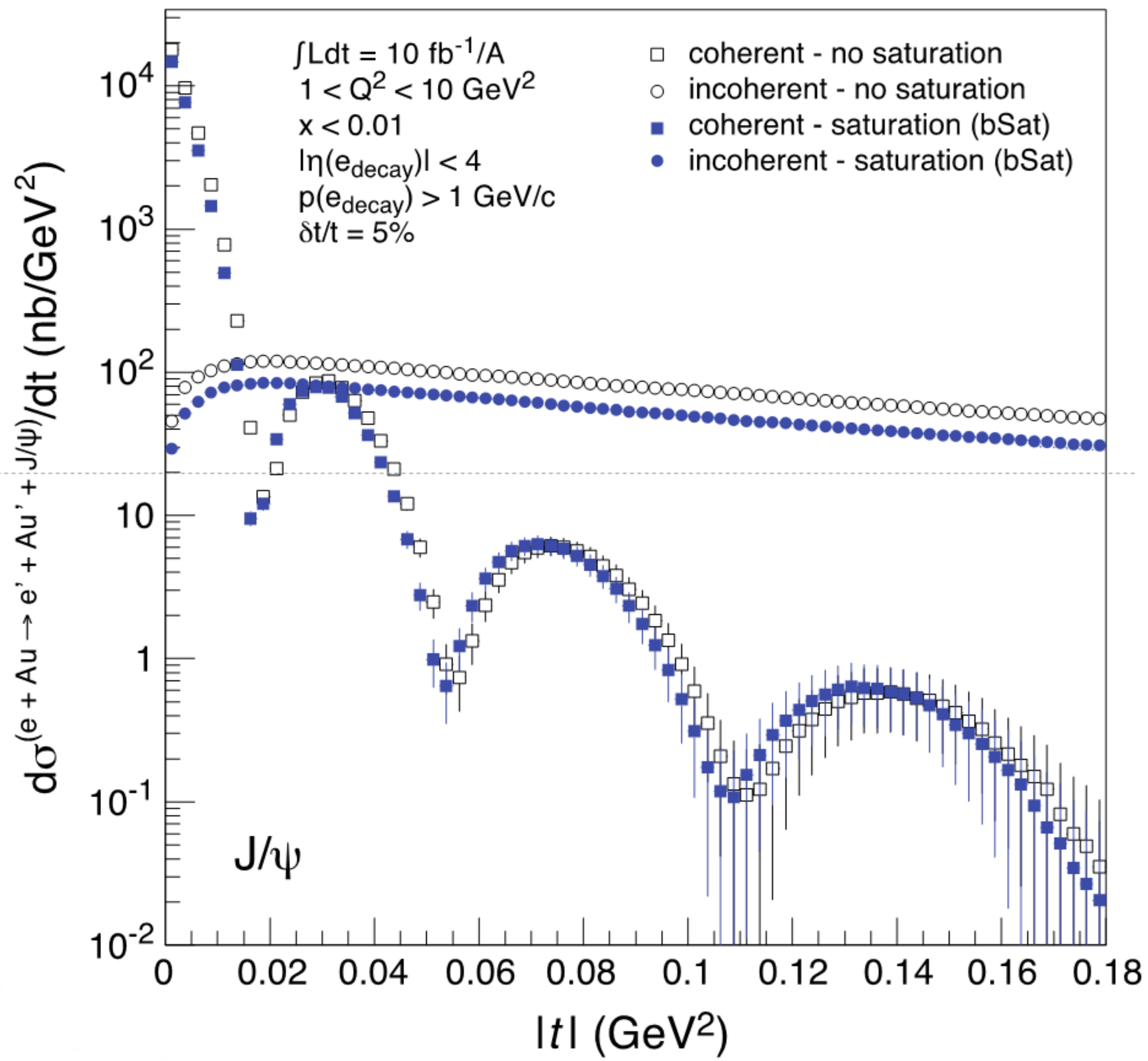



V. Sola, Moriond QCD 2010

30 June 2007 at 11:23 pm, HERA was shut down; analyses still ongoing

# why diffraction?



https://indico.cern.ch/event/1199314/contributions/5240564/attachments/2621916/4534048/EIC.DIS2023.eca.pptx

# "HERA" physics is not dead…

## What is the EIC Facility

### What is the EIC:

A high luminosity ($10^{33} – 10^{34}$ $cm^{-2}s^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 28 – 140 GeV

### What is special:

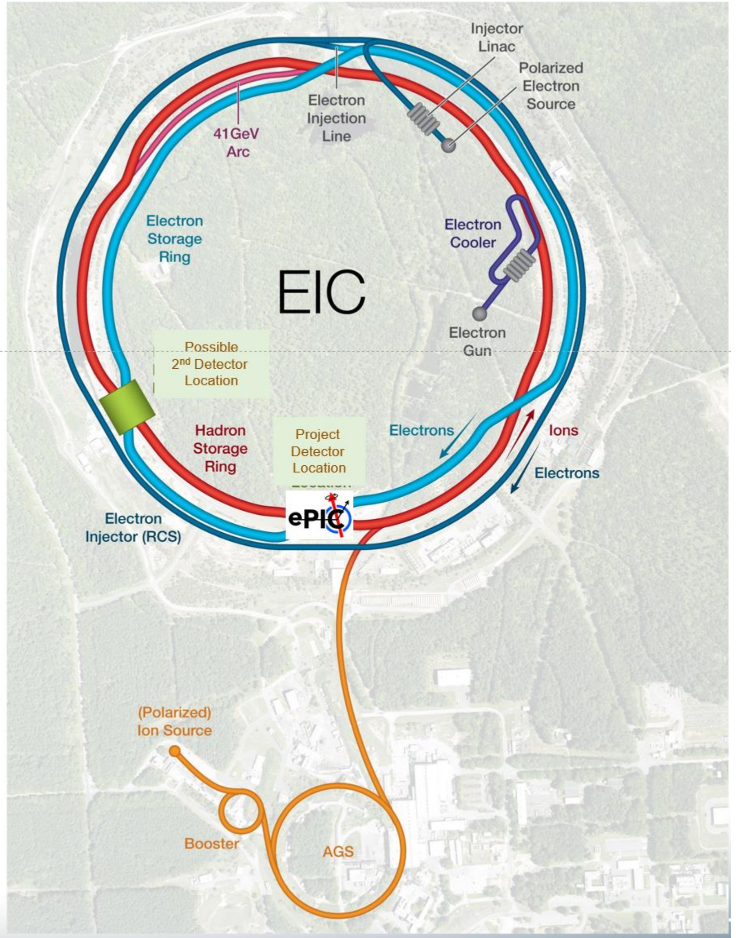
EIC is the ONLY world-wide new collider in foreseeable future. Allows to remain at frontier of Accelerator S&T.

factor 100 to 1000 higher luminosity as HERA
both electrons and protons / light nuclei polarized,
nuclear beams: d to U

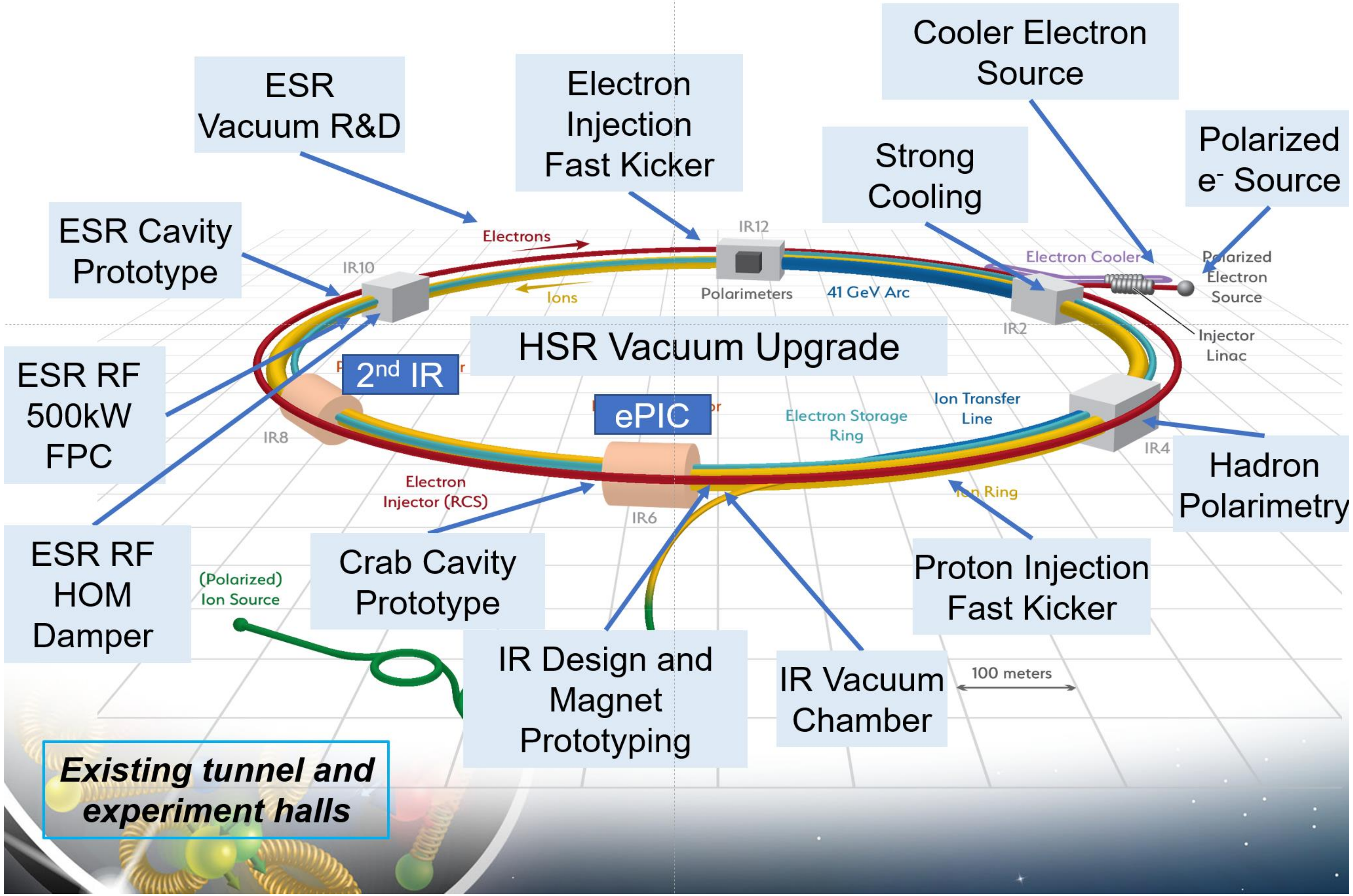
Fixed Target Facilities i.e.:
at minimum > 2 decades increase in kinematic coverage in x and $Q^2$

State of the art general purpose collider detector

Science Program: An EIC can uniquely address three profound questions about nucleons — neutrons and protons — and how they are assembled to form the nuclei of atoms:



# Accelerator Science and Technology – Ongoing EIC R&D

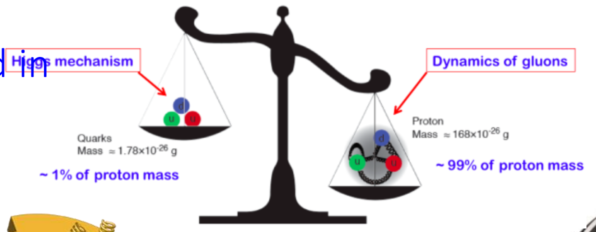


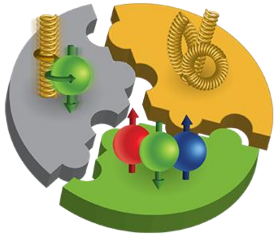

**start of building 2025**

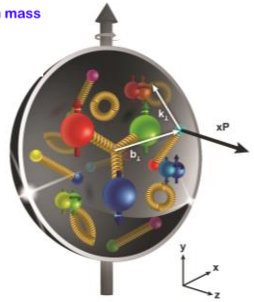
# The EIC Physics

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?





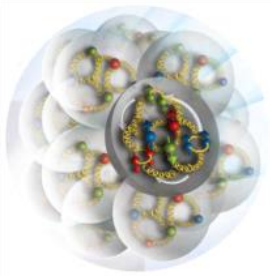
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

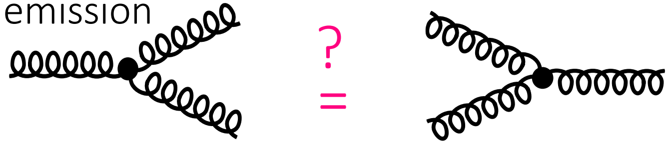
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

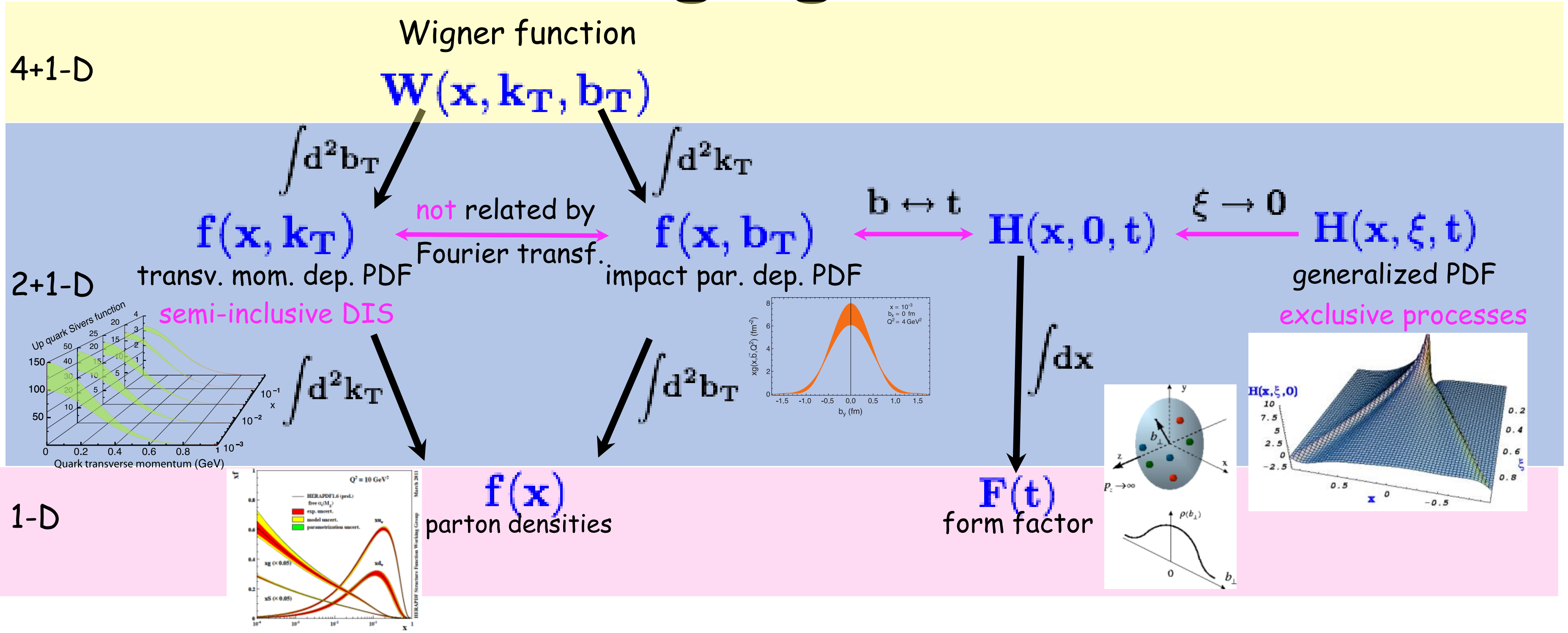
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?





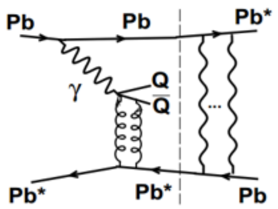
# EIC: The Path to Imaging Quarks and Gluons



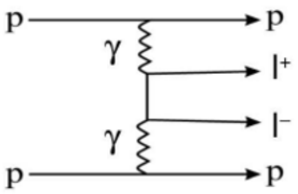

There are many reasons why one wants to have a 3d picture of nucleons and nuclei collective effects are one of them.

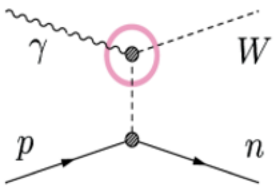
Obtaining a full picture is definitely an other one back to slide 7

- elastic and diffractive collisions
  - central exclusive production [l.i.t.] (heavy particles & resonances) pp → p ⊕ X ⊕ p where X stands for a fully measured system like jet-jet, $l^+l^-$, γγ, H, $W^+W^-$, … and '⊕' represents Large Rap-Gap (Δη ≥ 4)
  - low-x QCD
    structure functions, factorization violation, parton saturation, non-linear QCD evolution, small-x PDFs, multi-parton scattering
  - models of hadron interactions for high energies – cosmic showers, measurement of dE/dη, dN/dη for p-p, p-A and A-A interactions, ultra peripheral collisions




- electroweak interactions
  anomalous coupling constants



Oldrich Kepka

- Photon-induced measurements in proton-proton at $\sqrt{s} = 13$ TeV
  - $\gamma\gamma \to W^+W^-$ [ATLAS-CONF-2020-038]: **Observation** of photon-induced diboson production, complete Run 2 dataset
  - $\gamma\gamma \to \ell^+\ell^-$ [ATLAS-CONF-2020-041]: Measurement of **forward proton scattering** in association with lepton pairs

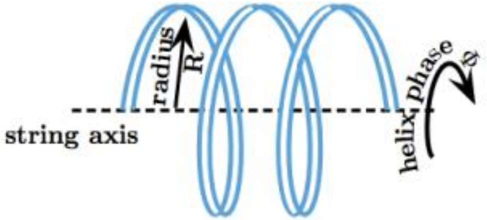
- Photon-induced measurements in ultra-peripheral lead-lead $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
  - $\gamma\gamma \to \mu^+\mu^-$ [CERN-EP-2020-138]: **Differential measurement** of exclusive dimuon production with **forward neutron** information
  - $\gamma\gamma \to \gamma\gamma$ [arXiv:2008.05355]: **Differential measurement** of light-by-light scattering and **search for axion-like particles**, complete Run 2 dataset

## hadronization

[is there anything(!) looking exciting? (at ATLAS)] idea

the correlation between like-sign (LS) hadrons is consequence of coherent hadron emission
linked to attempt to understand the shape of a QCD string in 3d and stabilization of the end of the parton shower cascade: B. Andersson, G. Gustafson, J. Hakkinen, M. Ringner and P. Sutton, "Is there screwiness at the end of the QCD cascades?" JHEP 09 (1998), p. 014

it was deduced, on the basis of optimal packing of non-collinear gluon emissions, that the shape of the QCD string should be, at the end, helix-like




one dimensional string -> 3d string & quantum tunneling -> gluon splitting to quark-antiquark pair

**fragmentation generates intrinsic transverse momentum** that depends on the folding of the string and **implies azimuthal correlations between hadrons**

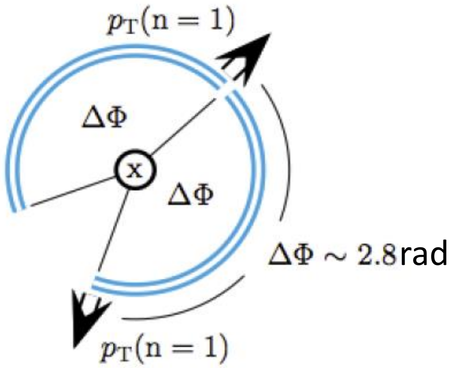
azimuthal correlations compatible with the helical shape of the QCD string have been observed by ATLAS Phys. Rev. D 86, 052005, 2012

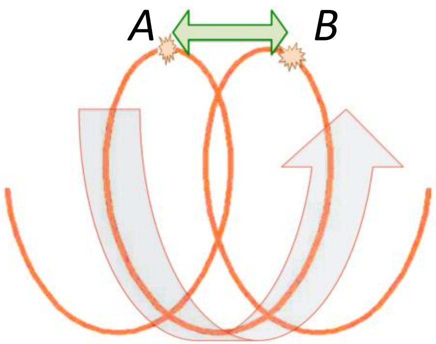
the helix model was refined in Š. Todorova-Nová, "Quantization of the QCD string with a helical structure", Phys.Rev. D89902 (2014) 015002 & "Baryon production in the quantized fragmentation of helical QCD string", Phys.Rev. D104 (2021) 034012

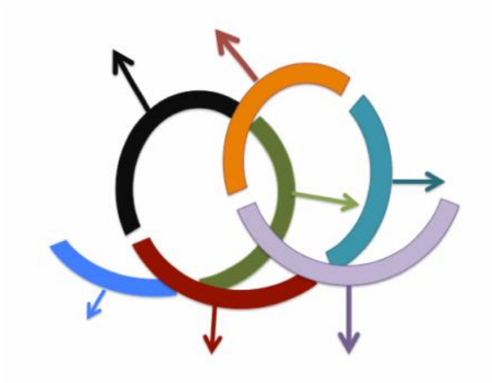
# string fragmentation

Phys. Rev. D 89 (2014), p. 015002

3d fragmentation model enables cross talk between break-up vertices; causal constraints imposed on the fragmentation, the mass spectrum of light mesons is reproduced, if string breaks in **regular multiple of ΔΦ** intervals



a fit of mass spectrum **predicts** rather narrow radius of the helix, $\kappa R$ = 68±2 MeV, where $\kappa$ ~ 1 GeV/fm is the string tension, and ΔΦ = 2.82±0.06 rad, i.e. almost back-to-back

$$m^{AB} = \kappa R \sqrt{(\Phi^B - \Phi^A)^2 - \left(2\sin\frac{\Phi^B - \Phi^A}{2}\right)^2}$$

$$= \kappa R \sqrt{(n\Delta\Phi)^2 - \left(2\sin\frac{n\Delta\Phi}{2}\right)^2}$$

| $\kappa\xi$ [MeV] | $\kappa$ R [MeV] | ΔΦ |
|---|---|---|
| 192.5 ± 0.5 | 68 ± 2 | 2.82 ± 0.06 |
| Meson | PDG mass [MeV] | Model estimate [MeV] |
| $\pi$ | 135–140 | 137 |
| $\eta$ | 548 | 565 |
| $\eta'$ | 958 | 958 |

for the definition od kinematics variables – see backup

# rank and anomalous production of LS pairs

$$Q(p_i, p_j) = \sqrt{-(p_i - p_j)^2} = 2p_{\mathrm{T}} \left| \sin \frac{r\Delta\Phi}{2} \right|$$

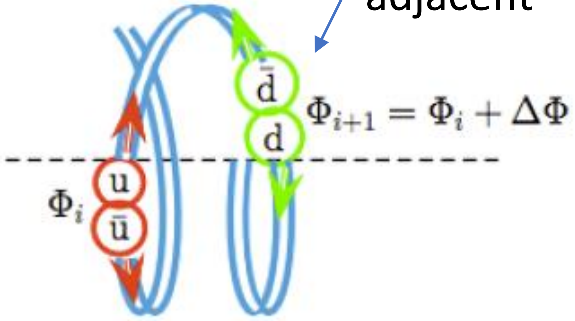
where $p_i, p_j$ are 4-momenta of particles in the considered pair

rank variable $r$ characterizes the relation, due to ordering within the helix, between products

| Pair rank difference $r$ | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $Q$ expected [MeV] | 266 ± 8 | 91 ± 3 | 236 ± 7 | 171 ± 5 | 178 ± 5 |

calculated in the limit of locally homogeneous string field

adjacent




local charge conservation -> production of pairs of pions with

LS charge for $r$ = 2, 4, ...

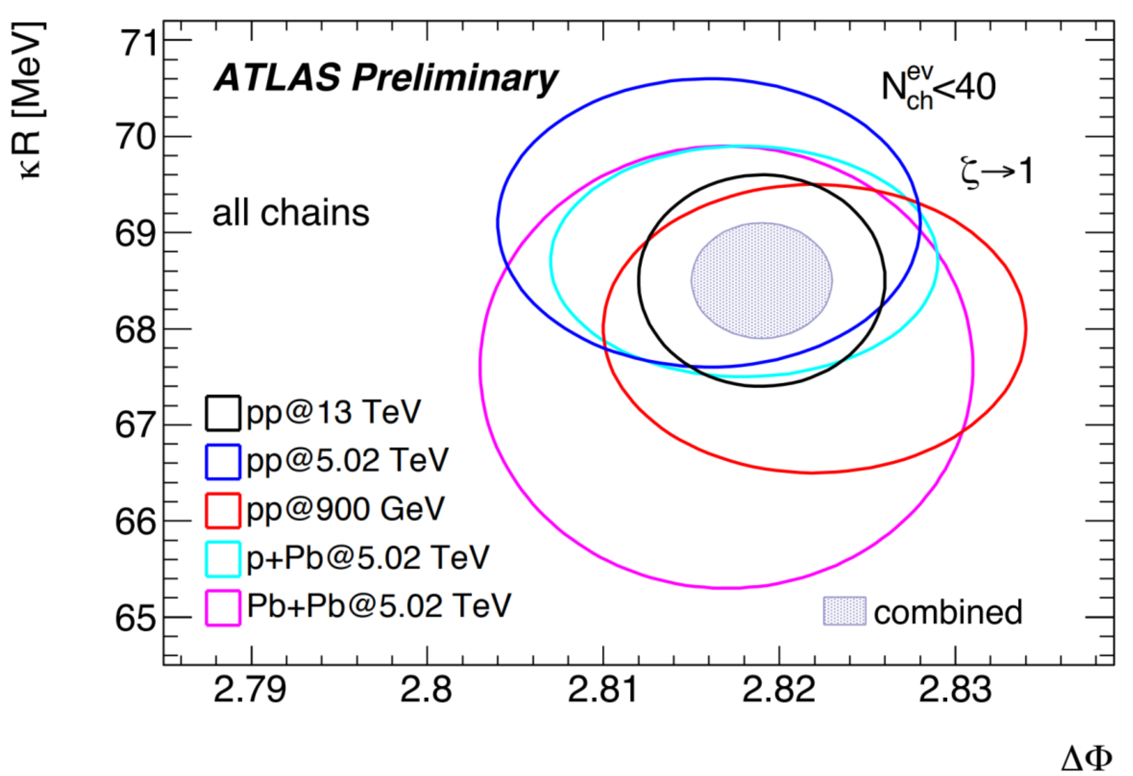
and

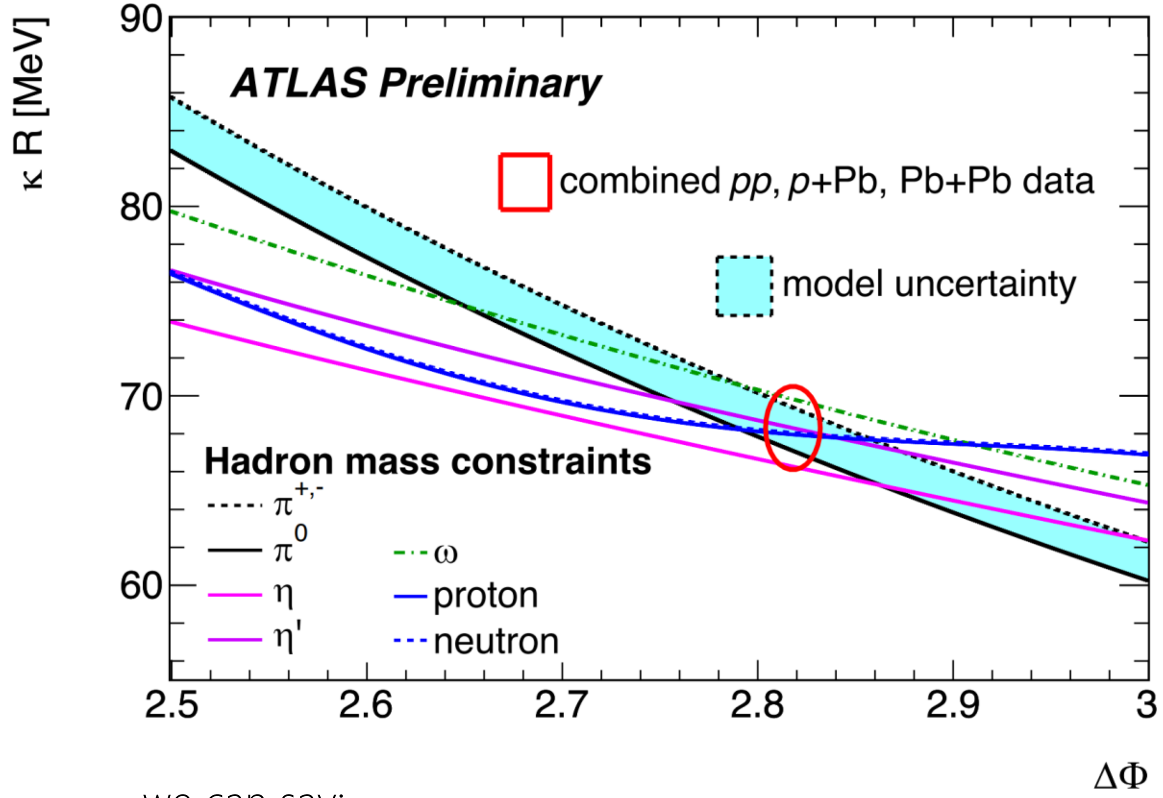
OS for $r$ = 1, 3, ...

region Q < 100 MeV is occupied by pairs with $r$ = 2 -> production of LS pairs – it is the prediction of the model

# quantized string parameters from pp, p+Pb and Pb+Pb data

ATLAS-CONF-2022-055




a good agreement between pp data at various collision energies

an excellent agreement between p-p and HI data

we can say:

- quantized fragmentation capable to explain ALL data previously associated with Bose-Einstein interference
- anomalous production of close LS pions strongly suggests it is a hadronization effect

## observable sensitive to local evolution of fragmentation function
(for color-adjacent hadrons)

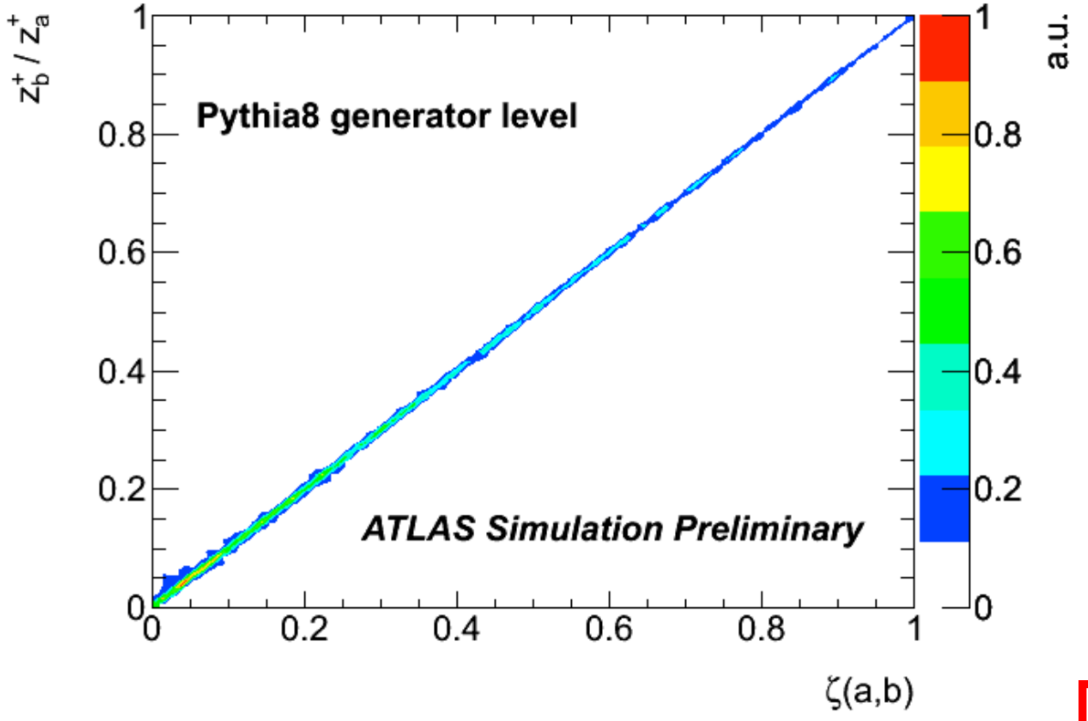
$z^+$, $z^-$ fractions of longitudinal partons of a hadron (*a* or *b*)

$$Q^2(p_a,p_b) = (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t,a}^2\left(\frac{z_b^+}{z_a^+} - 1\right) + m_{t,b}^2\left(\frac{z_a^+}{z_b^+} - 1\right)$$

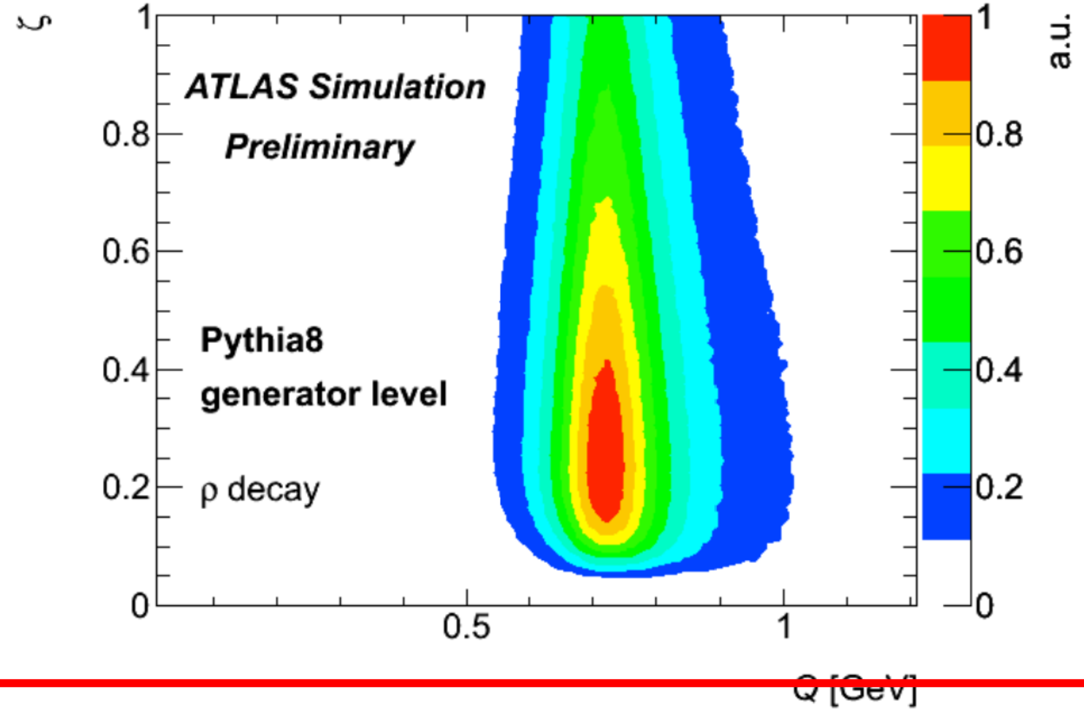
$$\sim (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t_a}^2(\zeta(p_a,p_b) - 1) + m_{t_b}^2(1/\zeta(p_a,p_b) - 1), \quad \text{for } |\vec{p}_a| > |\vec{p}_b|$$

$$p = (E,\vec{p}) = (0,\vec{p}_T) + z^+(|\vec{P}|,\vec{P}) + z^-(|\vec{P}|,-\vec{P})$$

$$\zeta(\vec{p}_i,\vec{p}_j) = min\left(\frac{|\vec{p}_j|}{|\vec{p}_i|}, \frac{|\vec{p}_i|}{|\vec{p}_j|}\right)$$



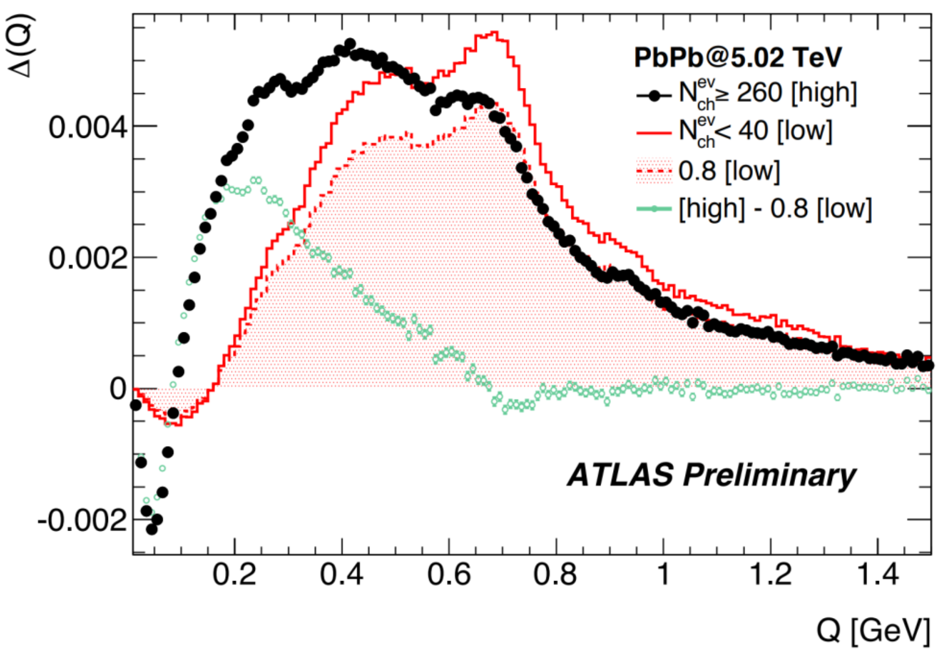

the "check" of how the approximations works

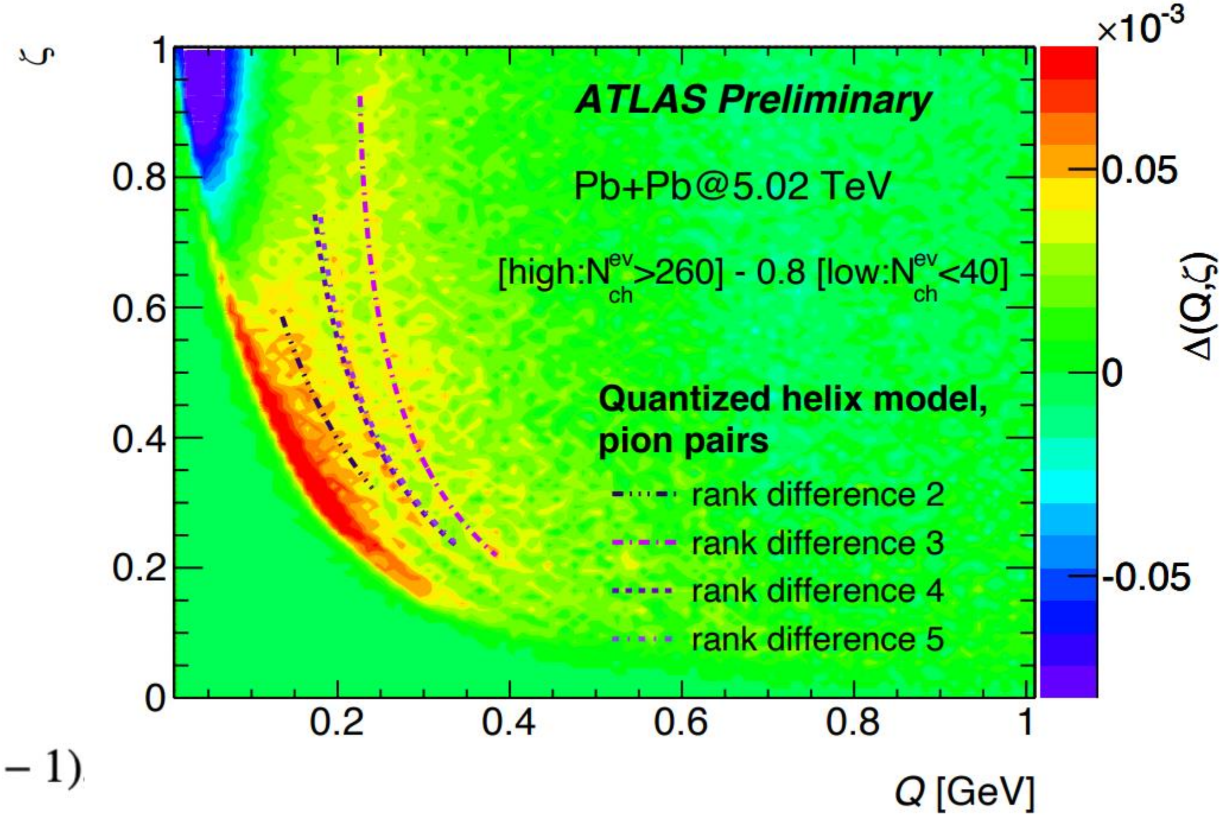



a way to distinguish between rank 0 and rank 1 contributions
isotropic decays (r = 0) independent from ζ and produce a vertical band

# quantized fragmentation, signature of long chains found in Pb+Pb – the first observation

ATLAS-CONF-2022-055




$$Q^2 \sim (\vec{p_{t_a}} - \vec{p_{t_b}})^2 + m_{t_a}^2(\zeta(p_a, p_b) - 1) + m_{t_b}^2(1/\zeta(p_a, p_b) - 1)$$

| Pair rank difference $r$ | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| $Q$ expected (MeV) | $266 \pm 8$ | $91 \pm 3$ | $236 \pm 7$ | $171 \pm 5$ | $178 \pm 5$ |

the observation of long pion chains demonstrates the predictive power of the model and validates the whole framework

## instantons

[is there anything(!) looking exciting? (at ATLAS, LHC, …)]

Radek Vavřička (Matthias Schott; seminar: light through wall…)

**PSEUDOPARTICLE SOLUTIONS OF THE YANG-MILLS EQUATIONS**

A.A. BELAVIN, A.M. POLYAKOV, A.S. SCHWARTZ and Yu.S. TYUPKIN
*Landau Institute for Theoretical Physics, Academy of Sciences, Moscow, USSR*

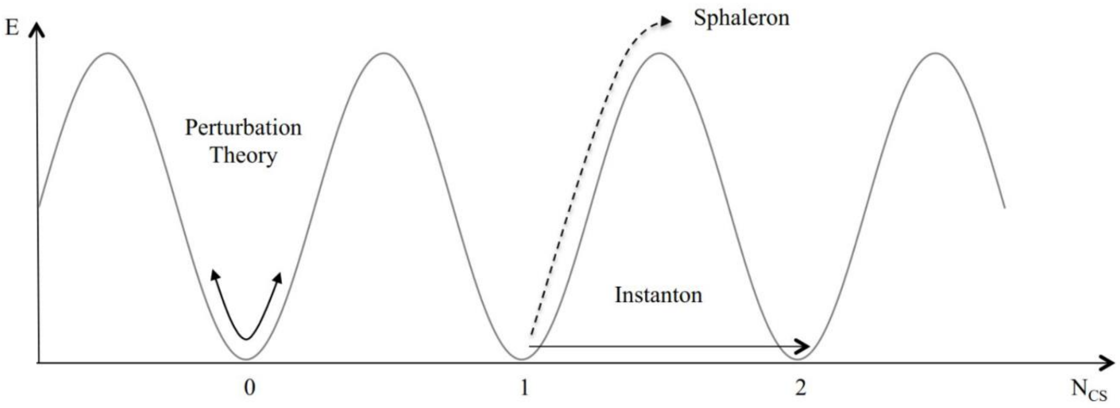
Received 19 August 1975

**Symmetry Breaking through Bell-Jackiw Anomalies***

G. 't Hooft†
*Department of Physics, Harvard University, Cambridge, Massachusetts 02138*
(Received 22 March 1976)

**Instantons:** semiclassical (small ħ) solutions of the Yang-Mills equations that correspond to tunnelling between topologically-distinct vacuum sectors

'Instant' + 'on' ~ *event-like* + *soliton-like*

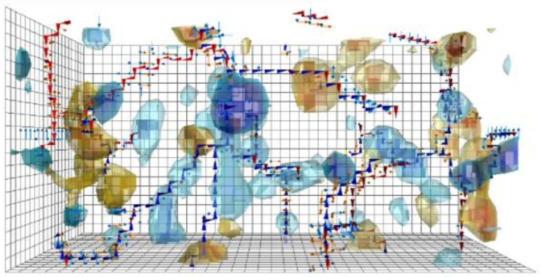



The QCD vacuum is a superposition of topologically-distinct sectors

— Jackiw and Rebbi [PRL 37, 172], Callan, Dashen and Gross [PLB 59, 334]

**IOP** Ynyr Harris — 5 Apr 2023

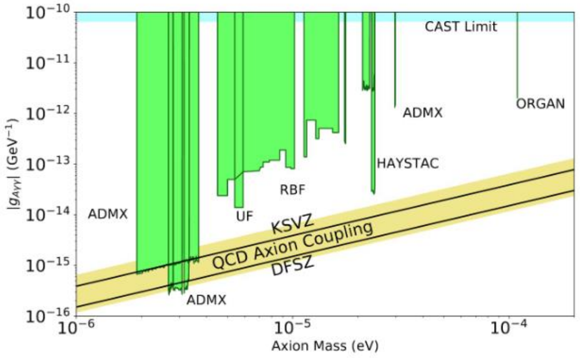
## Hadronic Structure



Ubiquitous in Lattice QCD!

[Shuryak (2021), Leinweber]

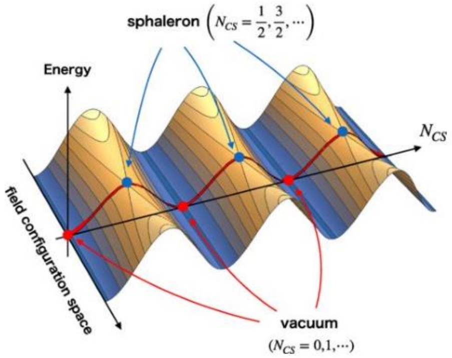
## Axions?




θ-vacuum structure…

[Peccei and Quinn, PDG]

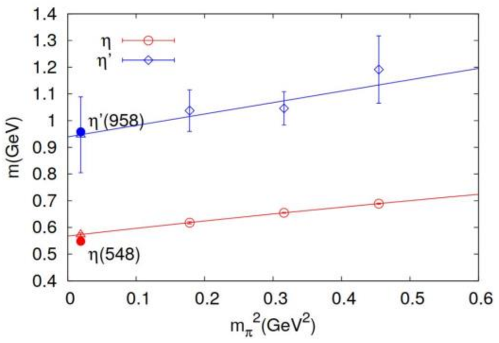
## Sphalerons?




Baryon Asymmetry of Universe…

[Hamada and Kikuchi]

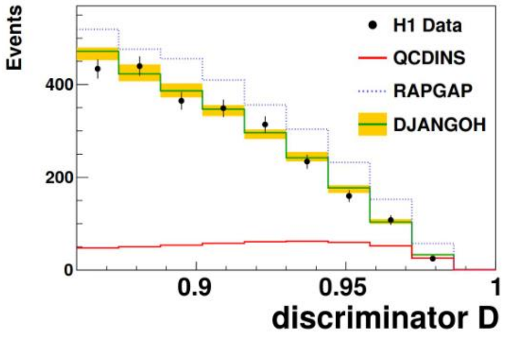
## Solution to the 'U(1) problem'




The η' meson is too heavy!

['t Hooft, RBC & UKQCD, PDG]

## HERA-era direct searches

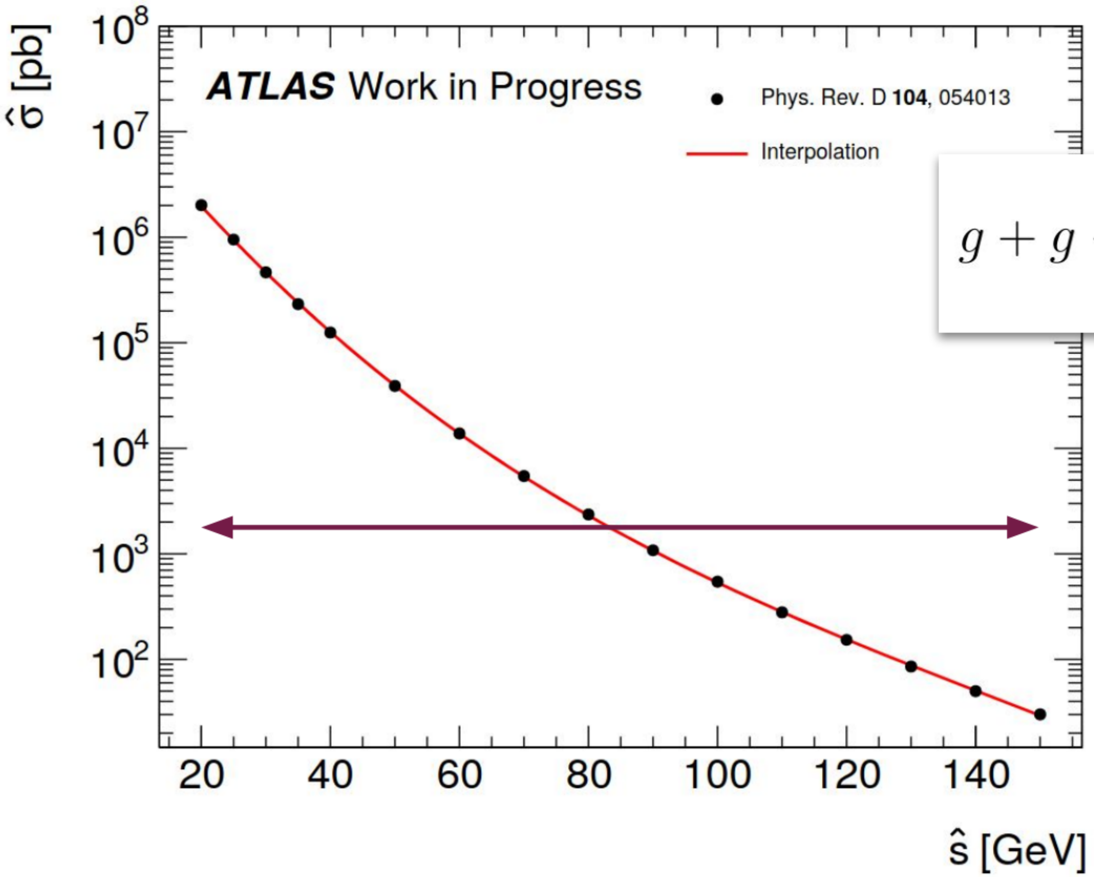



Inconclusive?

[H1, Achim Geiser]...

## For phenomenology, do perturbation theory in the instanton background

[Khoze *et al.* 2] + [Khoze *et al.* 1, Khoze *et al.* 3, Amoroso *et al.*]

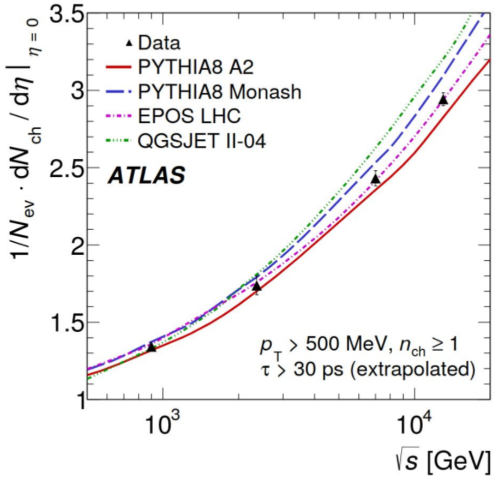


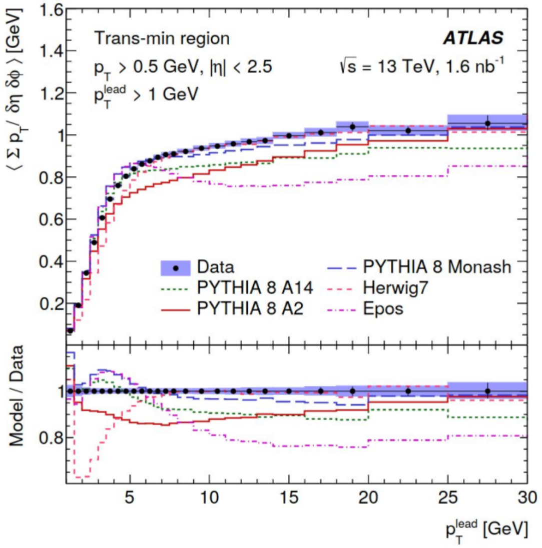

$$g + g \rightarrow n_g \times g + \sum_{f=1}^{N_f} (q_{Rf} + \bar{q}_{Lf})$$

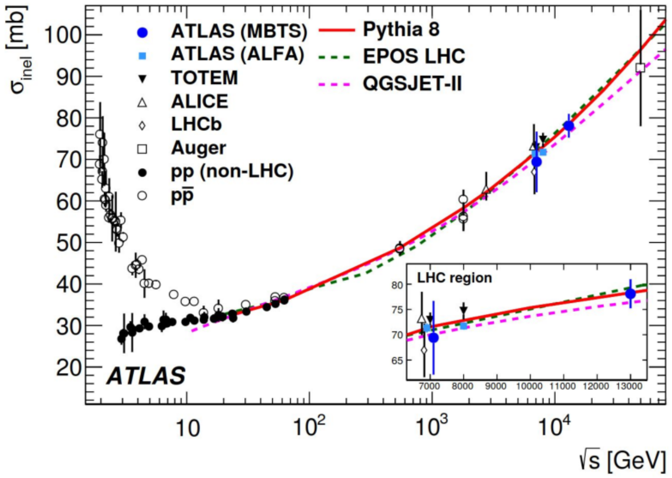
### Instanton event / decay properties

- Isotropic, non-resonant
- Constrained heavy flavour content
- Chirality violation
- *O*(100) theory systematics on cross-section normalisation
- Shape of cross-section is good

**This low-energy, non-perturbative subject-matter makes this an analysis of the Soft QCD group**




### Minimum Bias (MB)

13 TeV, tracks-based: 1602.01633

13 TeV, low-pT tracks-based: 1606.01133

≤ 7 TeV, tracks-based: 1012.5104, etc.

### Underlying Event (UE)

13 TeV, tracks-based: 1701.05390

13 TeV in Z-events: 1905.09752

7 TeV with jets: 1406.0392, etc.

### Total Inelastic *pp* Cross-Section

13 TeV: 1606.02625

7 TeV: 1104.0326, etc.

**Insights into low energy strong interactions**

Inputs to MC Event Generator tuning • Understanding for pile-up modelling

**Measurements performed in special LHC runs from 2015**

Ultra low pile-up values of μ ~ 0.03 • Minimum Bias triggers • Charged-particle tracking down to 100 MeV

**Borrow ideas!**

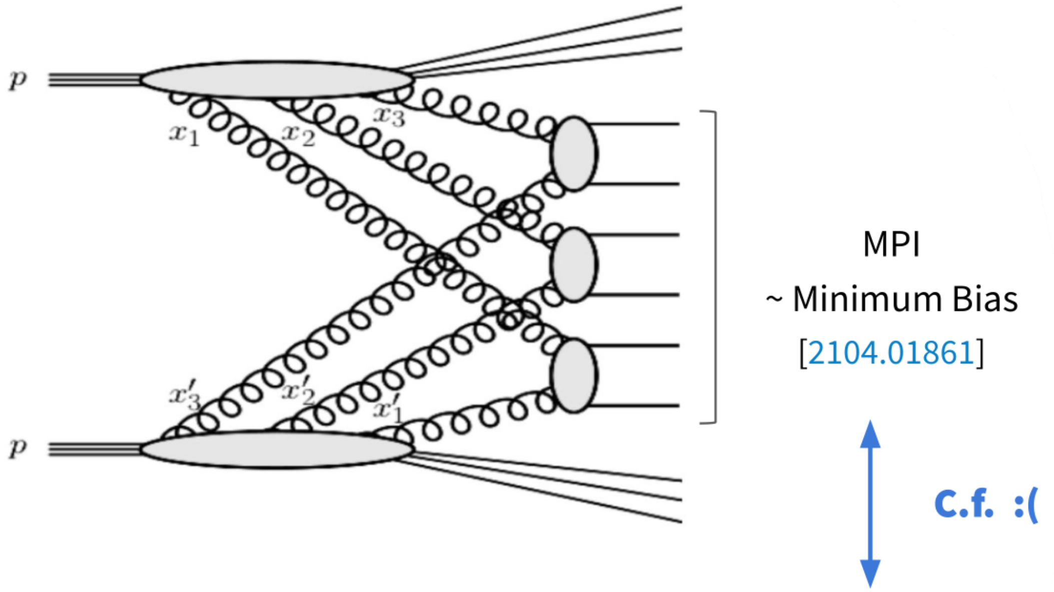
## Background: Soft QCD, σ ~ 111 mb

### Nominal model: EPOS LHC

Parton-based Gribov Regge theory with collective hadronisation [1306.0121]

### Alternative model: Pythia 8

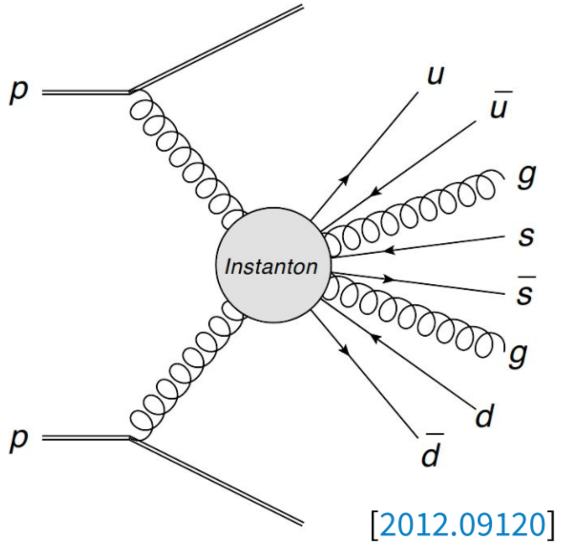
2 → 2 scatters with MPI based on the Sj\"ostrand–van Zijl model [PRD], Lund-string fragmentation




## Signal: gluon-induced instanton events, σ ~ 26 μb

### Model: SHERPA v3.0.0alpha1+ [`108e85a9 (master)`]

Final state assembled from an input table of cross-section values • RAMBO* phase-space generation [CPC 40 (1986) 369] • Cluster fragmentation [0311085] • Custom tuning of the Underlying Event




*RAndom Momenta Beautifully Organised

## to make measurement real – teams, students detectors

AFP Time-of-Flight Jakub Bucko

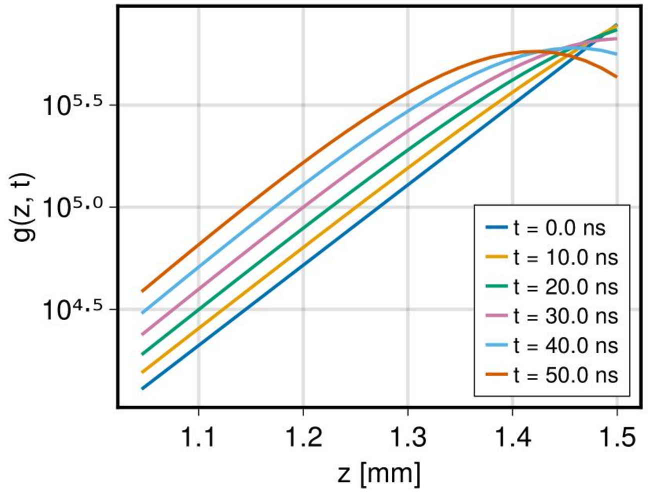



Figure 3. Time and space evolution of gain. Calculation was done using model from [3]. Constant current pulse with width of 50 ns was used as input signal. MCP-PMT modeled here is different from the one used for AFP. One can clearly see how the gain saturates due to wall charge depletion. This happens when current flowing through the wall can't replenish the electrons quickly enough.

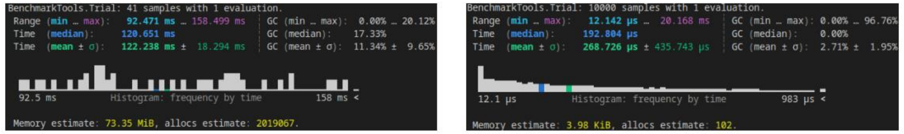


Figure 4. Comparison of performance. One can see that the PIC simulation (left) runs much slower. However, the PIC simulation simulates predefined time range, while the second simulation iterates over the electrons inside the channel. This means that the runtime of the PIC simulation should scale better with number of electrons.

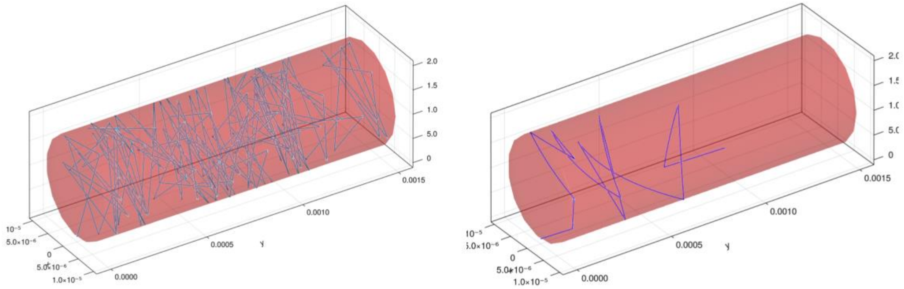


Figure 5. Comparison of paths of an electron inside a channel

Figure 6. Comparison of PIC Monte Carlo simulation (left) with simulation using parameterised paths (right). Propagation of a single electron was simulated.

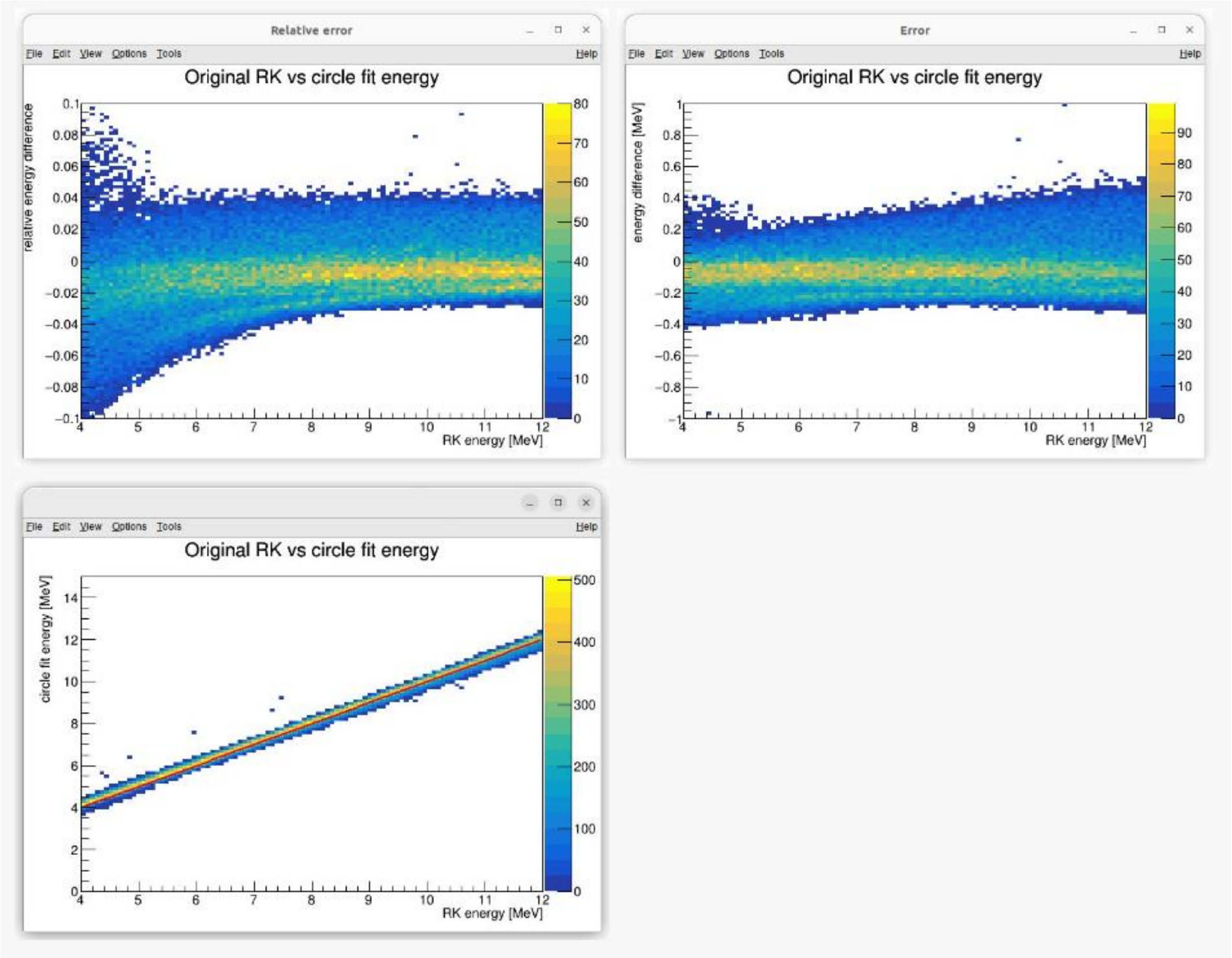
CERN Summer Studente Programme 2023

1) Easy Tracker - the tool for imaging charged particle trajectories in an accelerator and its further development
2) ATLAS Forward Proton Time-of-Flight subdetector – detector testbed studies
3) Searches for QCD instantons with forward proton tagging - feasibility study

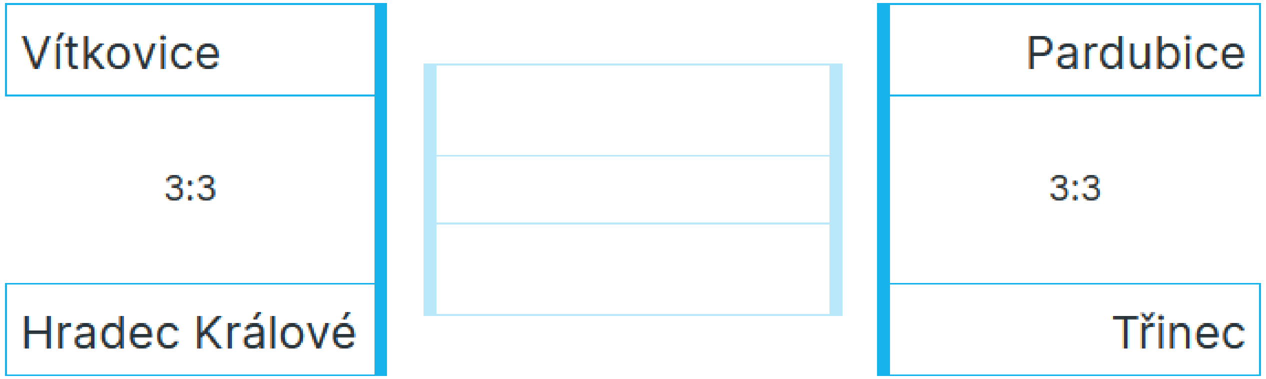
# to make measurement real – teams, students…

Martin Vavřík (Ferreira Natal Da Luz, Pedro Hugo)

X17 physics -> kTeV, g-2, instantons,…



what to take away?



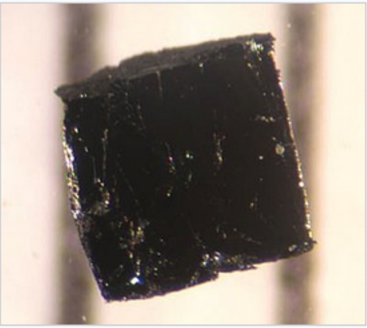

| | |
|---|---|
| Pardubice – Hradec Králové | 23 km |
| Třinec – Vítkovice | 43 km |
| | |
| Zlín – Vsetín | 33 km |

náhoda?

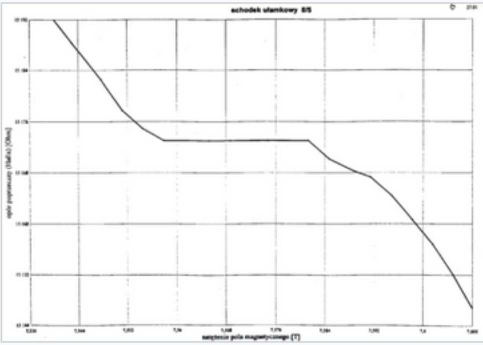
## Condensed matter physics [ edit ]

should we have a look at solid state physics…? (motivation)

- High-temperature superconductors: What is the mechanism that causes certain materials to exhibit superconductivity at temperatures much higher than around 25 kelvins? Is it possible to make a material that is a superconductor at room temperature and atmospheric pressure?[45]
- Amorphous solids: What is the nature of the glass transition between a fluid or regular solid and a glassy phase? What are the physical processes giving rise to the general properties of glasses and the glass transition?[71][72]
- Cryogenic electron emission: Why does the electron emission in the absence of light increase as the temperature of a photomultiplier is decreased?[73][74]
- Sonoluminescence: What causes the emission of short bursts of light from imploding bubbles in a liquid when excited by sound?[75][76]
- Topological order: Is topological order stable at non-zero temperature? Equivalently, is it possible to have three-dimensional self-correcting quantum memory?[77]
- Fractional Hall effect: What mechanism explains the existence of the $u = 5/2$ state in the fractional quantum Hall effect? Does it describe quasiparticles with non-Abelian fractional statistics?[78]
- Liquid crystals: Can the nematic to smectic (A) phase transition in liquid crystal states be characterized as a universal phase transition?[79][80]
- Semiconductor nanocrystals: What is the cause of the nonparabolicity of the energy-size dependence for the lowest optical absorption transition of quantum dots?[81]
- Metal whiskering: In electrical devices, some metallic surfaces may spontaneously grow fine metallic whiskers, which can lead to equipment failures. While compressive mechanical stress is known to encourage whisker formation, the growth mechanism has yet to be determined.
- Superfluid transition in helium-4: Explain the discrepancy between the experimental[82] and theoretical[83][84][85] determinations of the heat capacity critical exponent $\alpha$.[86]



A sample of a cuprate superconductor (specifically BSCCO). The mechanism for superconductivity of these materials is unknown.



Magnetoresistance in a $u = 8/5$ fractional quantum Hall state

higgs, …, non-abelian realization?