LTS1 - Workshop on the Long Term Strategy of INFN-CSN1
Isola d'Elba, May 21-24 2014

Working group "NP-QCD"

Convenors: Mauro Anselmino, Marta Ruspa, Luca Trentadue

Summary

Part I

Marta Ruspa
Università del Piemonte Orientale & INFN

Many thanks to

- Organizers
- Mauro and Luca
- All our speakers
- The 

community

Various topics

Parton distribution functions
Nucleon in 3D

Total cross section, elastic cross section
Link to cosmic ray physics
Underlying event & multi parton interactions
Diffraction

Hadron spectroscopy

Lattice, confinement

Not going to summarize each of them but
rather discuss future projects/implications

Various topics

Parton distribution functions
Nucleon in 3D

Total cross section, elastic cross section
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Underlying event & multi parton interactions
Diffraction

Hadron spectroscopy

A dedicated NP-QCD workshop?

Lattice, confinement

Not going to summarize each of them but rather discuss future projects/implications

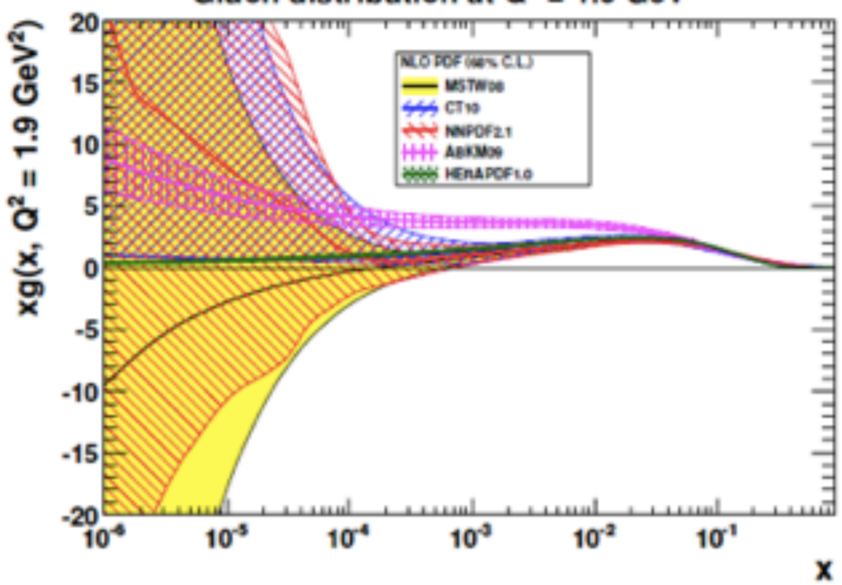
The gluon - much less known than we wish

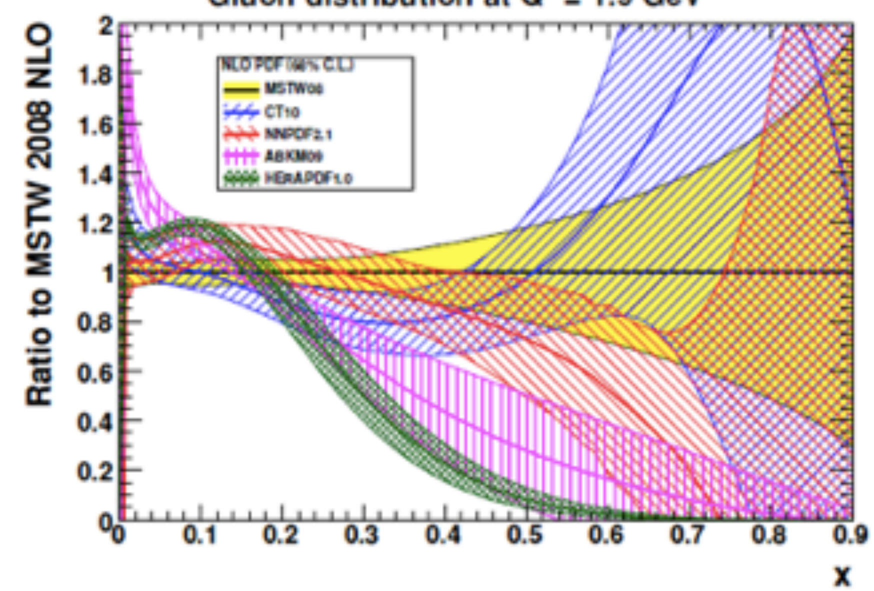
You may not realize that you will need it…

LOGARITHMIC Bjorken x SCALE

LINEAR Bjorken x SCALE

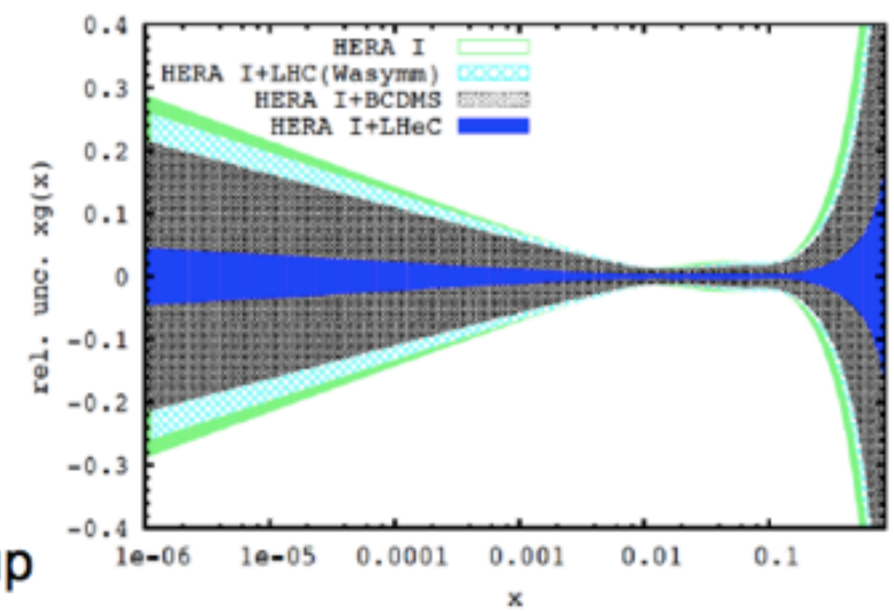
CURRENT

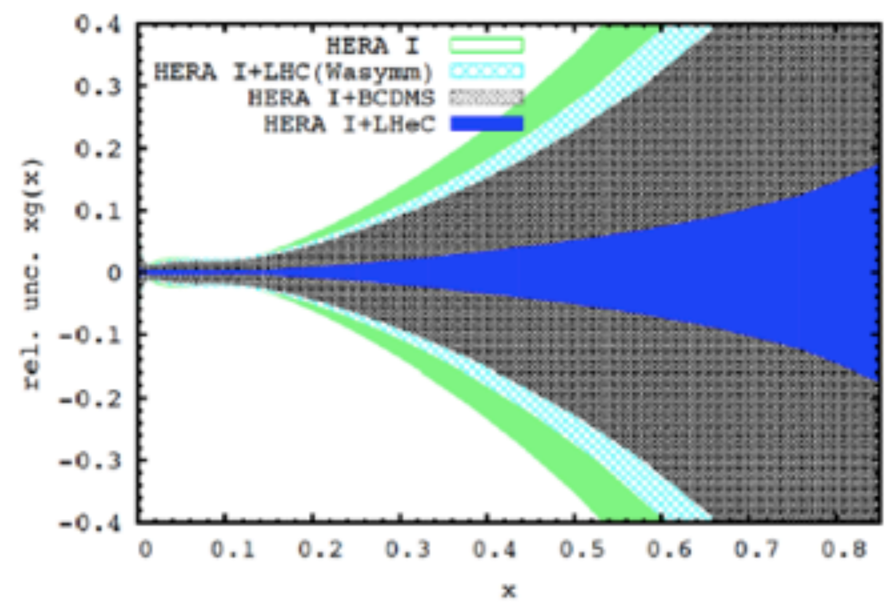




FUTURE

LHeC Study Group





Katarzyna Wichmann

The proton spin budget?

Since EMC (1988, the “spin crisis”)
we can’t yet explain the proton spin
in terms of its constituents

$$1/2 \stackrel{?}{=} 1/2\,\Delta\Sigma + \Delta g + L_q + L_g$$

Marco Radici

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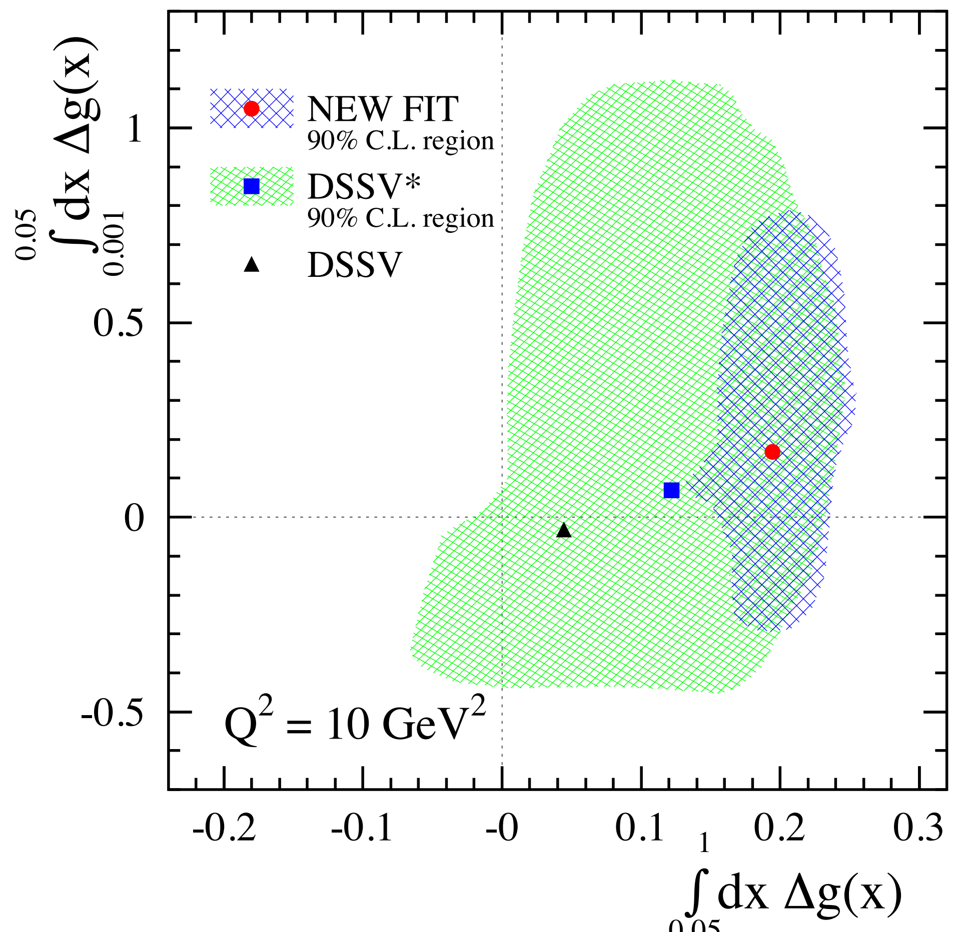
$$1/2 \stackrel{?}{=} 1/2\,\Delta\Sigma + \Delta g + L_q + L_g$$

De Florian, Sassot, Stratmann, Vogelsang (DSSV), arXiv:1404.4293

low x

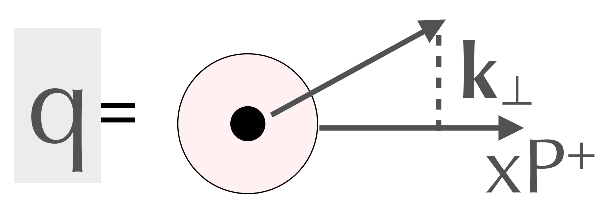


valence

We don't even know the gluon helicity
$-0.13 \lesssim \Delta g \lesssim 1$
at 90% c.l.

Quark orbital motion

$$1/2 = 1/2\,\Delta\Sigma + \Delta g + L_q + L_g$$



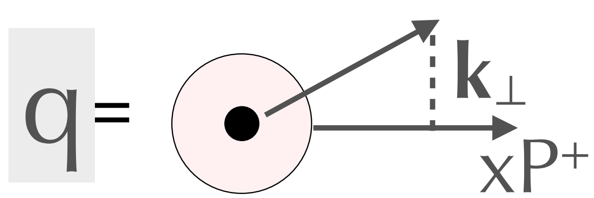
Marco Radici

Quark orbital motion

$$1/2 \stackrel{?}{=} 1/2\,\Delta\Sigma + \Delta g + L_q + L_g$$

~ 0.125 small ? ??

Need to know $\mathbf{k}_T$-dependent parton densities

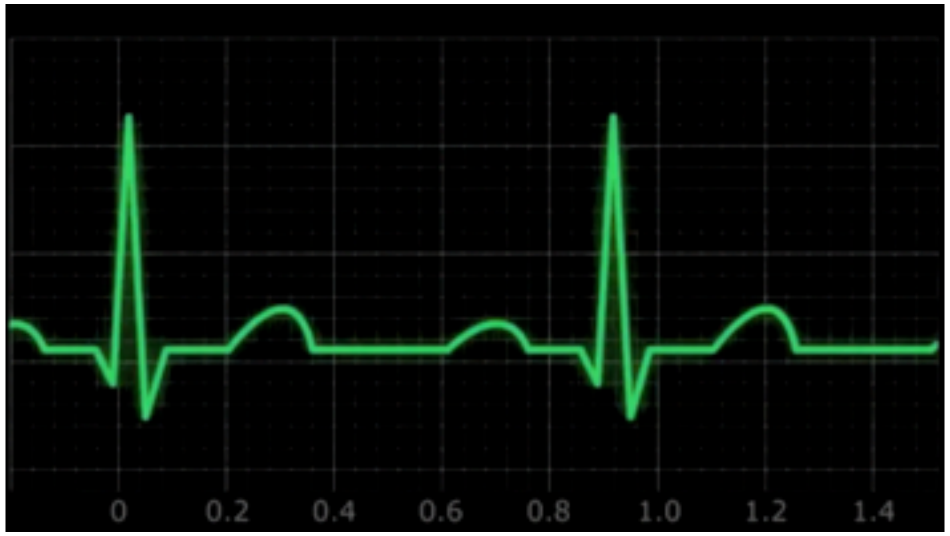


The 3D structure of the nucleon

The 3D structure of the nucleon

mono-dim. info
on heart activity

ECG



Marco Radici

The 3D structure of the nucleon

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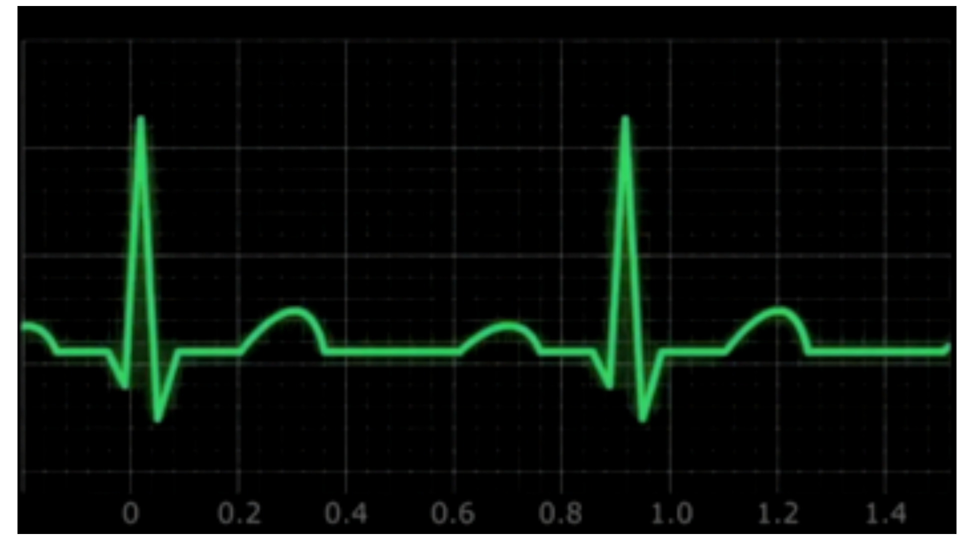
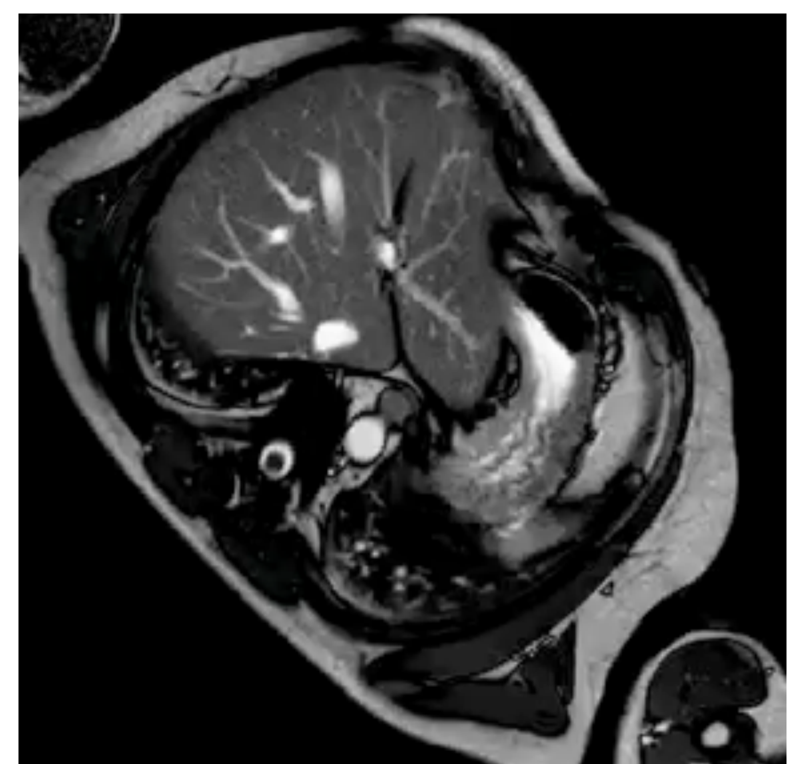


3-dim. tomography
of heart activity

cardio
MR

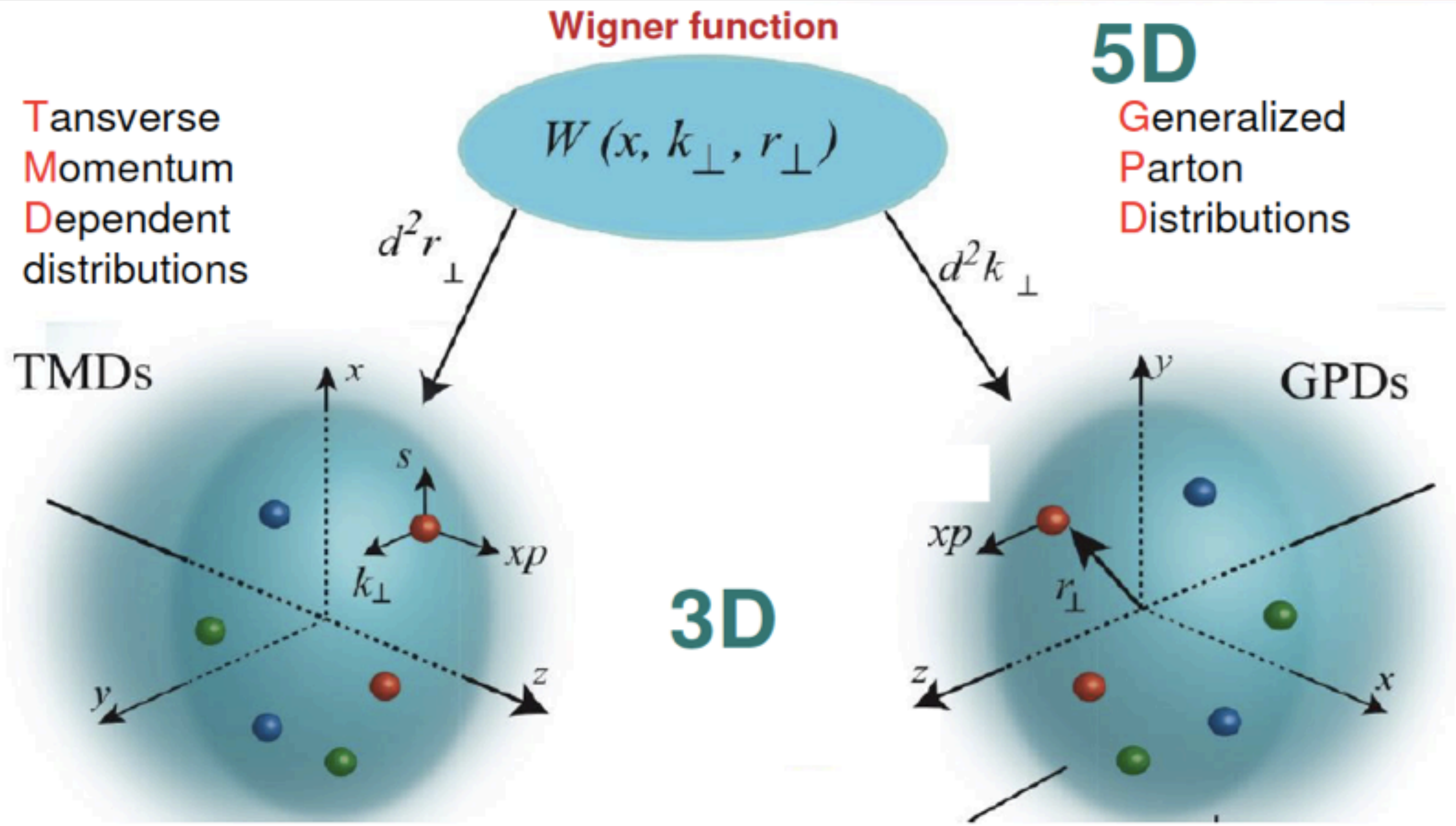


Marco Radici

COMPASS

INFN
Istituto Nazionale di Fisica Nucleare Sezione di Torino

Unified View of Nucleon Structure

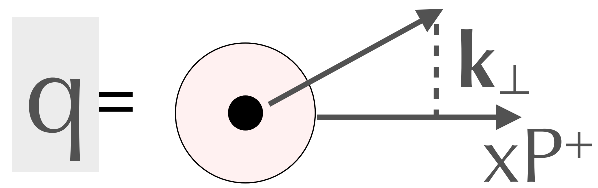


Jefferson Lab

Oleg Denisov

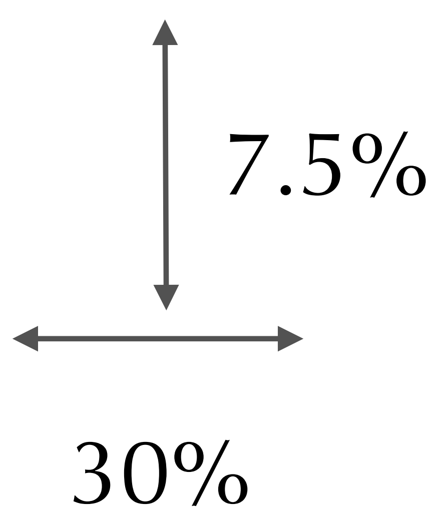
TMDs affect results also at high energy!

$q(x, \mathbf{k}_\perp) \to$ **LHC**

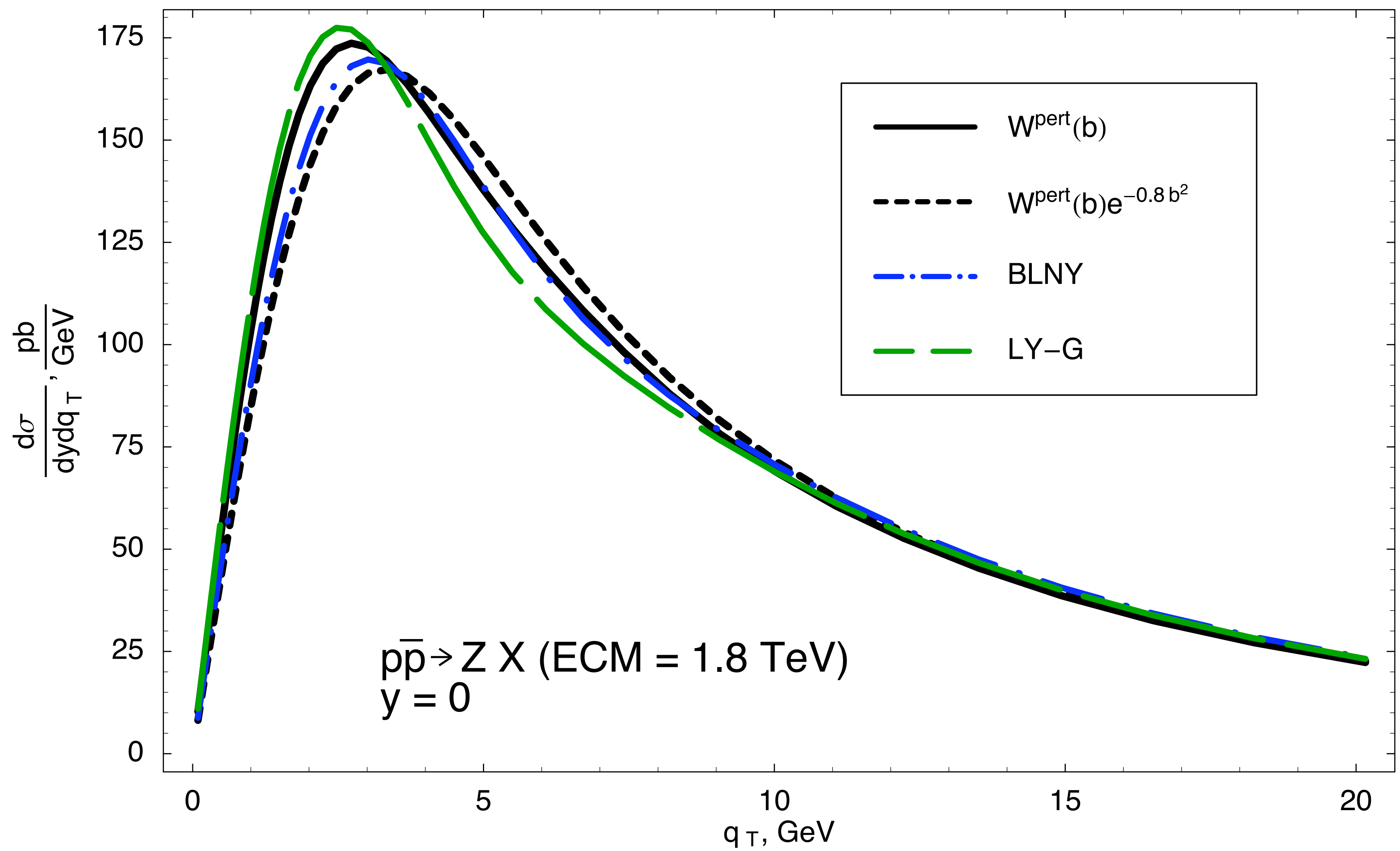


impact of TMD on Z^0 peak → W mass

P. Nadolski, hep-ph/0412146



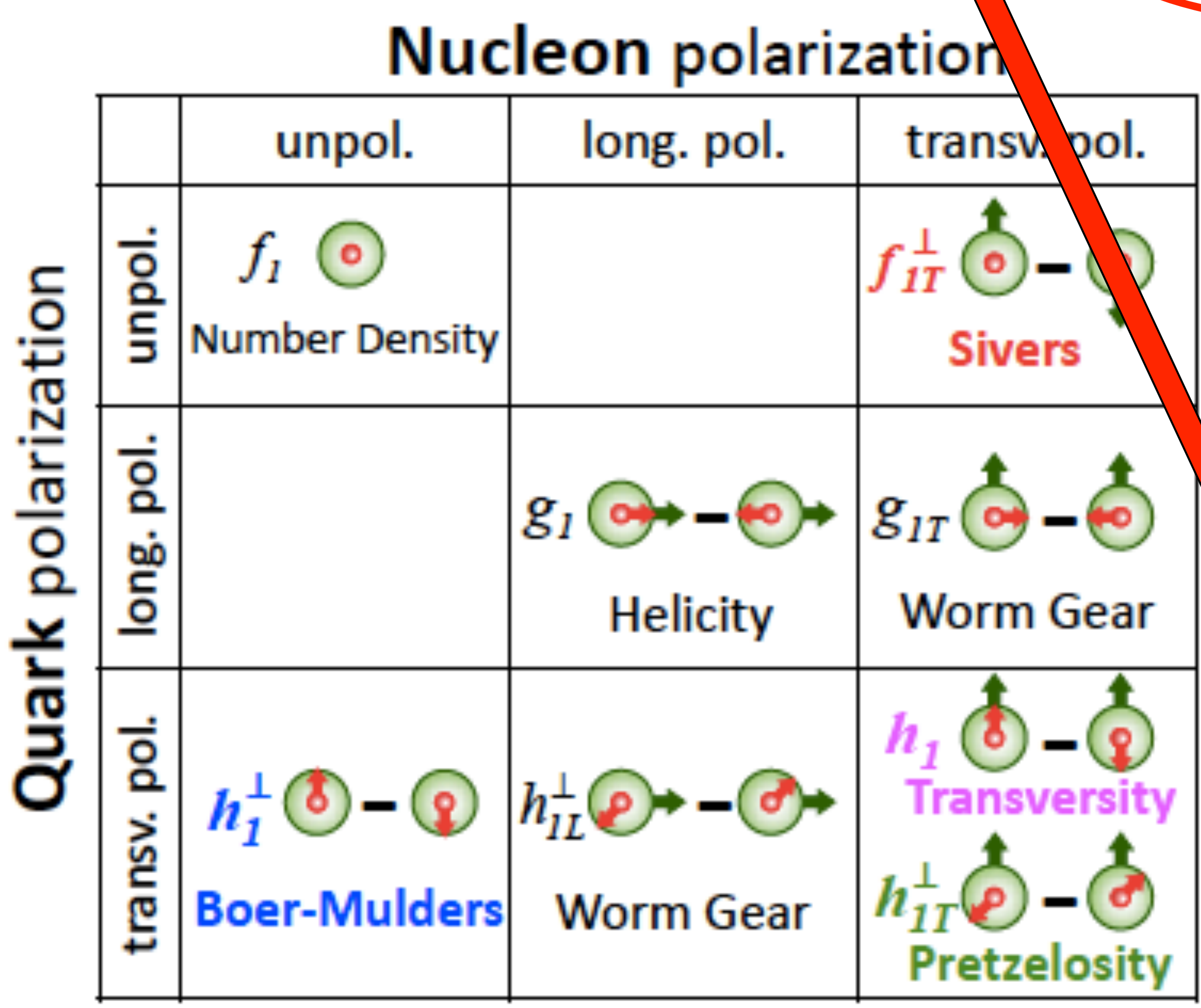
uncertainty



Leading order TMD PDFs

At leading order, three PDFs are needed to describe the nucleon in the collinear case.
If one admit a non-zero transverse quark momentum k_T in the nucleon five more PDFs (TMD PDFs) are needed.

Access to angular momentum



$f_{1T}^{\perp}(x,k_T^2)$ Sivers function
the correlation between the transverse spin of the nucleon and the transverse momentum of the quark.

$h_1^{\perp}(x,k_T^2)$ Boer-Mulders function
the correlation between the transverse spin and the transverse momentum of a quark in unpolarized nucleon.

$h_{1T}^{\perp}(x,k_T^2)$ Pretzelosity function
the polarization of a quark along its k_T direction, making accessible to the orbital angular momentum information.

Drell-Yan experiments 10 years running time

Fermilab E-906 (FNAL, USA): data taking will resume in September 2013 and will last for at least 1 year (experiment is approved for 2 years running period).

Polarised DY at Fermilab – hopefully in a few years from now

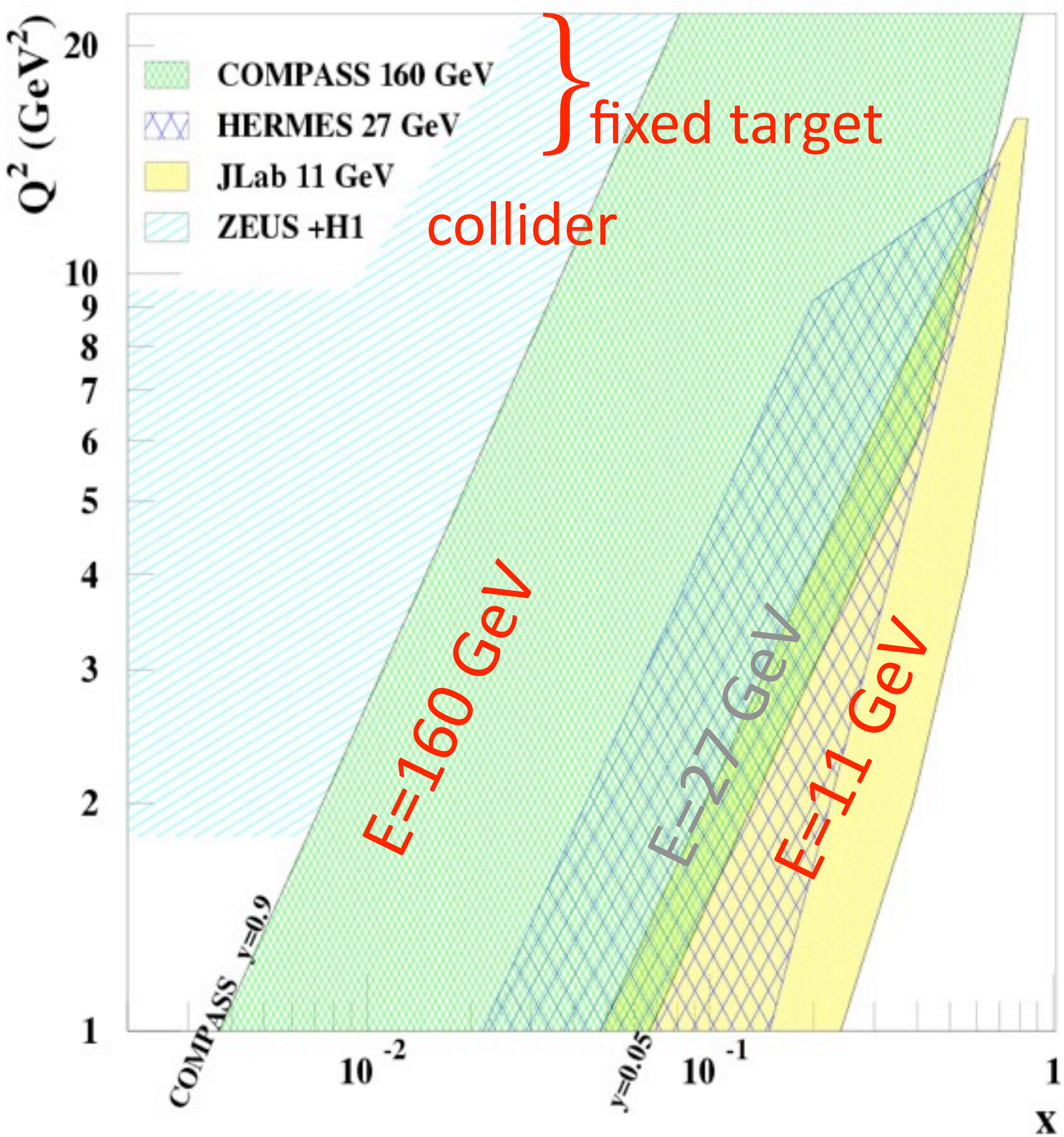
FIRT EVER POLARISED DRELL-YAN: COMPASS polarized Drell-Yan measurement will be started in the mid of October 2014, with a Pilot Run. Physics data taking will take place over the whole 2015.

STAR at RHIC (BNL, USA) > 2016

SPD at NICA Collider (JINR, Dubna, Russia) > 2020

Oleg Denisov
Andrea Bressan

Access to GPDs



COMPASS unique for GPDs

CERN High energy muon beam

- ✓ **100 - 190 GeV**
- ✓ **$\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ available**
- ✓ **80% Polarisation with opposite polarization**

- ✓ **4.6 10^{8} μ^{+}**
- ➔ **Lumi= 10^{32} cm^{-2} s^{-1} with 2.5m LH2 target**

- ➢ Explore the intermediate x_{Bj} region
- ➢ Uncovered region between ZEUS+H1 & HERMES **+ Jlab** before new colliders may be available

It's time to show the impact of COMPASS

=> goal of the 2012 DVCS pilot run

Near Compass future is more or less defined

- 2014-2015: Transversely polarized DY to check pseudo-universality
  $([f_{1T}^{\perp}(x,Q^2)]_{DY} \approx -[f_{1T}^{\perp}(x,Q^2)]_{SIDIS})$
- 2016-2017: Unpolarised DVCS/HVMP
  (B slope and GPD H)
  and unpolarised SIDIS on LH_2
  $dn^h/(dN^\mu dz\, dp_T^2)$ i.e. p_T dependent multiplicities, and $h_{1T}^{\perp}$ Boer-Mulders TMD PDF
- 2018 to be discussed having in hand the performances in the previous years

More in the future

	physics item	key aspects of the measurement
Hadron	glueballs	280 GeV beam, higher intensity, π, K and $\bar{p}$ separation
GPD	E	transversely polarized proton target
SIDIS	h_1^d with same accuracy as h_1^u $f_1^\perp$ evolution	transversely polarized deuteron target 100 GeV and transversely polarized proton target
DY	universality of TMD PDFs flavor separation test of the Lam-Tung relation EMC effect in DY	higher statistics with transversely polarized proton target transversely polarized deuteron target hydrogen target different nuclear targets

For the next 10 years

- **before any collider is available,**
- **and complementary to Jlab 12 GeV**

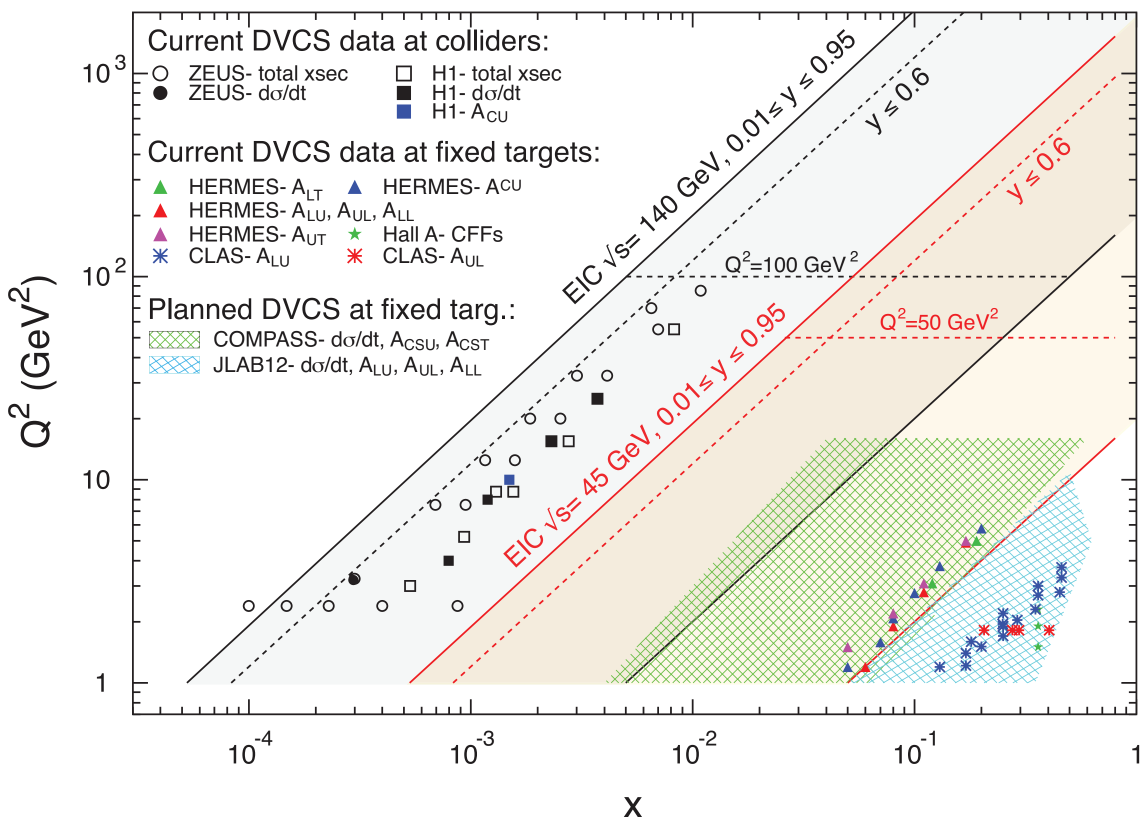
COMPASS@CERN can be a major player in QCD physics using its unique high energy both:

- **hadron beam and**
- **positive and negative muon beams**

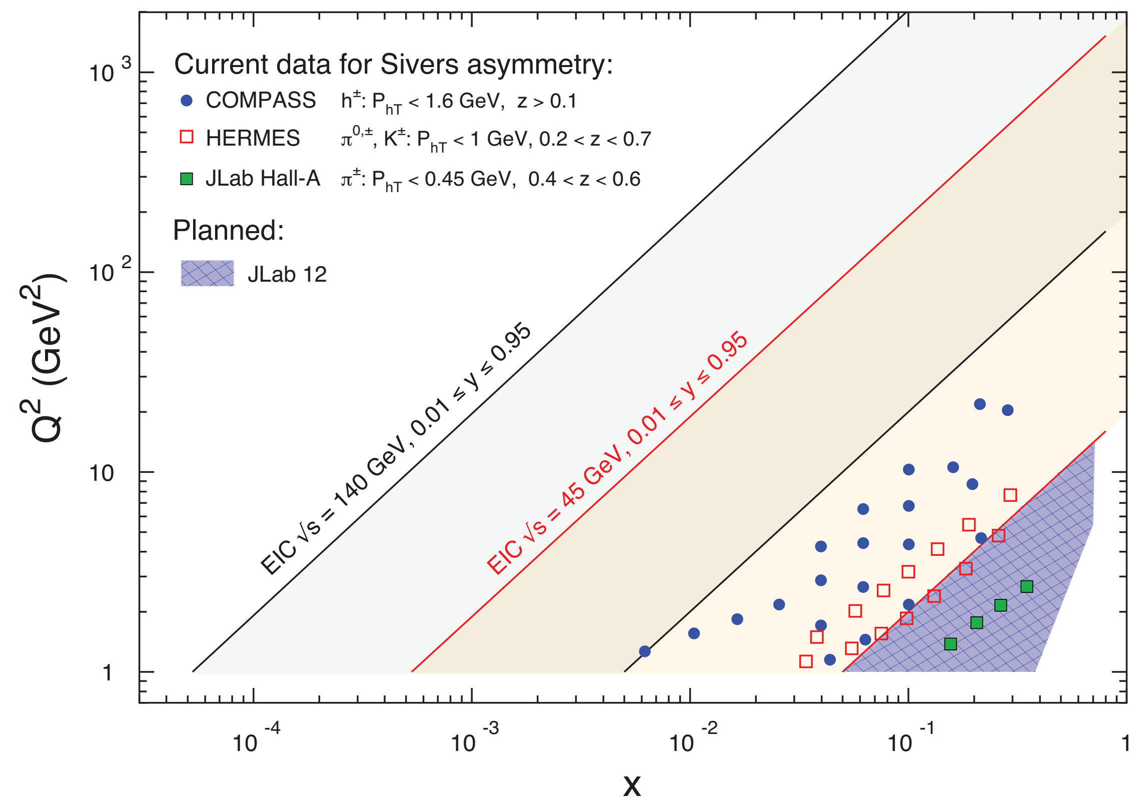
Looking even further...a polarized lepton-nucleon collider well be a mandatory tool

Future facilities

DVCS



SIDIS



EIC white paper, arXiv:1212.1701

Rolf Ent

Future facilities

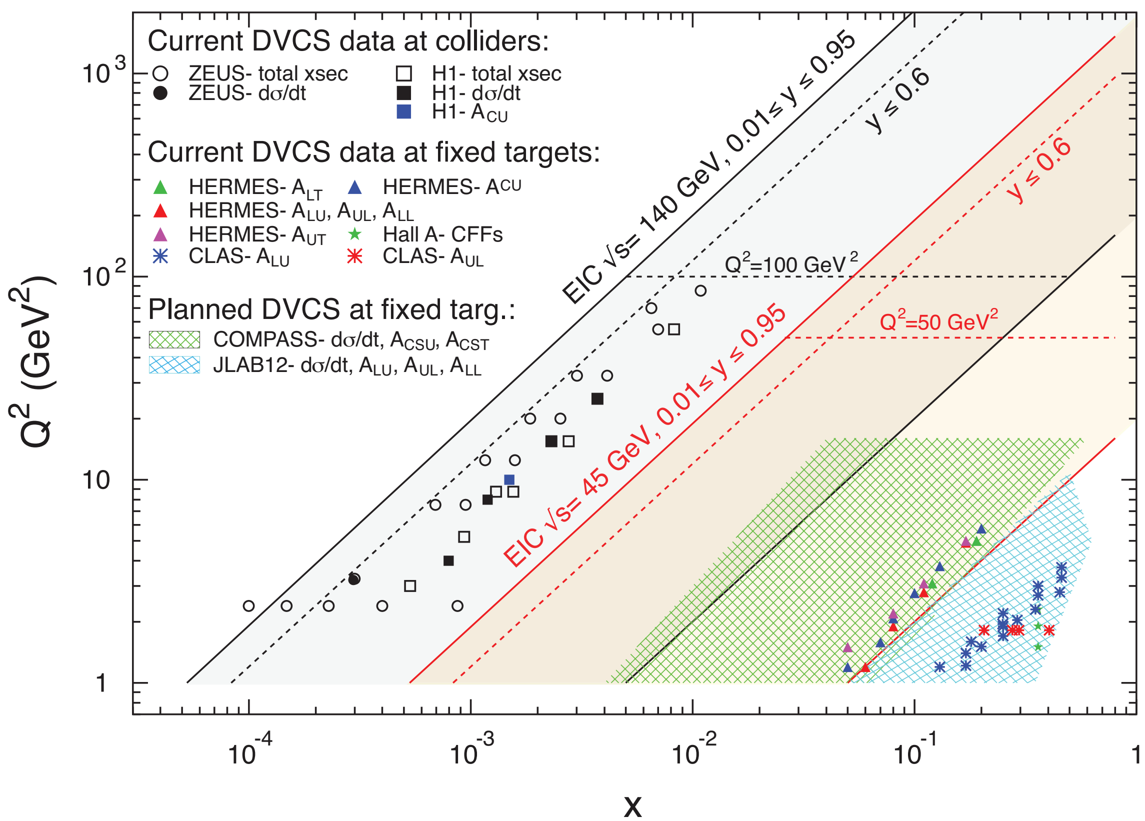
multidim. analysis : $d\sigma$ in $\{x, z, Q^2, P_{hT}^2, \Phi_h\}$ bins

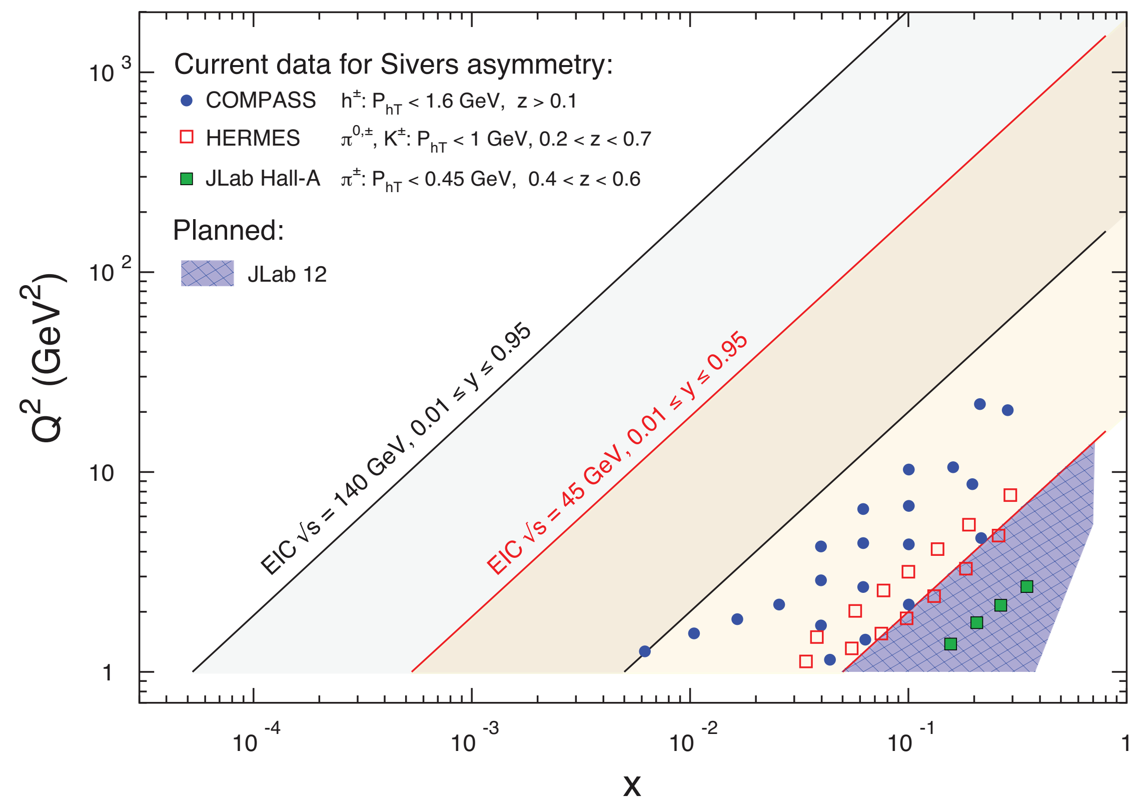
$\Rightarrow$ high luminosity

$\Rightarrow$ span larger $\{x, Q^2\}$ phase space

DVCS

SIDIS





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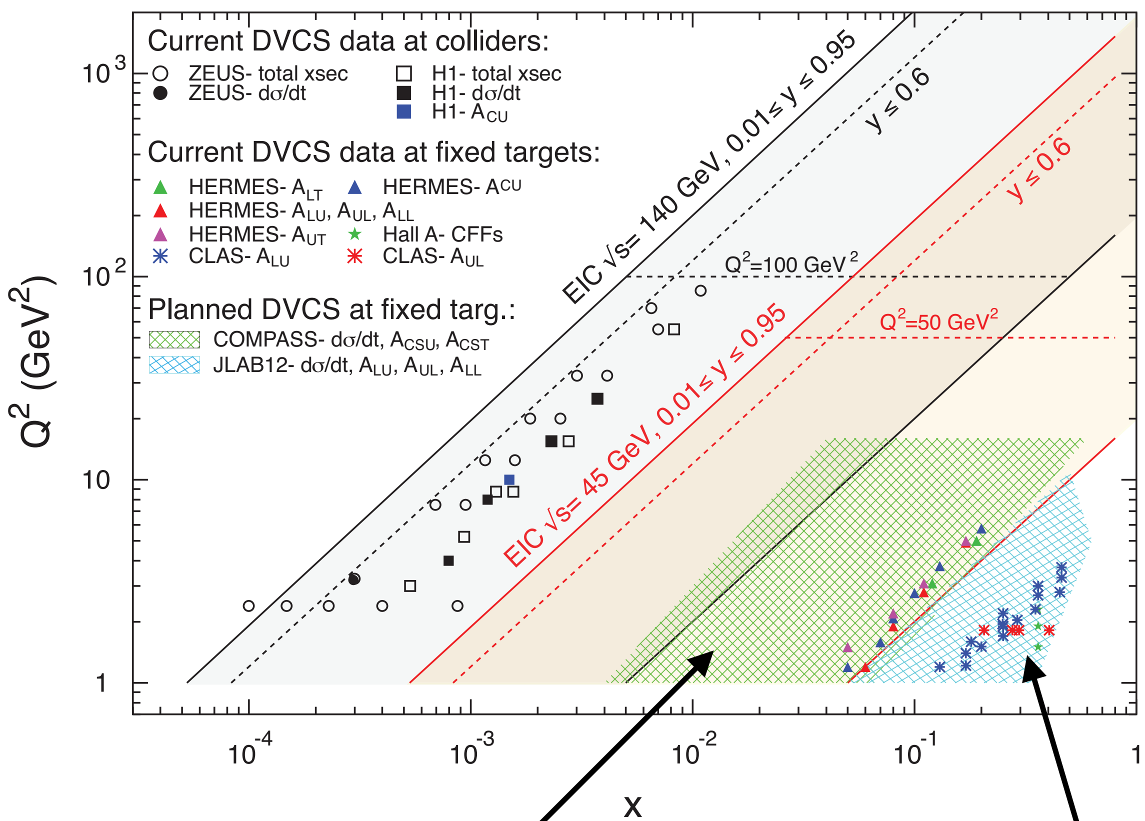
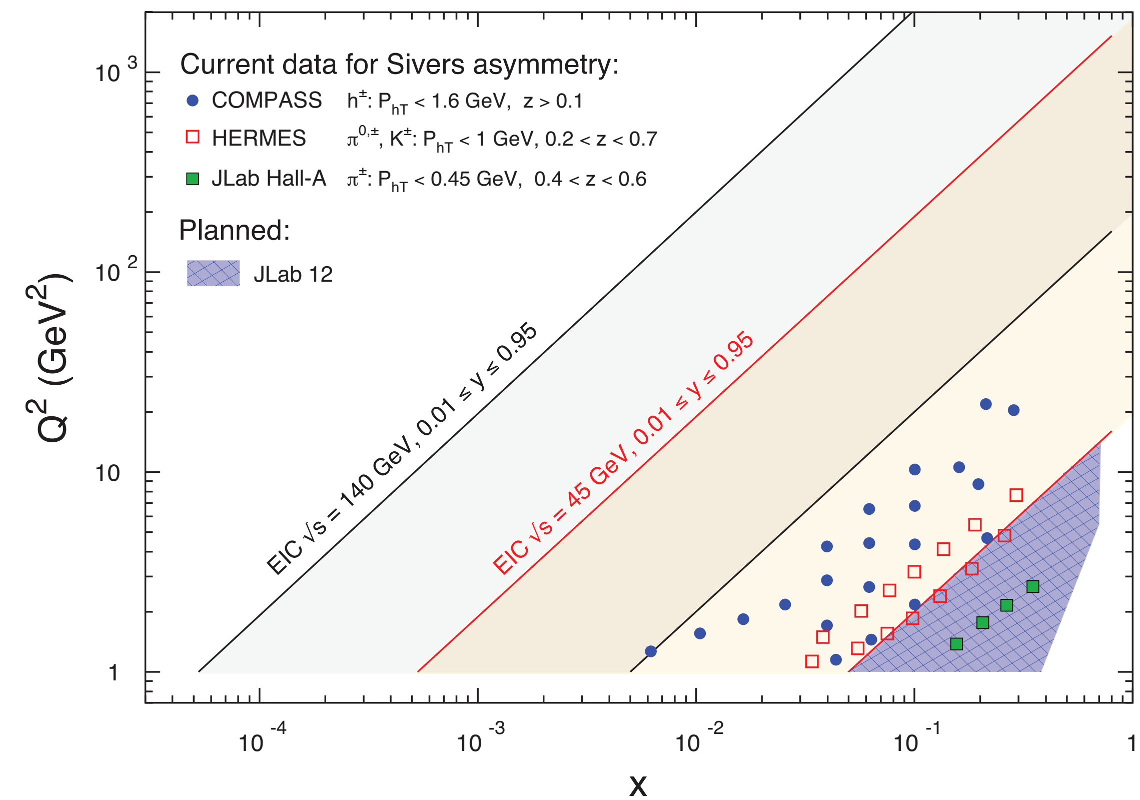


COMPASS

Jefferson Lab

SIDIS



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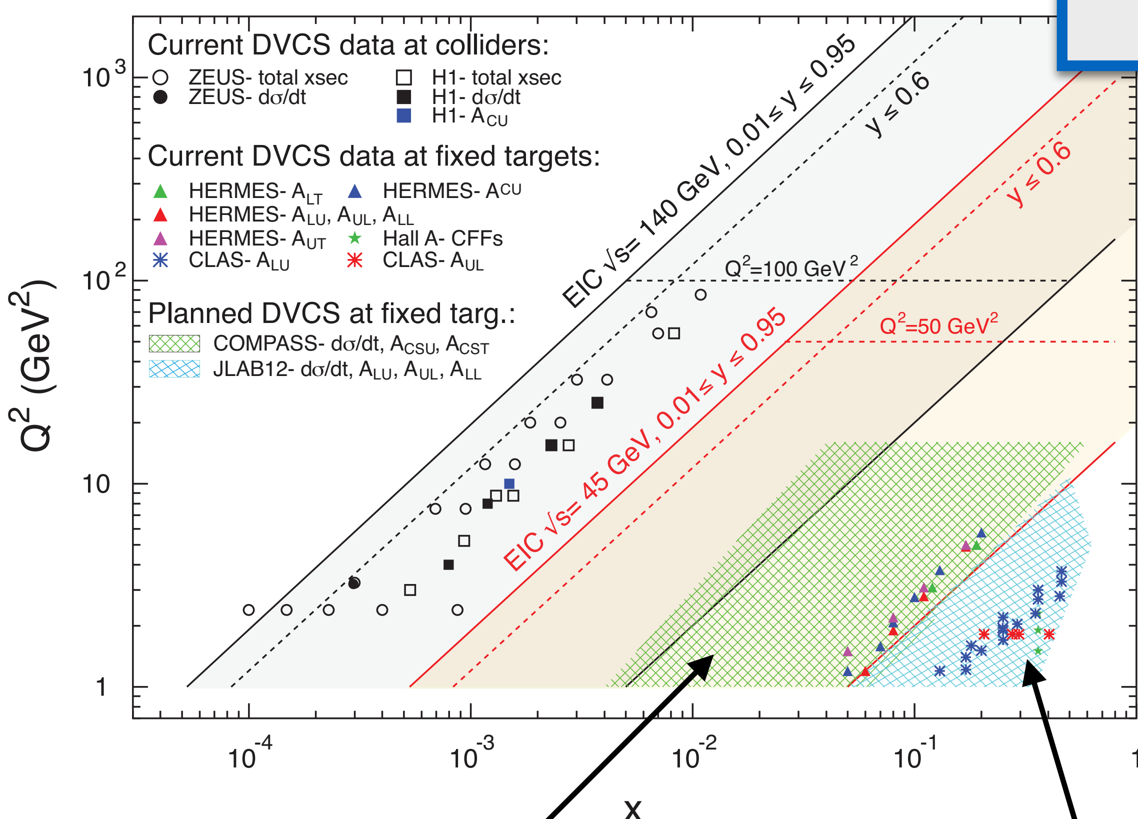
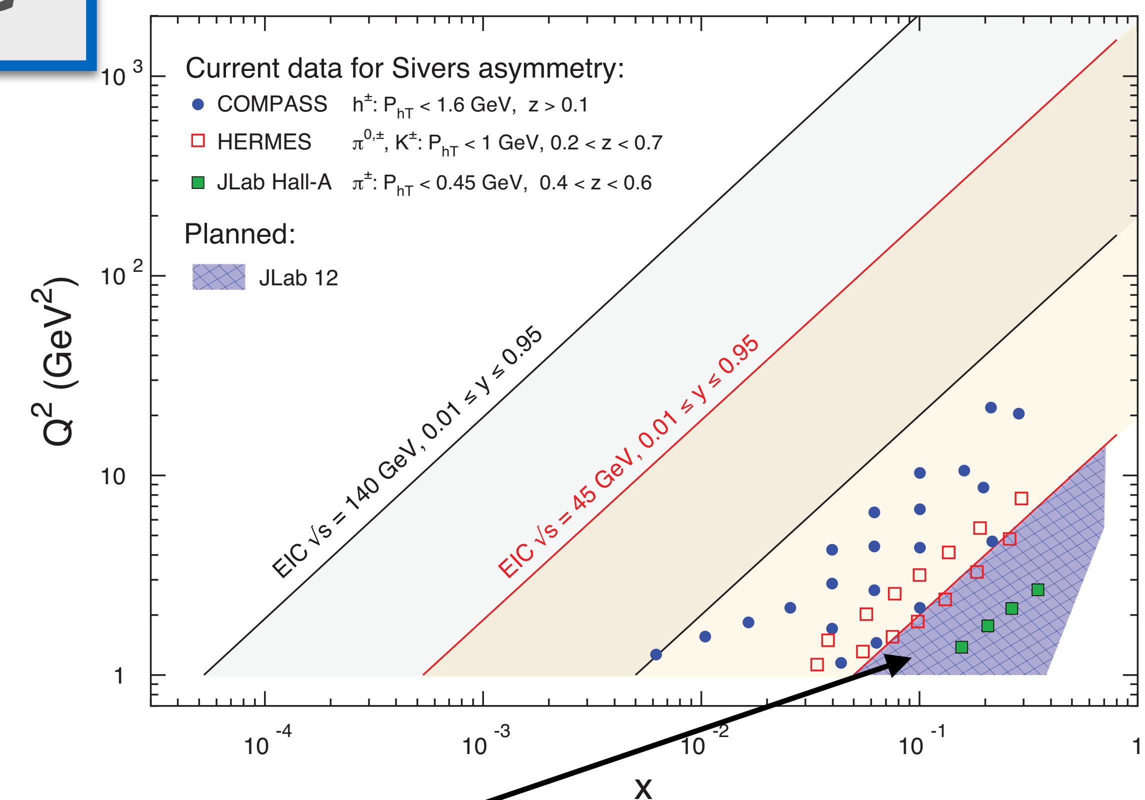
EIC (and **LHeC**)

DVCS



SIDIS



COMPASS

Jefferson Lab @12 GeV

EIC white paper, arXiv:1212.1701

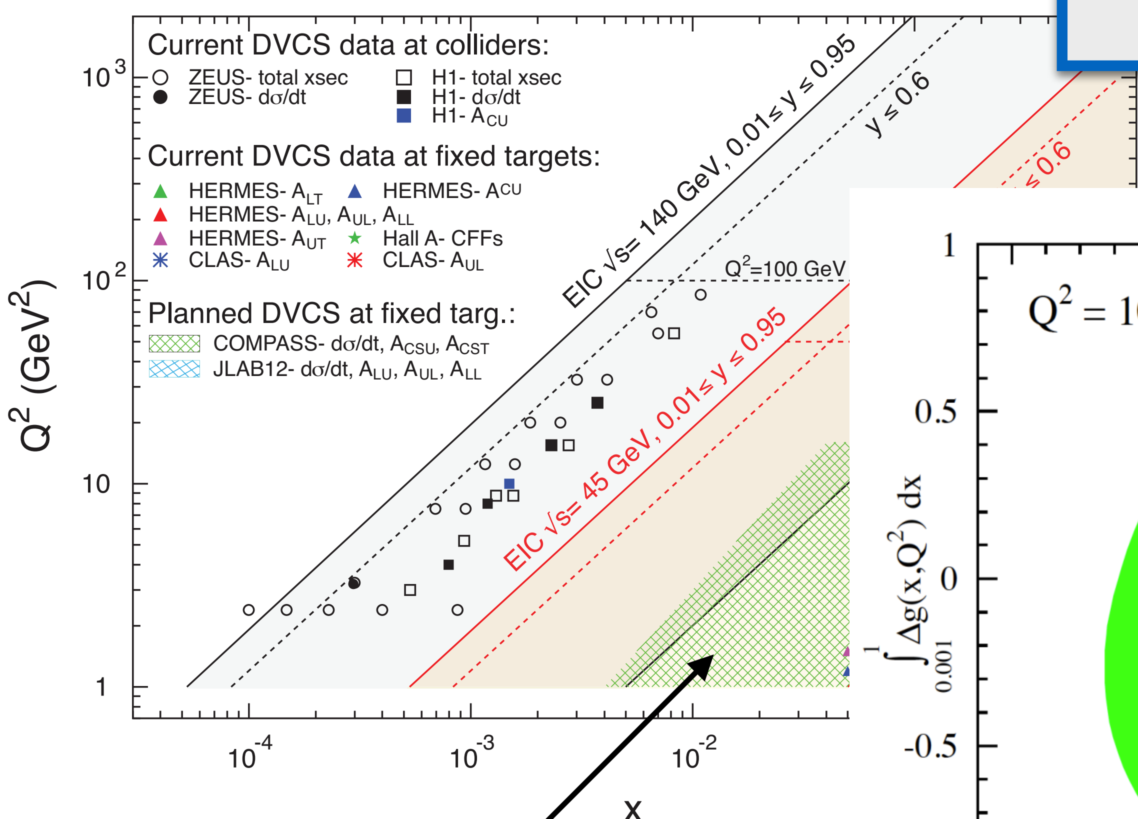
Future facilities

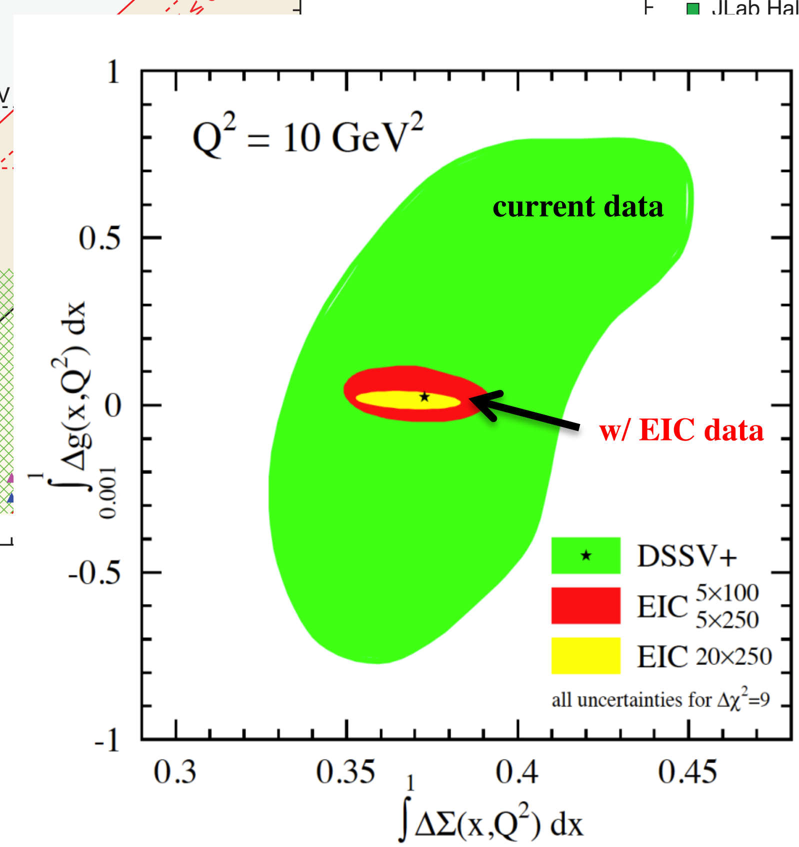
multidim. analysis : dσ in $\{x, z, Q^2, P_{hT}^2, \Phi_h\}$ bins

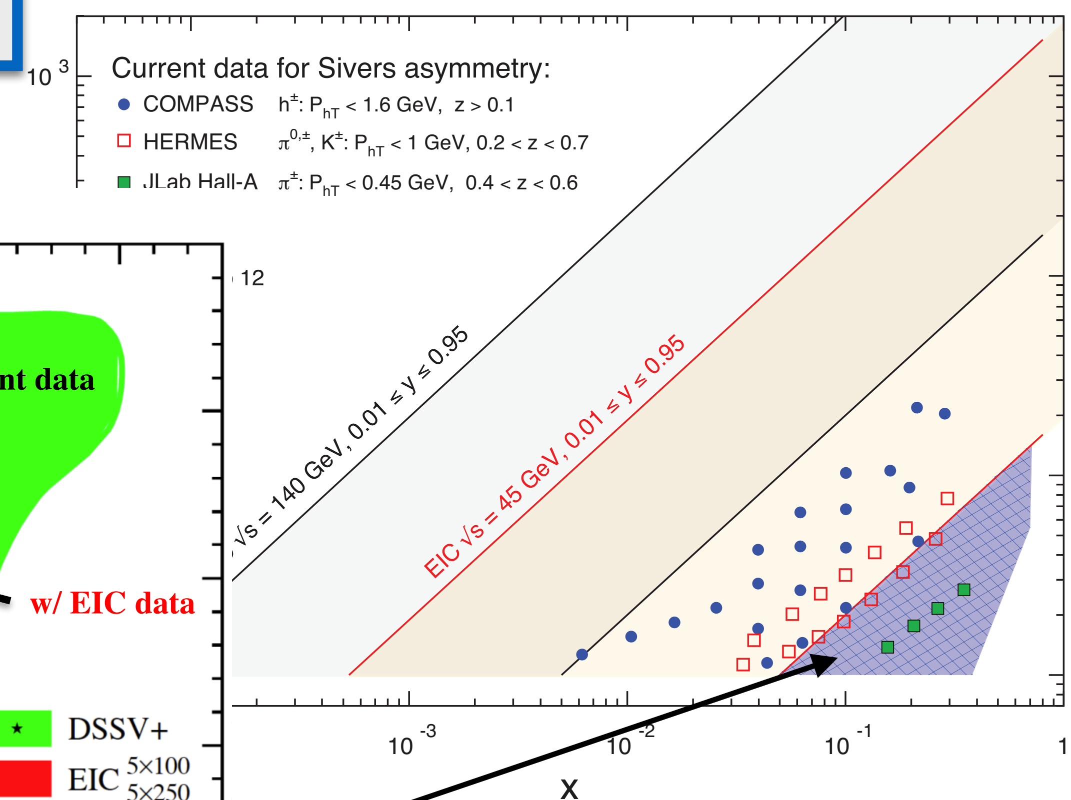
⇒ high luminosity

⇒ span larger $\{x, Q^2\}$ phase space

DVCS **EIC** (and **LHeC**) SIDIS



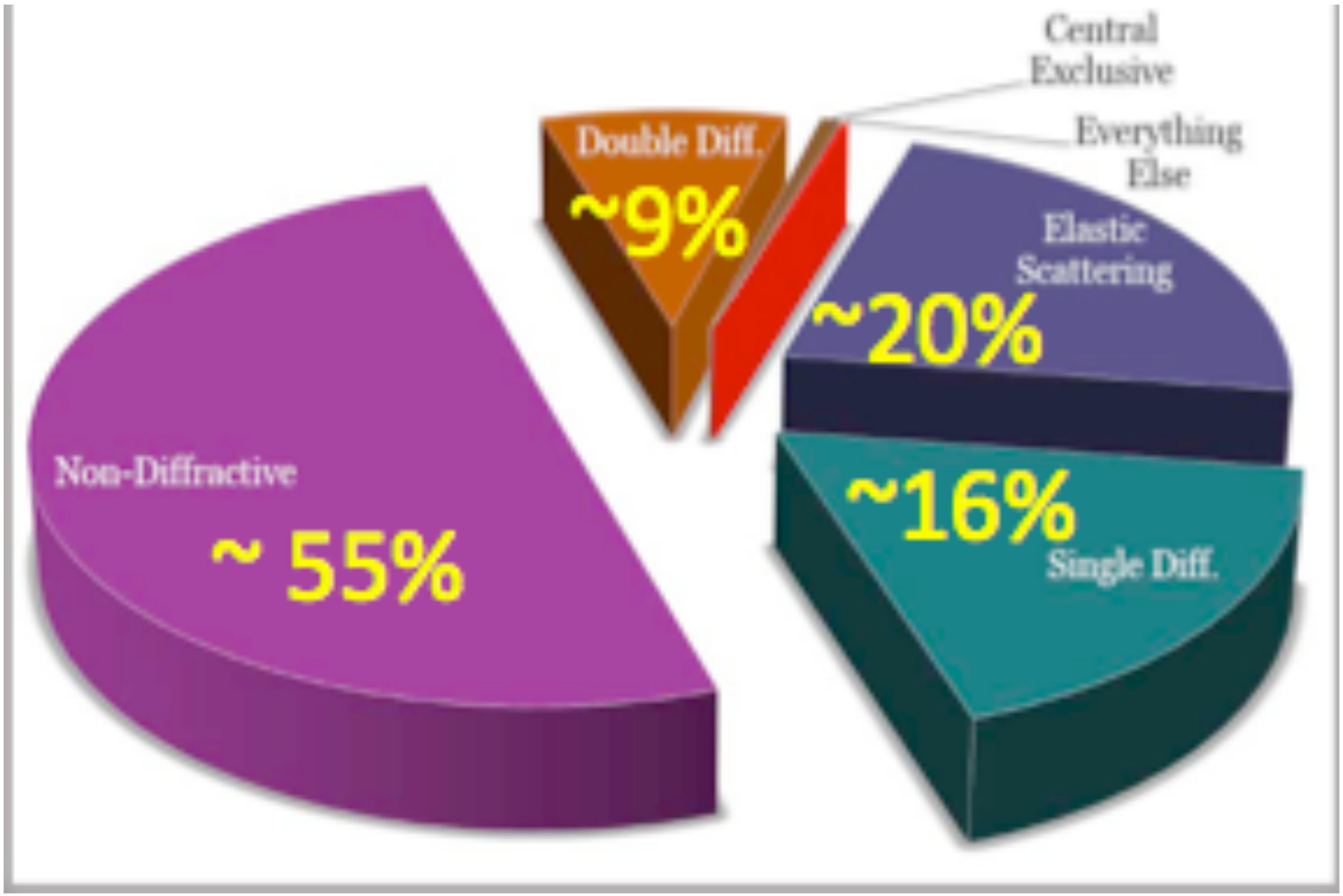




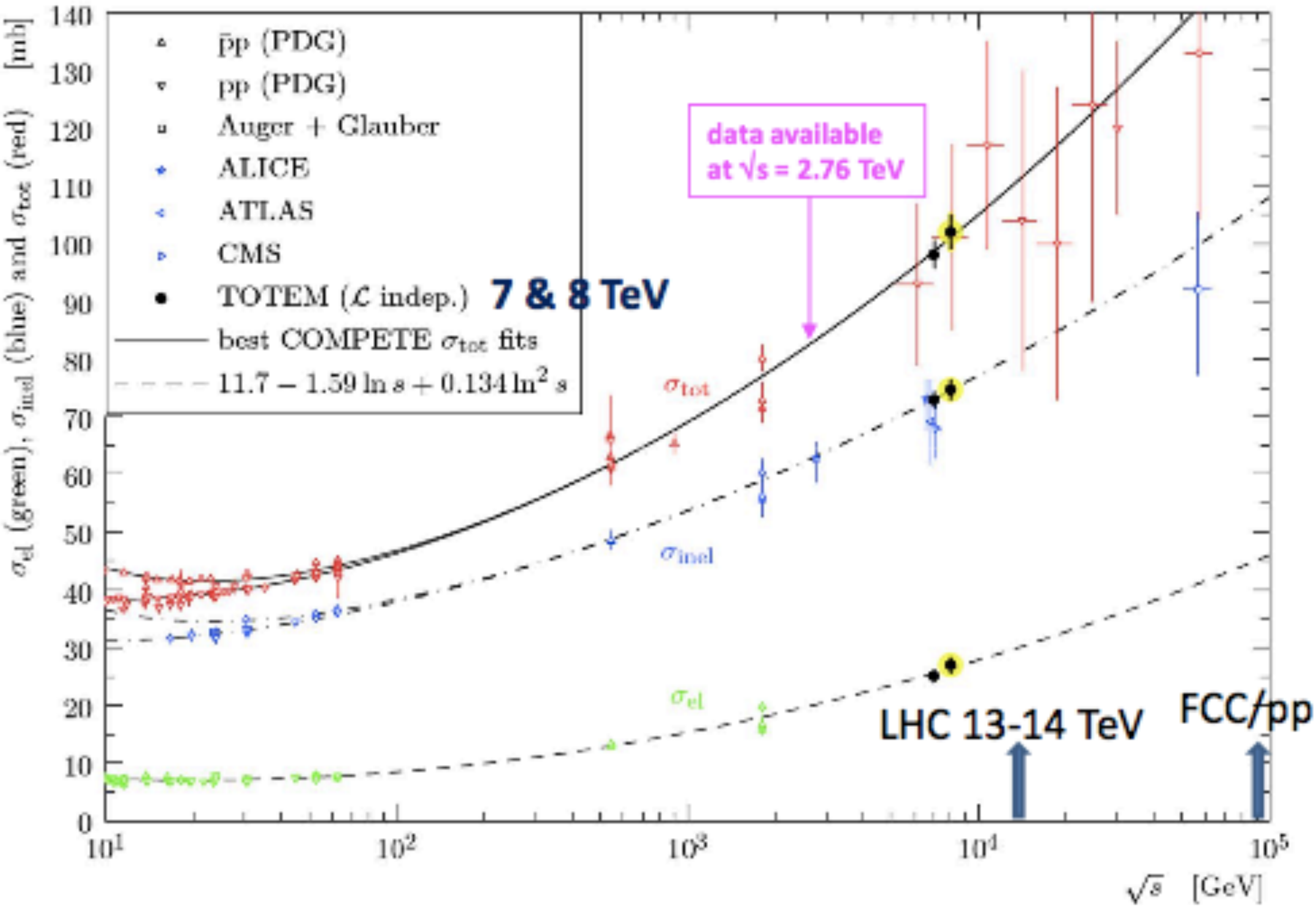
EIC white paper, arXiv:1212.1701

Rolf Ent

Proton-proton collisions



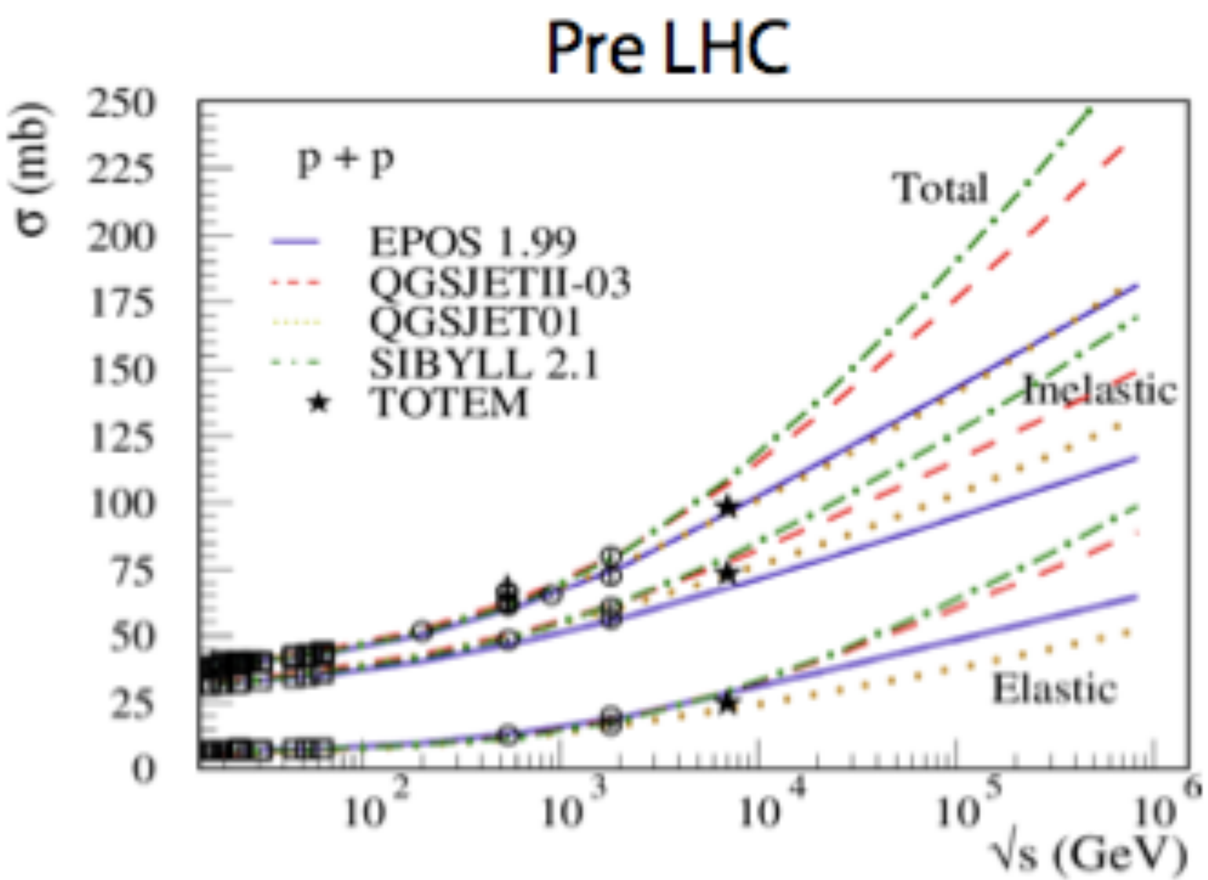
Total & inelastic cross section

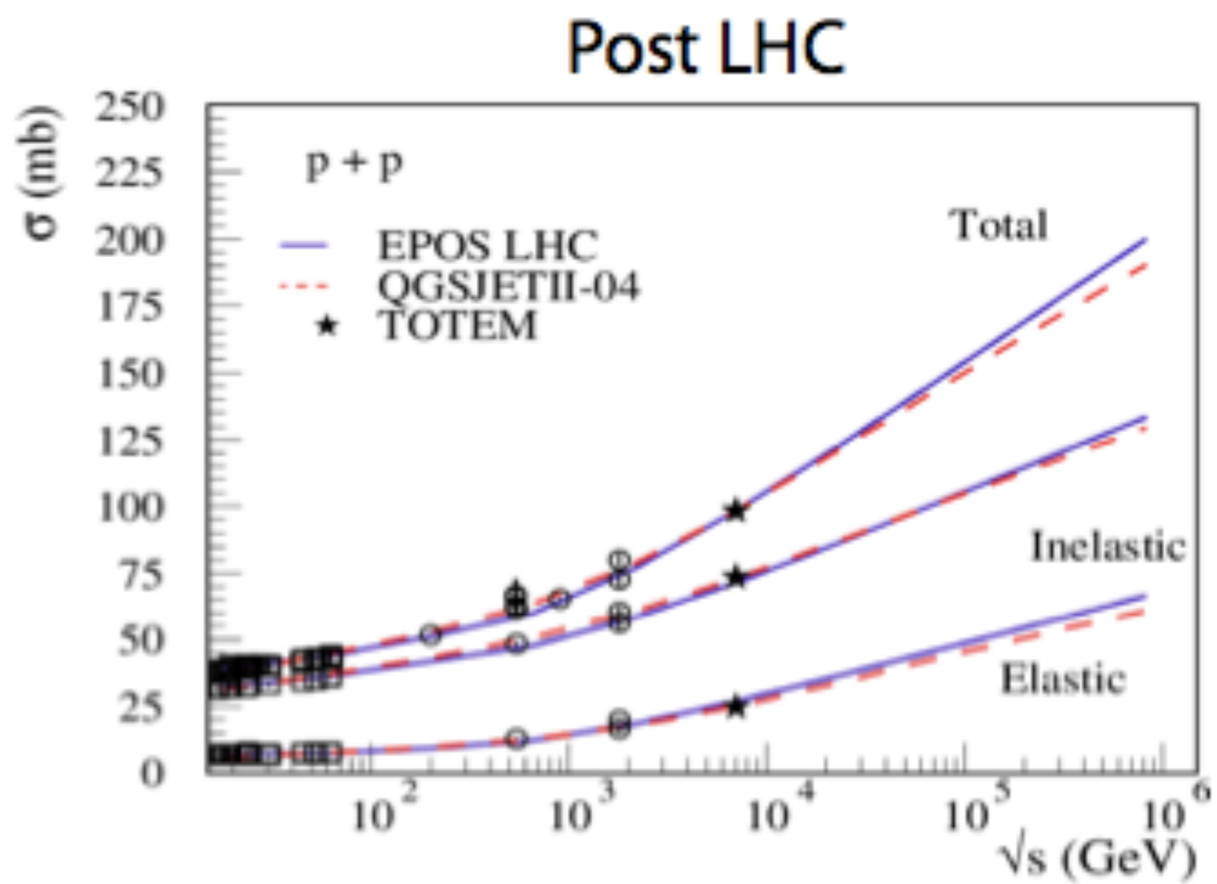


Also important input to cosmic air shower modeling

(together with multiplicity, forward particle flows, ...)

Kenneth Osterberg



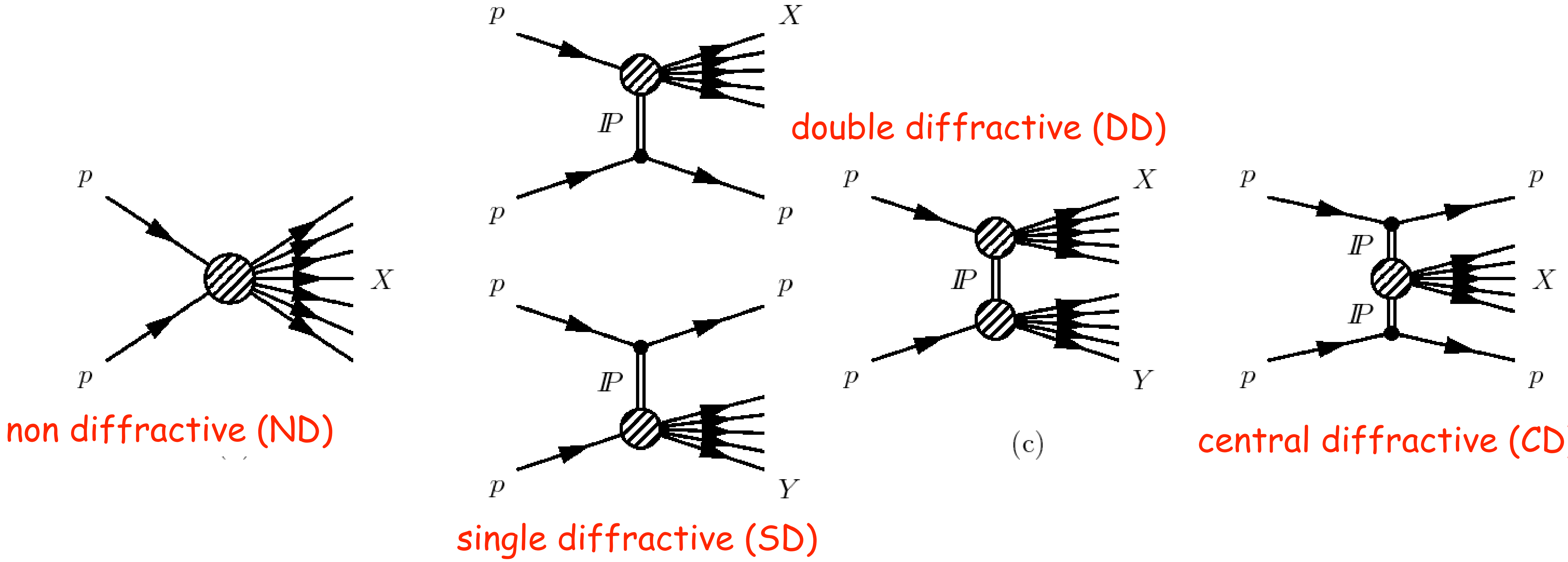


(T. Pierog)

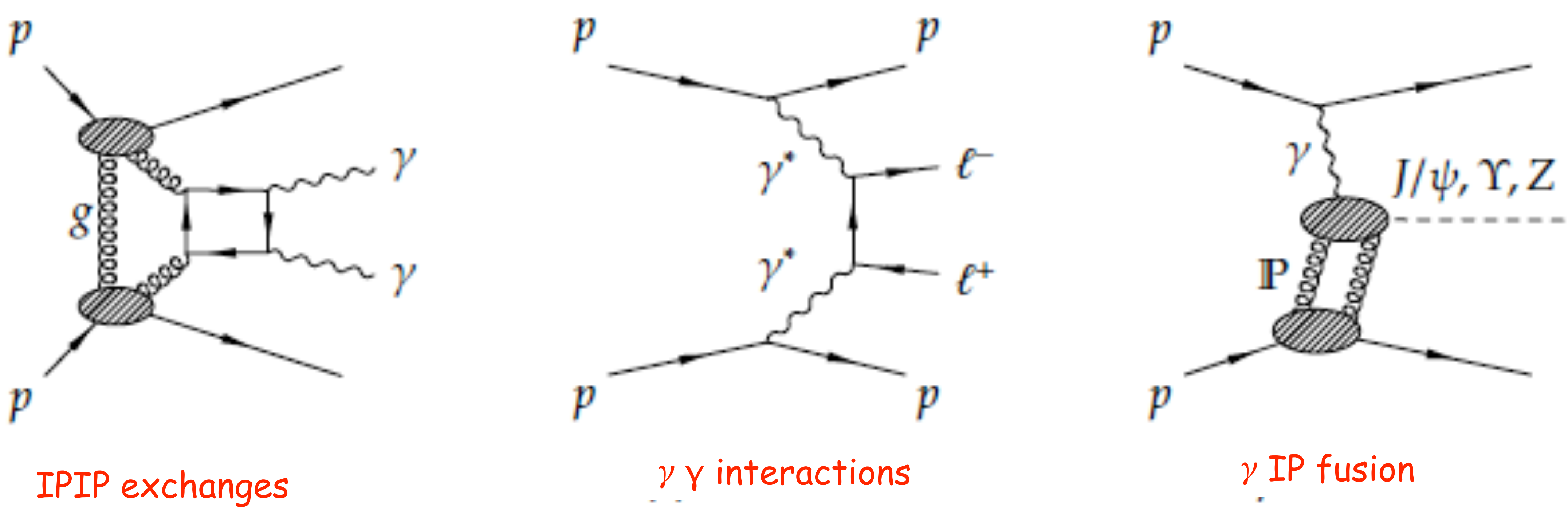
Nucleon-light ion collisions needed (e.g. p-N/O)

Gaku Mitsuka

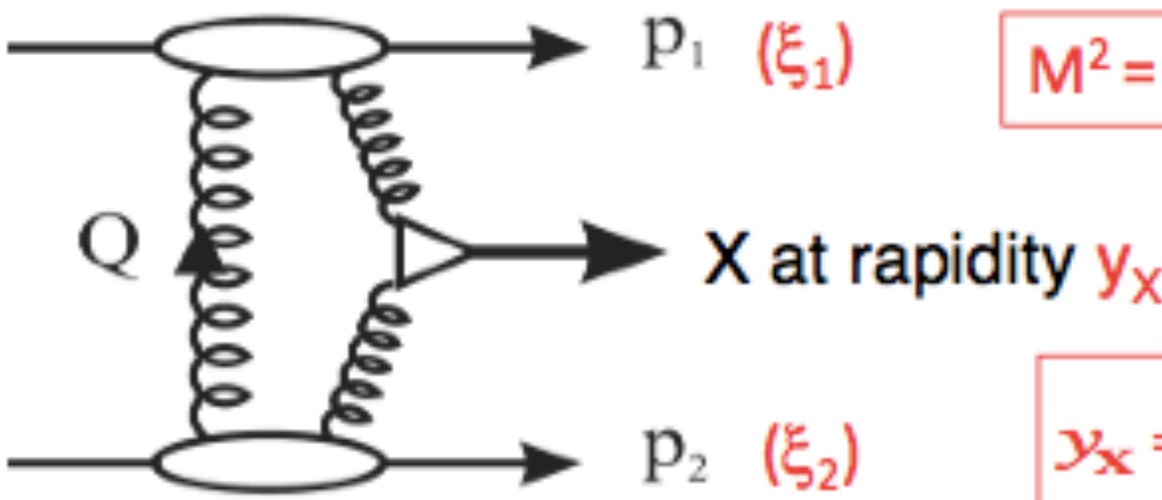
About diffractive...



...and exclusive reactions



Central exclusive production



$M^2 = \xi_1 \, \xi_2 \, s$

$y_X = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}$

also $\gamma\gamma$ fusion & photoproduction

gg collider !

exchange of colour singlets with vacuum quantum numbers ⇒ Selection rules for system X: $J^{PC} = 0^{++}, 2^{++}$

$X = 0^{++}$ & 2^{++} (light q, c & b) resonances, jets,?....

- $M = m_{\pi\pi} - \sim 1$ TeV,
- $\sigma = O(\mu b) - O(fb)$

With proton tagging:

Normal LHC runs: M(pp) acceptance > 350 GeV

⇒ σ's small (fb), need high lumi, only accessible with CT PPS & AFP

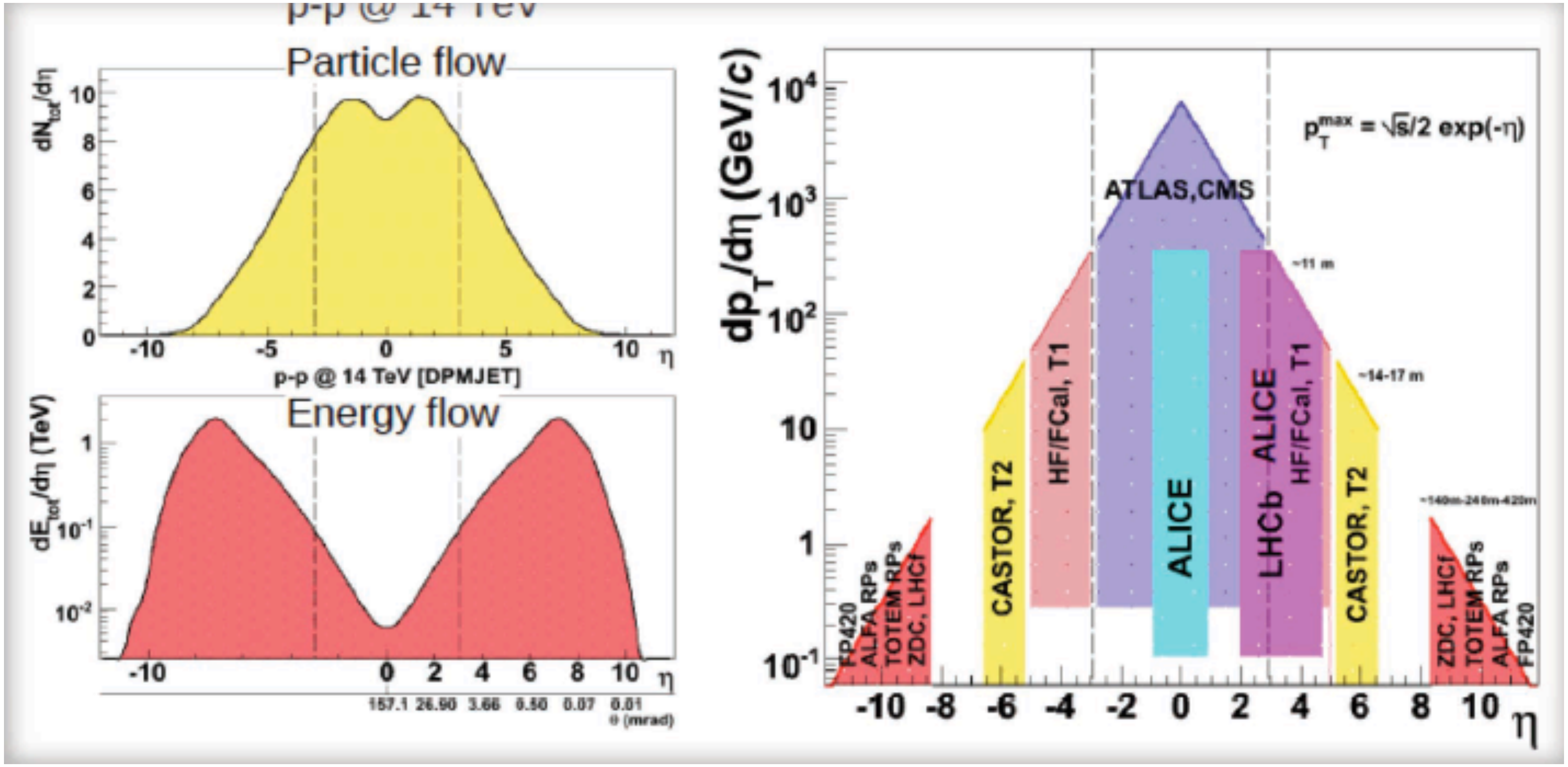
Special runs: all M(pp), $\mu \sim 0.05 - 0.5$ ⇒ $O(0.1\text{-}10\ pb^{-1}/day)$

CMS & TOTEM common runs: if $\mu \sim 0.5$ need timing in vertical TOTEM RPs

With rapidity gaps (also ALICE, ATLAS & CMS):

LHCb in normal LHC runs, σ's (≥ fb), improved with Herschel .

Kenneth Osterberg



p-p @ 14 TeV
Particle flow
dN_tot/dη
p-p @ 14 TeV [DPMJET]
Energy flow
dE_tot/dη (TeV)
θ (mrad)
dp_T/dη (GeV/c)
p_T^max = √s/2 exp(-η)
ATLAS,CMS
ALICE
LHCb
HF/FCal, T1
CASTOR, T2
FP420
ALFA RPs
TOTEM RPs
ZDC, LHCf

Part II

Luca Trentadue

Università di Parma & INFN

Spectroscopy

Roberto Mussa
Elena Santopinto

The HASPECT Project
Hadron SPEctroscopy CenTer in Genoa

Haspect: example of collaboration between experimentalists and theoreticians

- M. Battaglieri, R. De Vita, E. Santopinto *(Genova)*
- *A.Sczpaniack and V. Mathiew (Indina U. and Jlab*)
- D. Glazier (U. Glasgow)
- D. Watts and S. Hugs (U. Edinburgh)
- A. Filippi *(INFN Sezione di Torino)*
- S. Lombardo (Indiana University
- J. Ferretti (*UNAM*)
- S. Fegan, A. Celentano (*INFN sezione di Genova*)
- *A. d'Angelo and A. Rizzo (Roma Tor Vergata)*

Hadron spectroscopy and Hybrids

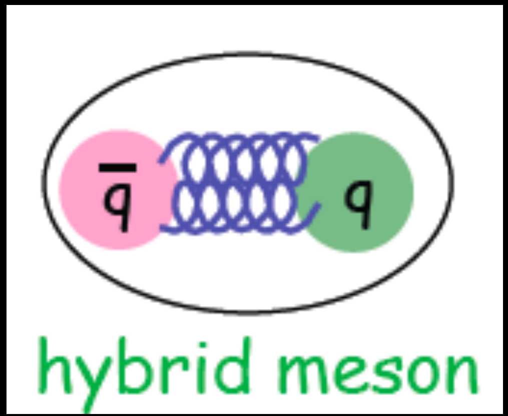
E.Santopinto
INFN-GE
LTS2014 Elba 21-23 may 2014

-Theory on hybrids

-Hybrids important to understand confinement

-Experiments on hybrids present and future

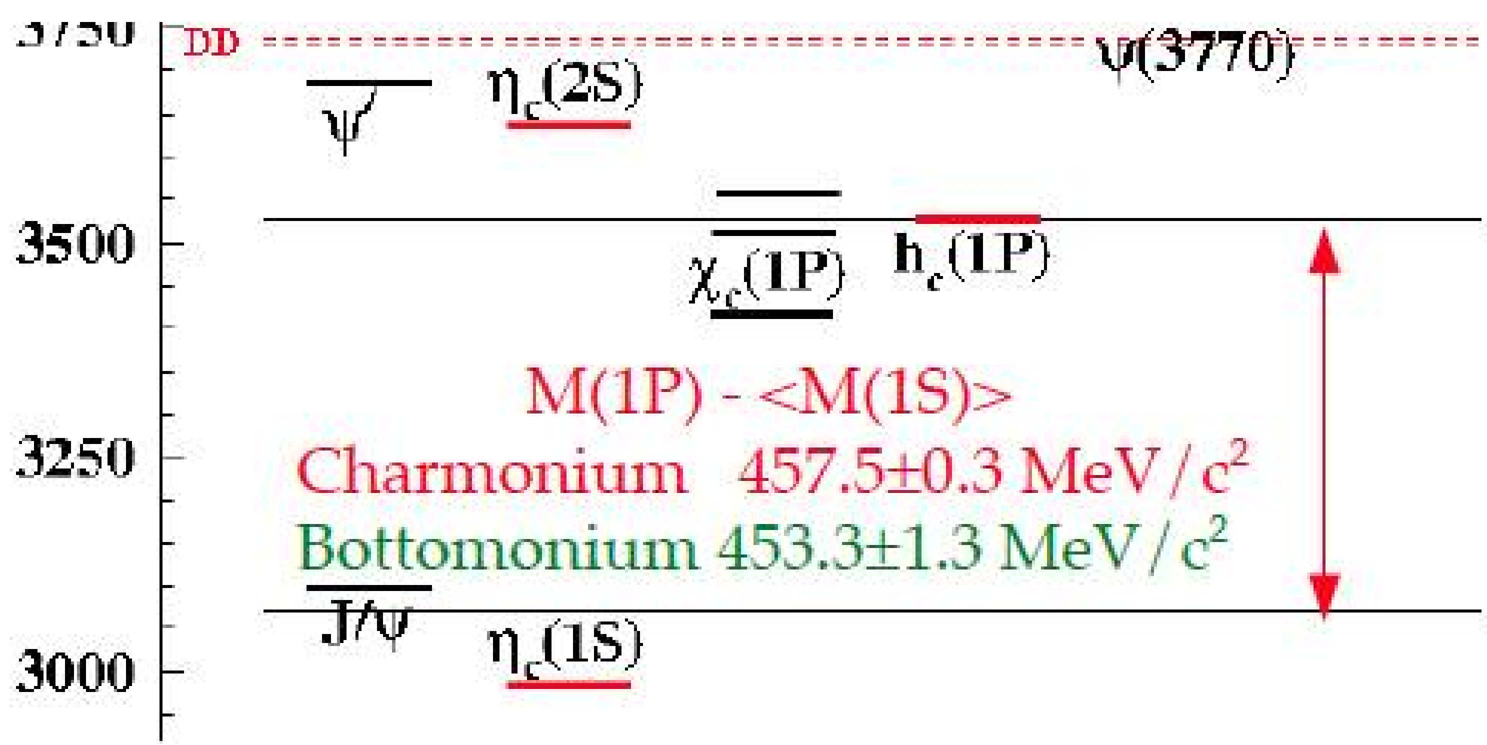
-Haspect:hadron spectroscopy center @genoa (experimentalists and theoreticians collaboration)



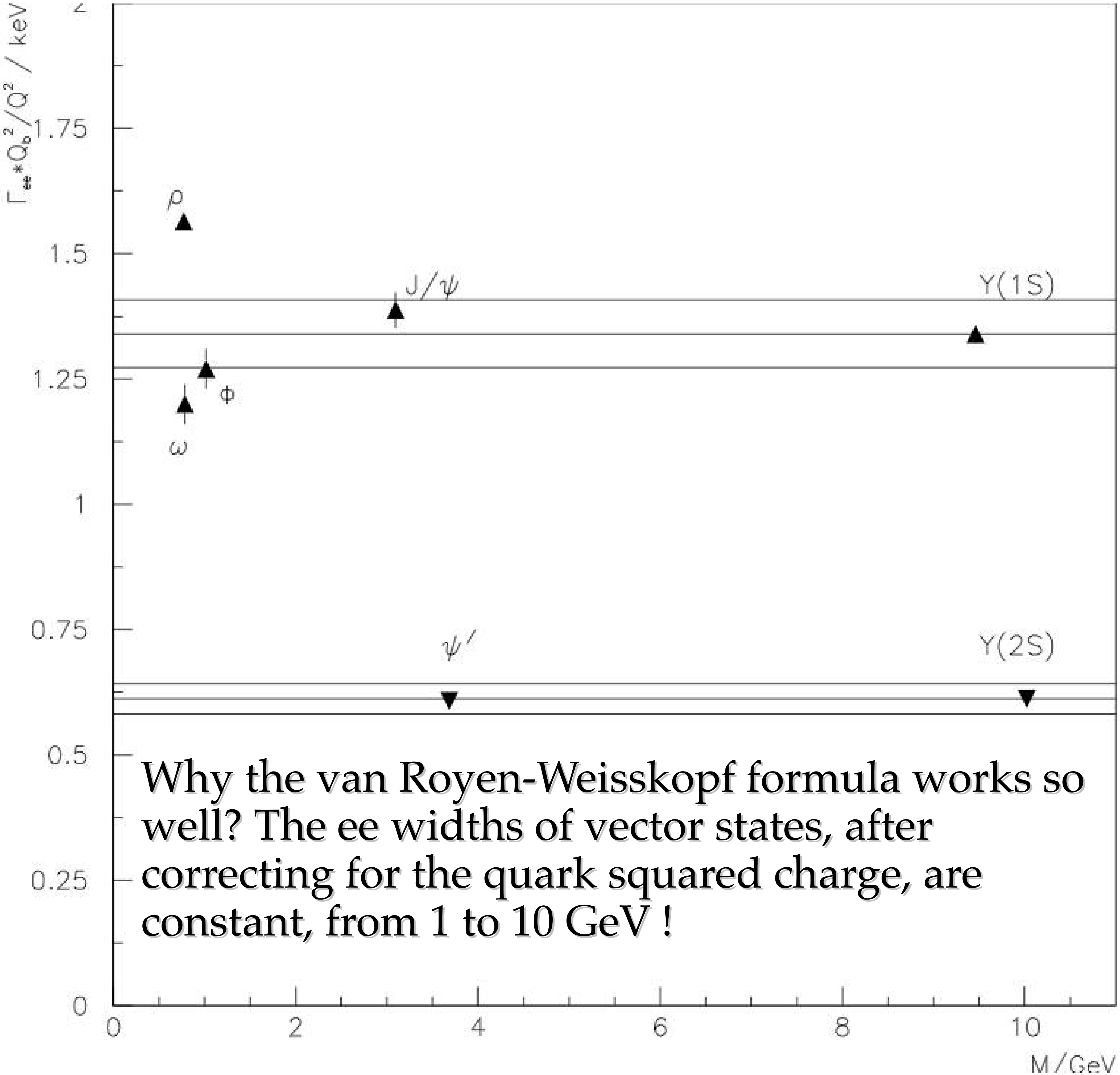
Why the constituent quark model is so succesful?

Despite the large scale variation (from s to c to b) , the ground states of S wave mesons are equally spaced (within 2-3%) from the lowest lying heavy baryons (205-210 MeV) and from the first excitation, made of a heavy quark and a vector diquark (310-323 MeV). Baryons behave like two-body systems, as three-body forces seem negligible.

Spin averaged 1P-1S splitting seems not to depend on scale: only 1% difference with charmonium: similarly, the tensor-vector splitting remains constant also in D,Ds.



	$c\bar{u}$	$c\bar{d}$	$c\bar{s}$	$c\bar{c}$	$b\bar{b}$
$M(2^+)$-$M(1^-)$, in MeV/c^2	452 ± 2	449 ± 4	461 ± 2	458.3 ± 0.1	452.3 ± 0.6



Why the van Royen-Weisskopf formula works so well? The ee widths of vector states, after correcting for the quark squared charge, are constant, from 1 to 10 GeV !

Multiple Parton Interactions

Livio Fanó

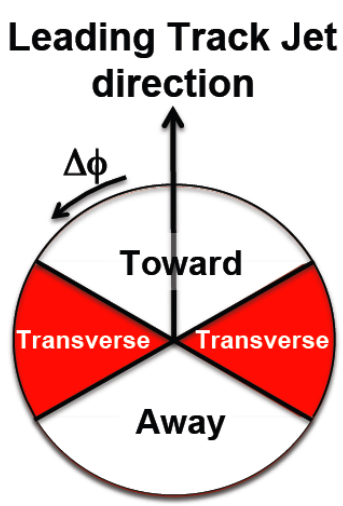
Multiple Parton Interactions

Multiple Parton Interactions have been introduced to solve the unitarity problem generated by the fast raise of the inclusive hard pp cross sections at small x

Turns out to be highly predictive on hadronic final states:
Several indication of MPI in pp collision. A characterization is needed

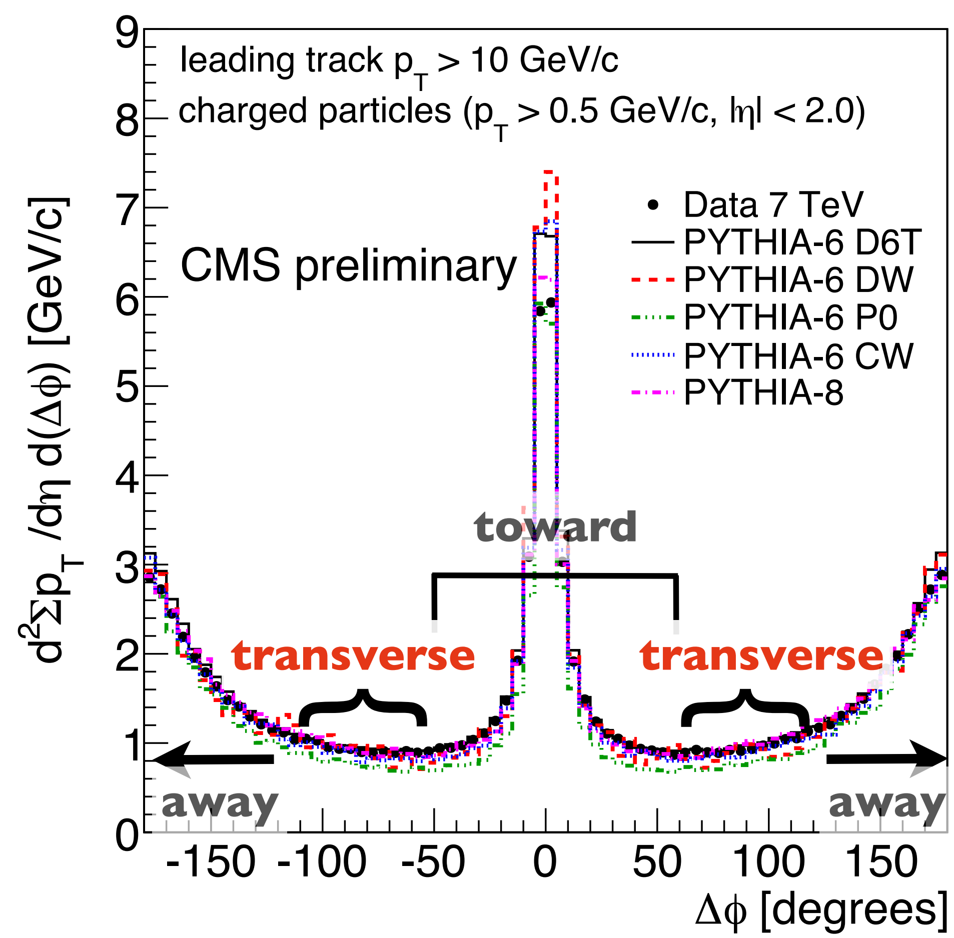
Why ? MPI helps in 1) probe proton matter distribution 2) understanding the collision dynamics and 3) define at the best background to new physics search

How ? soft dynamic with Underlying Event and hard with Double Hard Scattering



Leading Track-Jet define a direction in the phi plane for the HS

Eur.Phys.J.C70:555-572,2010, JHEP09 (2011) 109



Transverse region is expected to be sensitive to the UE (all activity except the hard-scattering component)

Observables are built from tracks:

$d^2N_{ch}/d\eta d\phi$ - multiplicity density

$d^2\Sigma p_T/d\eta d\phi$ - energy density

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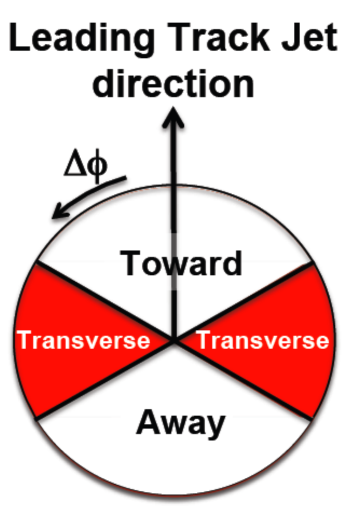

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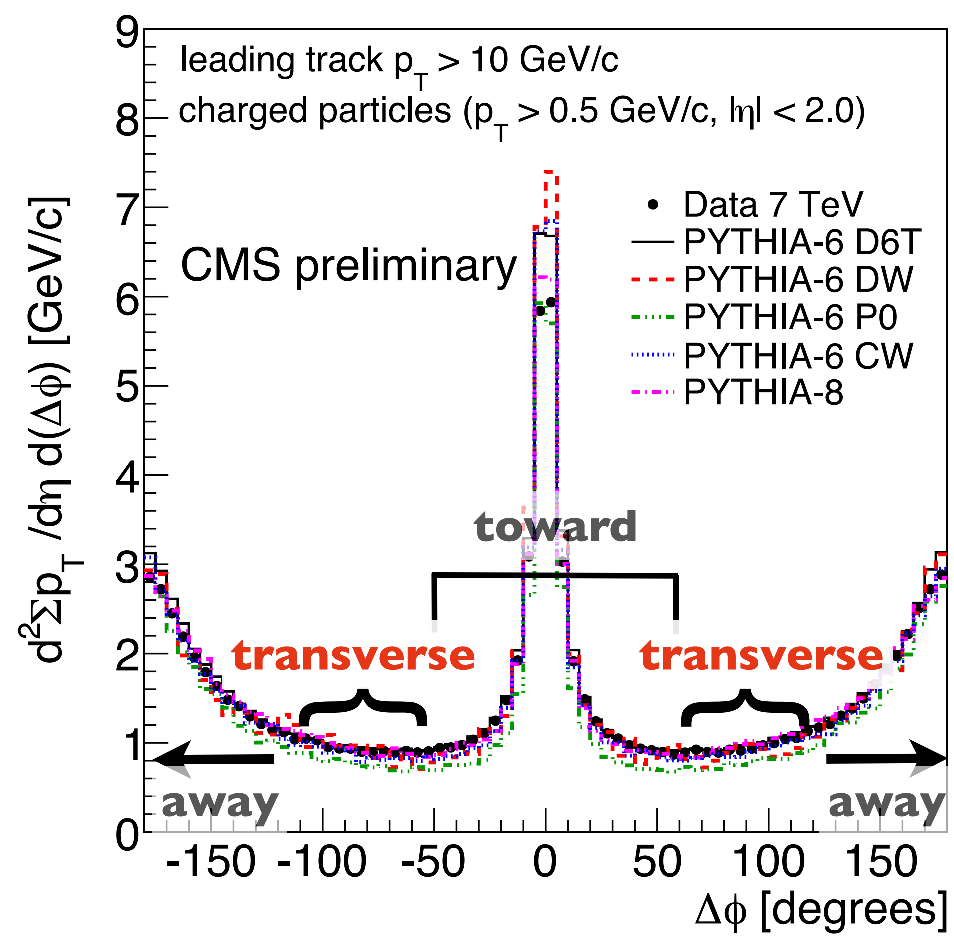
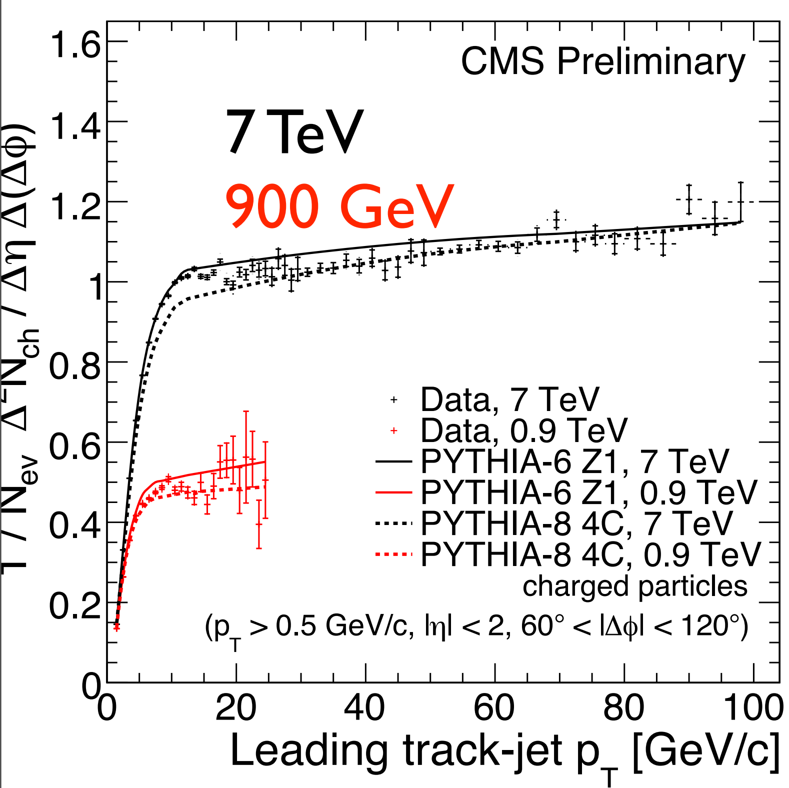
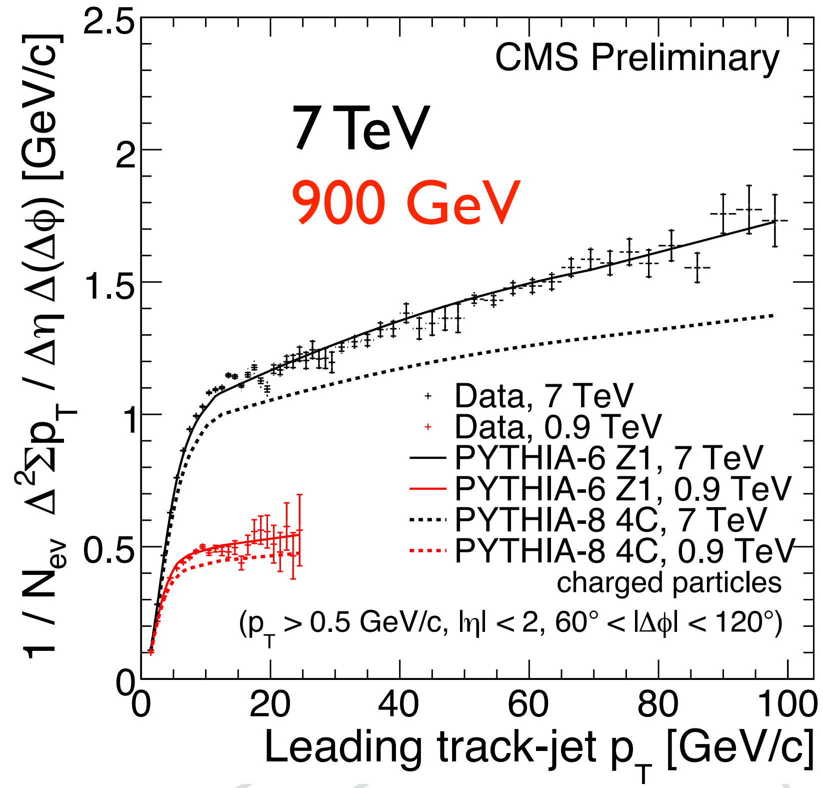
Eur.Phys.J.C70:555-572,2010, JHEP09 (2011) 109

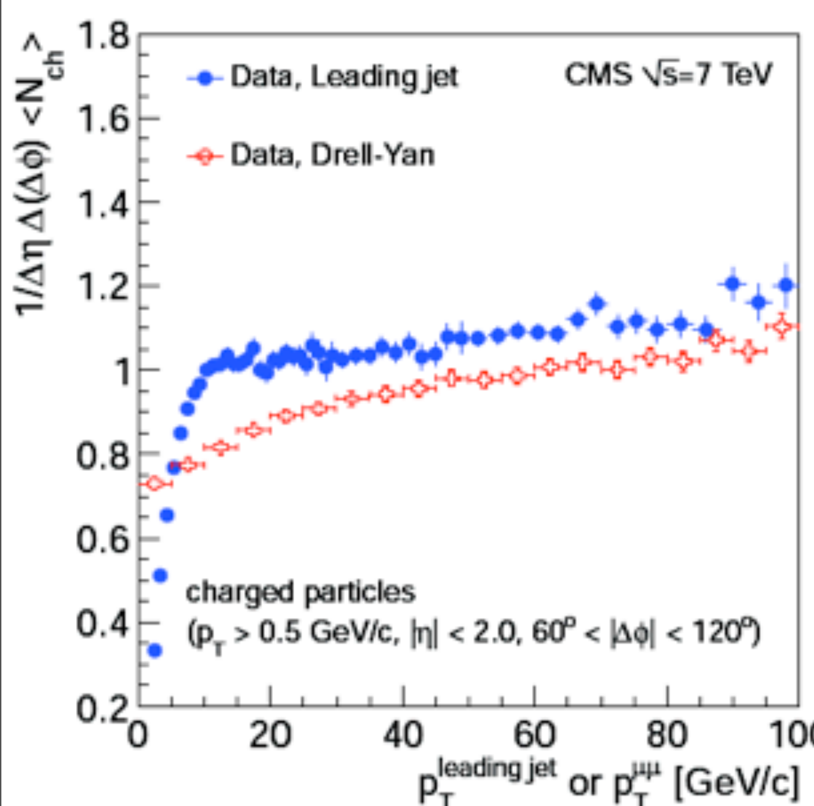


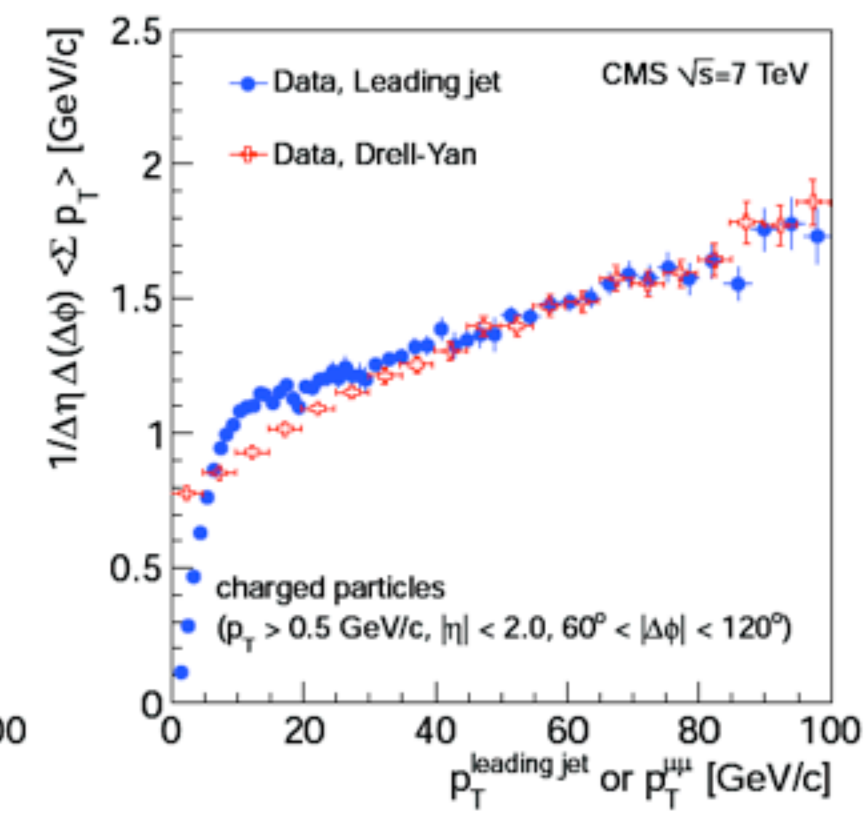
Soft MPI - The transverse region





JHEP09 (2011) 109





1) **Fast rise** - peripheral collisions increase of the MPI

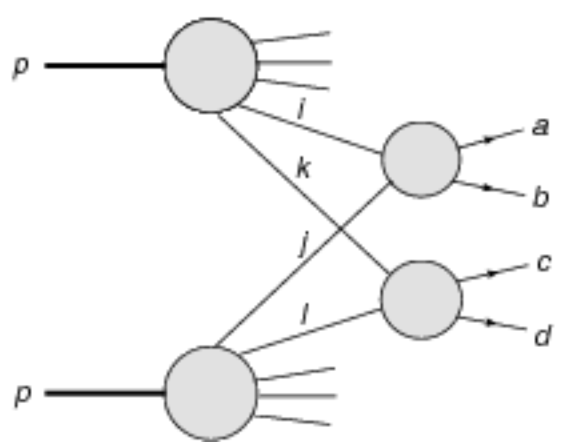
2) **Plateau region** - central collisions with ~constant charged density and increasing pT_sum (radiation)

3) Increase of the activity with $\sqrt{S}$ → more MPI

4) DY events have a smaller particle density with a harder p_T due to the presence of only ISR initiated by quarks

hep-ex:1204.1411

Hard MPI - Double Parton Scattering



$$\sigma(P_1,P_2)=\sum_{i,j}\int dx_1 dx_2 f_i(x_1,\mu^2) f_j(x_2,\mu^2)\hat{\sigma}_{i,j}(p_1,p_2,\alpha_s(\mu^2),\frac{Q^2}{\mu^2})$$

$$\sigma^{DPS}(ijkl\rightarrow abcd)=\frac{m\hat{\sigma}^A_{ij}\hat{\sigma}^B_{kl}}{2\sigma_{eff}}$$

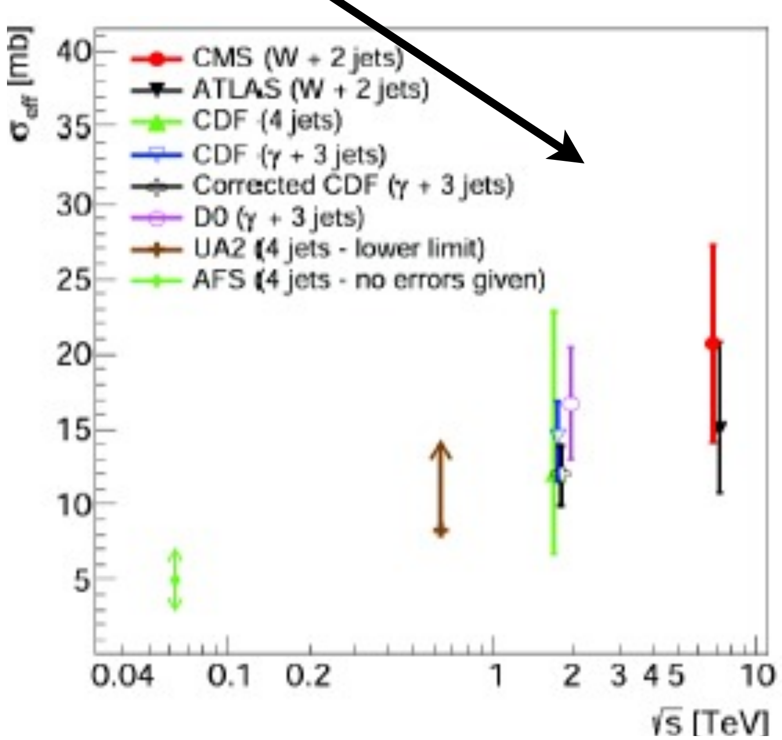
$$\sigma_{\text{eff}}=\frac{1}{\int d^2\beta F^2(\beta)}$$

prediction based on theoretical calculation and soft MPI tune:

expected σ_{eff} ≈ **20÷60 mb**

measured σ_{eff} ≈ **10÷20 mb**

?



Which role for Double Parton Correlations ?

[in actual model dPDF are factorized in 2 single PDF]!!

Korotkikh and Snigirev (2004), Gaunt and Stirling (2010), Diehl and Schafer (2011), Snigirev (2011), Blok et al. (2012), Schweitzer, Strikman and Weiss (2013), S. Scopetta et al. (2013),...

FUTURE

DPS measurement don't provide yet a crystal clear DPS evidence.

What should be considered to be the most striking evidence of MPI via DPS?

To what extent we can trust the general-purpose soft-MPI models?

Explore scaling properties: observables in pp, pPb and PbPb driven by charged multiplicity?

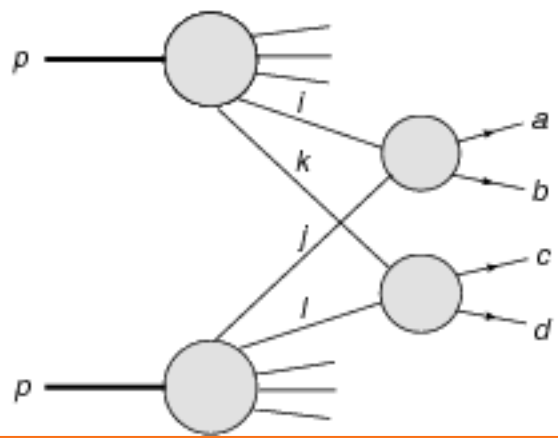
Higher Energies...higher luminosities...

DPS/SPS Heavy Flavors production is expected to increase with $\sqrt{S}$

Rare productions with top and heavy bosons, unavoidable BGs to new physics searches

With p-N DPS is enhanced, longitudinal and transverse correlations can be factorized

Hard MPI - Double Parton Scattering



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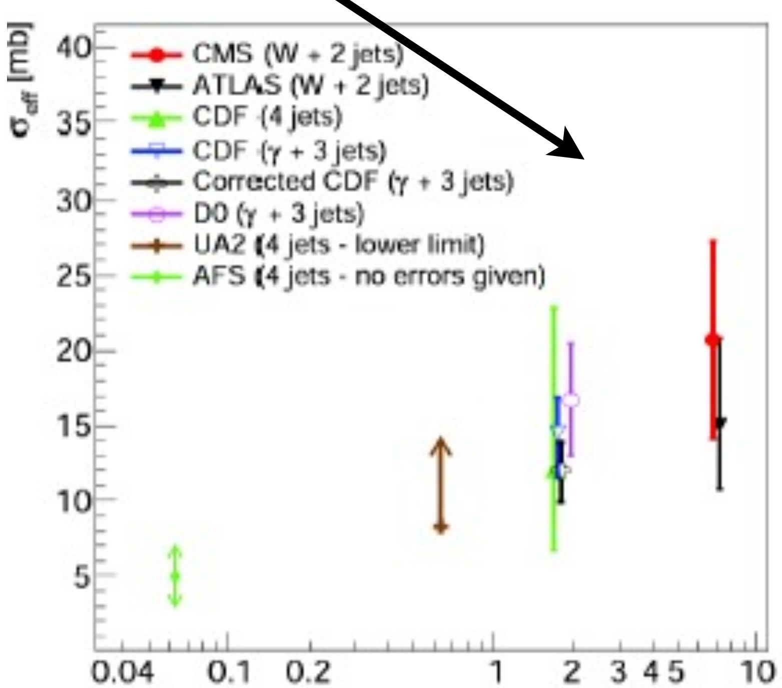

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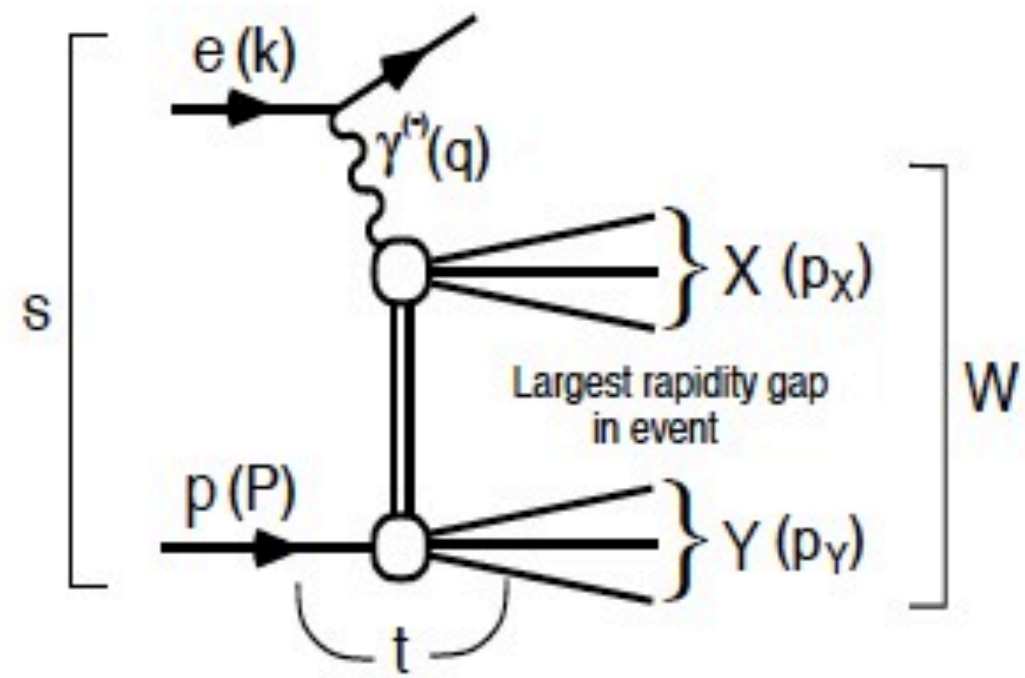
Hard Diffraction

Federico Alberto Ceccopieri

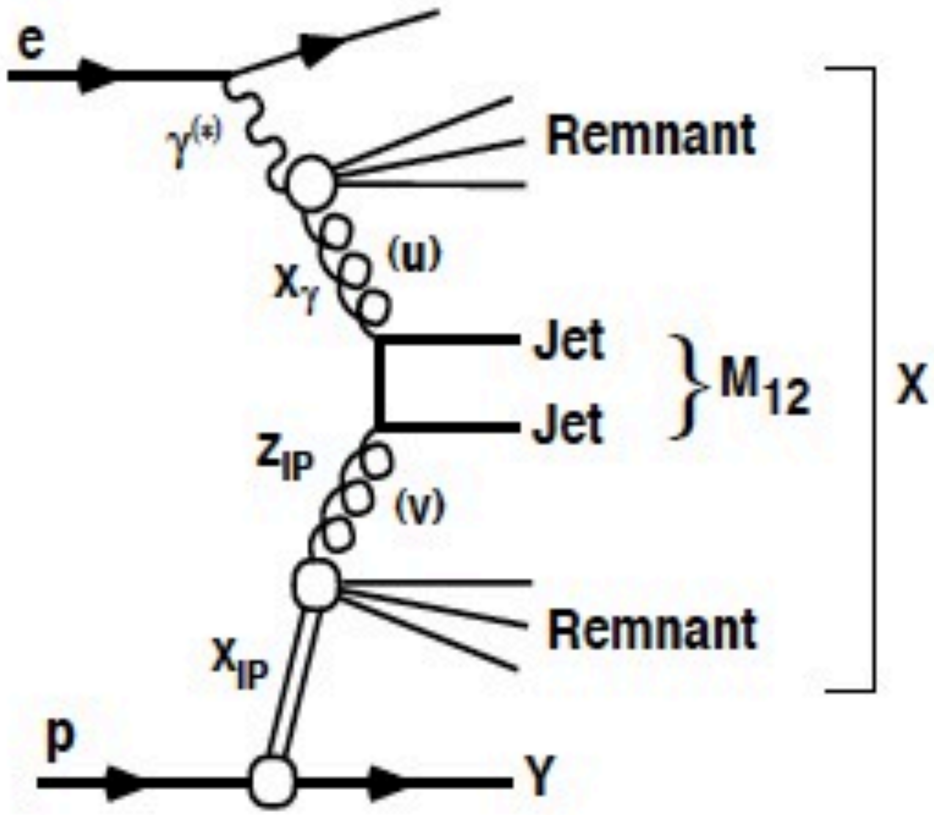
Hard diffraction in DIS

- Experiment
  - (hard) diffraction rebirth at HERA
  - Leading proton production in DIS
  - Target fragmentation region, $|t| \leq 1$ GeV^2
  - Leading twist: $\mathcal{O}(Q^{-4})$ (as iDIS)
  - scaling violations $\rightarrow$ parton dynamics
- Theory
  - Factorisation theorem for DDIS :
    $d\sigma \propto f_i^D \otimes d\hat{\sigma}$
  - pQCD evolution of f_i^D (DGLAP)
- Result
  - Partonic structure of the colourless exchange quite well known
  - Enconded in diffractive PDFs (i.e. Fracture Functions)



Diffractive parton distributions and factorization

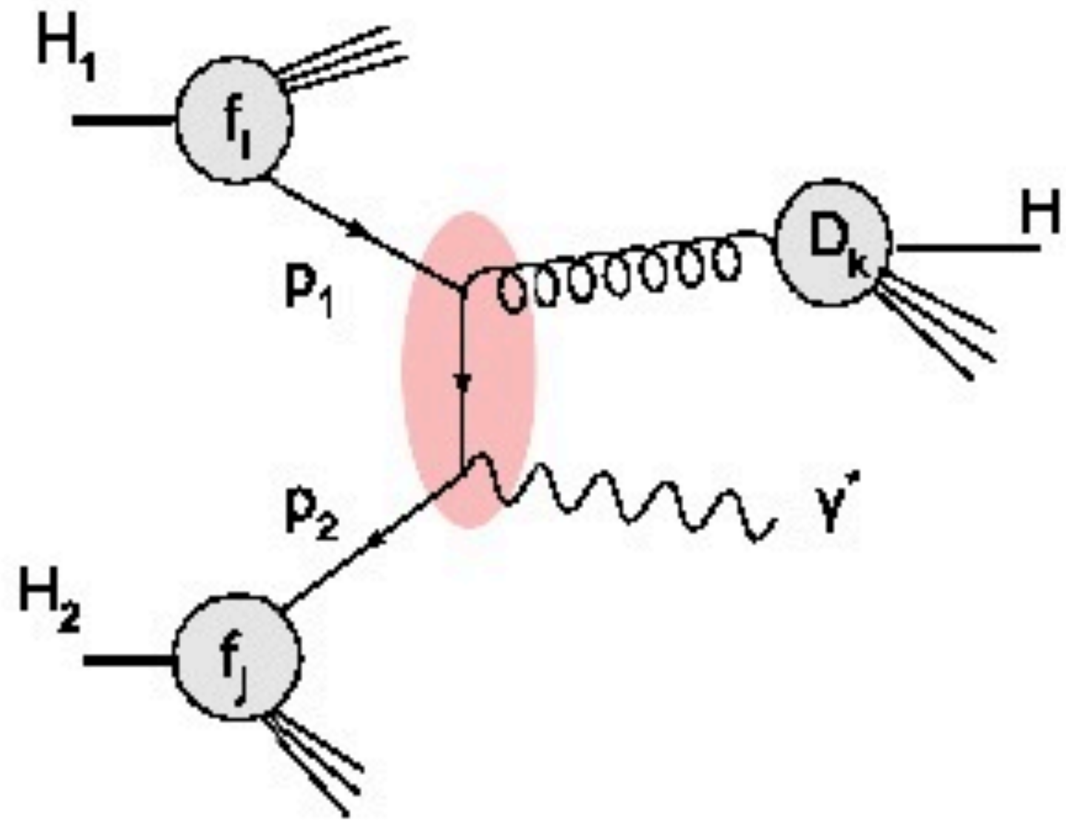
- Diffractive PDFs have bees used to test hard-scattering factorisation in
  - dijet in DIS
  - dijet in PHP ($Q^2 \simeq 0$, $E_T \sim 5, 6$ GeV)
  - dijet or $W^{\pm}$ in $p\bar{p}$ collisions



- Results:
  - dijet in DIS: data/NLO $\simeq 1$
  - dijet in PHP: debated
    H1 reports violation: data/NLO $\simeq 0.5$
    ZEUS consistent with no violation: data/NLO $\simeq 1$
  - pp : Striking breakdown confirmed at Tevatron: data/NLO $\simeq 0.1$

- NB: Factorisation predicted to fail in Resolved PHP and hadronic collisions

On hard-scattering factorisation



- Hard-scattering factorisation is at the basis of discovery and precision physics (especially) at hadron colliders.
- Consider $H_1 + H_2 \to H + \gamma^* + X$
- Assume hard scattering factorisation:
  $d\sigma \propto f_{H_1} \otimes f_{H_2} \otimes D_H \otimes d\hat{\sigma}$
  and test it against data.
- Beware! No factorisation theorem for generic QCD and/or BSM processes but it works!
- Factorisation proven only for inclusive Drell-Yan (where it is easier to show that soft exchanges are power suppressed when one sums over final states).

→ When factorisation fails (as it does in hard diffraction in pp collisions) it opens a window on NP physics and the hadronic structure: ..NP physics is in the way it fails..

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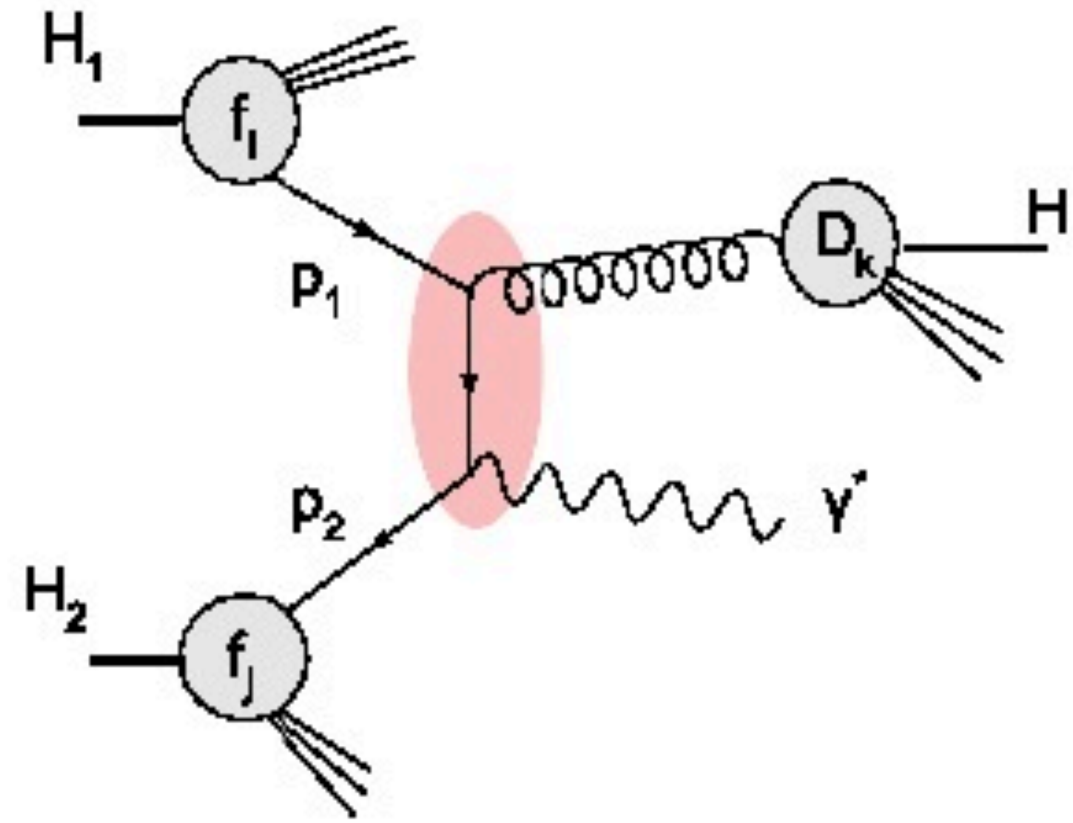

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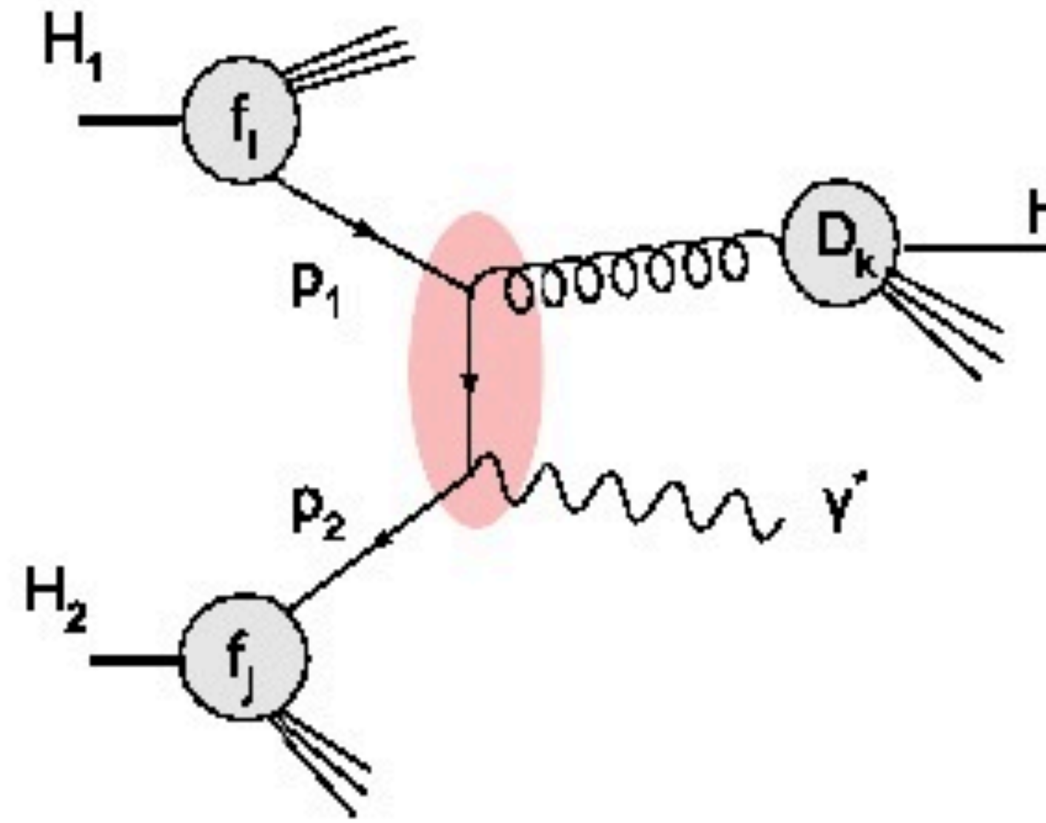

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Diffraction at LHC

- Numerous analyses on soft and hard diffraction are ongoing at LHC by all Collaborations.
- A number of them focuses on exclusive final state: prototype $p + p \to p \oplus X \oplus p$
- Opportunities also in heavy ions runs
- Method :
  - LRG with main detectors
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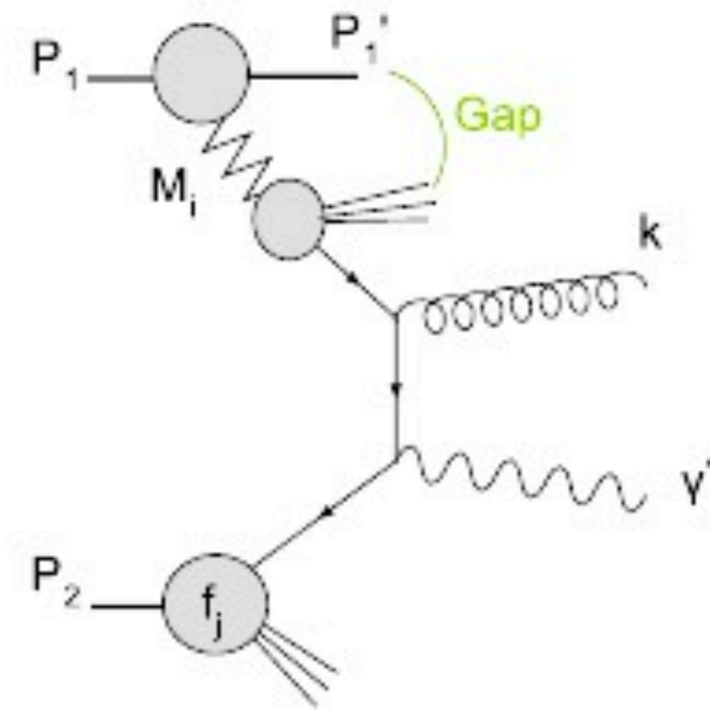

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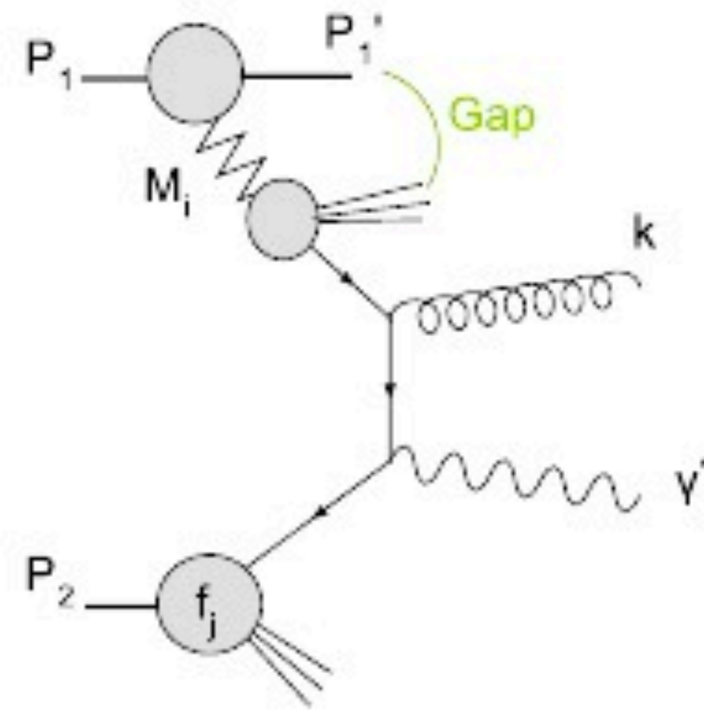

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Prototype process: diffractive DY

- consider the simplest process: $H_1 + H_2 \to H + \gamma^* + X$
- higher order corrections known (NNLO, pt, etc.)
- uncertainties under control (leptonic FS)

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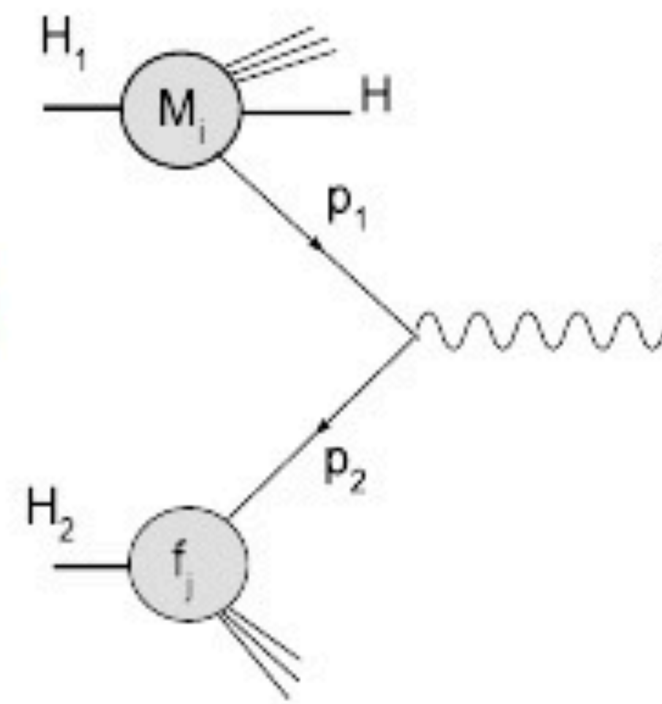

$$x_{I\!P}\frac{d\sigma^{DDY}}{dQ^2\,dY\,dx_{I\!P}} = \sigma_0 \sum_q e_q^2 M^D_{q/I\!P}\left(\frac{\sqrt{\tau}e^{Y}}{x_{I\!P}}, Q^2, x_{I\!P}\right) f_{\bar{q}/P_2}(\sqrt{\tau}e^{-Y}, Q^2)$$

- Dependencies of the cross section:
  - factorisation breaking vs Q^2 (vary DY mass)
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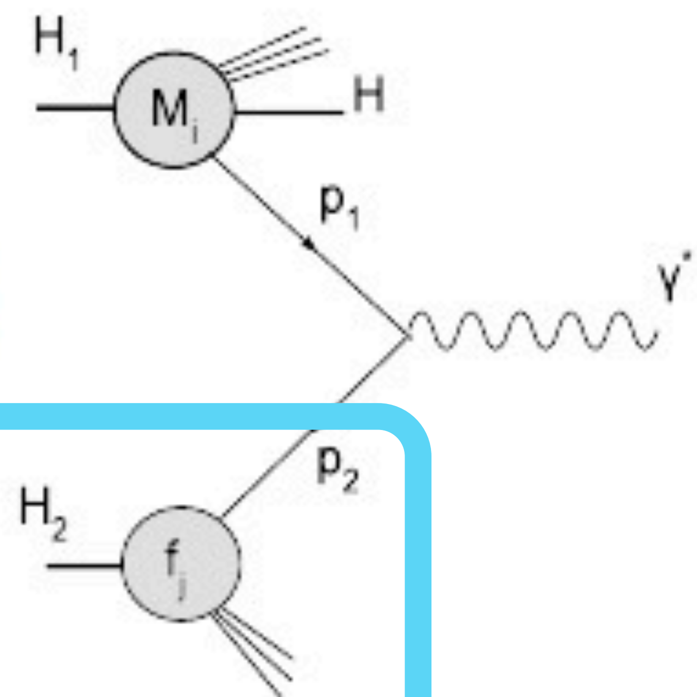

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- Can we correct the factorisation formula by a factor S?
  $d\sigma \propto f^D \otimes f \otimes d\hat{\sigma} \otimes S(..)$
- which are the dependences of S?
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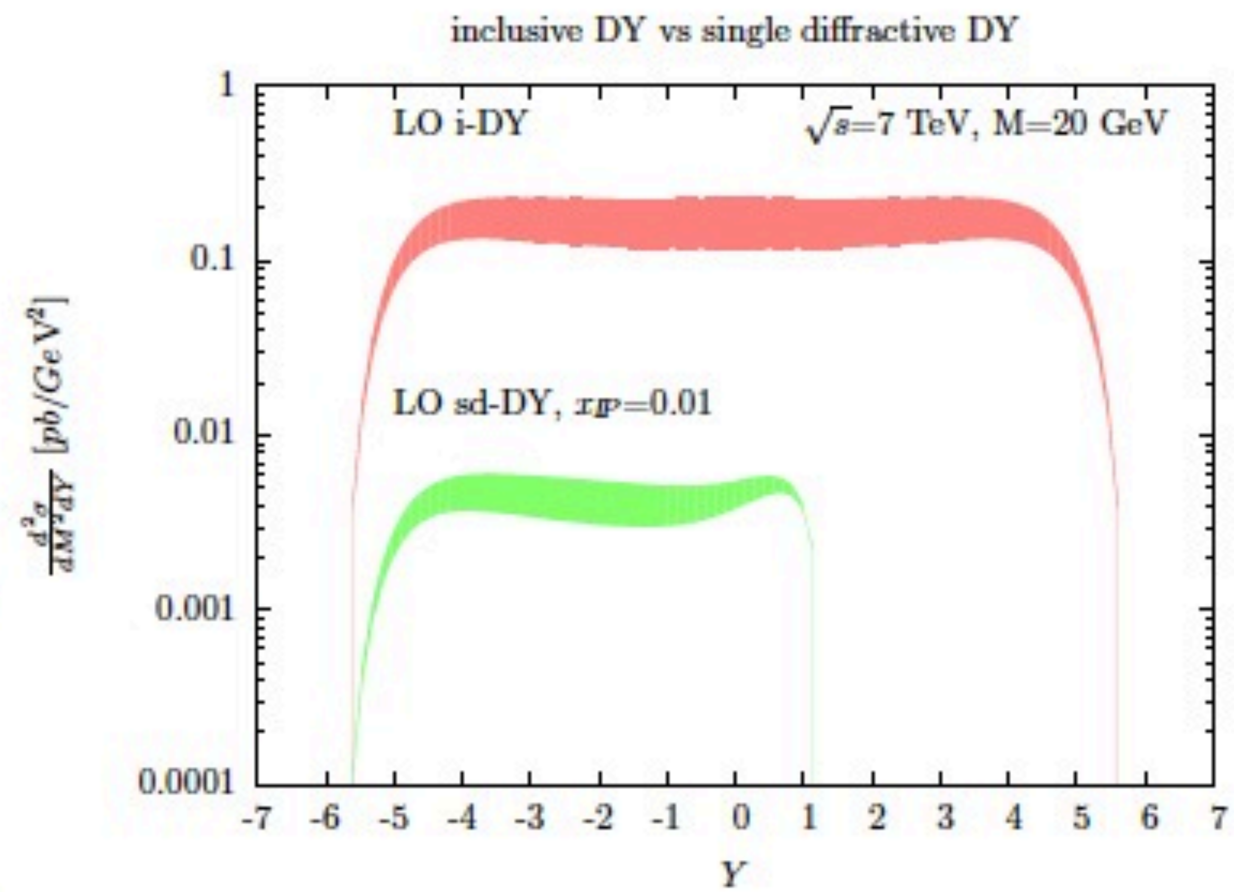

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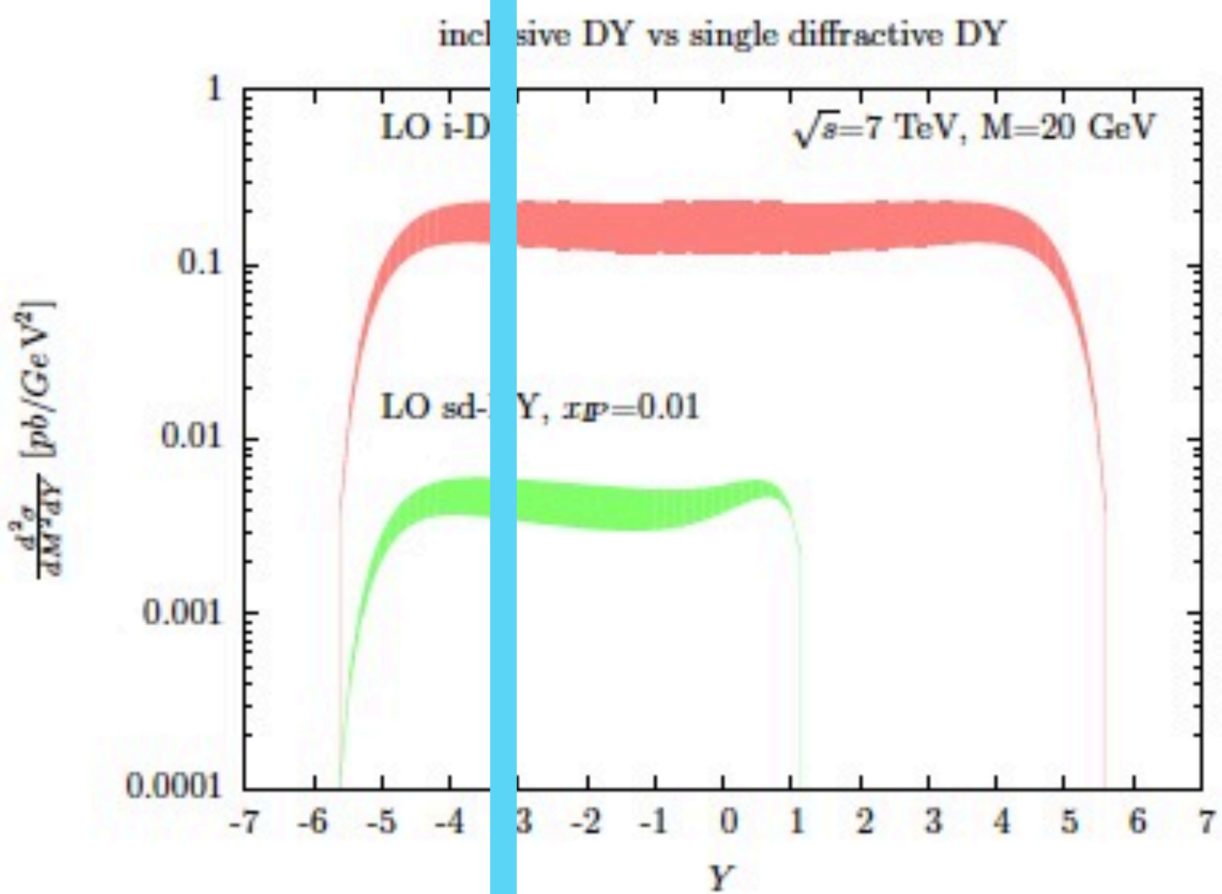

Hard diffraction : present and future

- Impressive knowledge on hard diffraction accumulated by HERA and Tevatron
- This knowledge is quantitative and predictive (dPDFs etc.)
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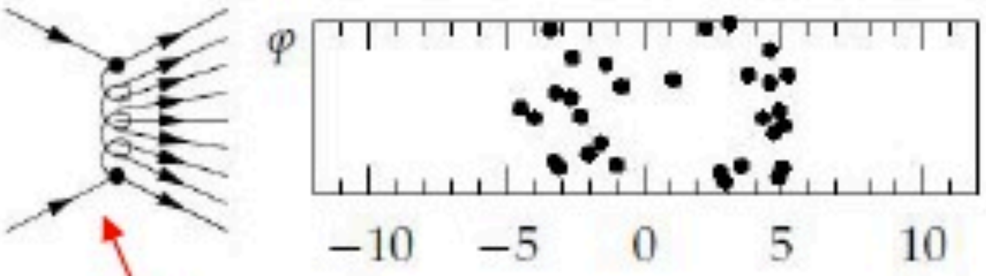
Diffractive Cross Sections
&
Events

Ken Österberg

Classification of soft pp events

Non-Diffractive process (ND) ≈ 60 mb @ $\sqrt{s}$ = 7 – 8 TeV



Non-diffractive

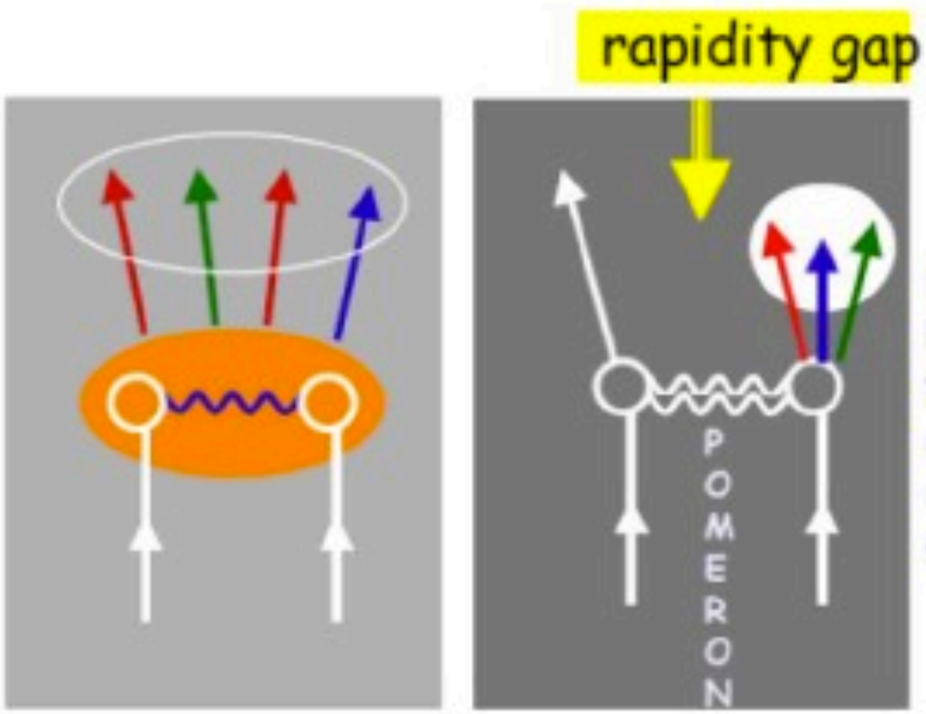
Colour exchange

dN / dΔη = exp (-Δη)

Diffractive

Colourless exchange with vacuum quantum numbers

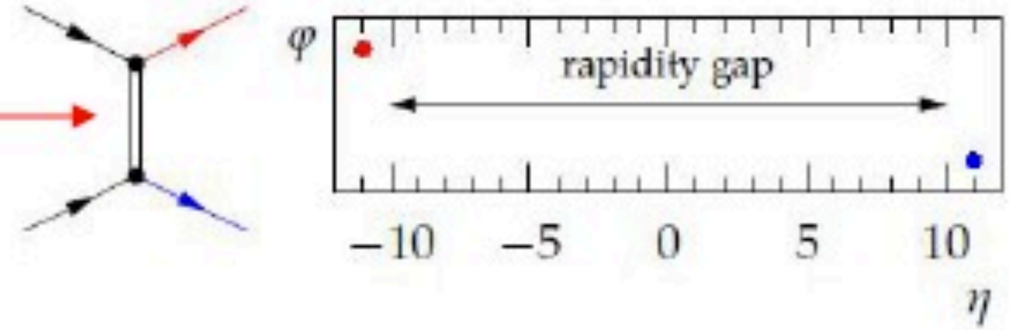
dN / dΔη = const



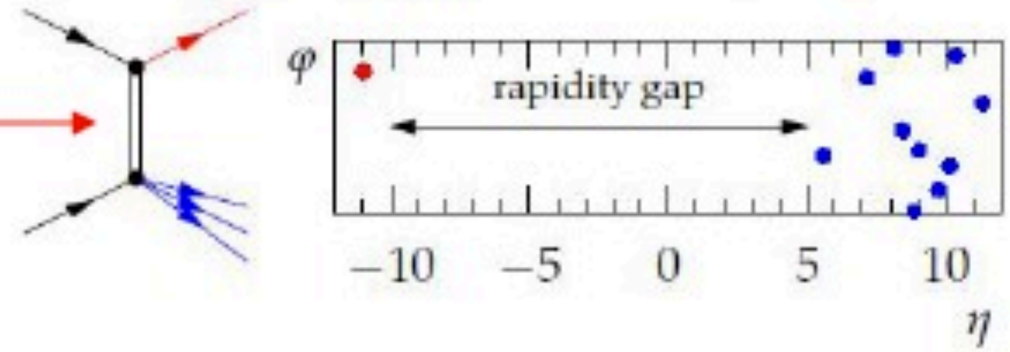
Incident hadrons retain their quantum numbers remaining colourless

- **Experimental signiture: leading protons and/or rapidity gaps**
- **QCD picture: pure combination of color-compensated gluons e.g. gluon pair/ladder**

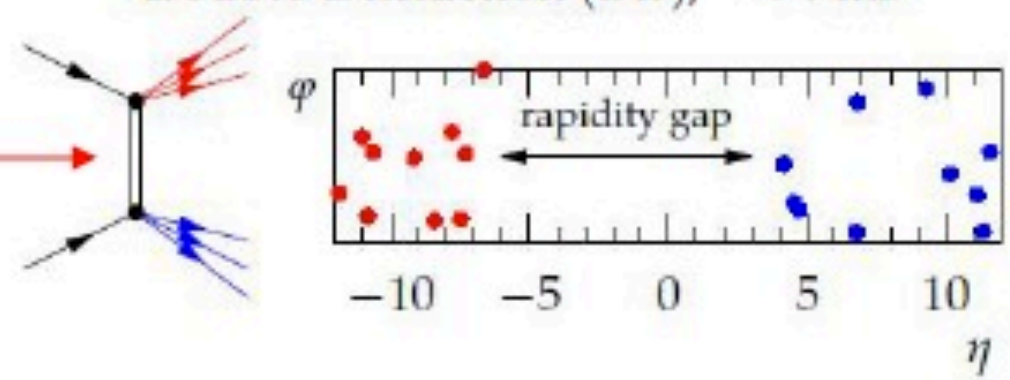
Elastic Scattering (ES), ≈ 25 mb



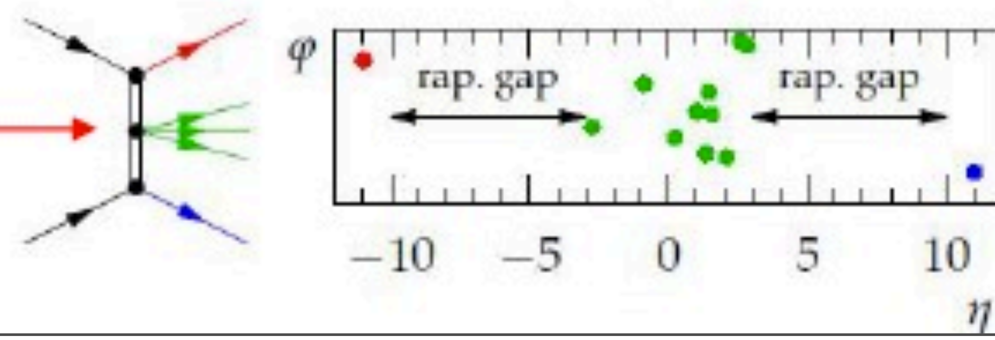
Single Diffraction (SD), ≈ 10 mb



Double Diffraction (DD), ≈ 5 mb



Central Diffraction (CD), ≈ 1 mb



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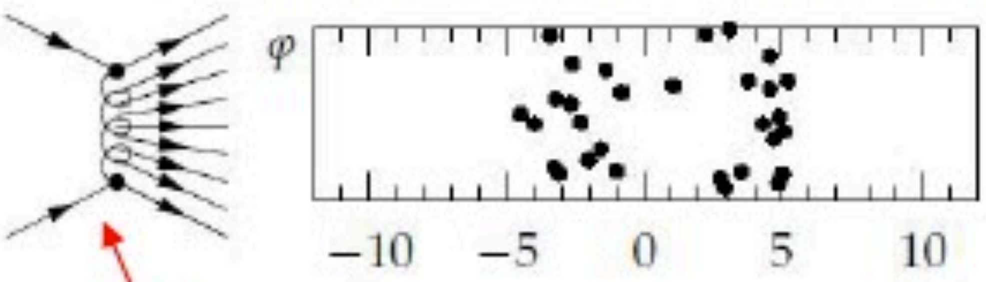

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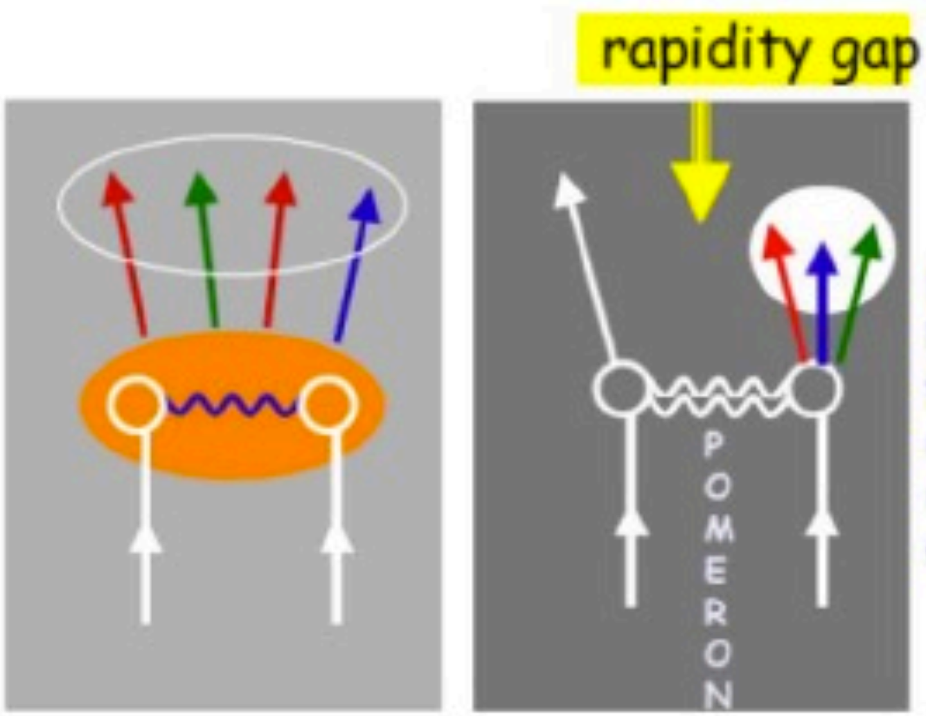

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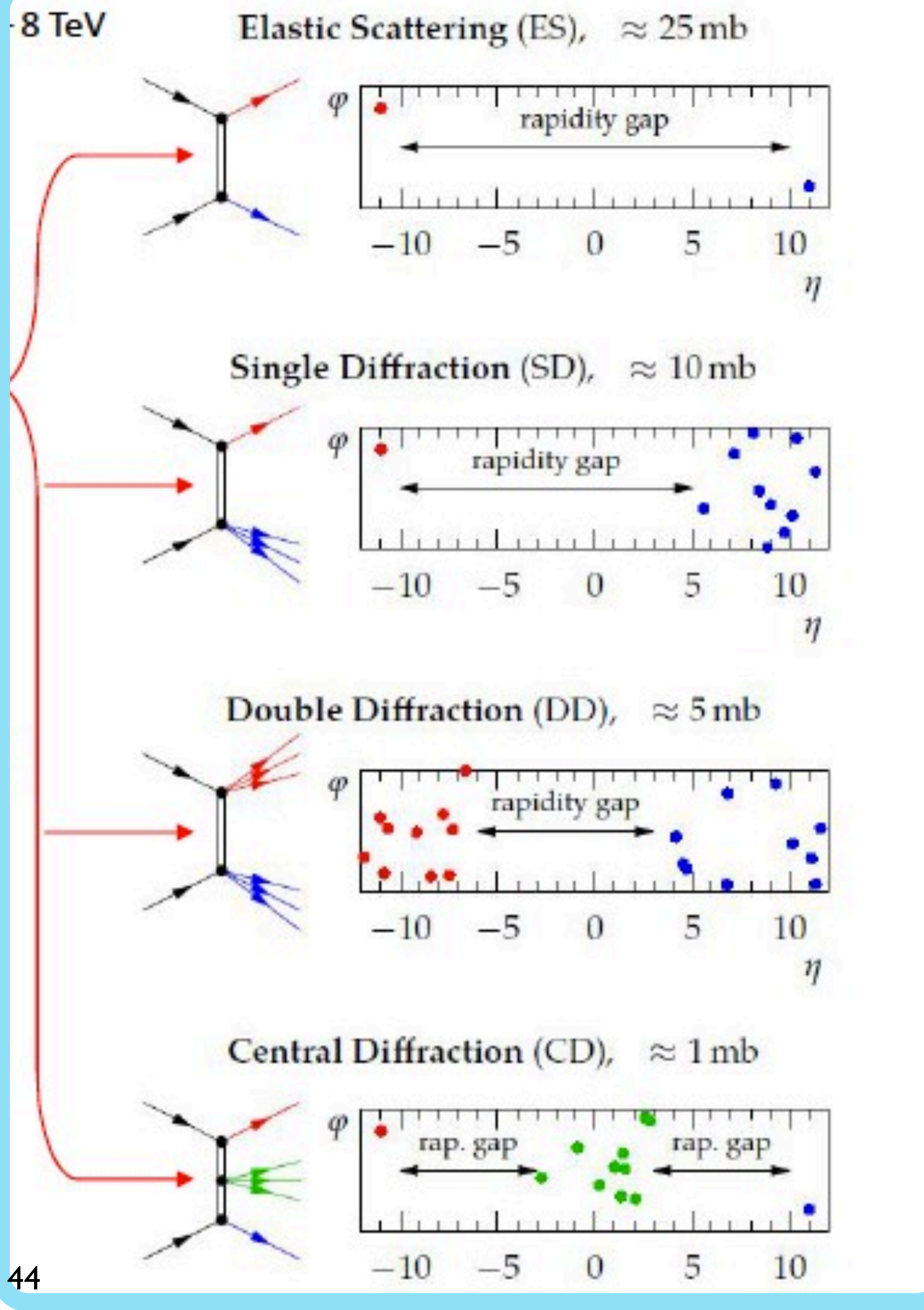

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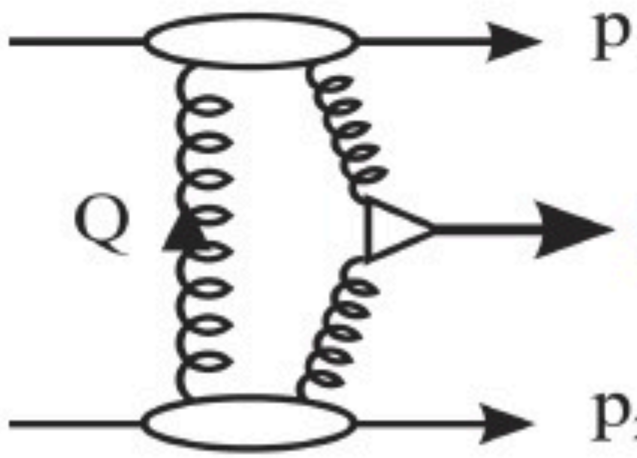


$M^2 = \xi_1 \xi_2 s$

$y_X = \frac{1}{2} \ln \frac{\xi_1}{\xi_2}$

also $\gamma\gamma$ fusion & photoproduction

gg collider !

exchange of colour singlets with vacuum quantum numbers ⇒ Selection rules for system X: $J^{PC} = 0^{++}, 2^{++}$

X = 0^{++} & 2^{++} (light q, c & b) resonances, jets,?....

$M = m_{\pi\pi} - \sim 1$ TeV,

$\sigma = O(\mu b) - O(fb)$

With proton tagging:

Normal LHC runs: M(pp) acceptance > 350 GeV

⇒ σ's small (fb), need high lumi, only accessible with CT PPS & AFP

Special runs: all M(pp), $\mu \sim 0.05 - 0.5$ ⇒ O(0.1-10 pb^{-1}/day)

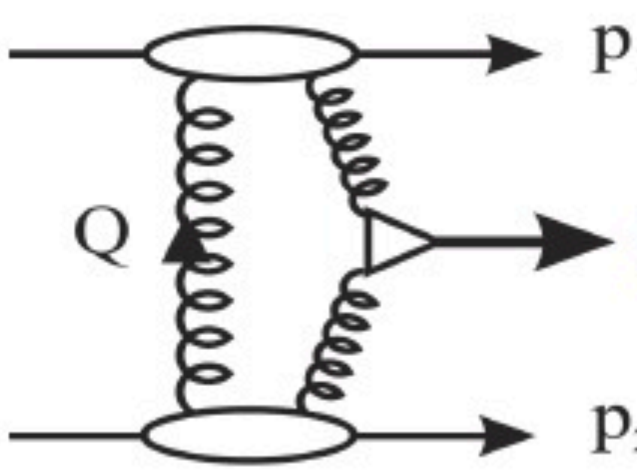
CMS & TOTEM common runs: if $\mu \sim 0.5$ need timing in vertical TOTEM RPs

With rapidity gaps (also ALICE, ATLAS & CMS):

LHCb in normal LHC runs, σ's (≥ fb), improved with Herschel .

14

Central exclusive production (CEP)



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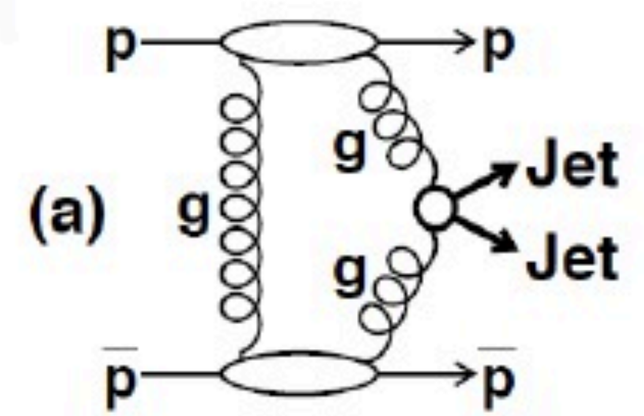
CEP jets

cross-sections, 3j/2j ratio, gluon jet studies

Durham group (KHARYS MC)



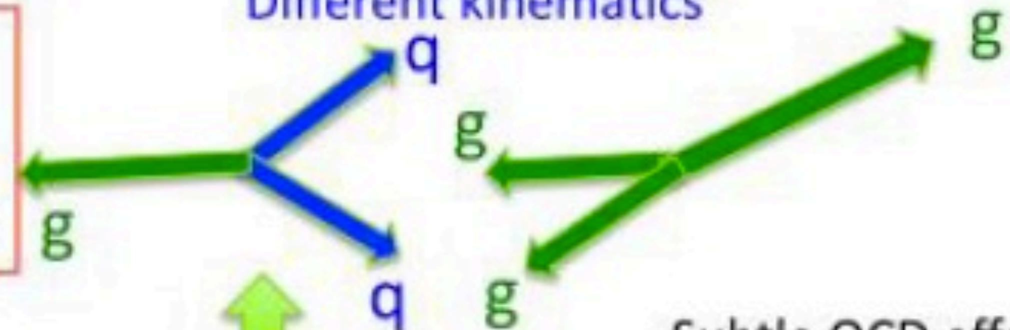
CDF Observed X = JJ at √s = 1.96 TeV to E_T = 30 GeV

At LEP: e+e- → Z → 2 jets (q-qbar) or 3 jets (q-qbar-g)

At LHC: IP + IP → 2 jets (g-g) or 3 jets (q-qbar-g) OR (g-g-g)

Different kinematics

99% of exclusive dijets are g-g (unique) 1% are b-bbar
→ uu, dd, ss, cc suppressed by $[m(q)/m(JJ)]^2$ (Durham theory gp)



Democratic so 1/5 each quark type:
20% b-bbar 20% c-cbar, ...

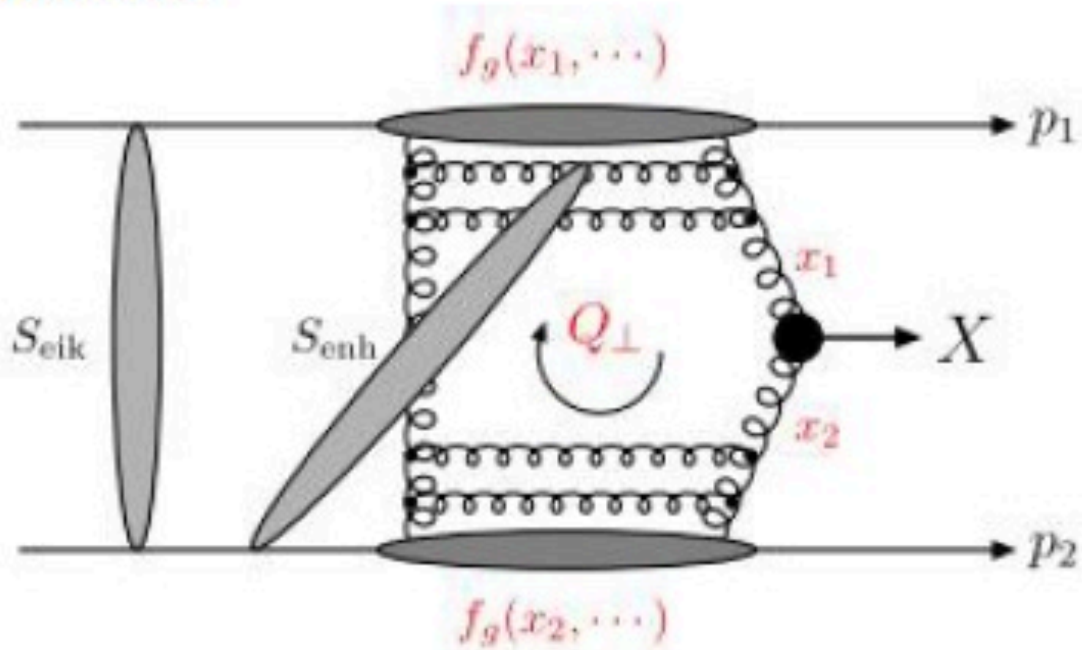
Subtle QCD effects:
No gluon radiation (Sudakov)
No other parton collisions
Test spin rule Jz = 0
Interplay of pQCD and npQCD
Distant relation to elastic scattering

Standard LHC runs: M(pp) acceptance > 350 GeV
⇒ σ's small (fb), need high lumi, only accessible with CT PPS & AFP

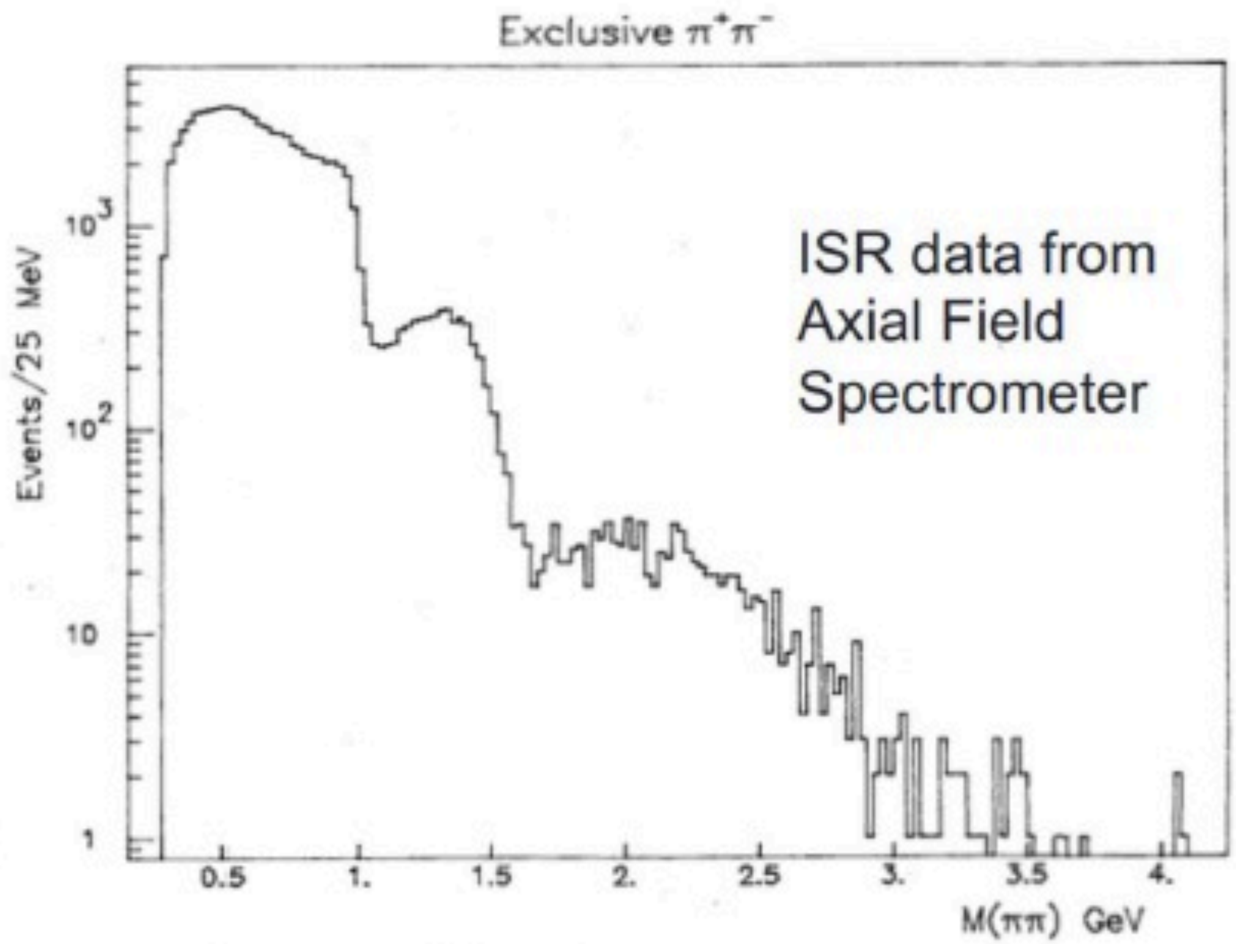
Special runs: all M(pp), μ ~ 0.5 & 1k bunches ⇒ $O(10\ pb^{-1})$
σ(M(pp) > 75 GeV) = ~100 pb @ s = 13 TeV (KHARYS)
only accessible with timing detectors in vertical TOTEM RPs

CEP low mass states & glueballs

KHARYS



X = low mass resonance /meson pair



LHC an excellent place to study CEP low mass states:

- small p_T's $\Rightarrow \Delta m \sim 10$ MeV from tracking (CMS-TOTEM & LHCb)
- excellent angular coverage (CMS-TOTEM & LHCb)
- proton tagging in special runs (CMS-TOTEM)

Pomeron = virtual glue ball ? $\Rightarrow$ likely to produce glue balls in Pomeron fusion

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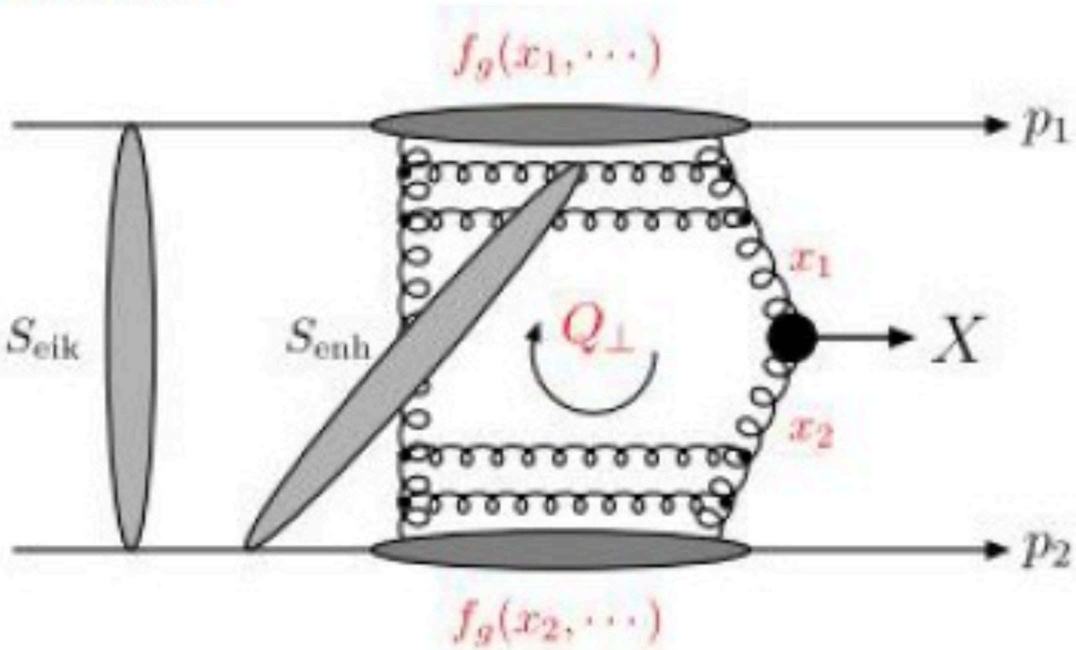

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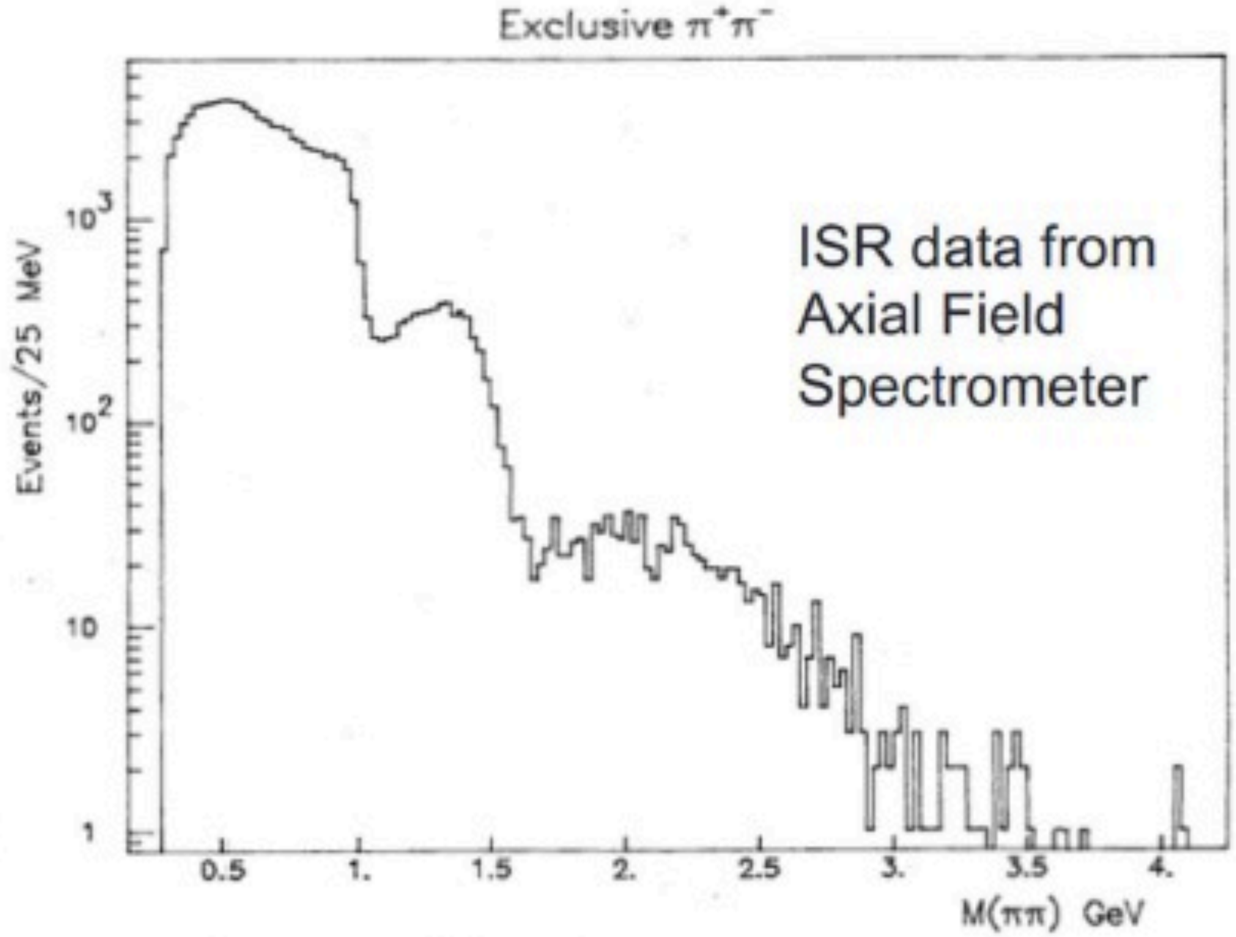

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Open questions: total, elastic and diffractive cross-section

1. **Understanding of low-t behaviour of $\sigma_{elastic}^{pp}$** : pure exponential behavior of hadronic amplitude? ↔ Interference Coulomb-hadronic interference & coherent effects, hadronic phase of elastic scattering: central or periheral

2. **Validity of optical theorem for hadron-hadron interactions?**

3. **Comprehensive picture of low mass diffraction**

4. **High energy behaviour of σ_{total}^{pp} / $\sigma_{inelastic}^{pp}$?** (↔ cosmic rays)

Open questions: Diffraction & central exclusive production (CEP)

1. Understanding factorisation breaking in hard diffraction?
2. Existence of glueballs (or gluon rich-resonances) & their hierarchy?
3. $\gamma\gamma$ fusion as probe for beyond SM physics ?

Color Confinement

Massimo D'Elia

- Luckily enough, many aspects of the Standard Model still puzzle and excite us.
  Some of the elementary degrees of freedom of the model, quark and gluons, never show up as free, asymptotic states.
  This is what is usually known as *color confinement*. And we do not why.

- The upper bound on observed fractional charges, compared to expectation from cosmological quark recombination, is suppressed by around 10^{-15}
  This is either the fruit of extremely very fine tuning, or the result of some symmetry principle which we have still not understood.

- Evidence for partons inside hadrons is well established. The problem is therefore that of bringing two partons far apart from each other.
  This is naturally related to long distance (i.e. low energy) physics.

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- Strong interactions are described by Quantum Chromodynamics, which is an asymptotically free theory at high energies (Gross, Politzer, Wilckez, 1973).
  That implies a growing coupling at large distances, where the theory is non-perturbative.
  But strong attraction is not enough to explain confinement.

- Color Confinement emerges as a property of the ground state of the theory. It is not possible to excite colored states over the ground state, just hadrons
  It goes along with other non-perturbative properties of QCD, like chiral symmetry breaking and mass gap generation.

- Understanding such non-perturbative properties is a major challenge
  It is not only an issue for the Standard Model. It can be placed in a more general framework of understanding the dynamics of strongly coupled (gauge) theories
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Deconfinement as a probe for Confinement

Is strongly interacting matter confined forever?

N. Cabibbo and G. Parisi (1975): a new, deconfined state of matter, corresponding to quark liberation, may exist in extreme conditions of high temperature or high baryon density.

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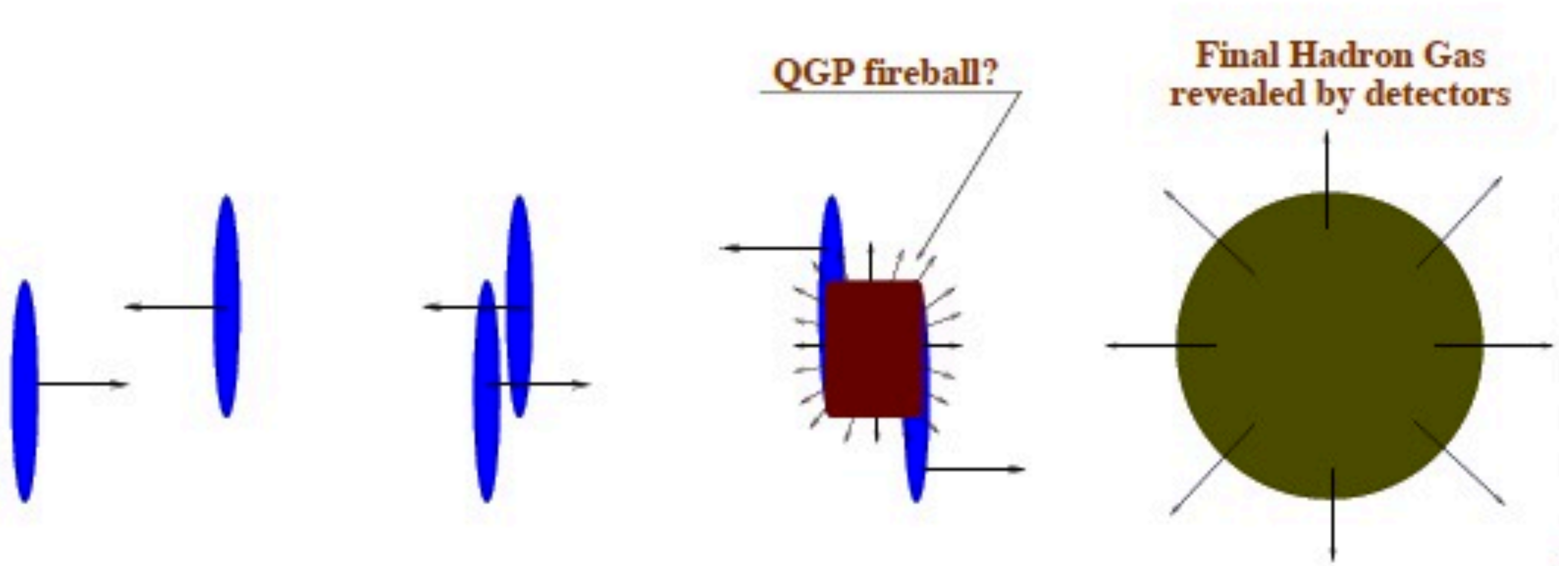
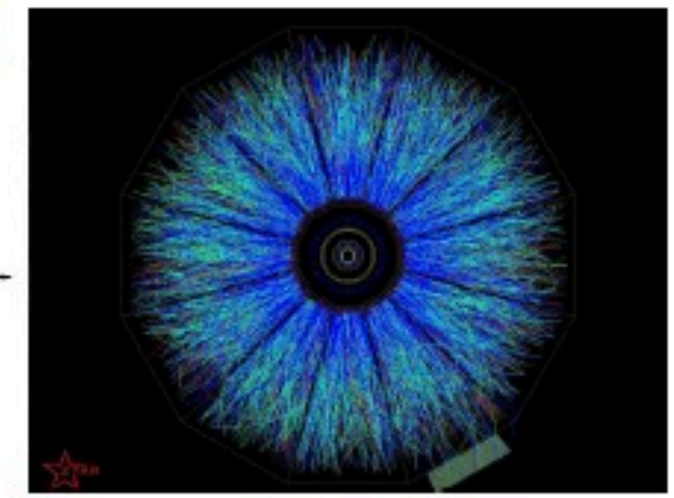
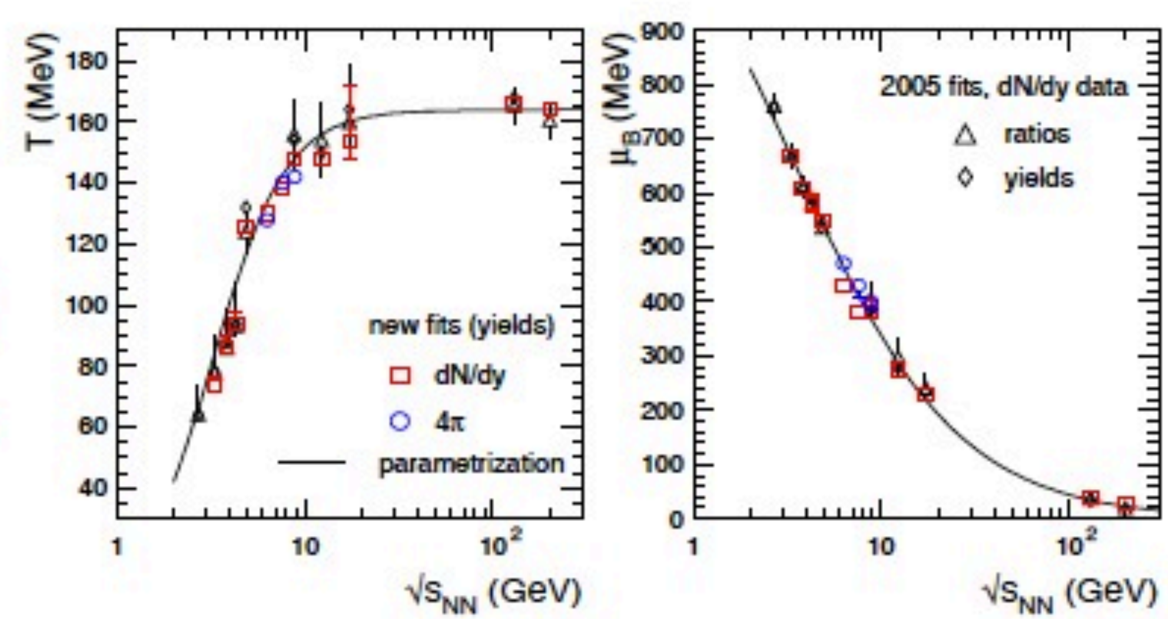
Experimental input? Heavy Ion Collisions (SPS, RHIC, LHC, ... FAIR)





- **Only final products directly accessible, particle multiplicities and ratios are well described by thermal distribution reached at chemical freeze-out**
  like for Cosmic Microwave Background after Big Bang

Depending on the c.m. energy, different values of T and μ_B reached at freeze-out:
$\mu_B \sim O(100)$ MeV at SPS, FAIR; $\mu_B \sim O(10)$ MeV at RHIC; $\mu_B \sim O(1)$ MeV at LHC; $\mu_B/T \sim 10^{-9}$ at the cosmological transition



Some considerations

How can confinement be an absolute property of the QCD vacuum, and deconfining be just a smooth change of properties (no transition)?

Maybe one should understand what the deconfined thermal medium really is.

Experimental input (heavy ion): liquid like behavior (elliptic flow) and jet quenching.

In which sense a quark is deconfined, and what are its transport properties through the deconfining thermal medium?

Unfortunately, lattice QCD is ideally suited only for the study of equilibrium properties

When considering real time dynamics, e.g. for transport properties, reaching a complete control over systematics is a very hard conceptual and numerical task.

(see M. Panero, K Rummukainen and A. Schaefer, PRL 112, 162001 (2014) for a recent study of soft mode contributions to jet quenching.)

Conclusions: goals and perspectives

- Understanding confinement at a fundamental level, likely in terms of weakly coupled dual variables.
  Perspective: many hints from QCD-like and string theories. Consistent indications about the role of topological objects from lattice simulations. A theoretical breakthrough is needed for a final answer in QCD

- Matching the computed and the observed hadron spectrum.
  Where are the glueballs? Do we understand the recently observed $Z_{c,b}$, X states?
  Perspective: waiting for future experiments and theoretical developments.

- Understanding equilibrium properties of thermal QCD, location and order of the finite T deconfining transition:
  Perspective: NOW. Present lattice techniques and computational resources allow control over statistical and systematic errors.

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