Selected Issues in Non-Perturbative QCD

Luca Trentadue
Universitá di Parma and INFN Milano Bicocca

QCD@WORK

Giovinazzo, June 17, 2014

This talk is a short selection of the topics presented and discussed at

INFN

The LTS1 2014 - Workshop on the Long Term Strategy of INFN-CSN1.
The next 10 years of accelerator based experiments

Isola d'Elba, May 21-24 2014

Many thanks to the organizers and to the colleagues conveners of the:

Working group "NP-QCD"

Mauro Anselmino and Marta Ruspa

and

...... many thanks to all the colleagues who contributed to the presentations and to the discussions, especially those who came from abroad,.............and finally I would like to thank the organizers

of this workshop for inviting me here....!

Nucleon 3D structure - Theory (Marco Radici, Pavia)
Nucleon 3D structure - Experimental data and perspectives (Andrea Bressan, Trieste)
Drell Yan scattering and the structure of hadrons, long term program (Oleg Denisov, Torino)
Parton distribution functions (Katarzyna Wichmann, DESY)
Cosmic ray physics at accelerators (Gaku Mistuka, Nagoya University & INFN Firenze)
Flavor and lattice - recent developments (Cecilia Tarantino, Roma3)
Spectroscopy (Roberto Mussa, Torino)
Multi parton interaction (Livio Fanó, Perugia)
New Ideas and a Project (Elena Santopinto, Genova)
Theoretical aspects of diffraction (Federico Ceccopieri, Liegi University)
Nucleon structure - strategy for the future (Rolf Ent, JLAB)
Total, elastic and diffractive cross sections (Kenneth Osterberg, Helsinki University)
Highlights on confinement (Massimo D'Elia, Pisa)

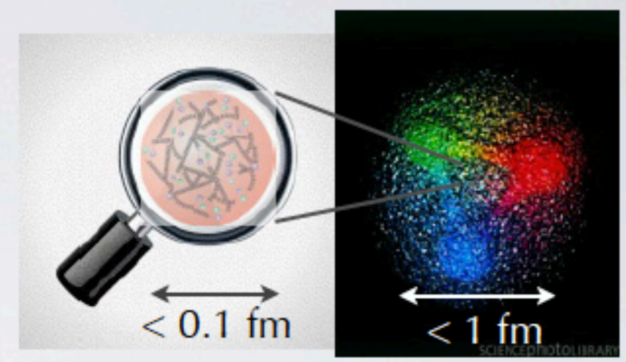
Nucleon 3D Structure theory

Marco Radici

INFN Pavia
Istituto Nazionale di Fisica Nucleare

the Infinite Momentum Frame (IMF)

probe short distances
⇒ Deep-Inelastic (DIS) regime



DIS regime
$Q^2 \to \infty$

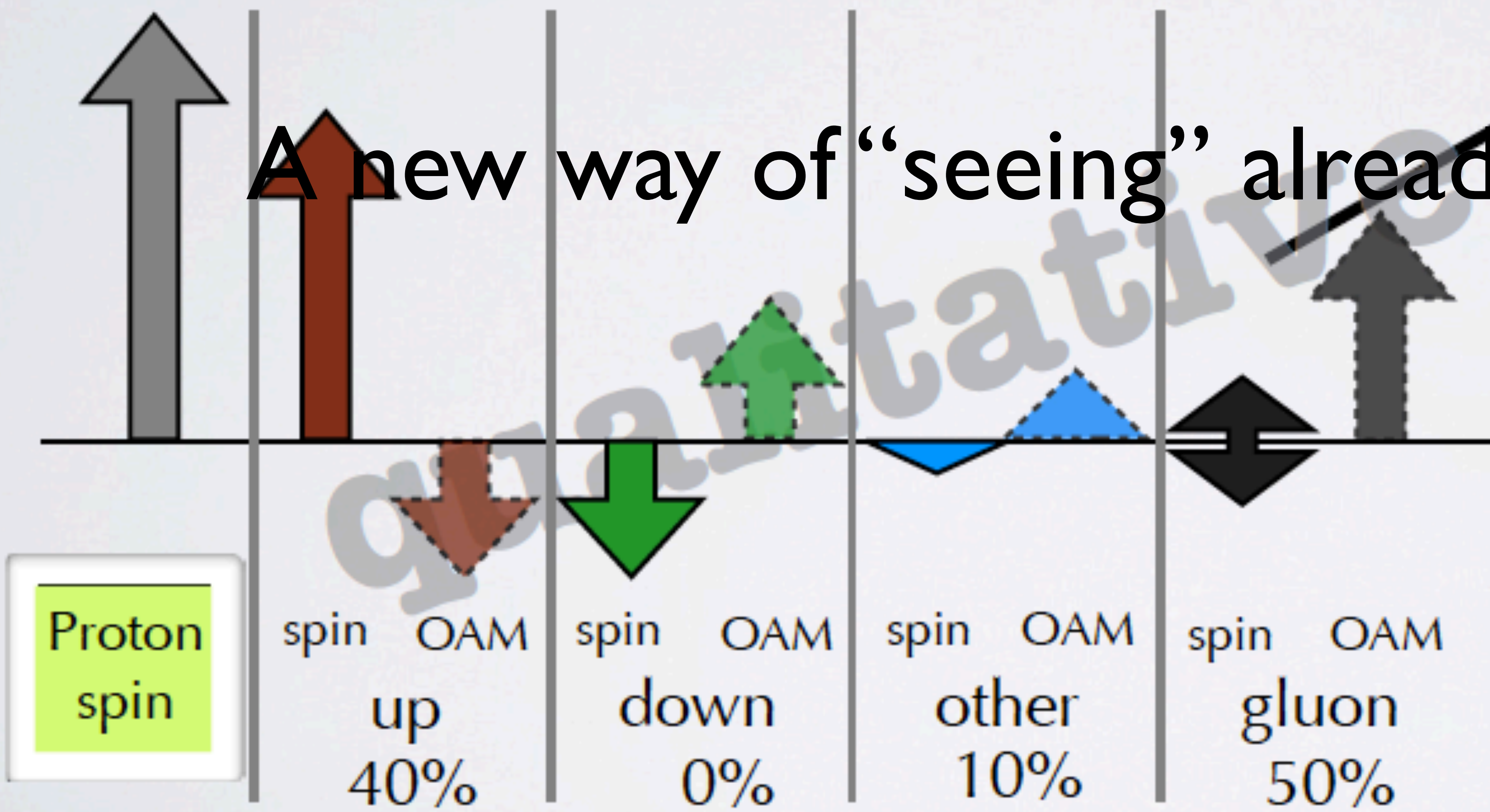
IMF <=> Light-Cone (LC) kin.

all partons ~ collinear
go beyond this approx.

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 = 1/2 ΔΣ + OAMq + Δg + OAMg

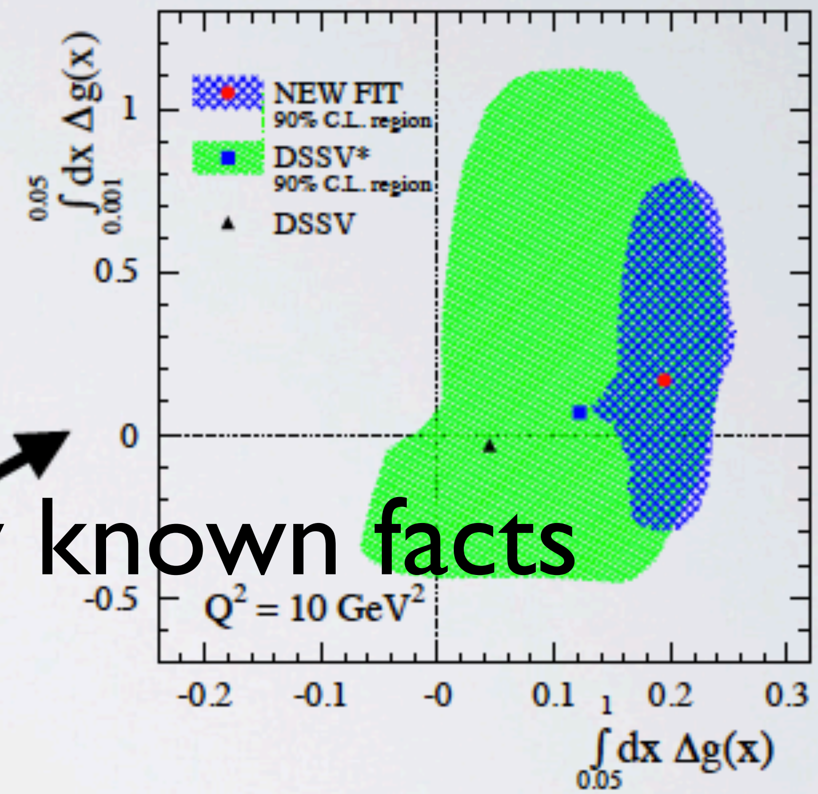


A new way of "seeing" already known facts

OAM = Orbital Angular Momentum

low x

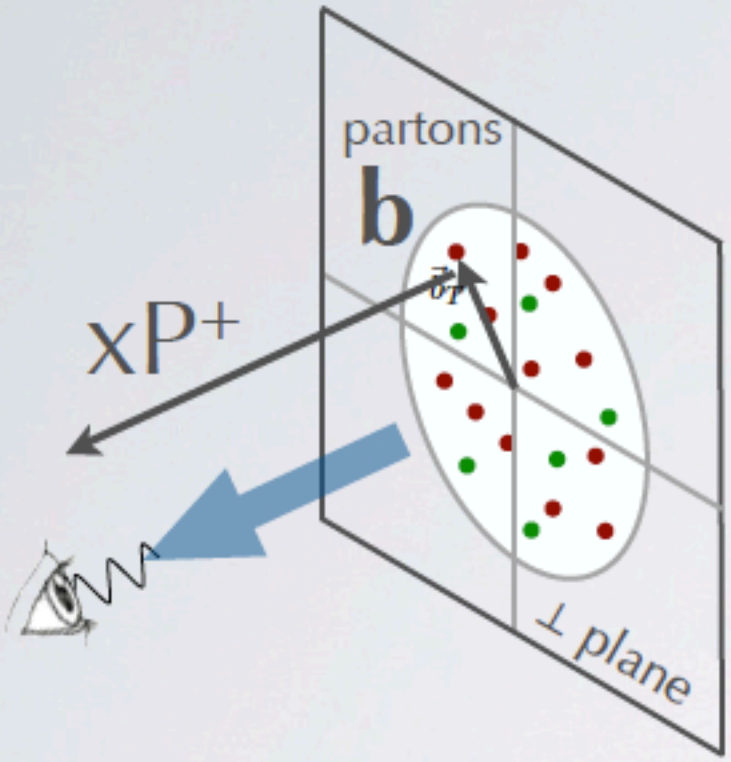
De Florian et al., arXiv:1404.4293



valence

we don't even know
the gluon helicity
$-0.15 \lesssim \Delta g \lesssim 1$

tomography of the Nucleon



GPD limit : $\xi \to 0$ ($P^+ = P'^+$) ; $t \to -(\mathbf{P}'_\perp - \mathbf{P}_\perp)^2 = -\mathbf{q}^2$

$$q(x, \mathbf{b}) = \int \frac{d\mathbf{q}}{(2\pi)^2} e^{i\mathbf{q}\cdot\mathbf{b}} H(x, 0, t = -\mathbf{q}^2)$$

q(x,**b**) is a density in **b** ↔ **q**=**P′**$_\perp$-**P**$_\perp$

density of partons with momentum x and position **b**

tomography of N

valid for all x ⇒

$$\rho^0(\mathbf{b}) = \int dx \int \frac{d\mathbf{q}}{(2\pi)^2} e^{i\mathbf{q}\cdot\mathbf{b}} H(x, 0, t = -\mathbf{q}^2)$$

$$= \int \frac{d\mathbf{q}}{(2\pi)^2} e^{i\mathbf{q}\cdot\mathbf{b}} F_1(t = -\mathbf{q}^2)$$

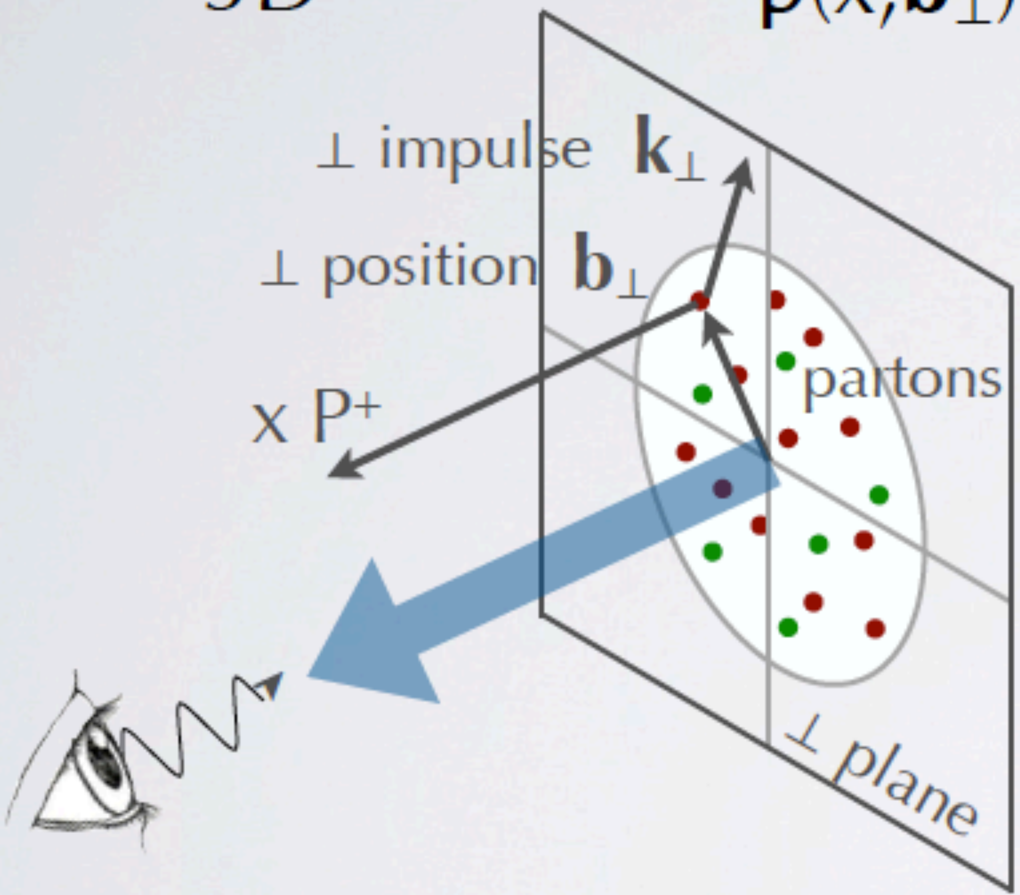
Dirac form factor

G.A. Miller, P.R.L. ***99*** *(07) 112001*

Wigner Distribution

5D ——— $W_{S_N,S_q}(x,\mathbf{k}_\perp,\mathbf{b}_\perp)$

3D ——— $\rho(x,\mathbf{b}_\perp)$



The "mother" distribution

correlation of quark ⊥ **momentum** and **position** for **S_N and S_q polarizations**

not positive-definite

but $\mathbf{b} \leftrightarrow \mathbf{q}=\mathbf{P}'_\perp-\mathbf{P}_\perp$

no constraint from Heisenberg principle

C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11) 041

Wigner Distribution

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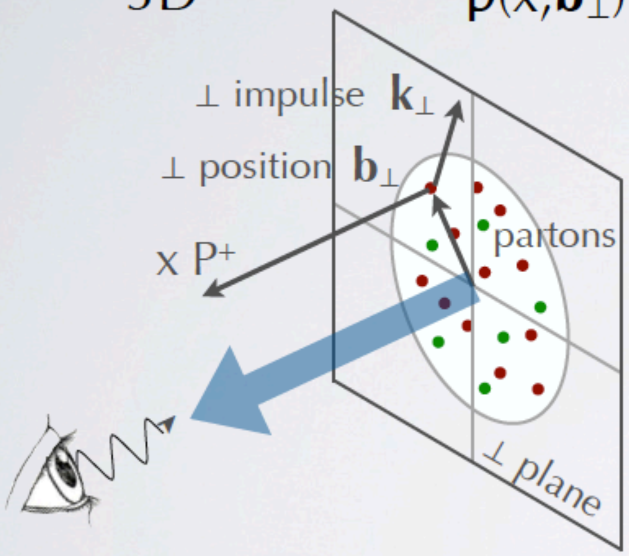

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$$\int d\mathbf{k}_\perp\, W(x,\mathbf{k}_\perp,\mathbf{b}_\perp) \to q(x,\mathbf{b}_\perp) \to \text{GPD}$$

in $\mathbf{b}_\perp$ space

$$f_1^q(x,\mathbf{b}_\perp;Q^2) = \sum_i [C_{q\,i} \otimes f_1^i]\left(x;\frac{c_0^2}{b_*^2}\right) e^{S_P(b_*;Q)}\, e^{S_{NP}(\mathbf{b}_\perp)\log Q/Q_0}\, f_1^q(x,\mathbf{b}_\perp;Q_0^2)$$

hard coeffs. — PDF — perturb. Sudakov — non-perturb. Sudakov — non-perturb. input TMD

all divergent for $b_\perp \to \infty$ $(k_\perp \to 0)$

prescription: $b_\perp \Rightarrow b_* = \dfrac{b_\perp}{\sqrt{1+\frac{b_\perp^2}{b_{\max}^2}}}$

depend on **parameters** to be fitted

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Physics Letters B 636 (2006) 310–316

PHYSICS LETTERS B

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Transverse momentum in semi-inclusive deep inelastic scattering

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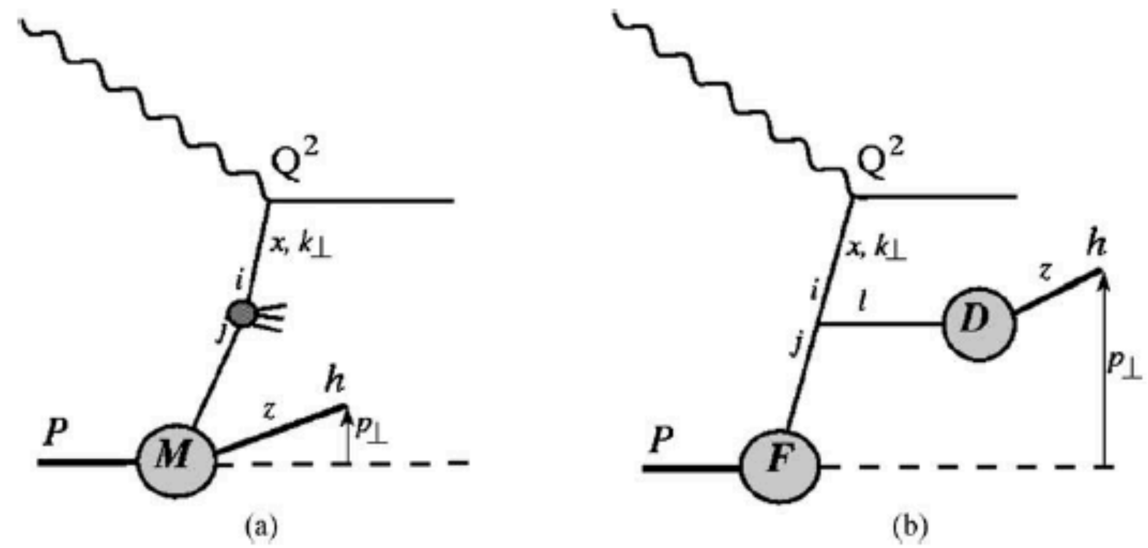
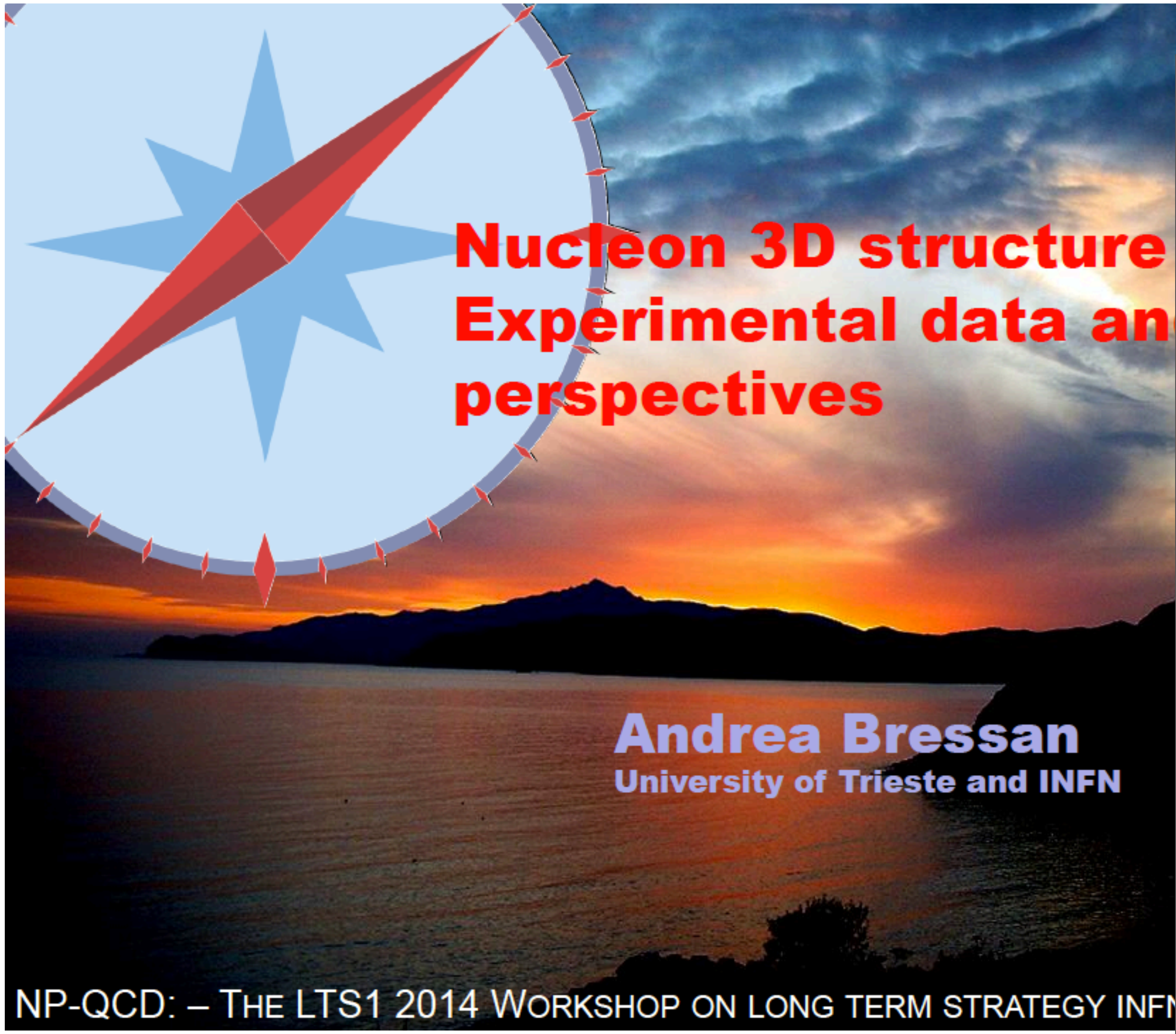
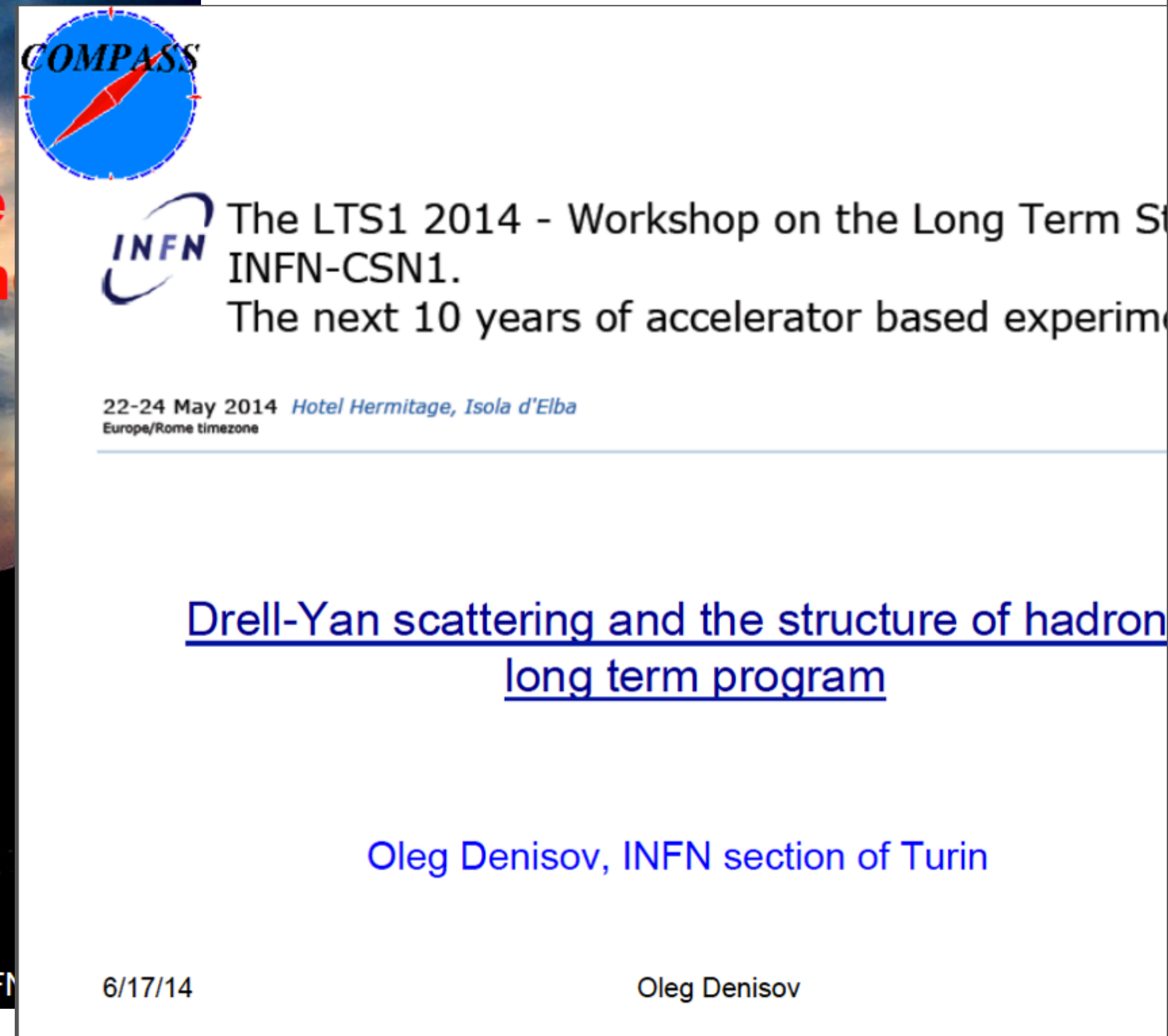


Fig. 3. Evolution of fracture functions M: (a) homogeneous term; (b) inhomogeneous one.

$$Q^2 \frac{\partial \mathcal{M}^i_{P,h}(x, \boldsymbol{k}_\perp, z, \boldsymbol{p}_\perp, Q^2)}{\partial Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \left\{ \int_{\frac{x}{1-z}}^{1} \frac{du}{u^3} P^i_j(u) \int \frac{d^2\boldsymbol{q}_\perp}{\pi} \delta\big((1-u)Q^2 - q_\perp^2\big) \mathcal{M}^j_{P,h}\left(Q^2, \frac{x}{u}, \frac{\boldsymbol{k}_\perp - \boldsymbol{q}_\perp}{u}, z, \boldsymbol{p}_\perp\right) + \int_x^{\frac{x}{x+z}} \frac{du}{x(1-u)u^2} \hat{P}^{i,l}_j(u) \frac{d^2\boldsymbol{q}_\perp}{\pi} \delta\big((1-u)Q^2 - q_\perp^2\big) \mathcal{F}^j_P\left(\frac{x}{u}, \frac{\boldsymbol{k}_\perp - \boldsymbol{q}_\perp}{u}, Q^2\right) \mathcal{D}^h_l\left(\frac{zu}{x(1-u)}, \boldsymbol{p}_\perp - \frac{zu}{x(1-u)}\boldsymbol{q}_\perp, Q^2\right) \right\}. \tag{12}$$

$$\int d^2\boldsymbol{k}_\perp \int d^2\boldsymbol{p}_\perp \, \mathcal{M}^i_{P,h}(x, \boldsymbol{k}_\perp, z, \boldsymbol{p}_\perp, Q^2) = \mathcal{M}^i_{P,h}(x, z, Q^2),$$





The COMPASS experiment at this Workshop:
Sebastian UHL, Vincent ANDRIEUX

Quantum tomography of the nucleon

COMPASS

QCD Evolution Workshop, Santa Fe, May 2014

E.C. Aschenauer

Join the real 3D experience !!

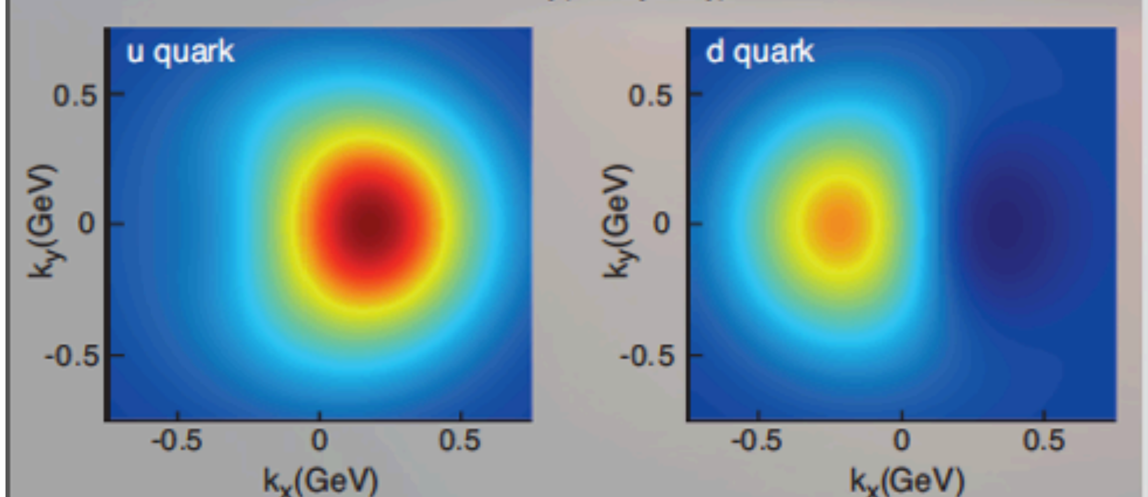
TMDs

2D+1 picture in momentum space

transverse momentum dependent distributions

$f_1 \rightarrow f_{1T}^{\perp}$

$x f_1(x, k_T, S_T)$



GPDs

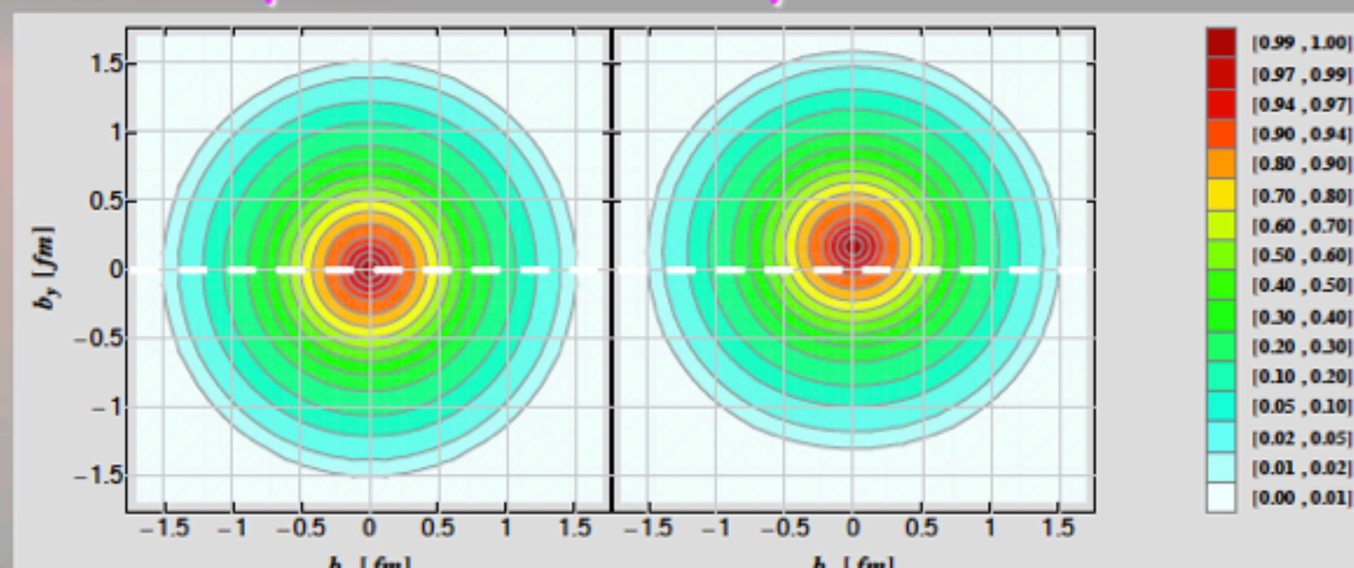
2D+1 picture in coordinate space

generalized parton distributions

→ exclusive reaction like DVCS

Quarks

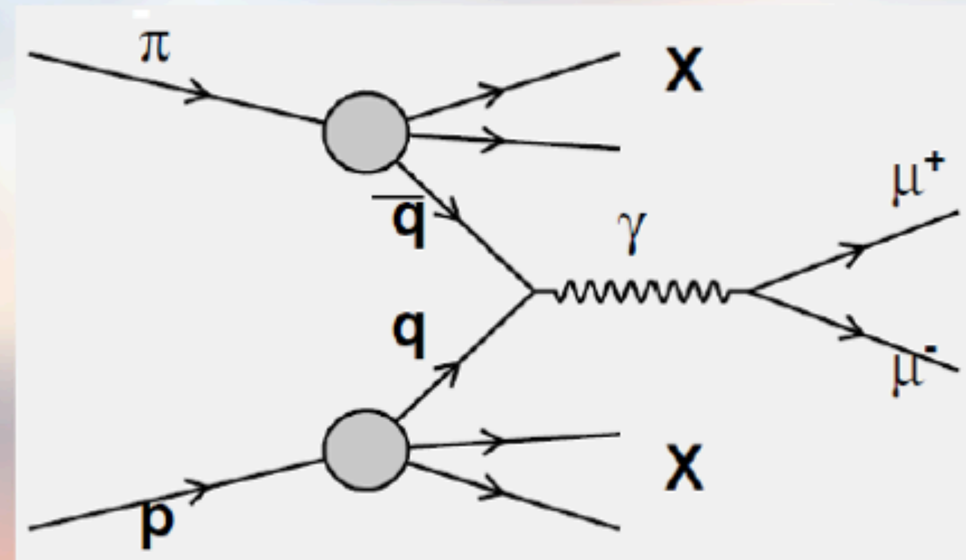
unpolarised polarised



Polarized Drell-Yan

Drell-Yan $\pi^{\uparrow -}\ p^{\uparrow\uparrow} \rightarrow \mu^{\uparrow +}\ \mu^{\uparrow -}\ X$

O. Denisov



Cross sections:

In SIDIS: convolution of a TMD with a fragmentation function

In DY: convolution of 2 TMDs $\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f_{u|p}$

→ complementary information and universality test

Parton Distribution Functions

Katarzyna Wichmann
DESY

here at this workshop
Marco GUZZI : parton distribution functions
of the proton

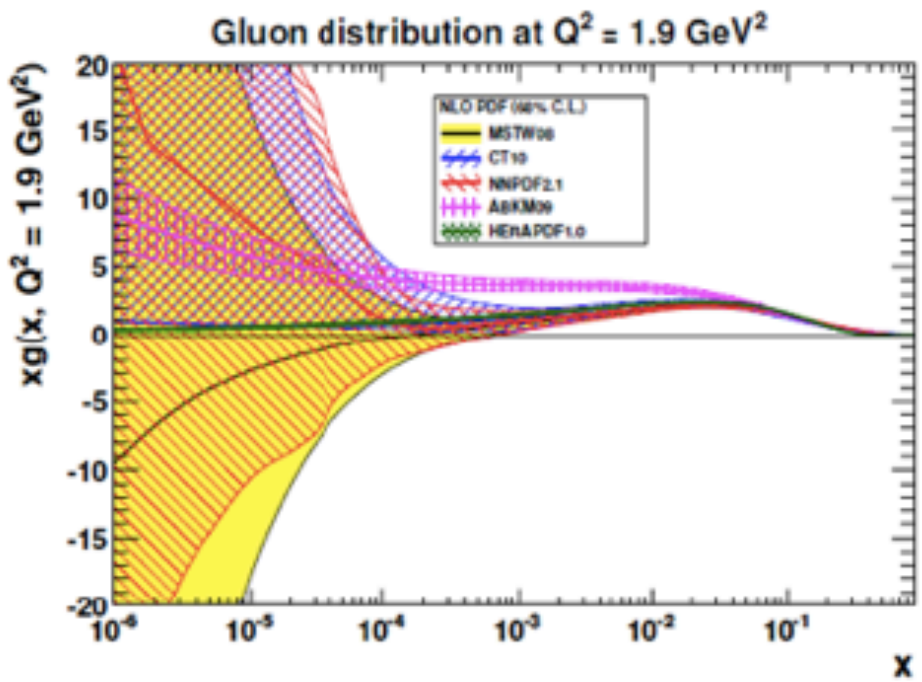
The gluon - much less known than we wish

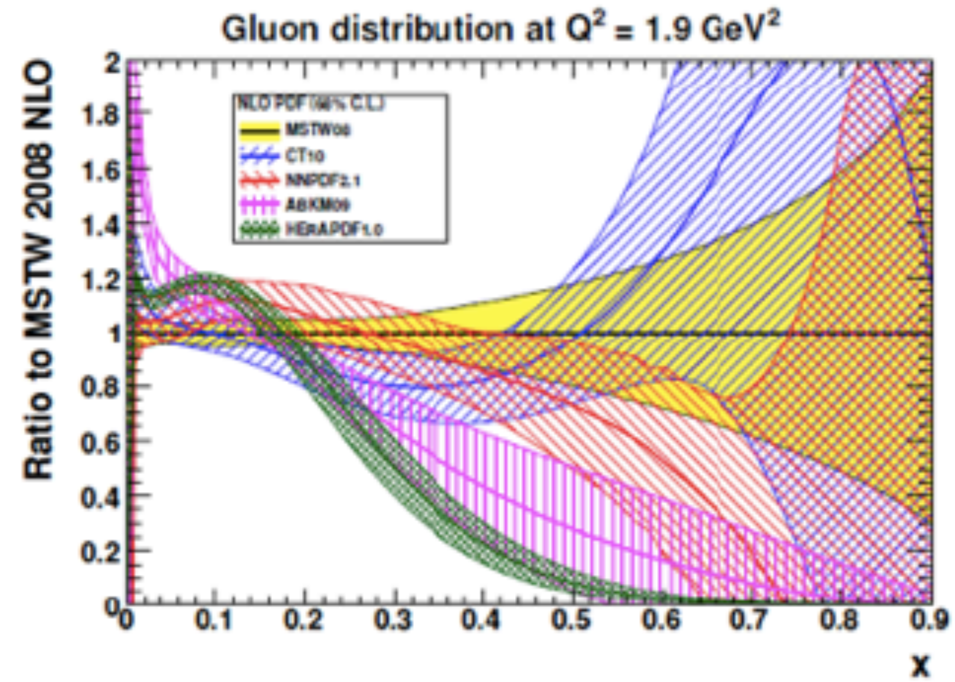
You may not realize that you will need it…

LOGARITHMIC Bjorken x SCALE

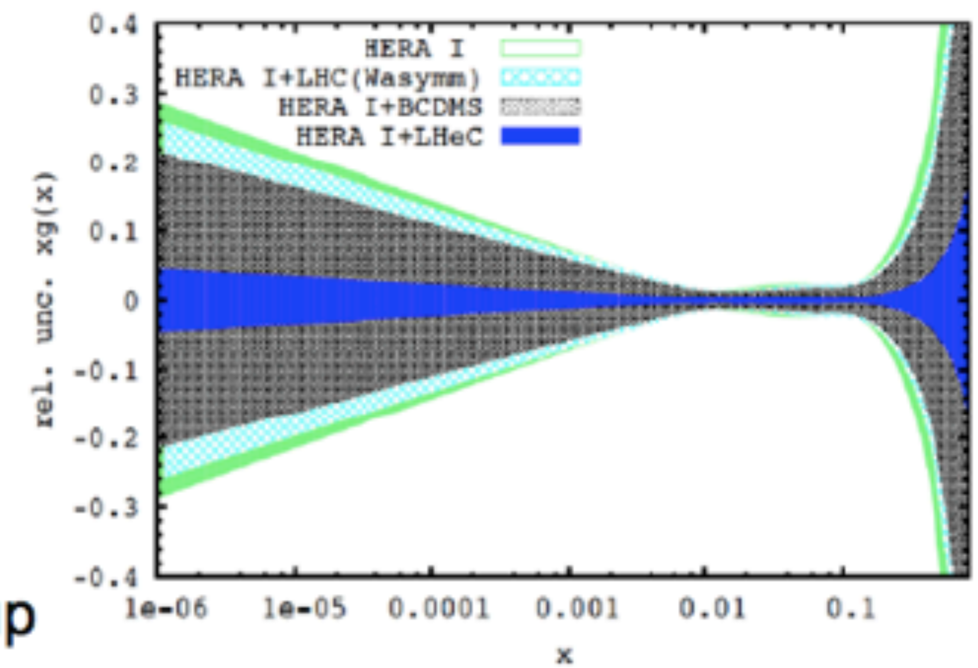
LINEAR Bjorken x SCALE

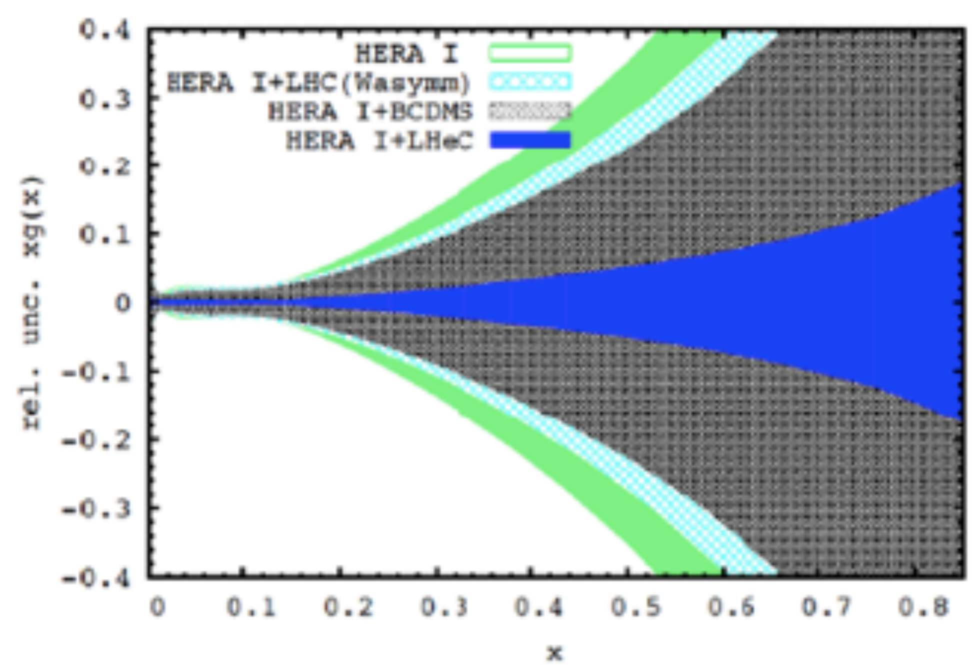
CURRENT





FUTURE





LHeC Study Group

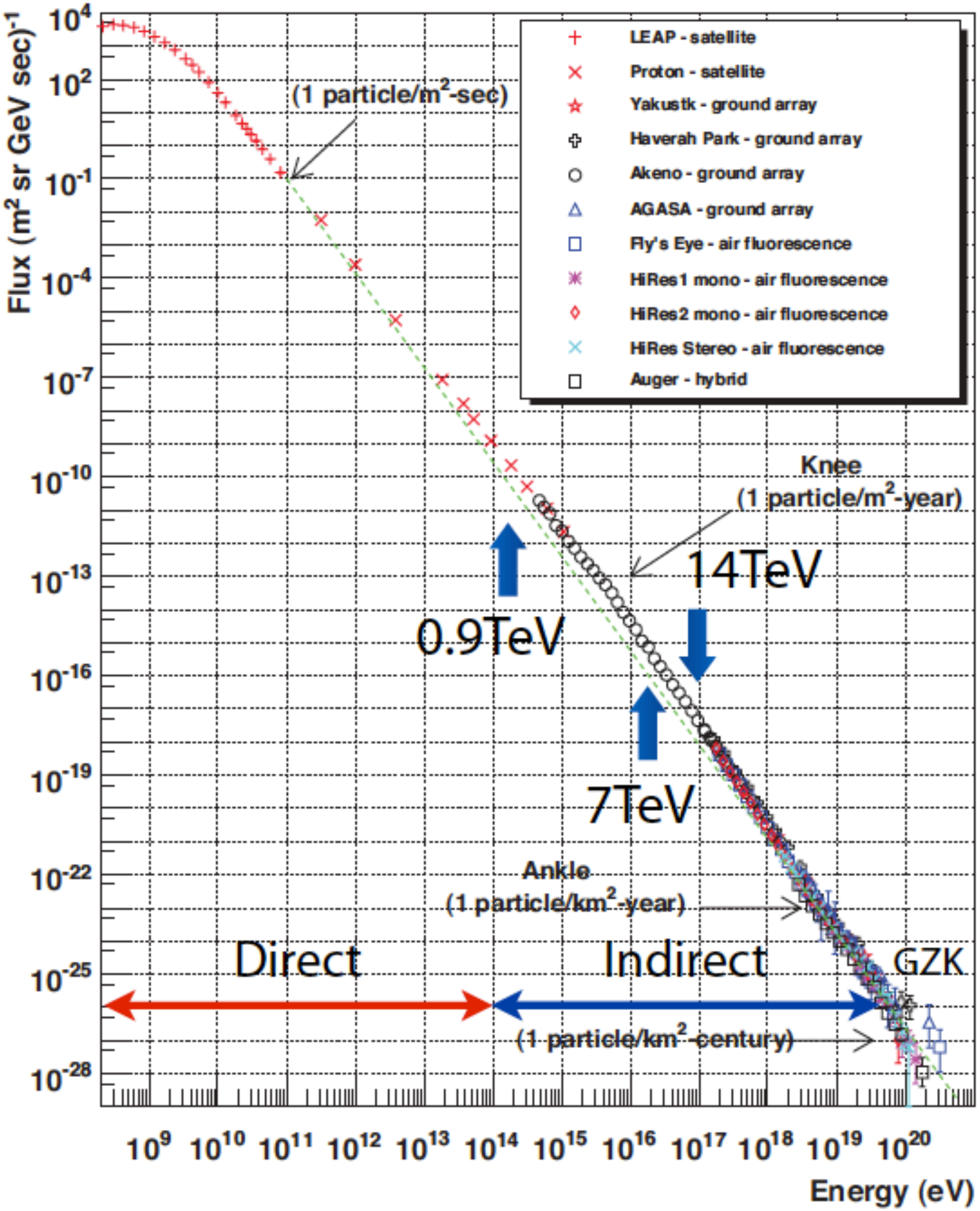
Cosmic ray physics at accelerators

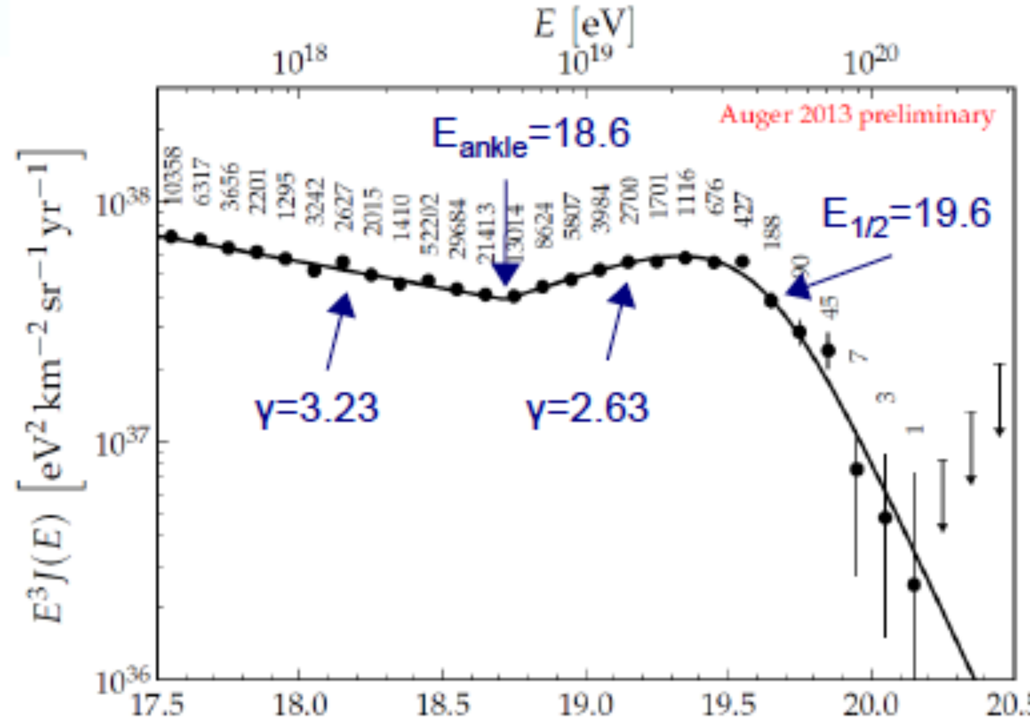
Gaku Mitsuka
(University of Florence, INFN Firenze, and JSPS fellow)

LTS1 Workshop, NP-QCD (22-24 May, 2014)

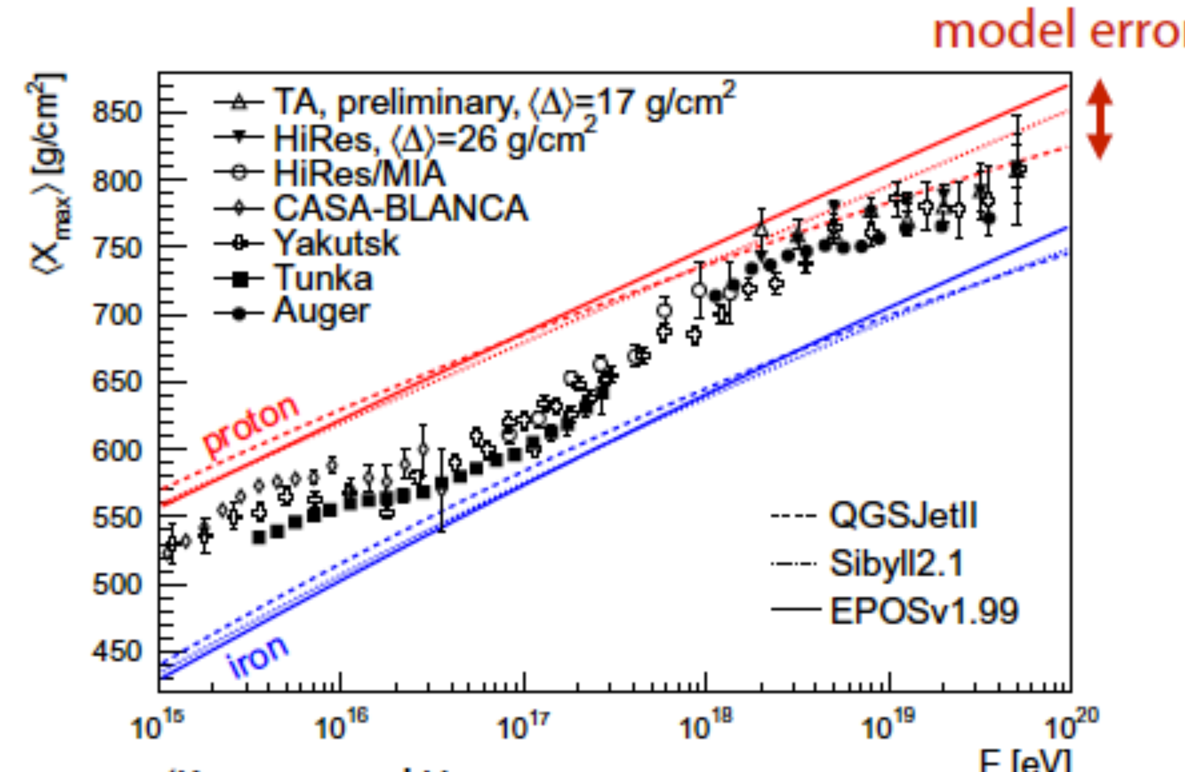
LHCf experiment

Cosmic ray observation





(ICRC2013, 769)



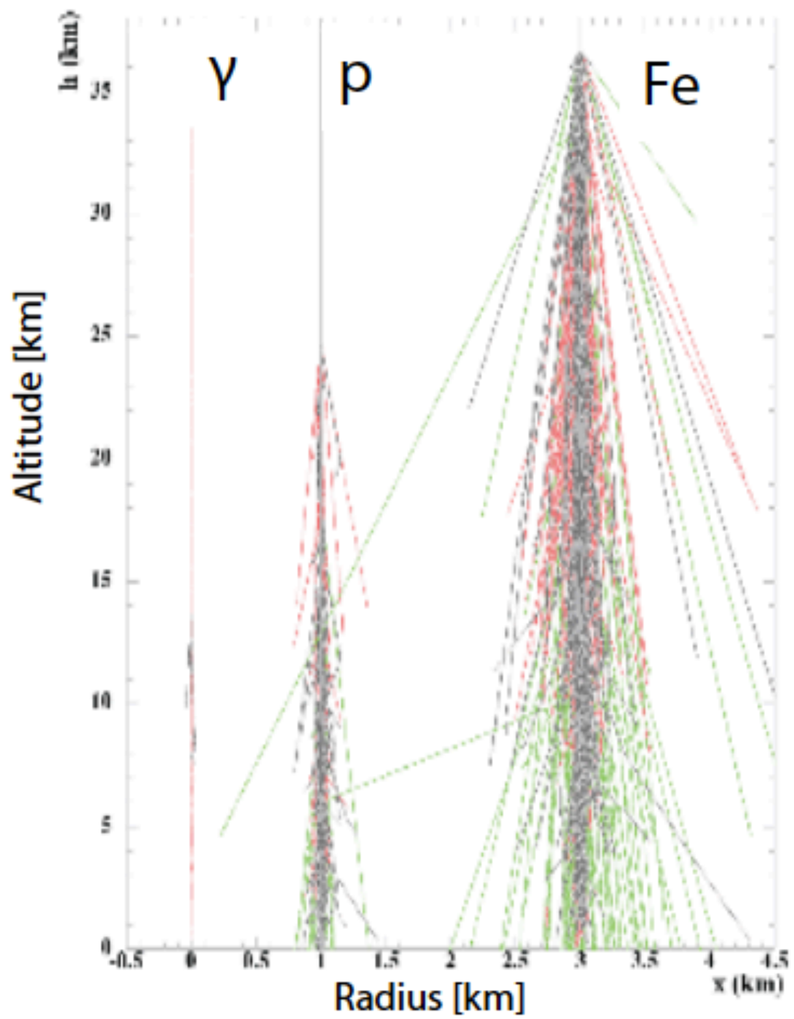
(Kampert and Unger, Astropartphys. 35, 660, (2012))

Energy, mass composition, and direction

→Source of cosmic ray

→Structure of the universe (goal)

Indirect observation of cosmic rays



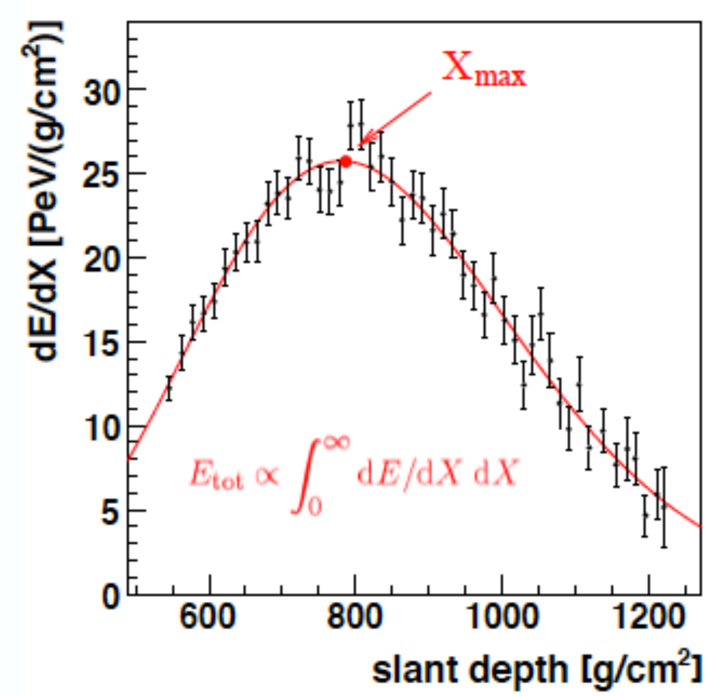
Surface detectors (charged+photon)

- It is impossible to directly* measure cosmic rays properties above 10^{14}eV, but **possible indirectly using the cascade shower of daughter particles, Extensive Air-Shower (EAS).**

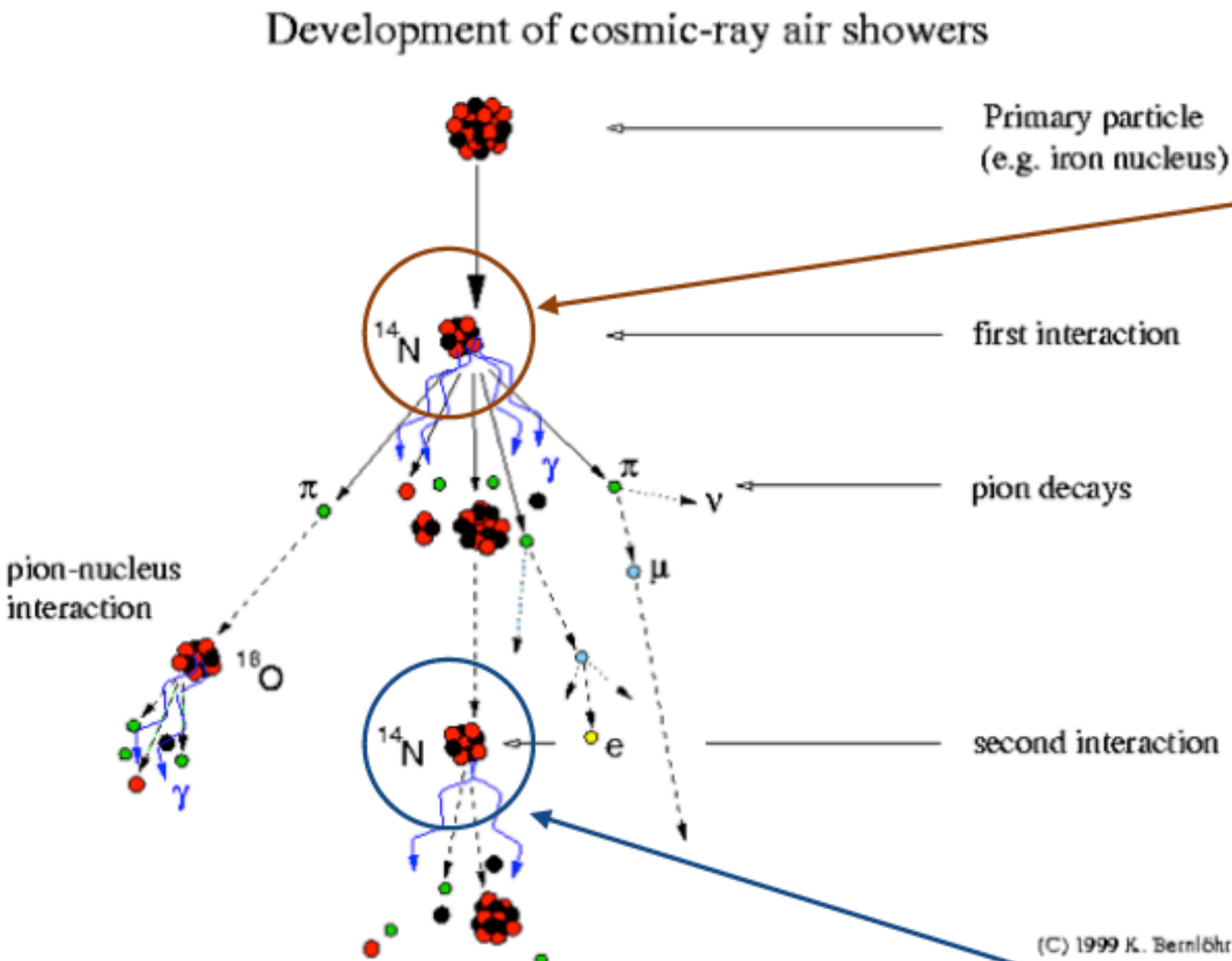
- Dependence of EAS on a mass composition and energy of cosmic rays is used for PID and energy reconstruction.

* direct measurement of cosmic ray <10^{14}eV is done by balloon, satellite, and ISS.

Fluorescence detectors (UV light from excited N_2)



Hadronic interaction in air shower



Largest systematic uncertainty of indirect measurement is in first interaction.

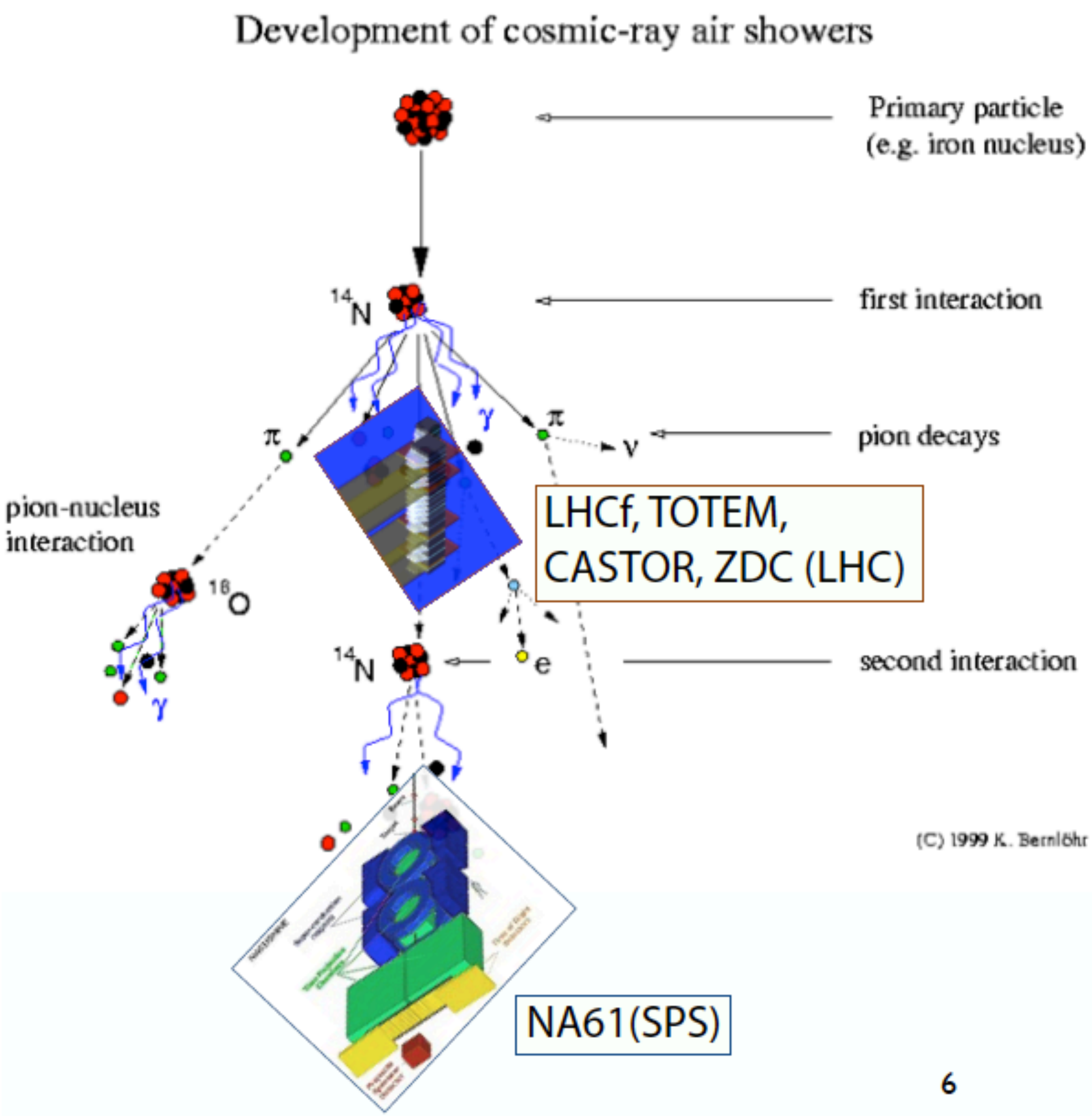
E~TeV

1. **Inelastic cross section**
   large → rapid development
   small → deep penetrating
2. **Inelasticity $k = 1 - p_{lead}/p_{beam}$**
   large → rapid development
   small → deep penetrating
3. **Forward energy spectrum**
   softer → rapid development
   harder → deep penetrating
4. **Nuclear effects**
5. **Extrapolation to high energy**
   precise measurements at available energies are crucial

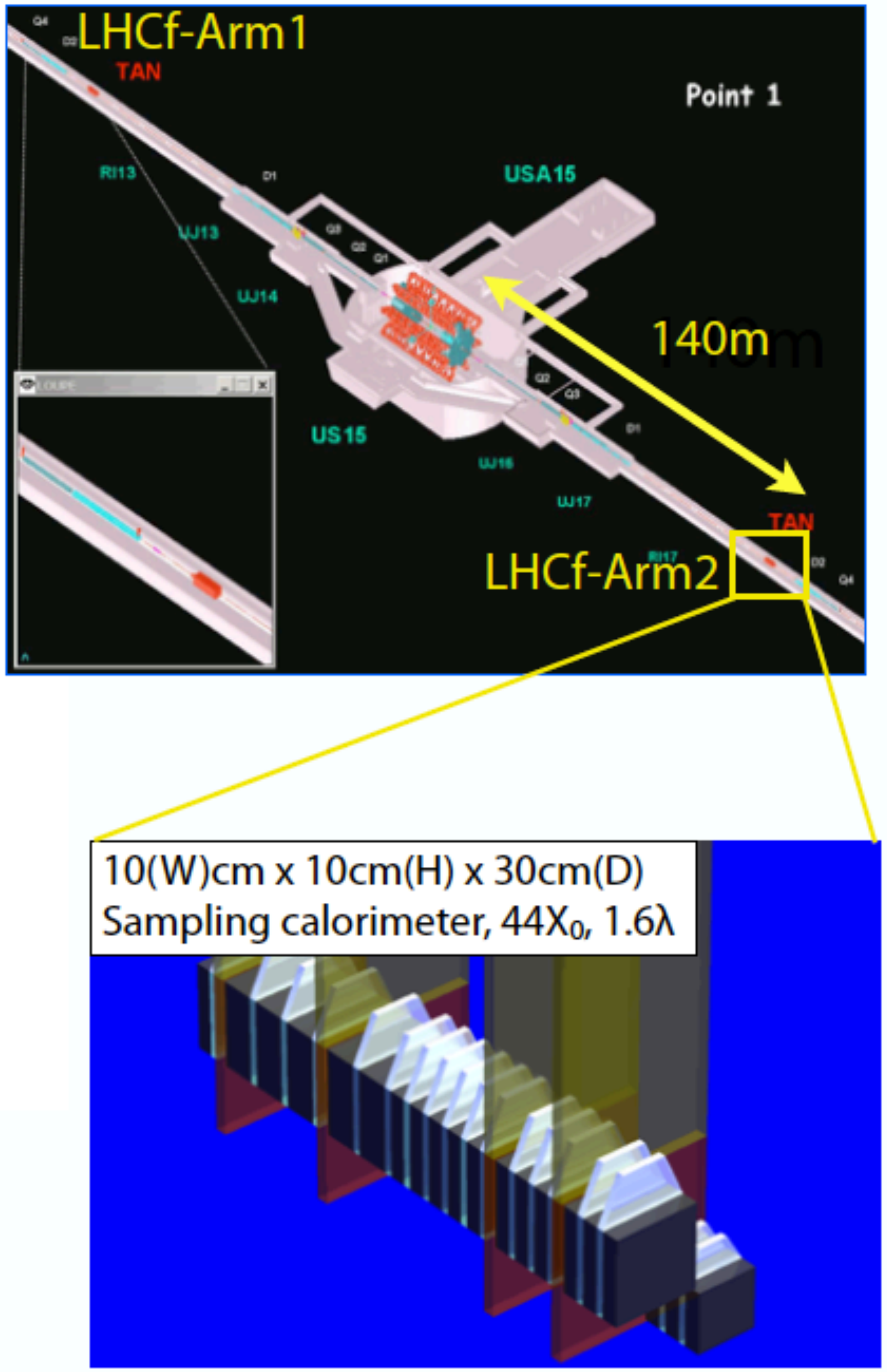
E~GeV

1. **Charge ratio**
2. **Multiplicity**
   number of muons in air shower sensitive to mass composition

Cosmic ray interaction at accelerator



The LHCf experiment



Results at the LHC: LHCf analyses

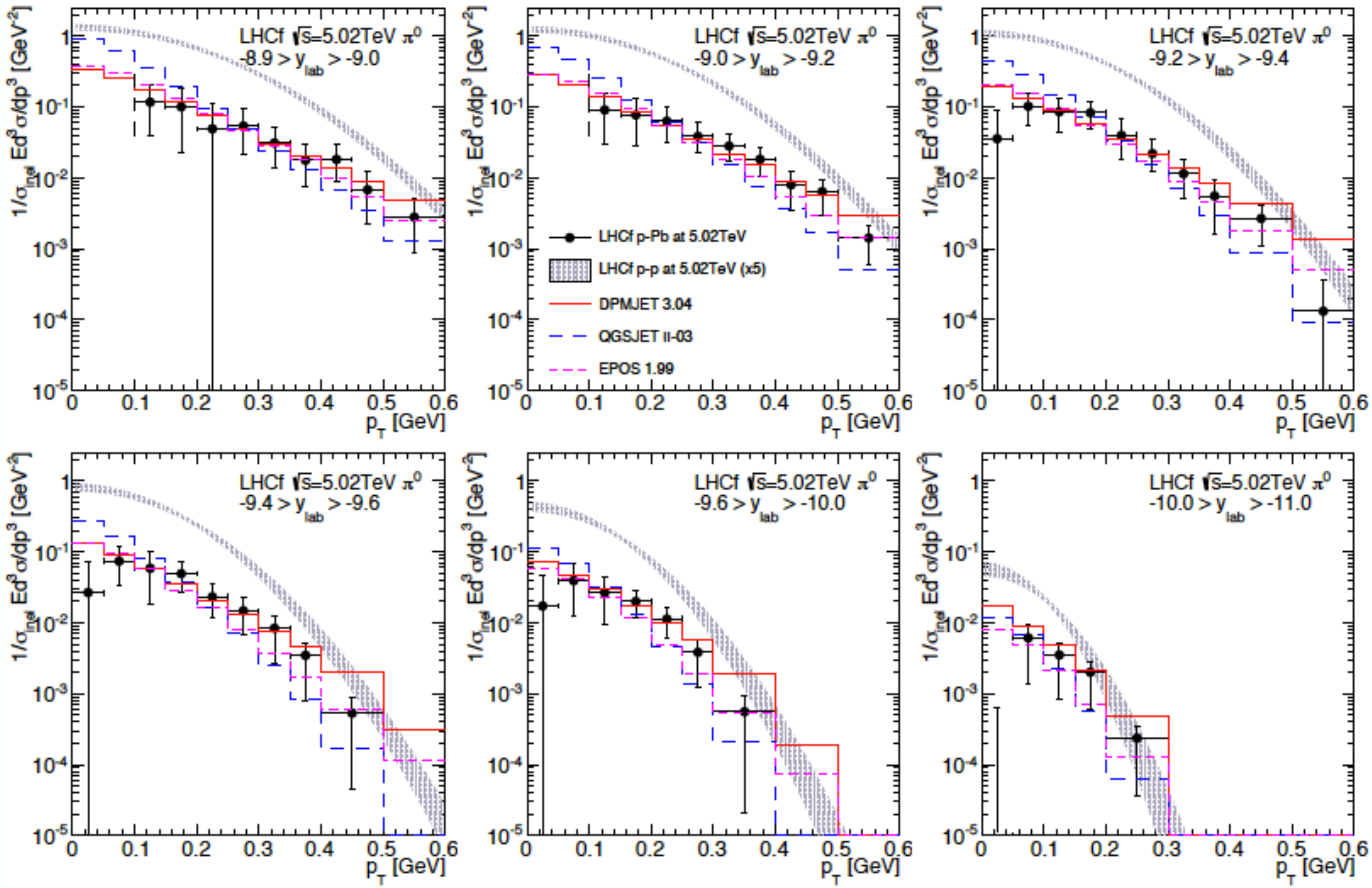
	Photon (EM shower)	Neutron (hadron shower)	π0 (EM shower)
Test beam at SPS	NIM. A 671, 129–136 (2012)	JINST 9 P03016 (2014)	
p-p at 900GeV	Phys. Lett. B 715, 298-303 (2012)		
p-p at 7TeV	Phys. Lett. B 703, 128–134 (2011)	To be submitted	Phys. Rev. D 86, 092001 (2012)
p-p at 2.76TeV			Submitted to Phys Rev. C arXiv:1403.7845, CERN-PH-EP-2014-059
p-Pb at 5.02TeV			

- LHCf analysis activity was so far directed to the EM shower events for its simplicity.
- We have extended the activity to neutron event analysis based on improved tools.
- Also we show the analysis results in p-Pb collisions (submitted to Phys. Rev. C).

Analysis on blank parts are ongoing or planed.

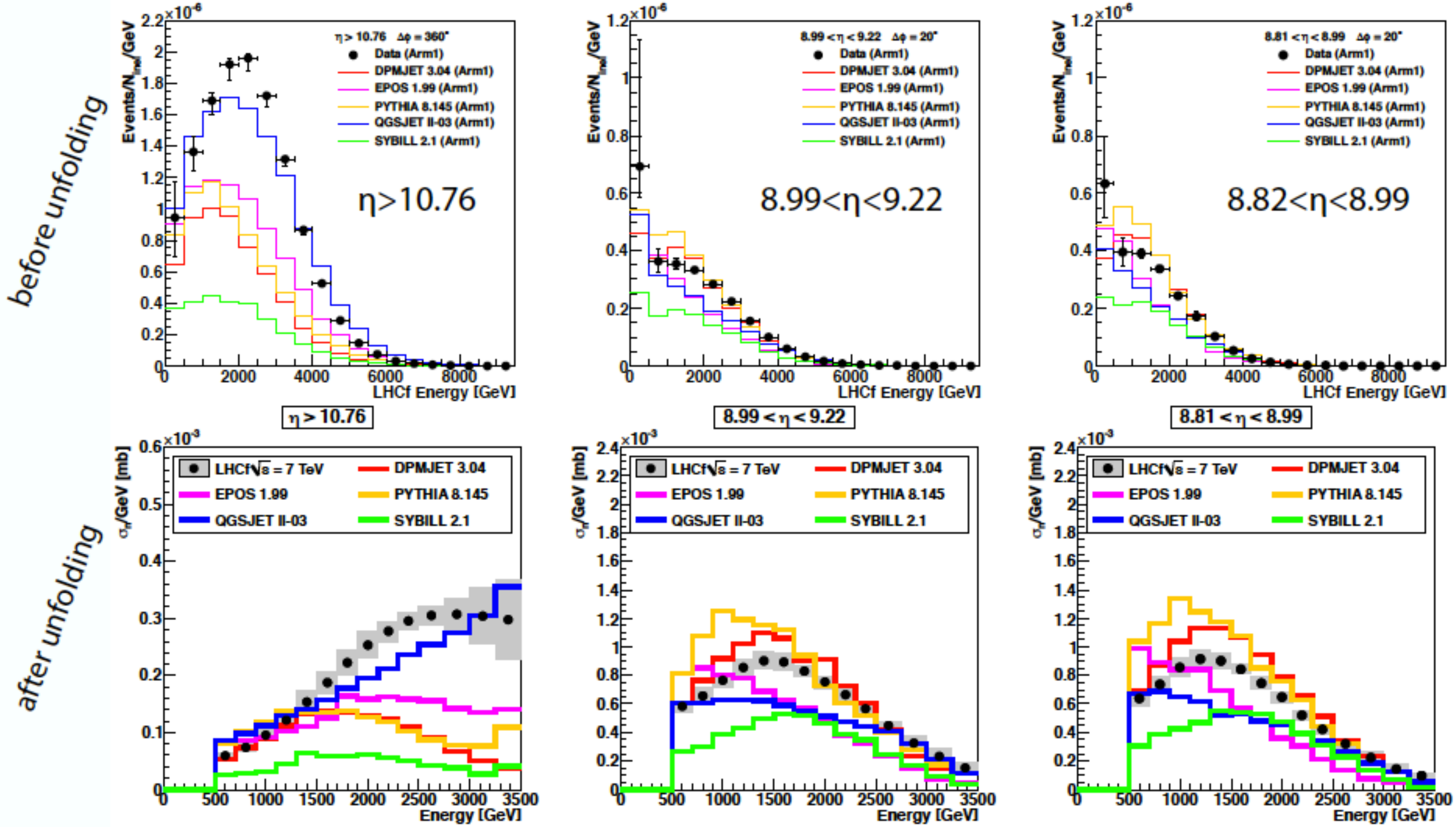
arXiv:1403.7845, CERN-PH-EP-2014-059

Inclusive π^0 p_T spectra in p-Pb at 5.02TeV



- The LHCf data in p-Pb (filled circles) show good agreement with DPMJET and EPOS.
- The LHCf data in p-Pb are clearly harder than the LHCf data in p-p at 5.02TeV (shaded area). The latter is interpolated from the results at 2.76TeV and 7TeV.

Inclusive neutron energy spectra in p-p at 7TeV



- In η>10.76 huge amount of neutron exists. Only QGSJET roughly reproduces the LHCf result.
- In other rapidity regions, the LHCf results are enclosed by the variation of models.
- These results may indicate small inelasticity in very forward region.

What's next ?

- Inelastic p-p cross section
  - It is and will be strongly constrained by the measurements at the LHC.

- Inelasticity and forward energy/p_T spectra
  - LHCf analyses at 7TeV were done. Similar analyses will be performed at 13TeV.

- Extrapolation to ultrahigh energy
  - Understanding of scaling raw is of importance to validate an extrapolation.
  - Precise measurements in many collision energies are necessary; 900GeV, 2.76TeV, 7TeV and 8TeV so far, and 13TeV soon.

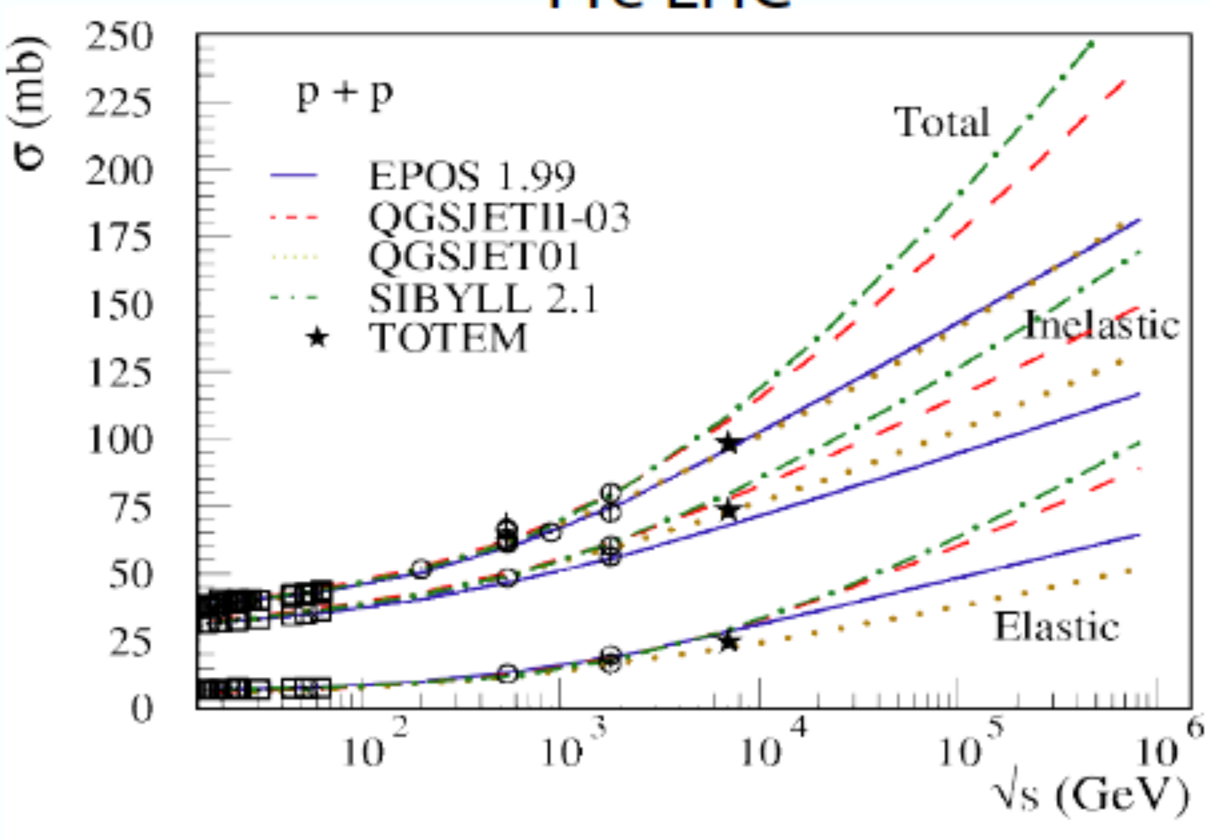
- Nuclear effects
  - p-Pb collision at 5.02TeV is good to imitate a very dense matter which can be realized in p-air collision at E>>TeV.
  - nucleon - light-ion collision (e.g. p-N/O) is needed to test the current implementation of hadronic interaction models at TeV energy region.

Summary

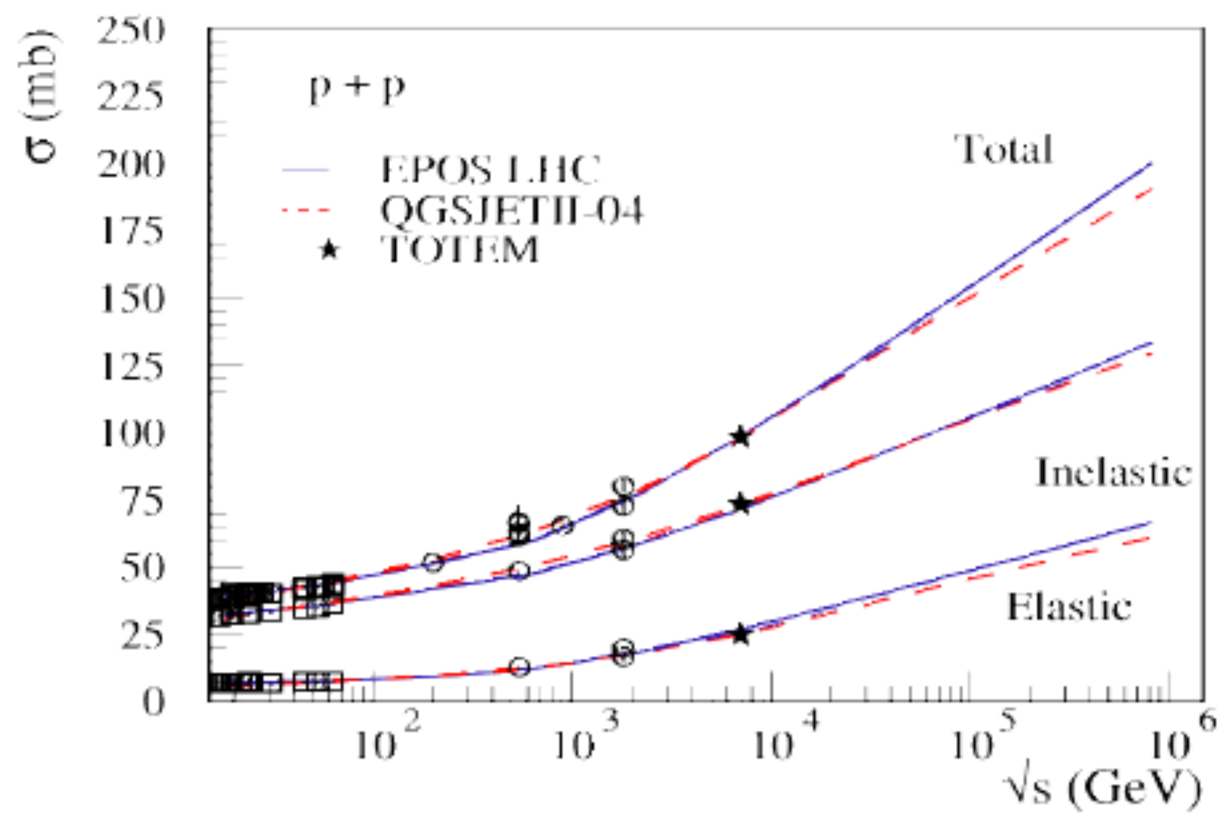
- Understanding of hadronic interaction is crucial to reduce an uncertainty in cosmic ray observation.
- LHC is the best occasion to improve/tune the hadronic interaction models towards an observation of ultrahigh energy cosmic ray.
- Retuned models with LHC data indeed show convergence at the LHC energy.
- Next target is
  - performing a precise extrapolation based on a robust scaling.
  - RHICf; an extension of the LHCf activity to low energy but to wide rapidity range.
  - (hopefully) light ion collision.

Results at the LHC: cross section

Pre LHC



Post LHC



(T. Pierog)

- There is no drastic change from EPOS 1.99 to EPOS LHC.
- Better agreement with TOTEM is found in QGSJET II-04 compared with QGSJET II-03.
- Post LHC models show overall good agreement with data up to the LHC energy.
- They are converged into similar values even at 10^6GeV.

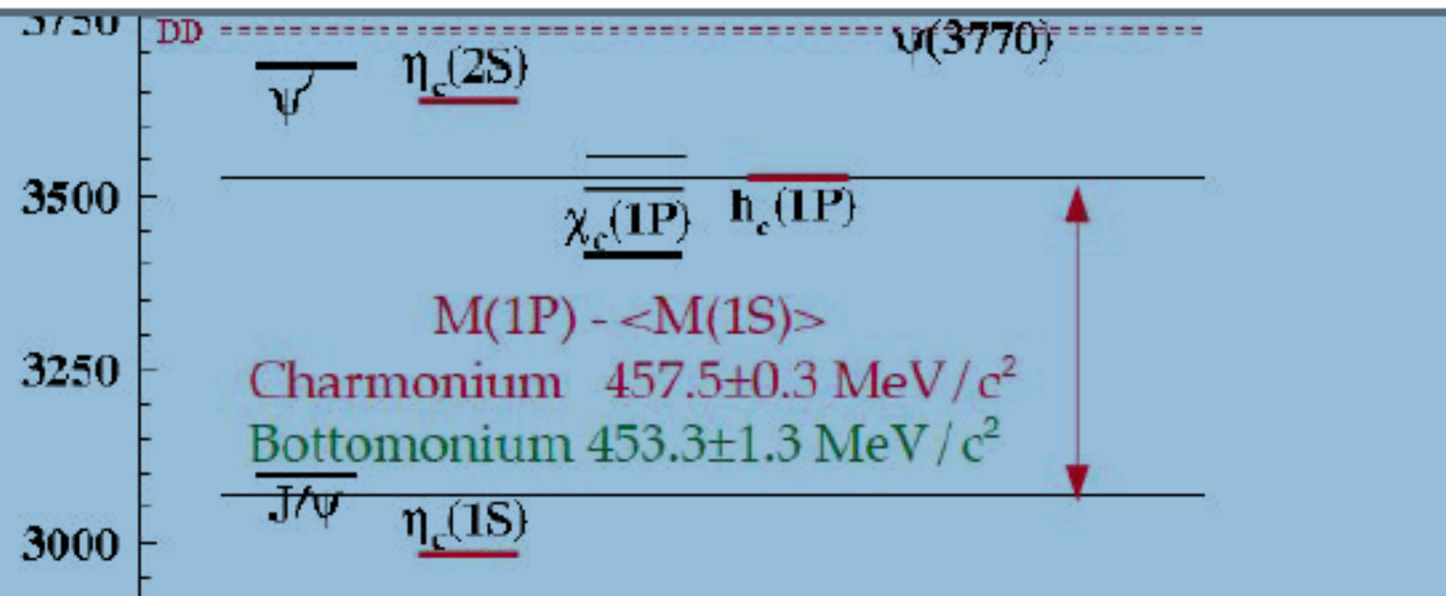
Spectroscopy

Roberto Mussa
Torino INFN

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

Multiple Parton Interactions

Livio Fanó

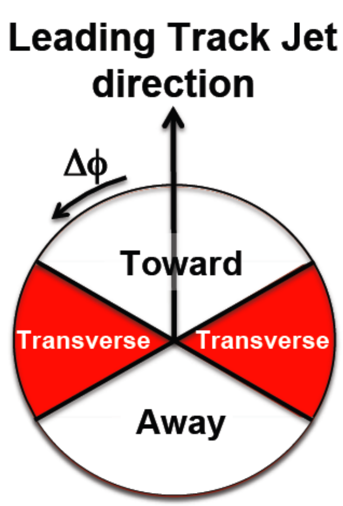
Multiple Parton Interactions

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

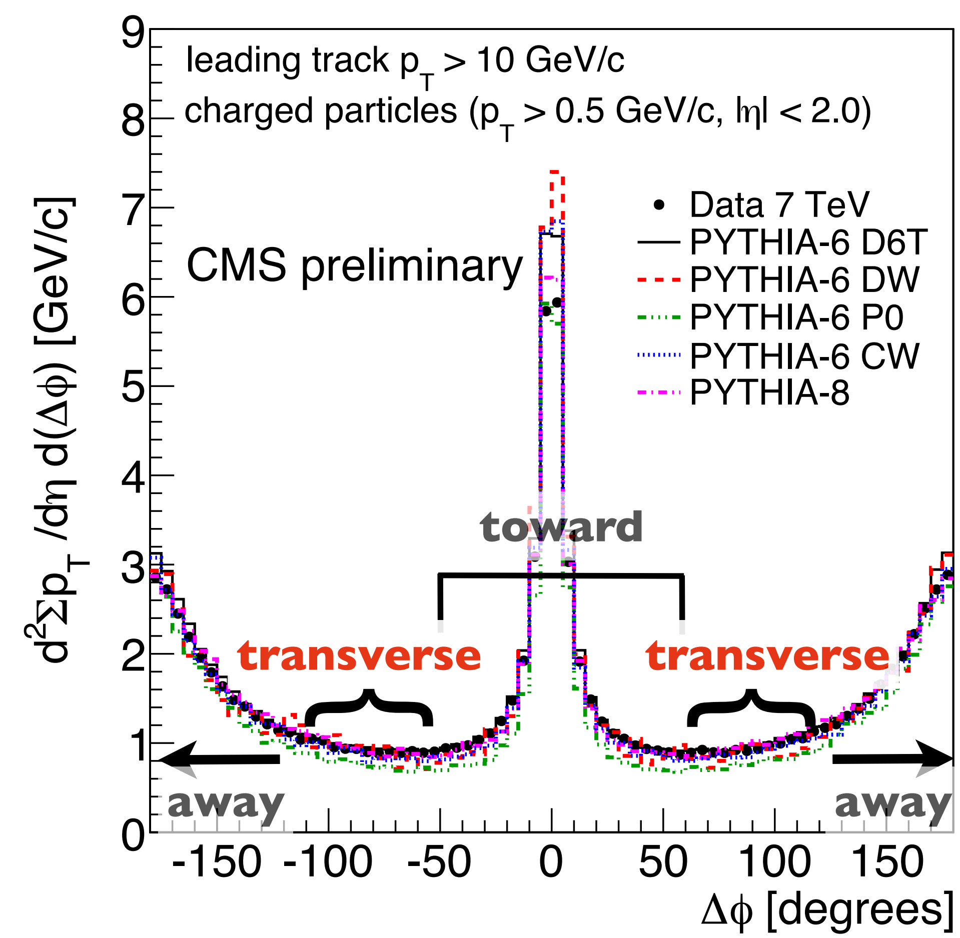
Transverse region is expected to be sensitive to the UE (all activity except the hard-scattering component)

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

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



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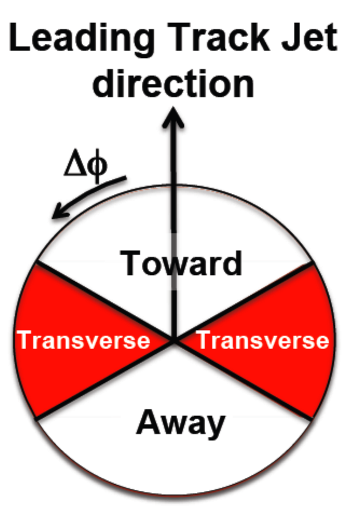

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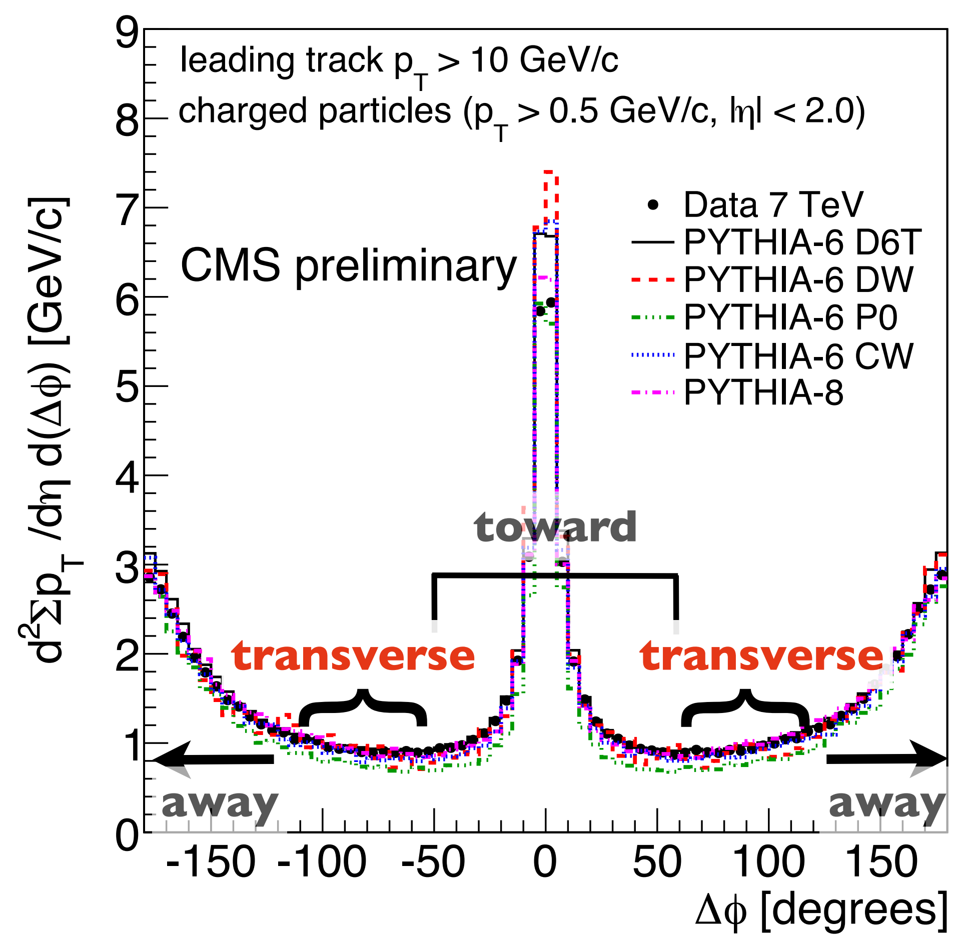
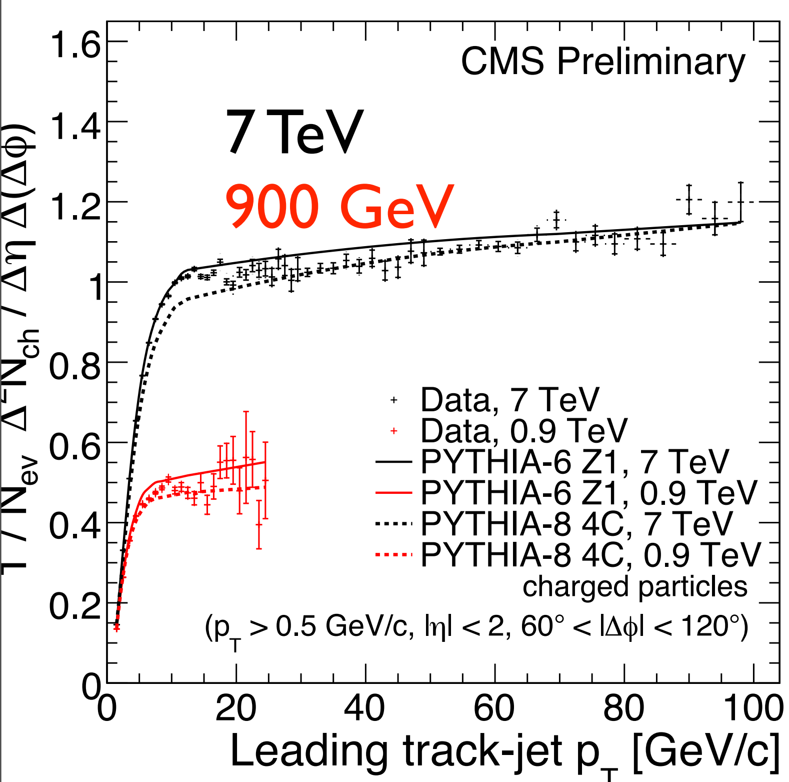
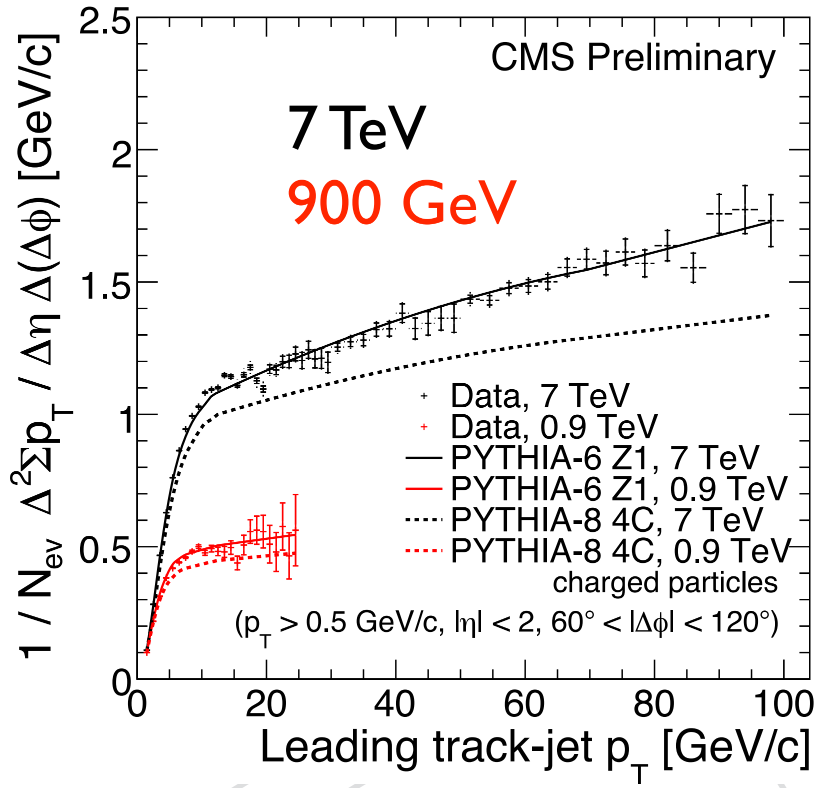
Eur.Phys.J.C70:555-572,2010, JHEP09 (2011) 109

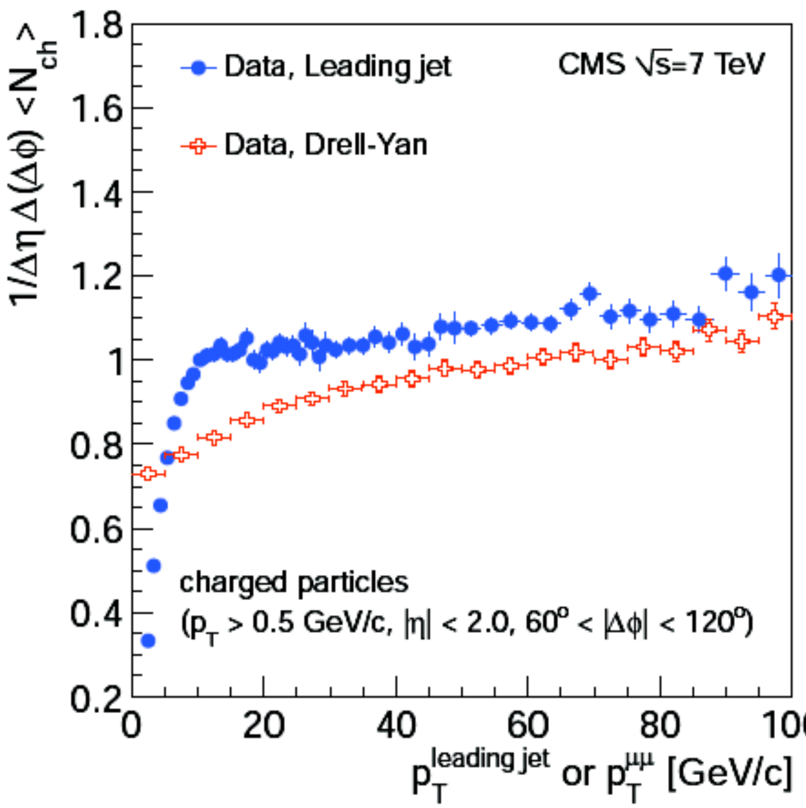


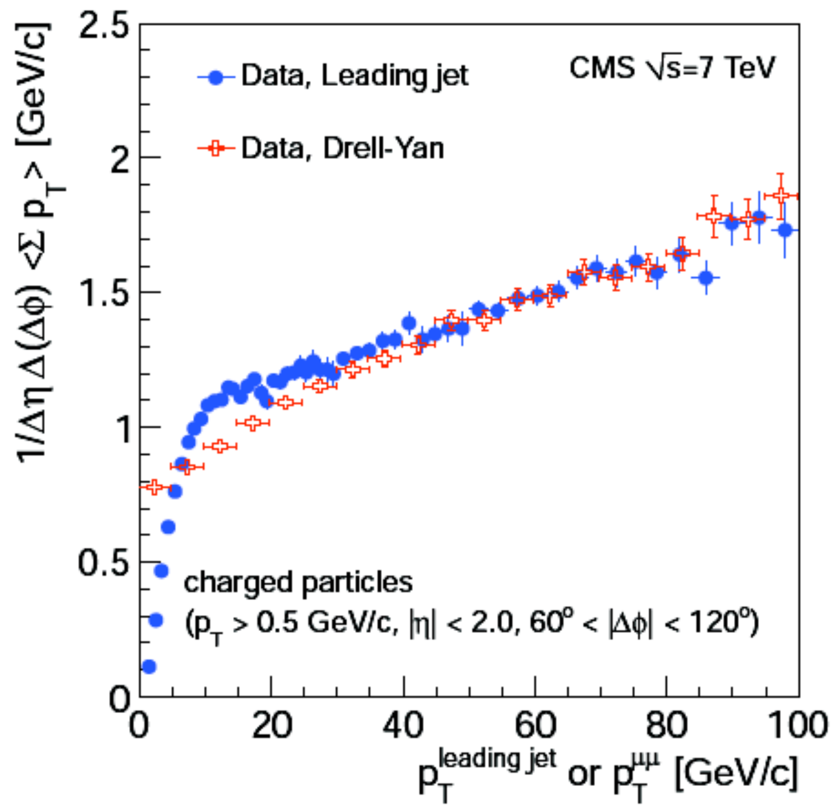
Soft MPI - The transverse region





JHEP09 (2011) 109





hep-ex:1204.1411

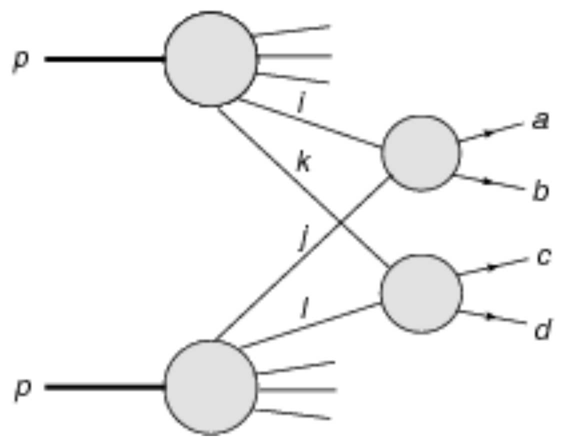
1) **Fast rise** - peripheral collisions increase of the MPI

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

Hard MPI - Double Parton Scattering



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

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

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

Which role for Double Parton Correlations ?

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

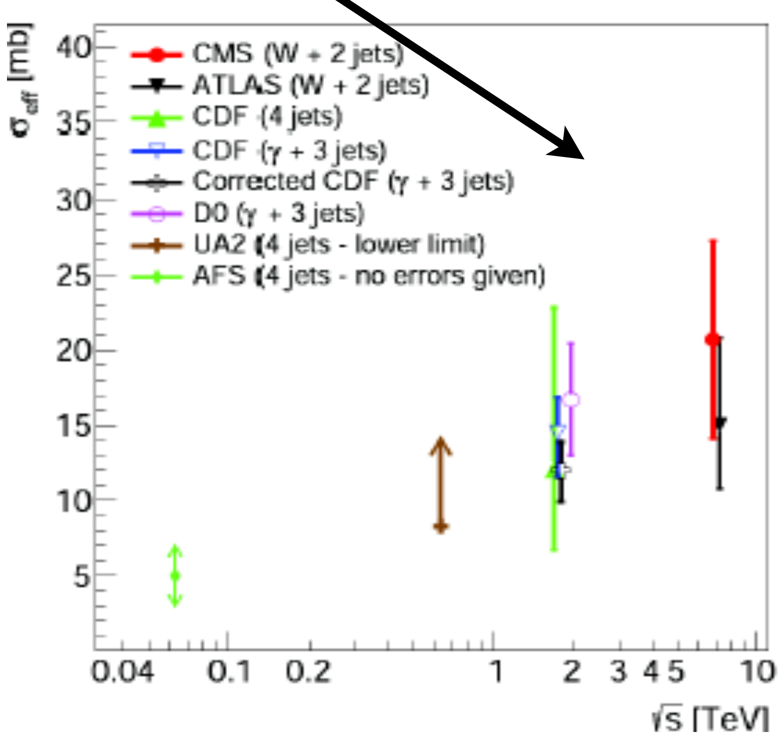
Korotkikh and Snigirev (2004), Gaunt and Stirling (2010), Diehl and Schafer (2011), Snigirev (2011), Blok et al. (2012), Schweitzer, Strikman and Weiss (2013), S. Scopetta et al. (2013),...

prediction based on theoretical calculation and soft MPI tune:

expected σ_{eff} ≈ **20÷60 mb**

?

measured σ_{eff} ≈ **10÷20 mb**



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?

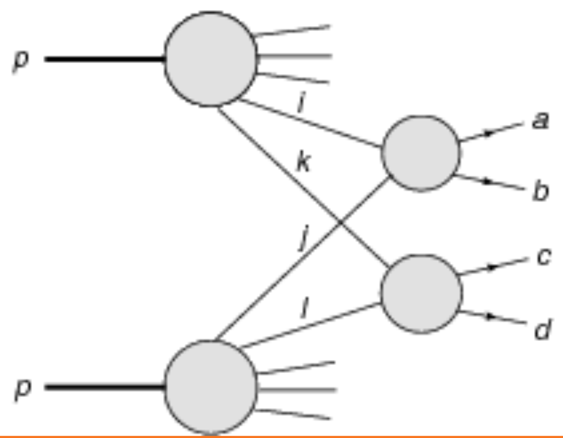
Higher Energies...higher luminosities...

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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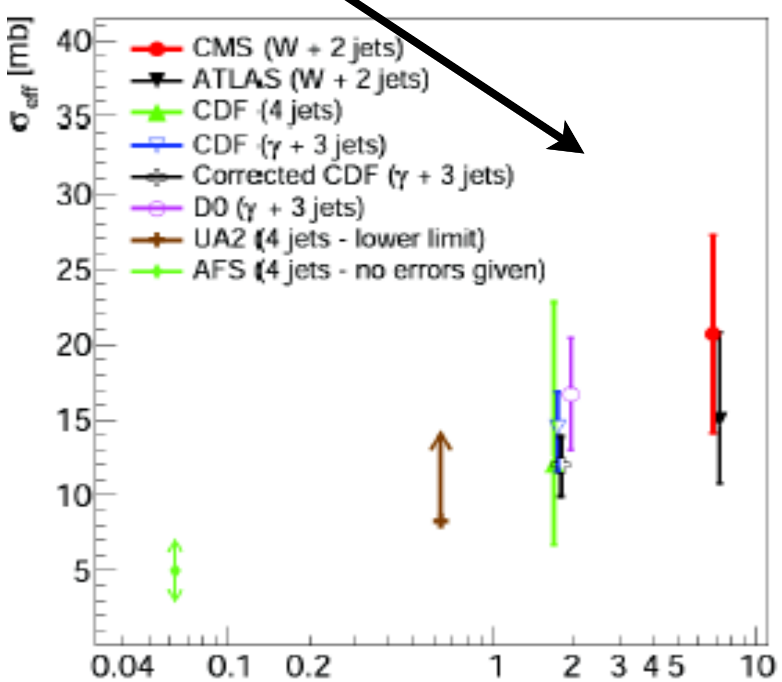

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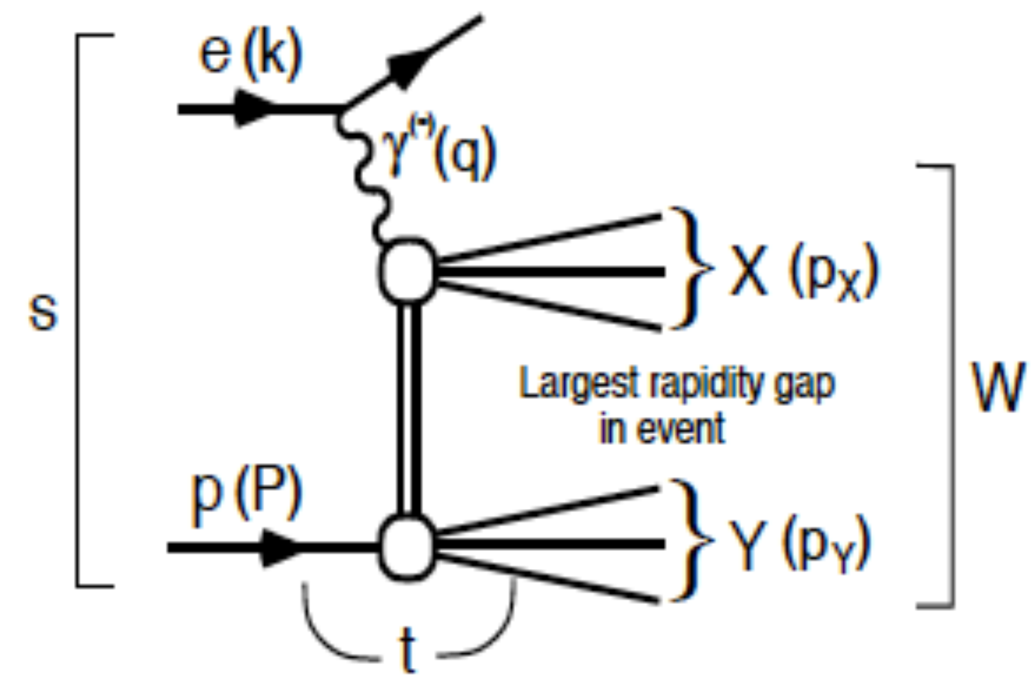
Hard Diffraction

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

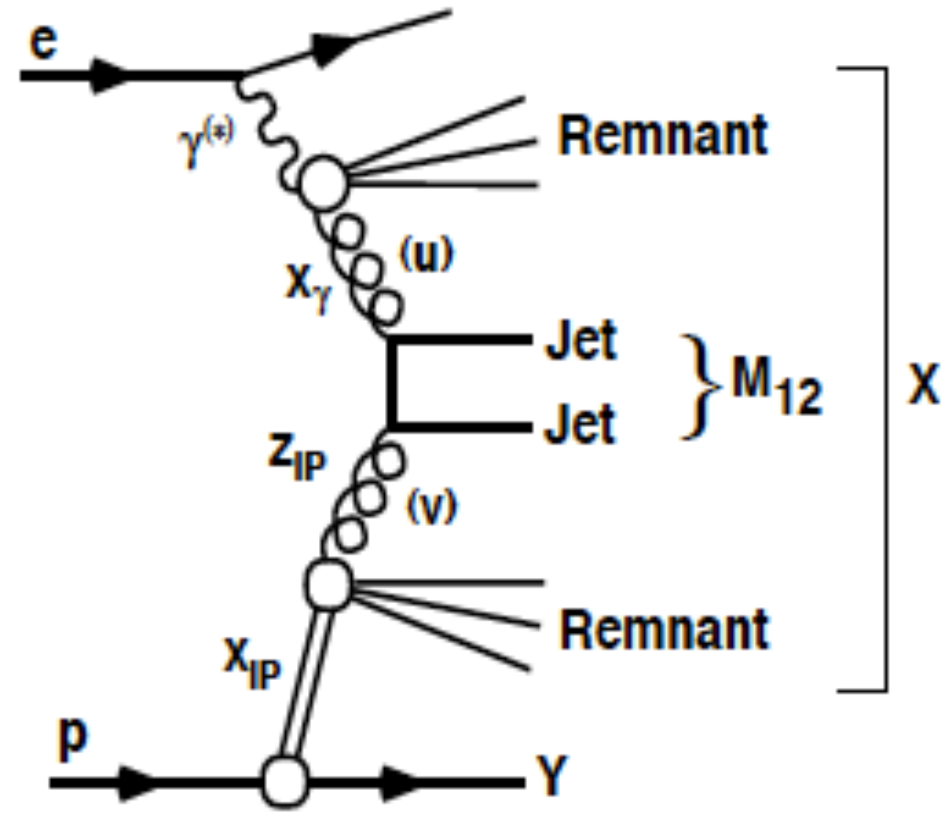


- Theory
  - Factorisation theorem for DDIS :
    $d\sigma \propto f_i^D \otimes d\hat{\sigma}$
  - pQCD evolution of f_i^D (DGLAP)

- Result
  - Partonic structure of the colourless exchange quite well known
  - Enconded in diffractive PDFs (i.e. Fracture Functions)

Diffractive parton distributions and factorization

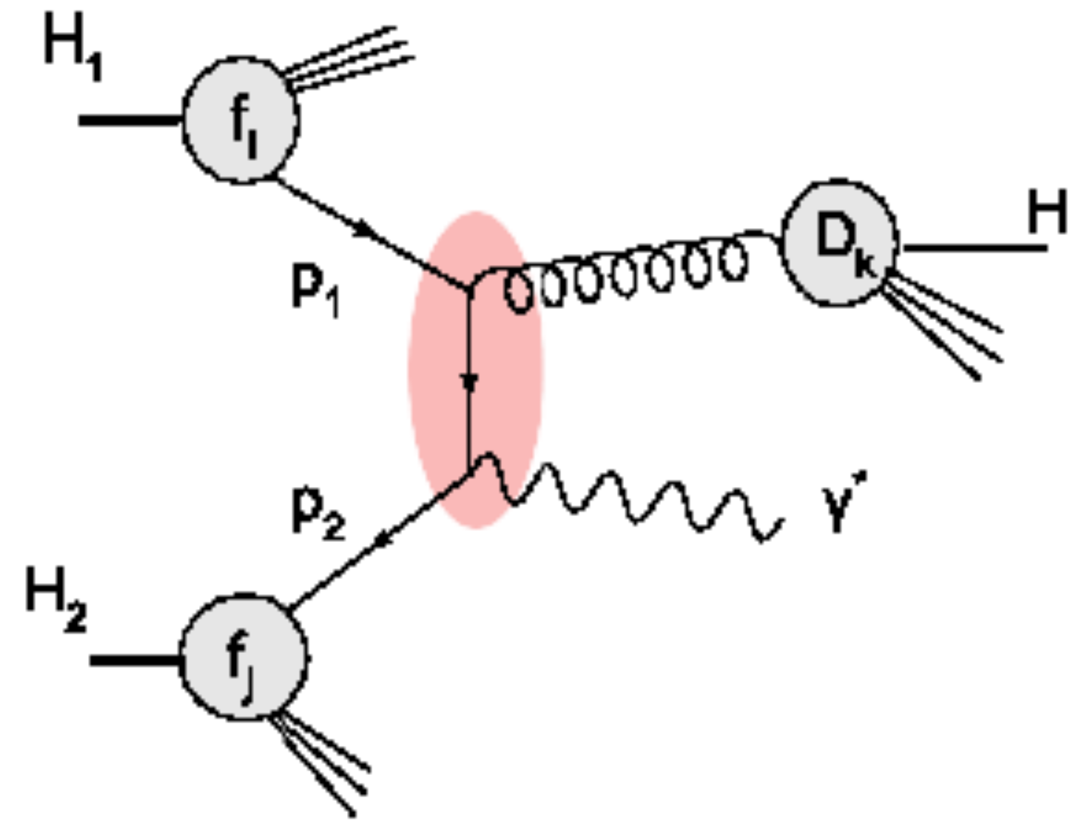
- Diffractive PDFs have bees used to test hard-scattering factorisation in
  - dijet in DIS
  - dijet in PHP ($Q^2 \simeq 0$, $E_T \sim 5, 6$ GeV)
  - dijet or $W^{\pm}$ in $p\bar{p}$ collisions



- 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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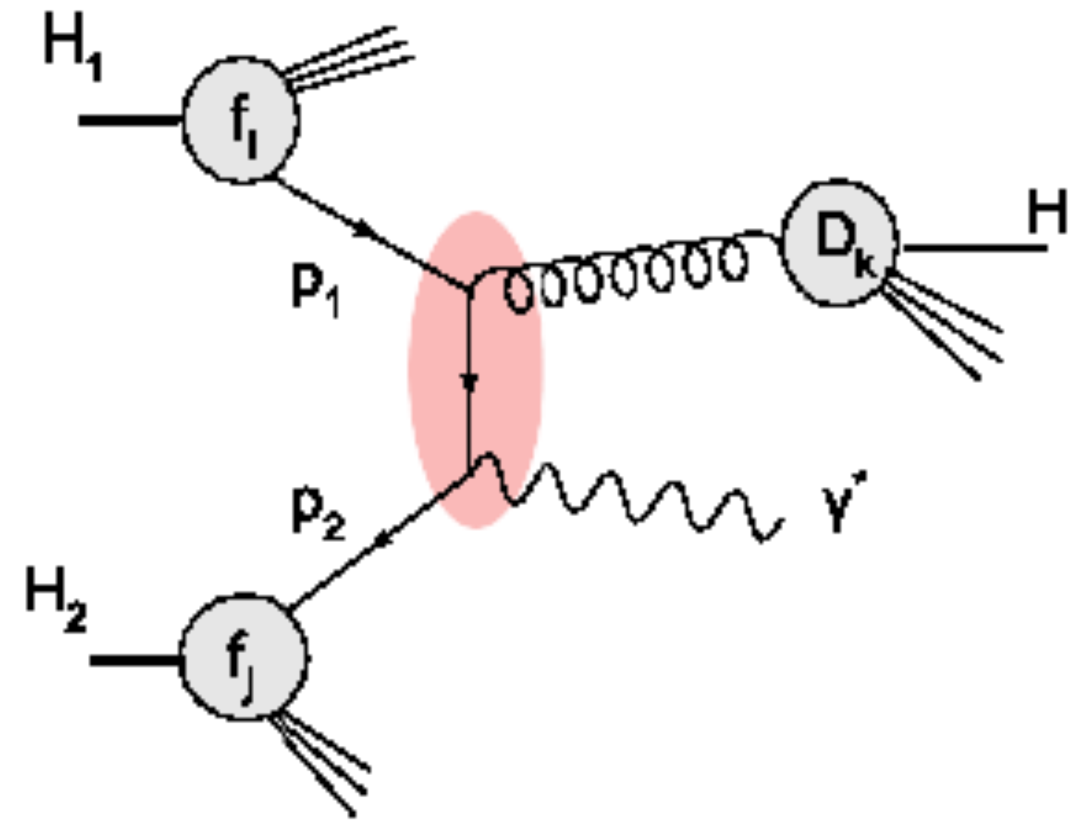

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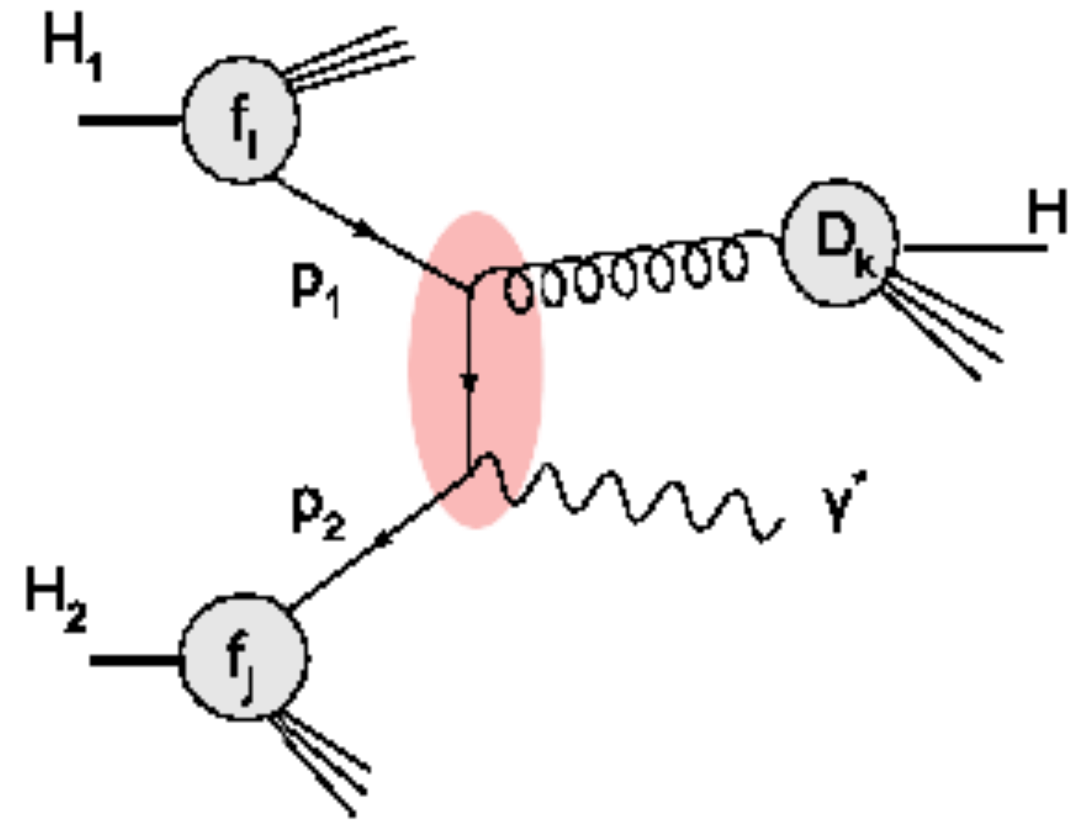

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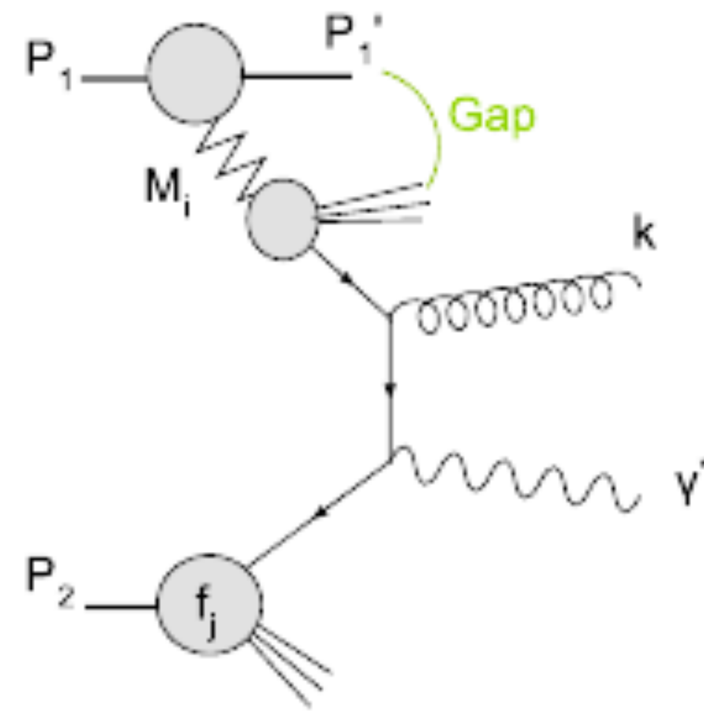
Diffraction at LHC

- 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
  - forward proton tagger



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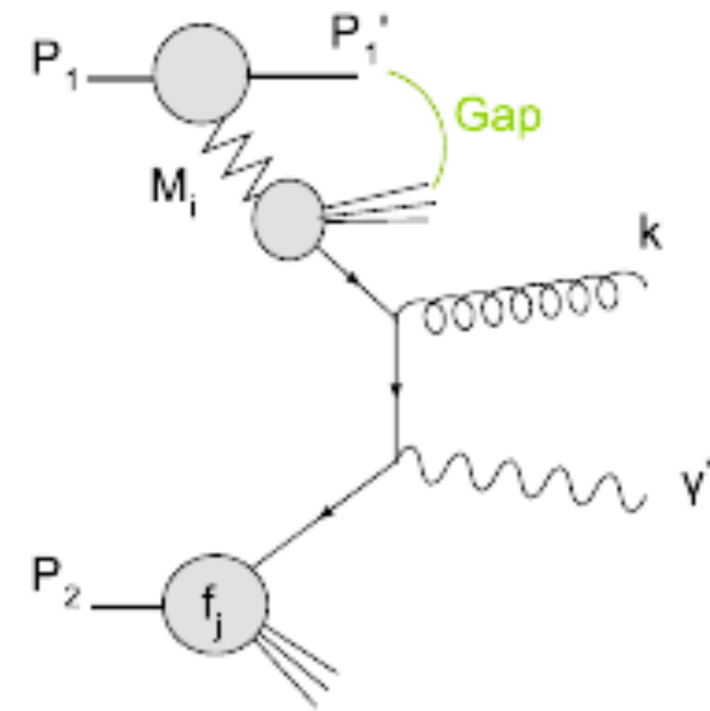

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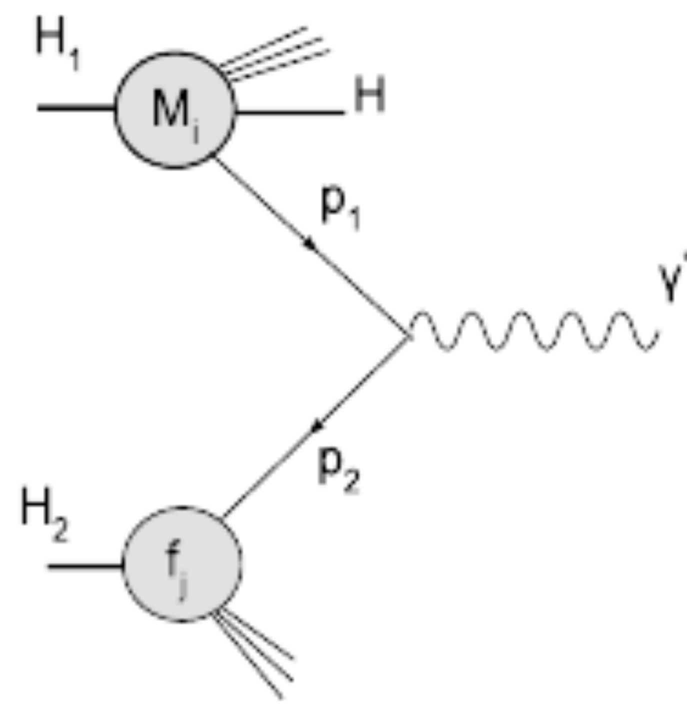
Prototype process: diffractive DY

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

▶ Let us assume factorisation:

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



- Dependencies of the cross section:
  - factorisation breaking vs Q^2 (vary DY mass)
  - different physics at different $x_{I\!P}$ (vary proton enery loss)
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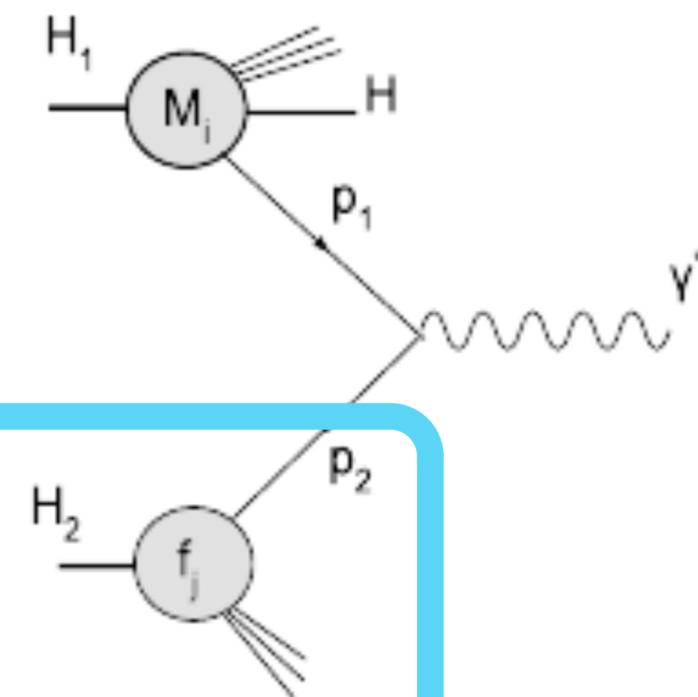

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- which are the dependences of S?
- do we see the same partonic structure oberved at HERA?
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- Compare Single and Double Diffraction
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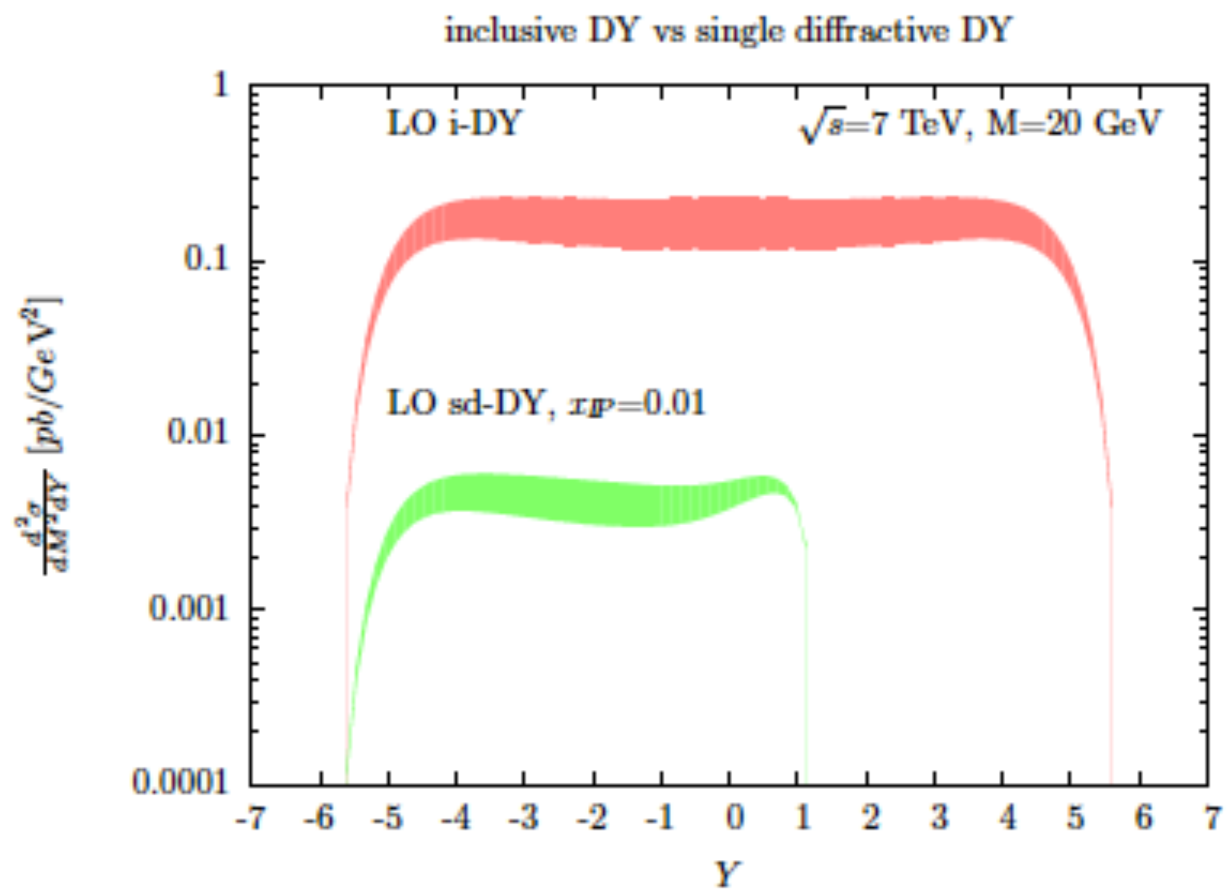
- what are the relations between S and S'?
- What if one measures forward neutron instead of protons?



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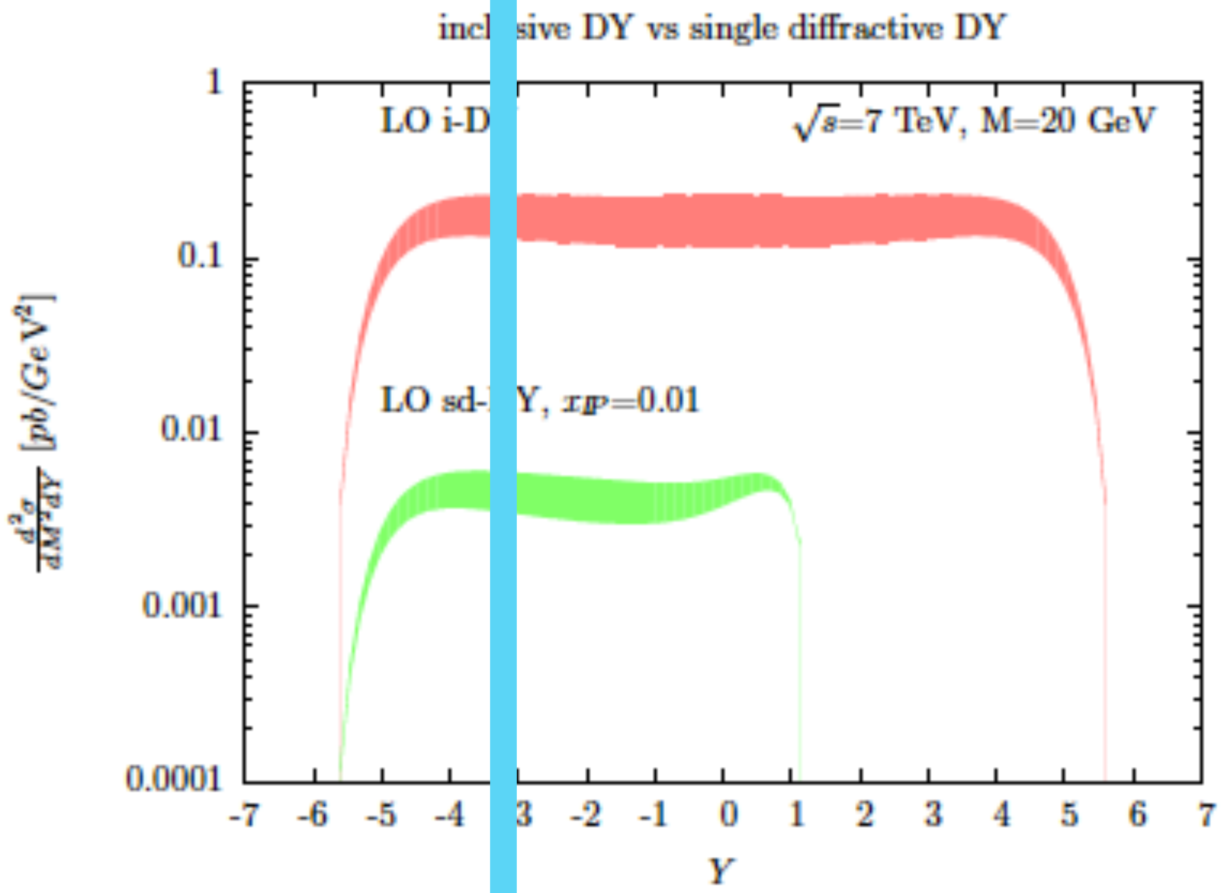

Hard diffraction : present and future

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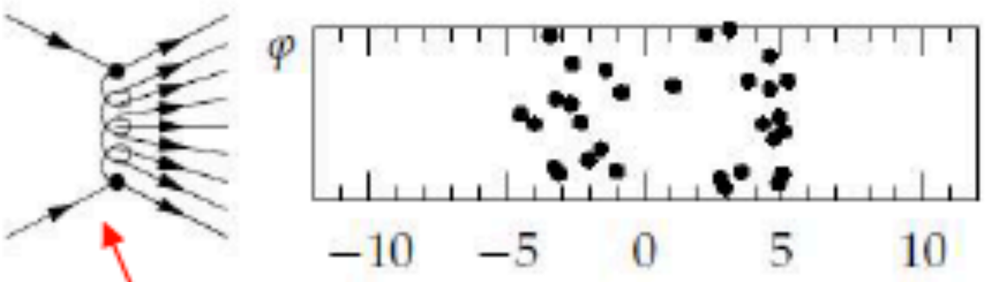
Diffractive Cross Sections
&
Events

Ken Österberg

Classification of soft pp events

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



Non-diffractive

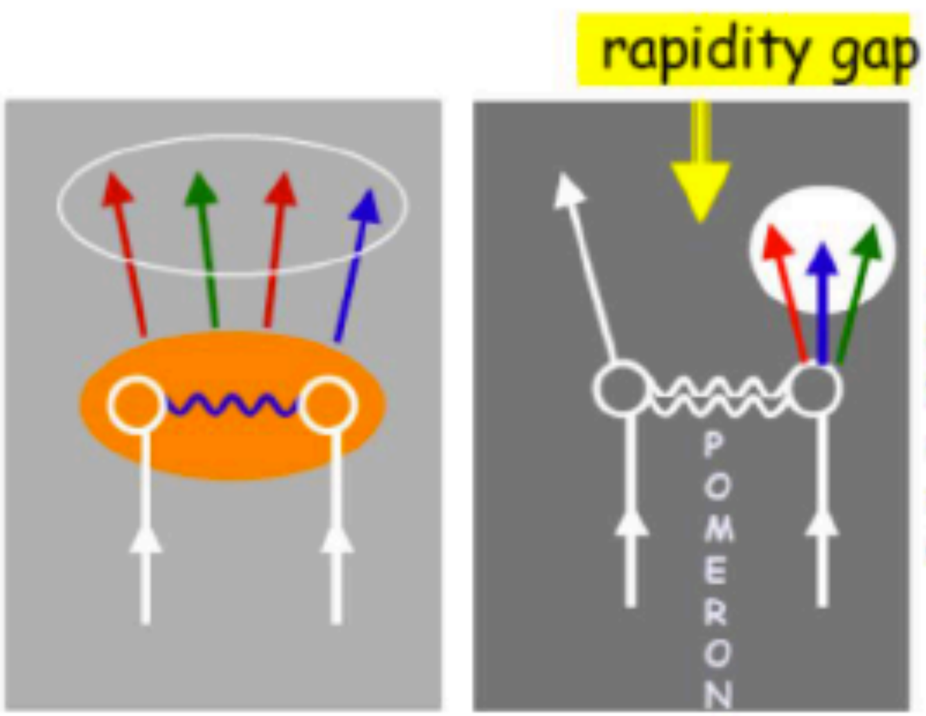
Colour exchange

$dN / d\Delta\eta = \exp(-\Delta\eta)$

Diffractive

Colourless exchange with vacuum quantum numbers

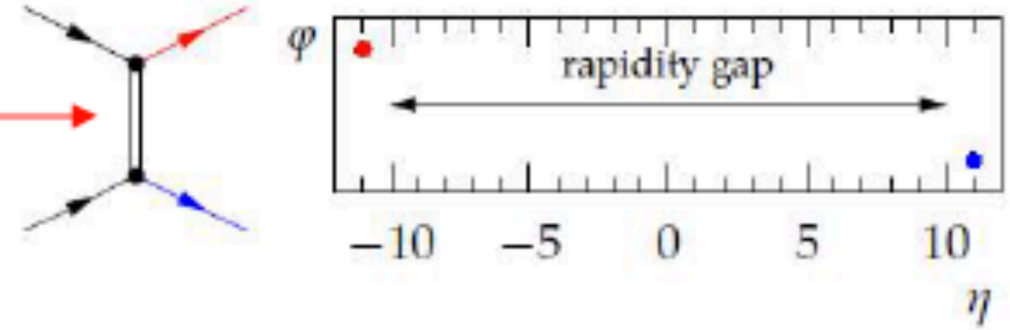
$dN / d\Delta\eta = \text{const}$



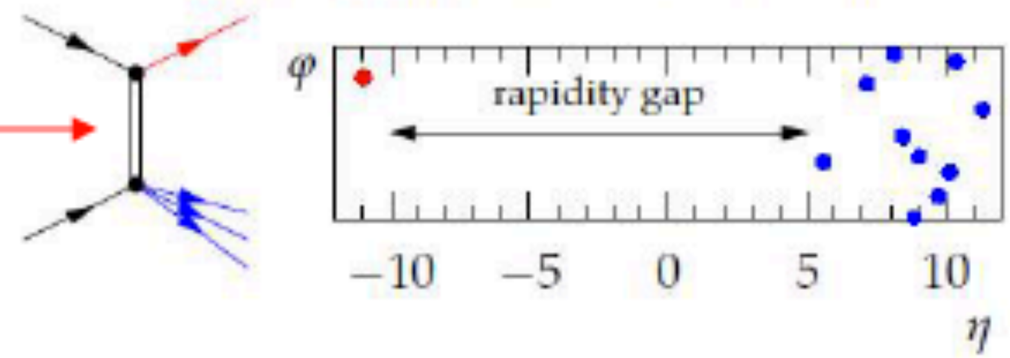
Incident hadrons retain their quantum numbers remaining colourless

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

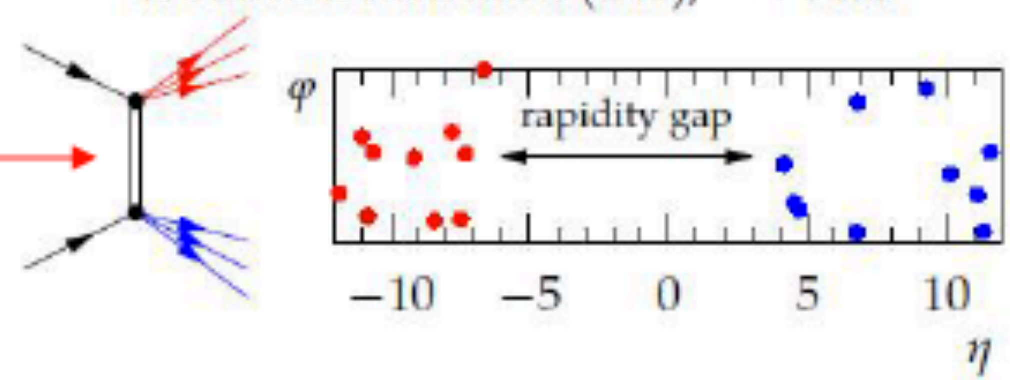
Elastic Scattering (ES), ≈ 25 mb



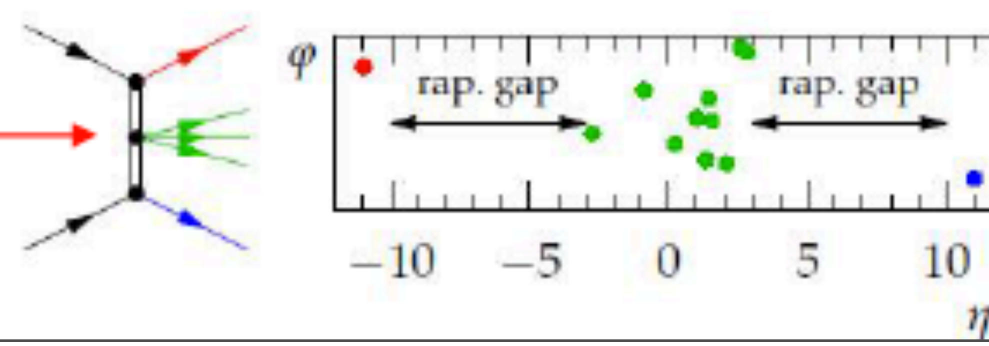
Single Diffraction (SD), ≈ 10 mb



Double Diffraction (DD), ≈ 5 mb



Central Diffraction (CD), ≈ 1 mb



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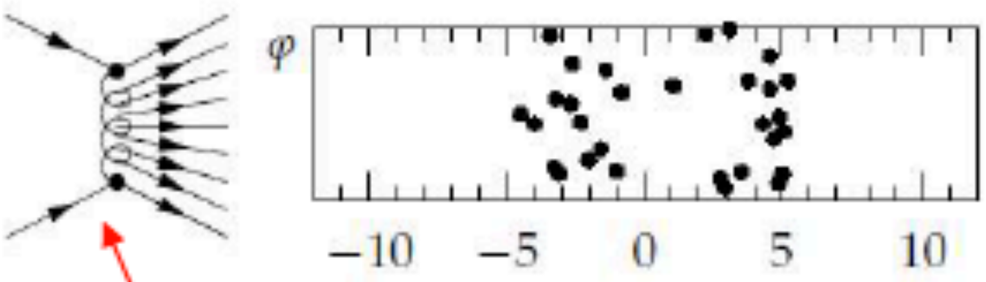

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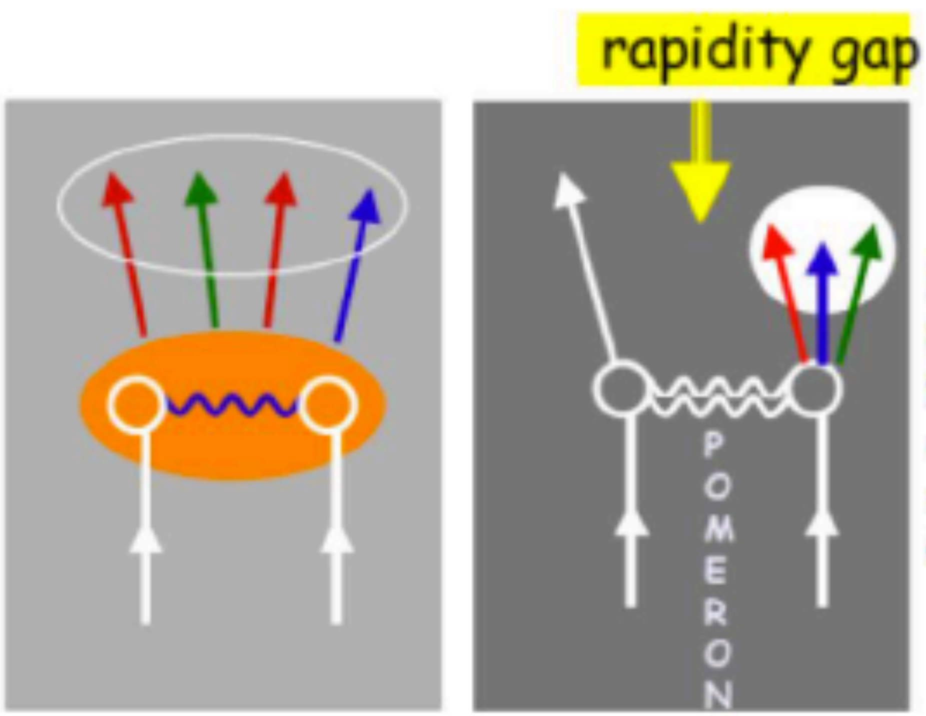

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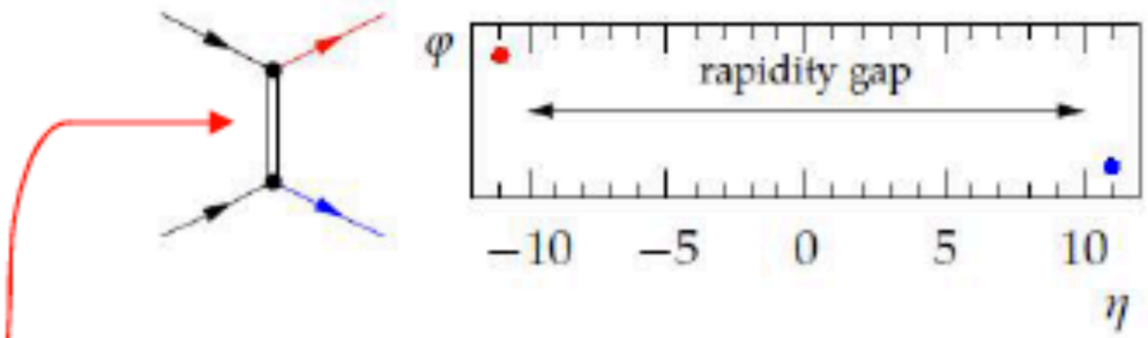

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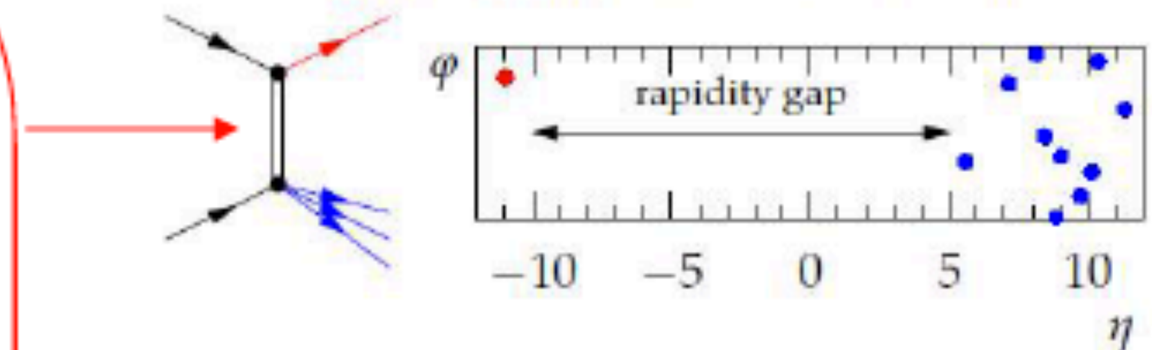

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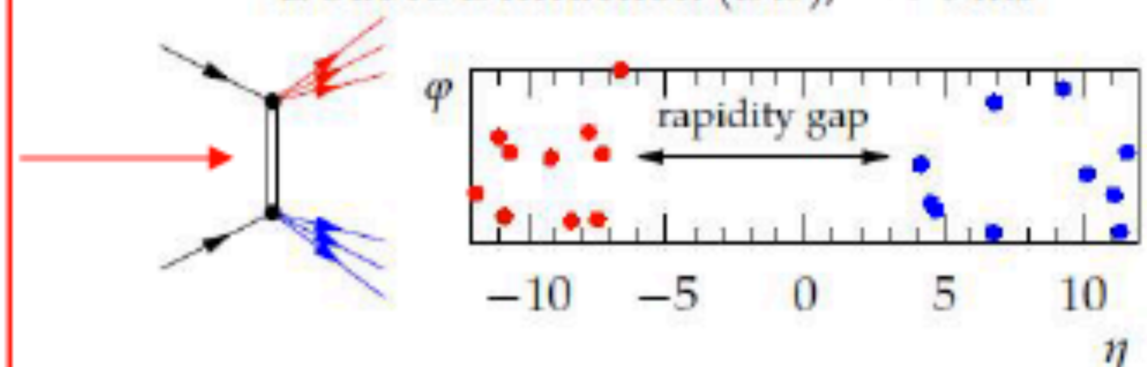

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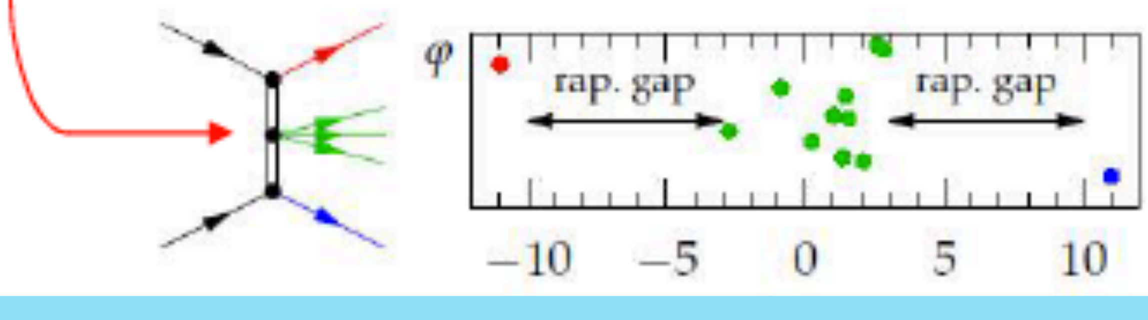

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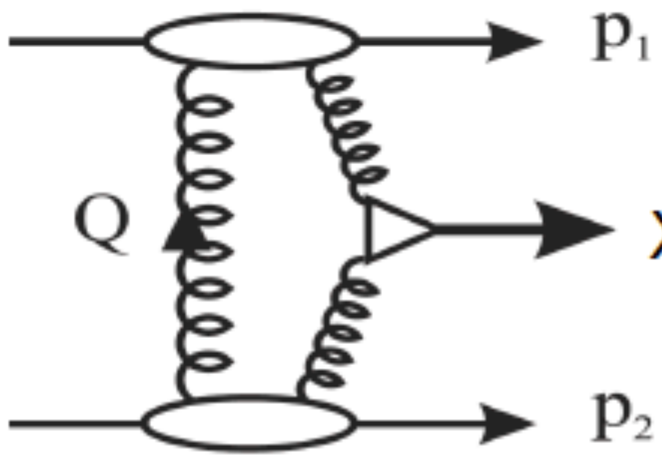
Central exclusive production (CEP)



(ξ_1)

$M^2 = \xi_1 \xi_2 s$

also $\gamma\gamma$ fusion & photoproduction

X at rapidity y_X

gg collider !

(ξ_2)

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

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

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

M= $m_{\pi\pi}$ – ~ 1 TeV,

σ = O(μb) – O(fb)

With proton tagging:

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

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

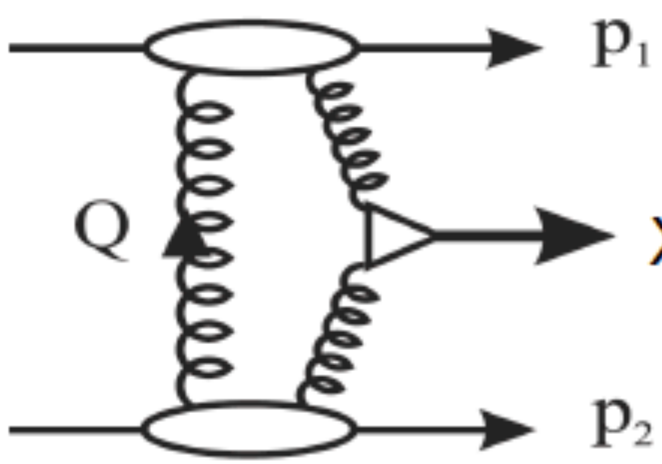
Special runs: all M(pp), $\mu \sim 0.05 - 0.5 \Rightarrow$ O(0.1-10 pb^{-1}/day)

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 ($\geq$ fb), improved with Herschel .

Central exclusive production (CEP)



p_1 (ξ_1) $M^2 = \xi_1 \xi_2 s$

X at rapidity y_X

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also $\gamma\gamma$ fusion & photoproduction

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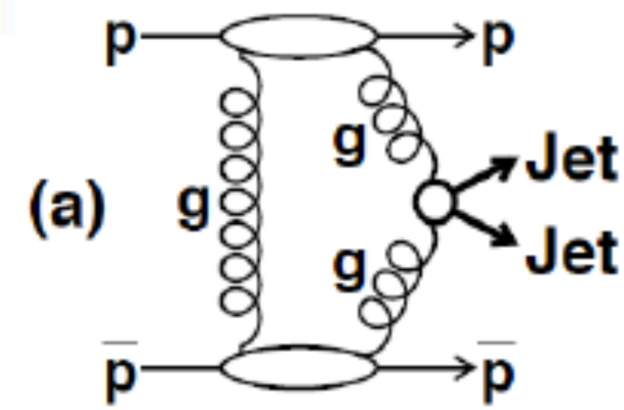
Special runs: all M(pp), $\mu \sim 0.05$ - 0.5 $\Rightarrow$ O(0.1-10 pb^{-1}/day)
CMS & TOTEM common runs: if $\mu \sim 0.5$ need timing in vertical TOTEM RPs

With rapidity gaps (also ALICE, ATLAS & CMS):
LHCb in normal LHC runs, σ's ($\geq$ fb), improved with Herschel .

CEP jets

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

Durham group (KHARYS MC)

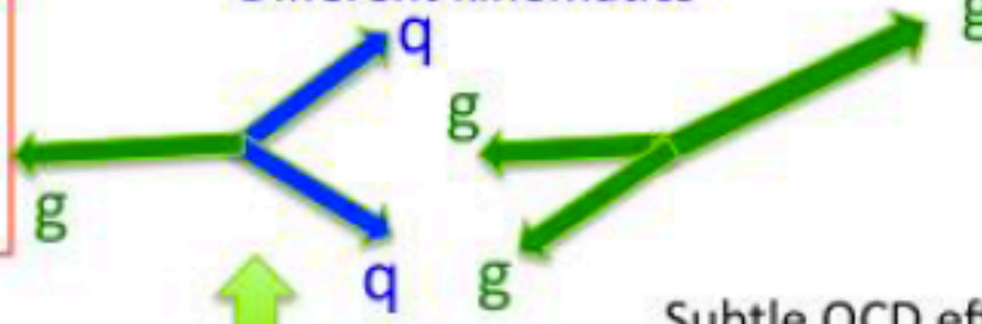


CDF Observed X = JJ at √s = 1.96 TeV to E_T = 30 GeV

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, ...

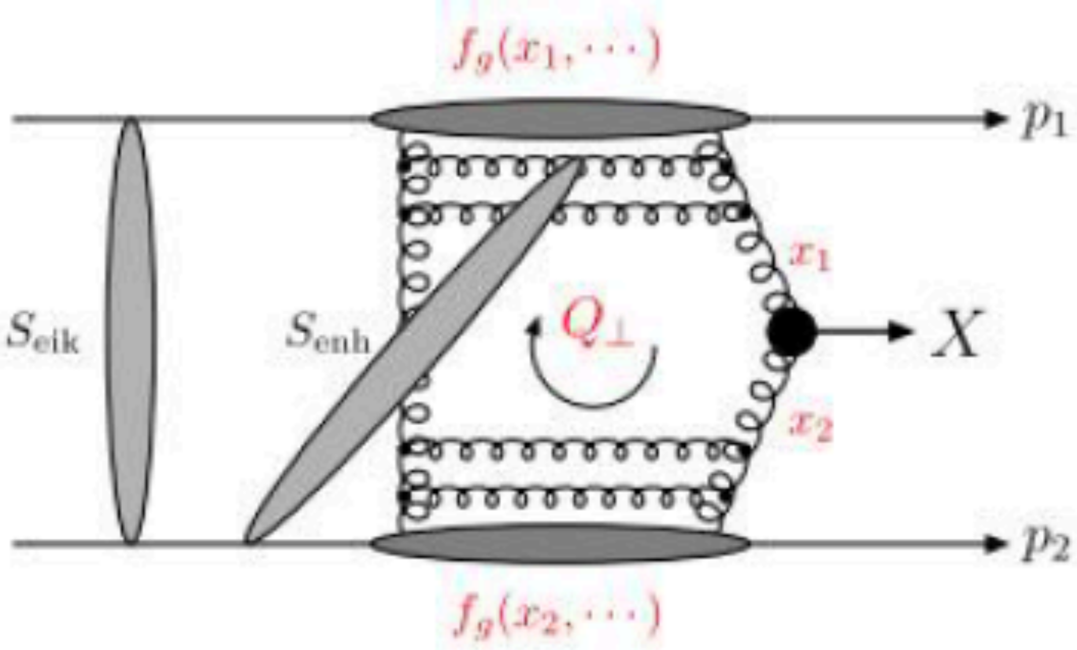
Subtle QCD effects:
No gluon radiation (Sudakov)
No other parton collisions
Test spin rule Jz = 0
Interplay of pQCD and npQCD
Distant relation to elastic scattering

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

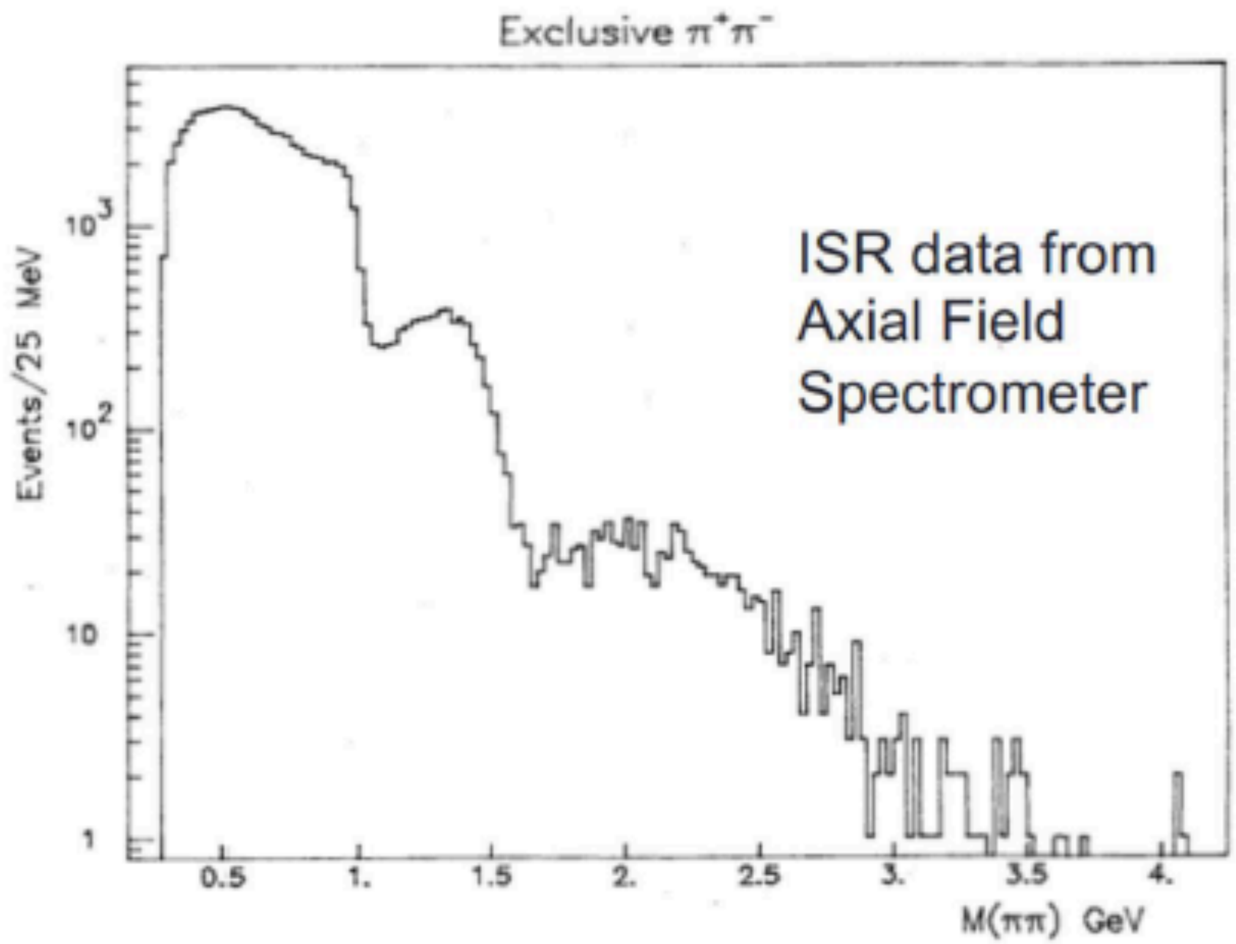
Special runs: all M(pp), μ ~ 0.5 & 1k bunches ⇒ O(10 pb^{-1})
σ(M(pp) > 75 GeV) = ~100 pb @ s = 13 TeV (KHARYS)
only accessible with timing detectors in vertical TOTEM RPs

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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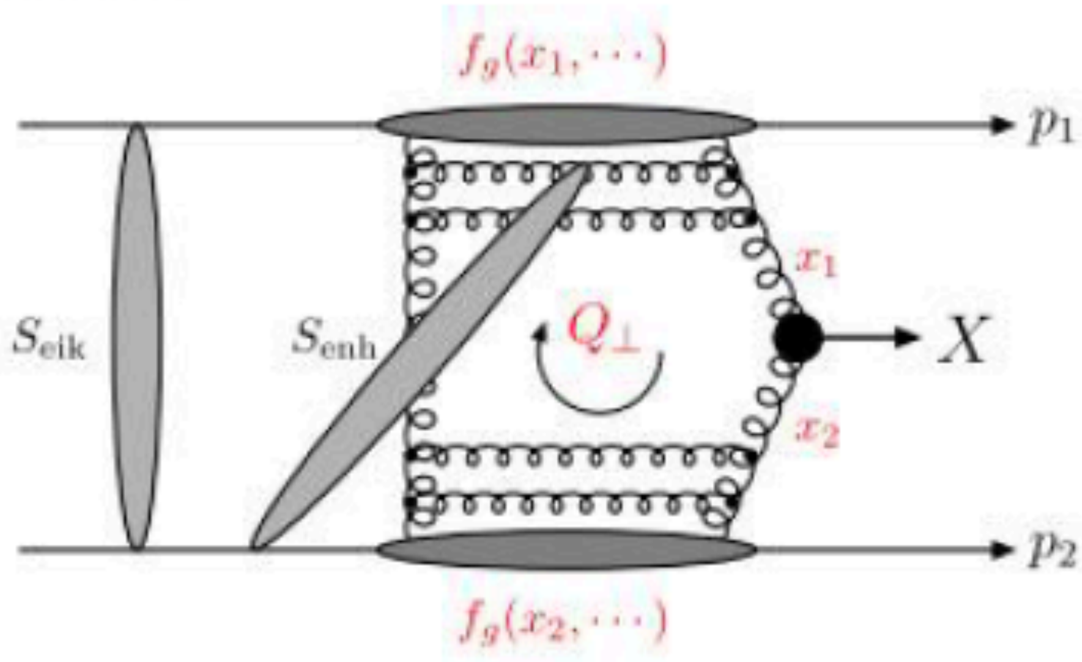

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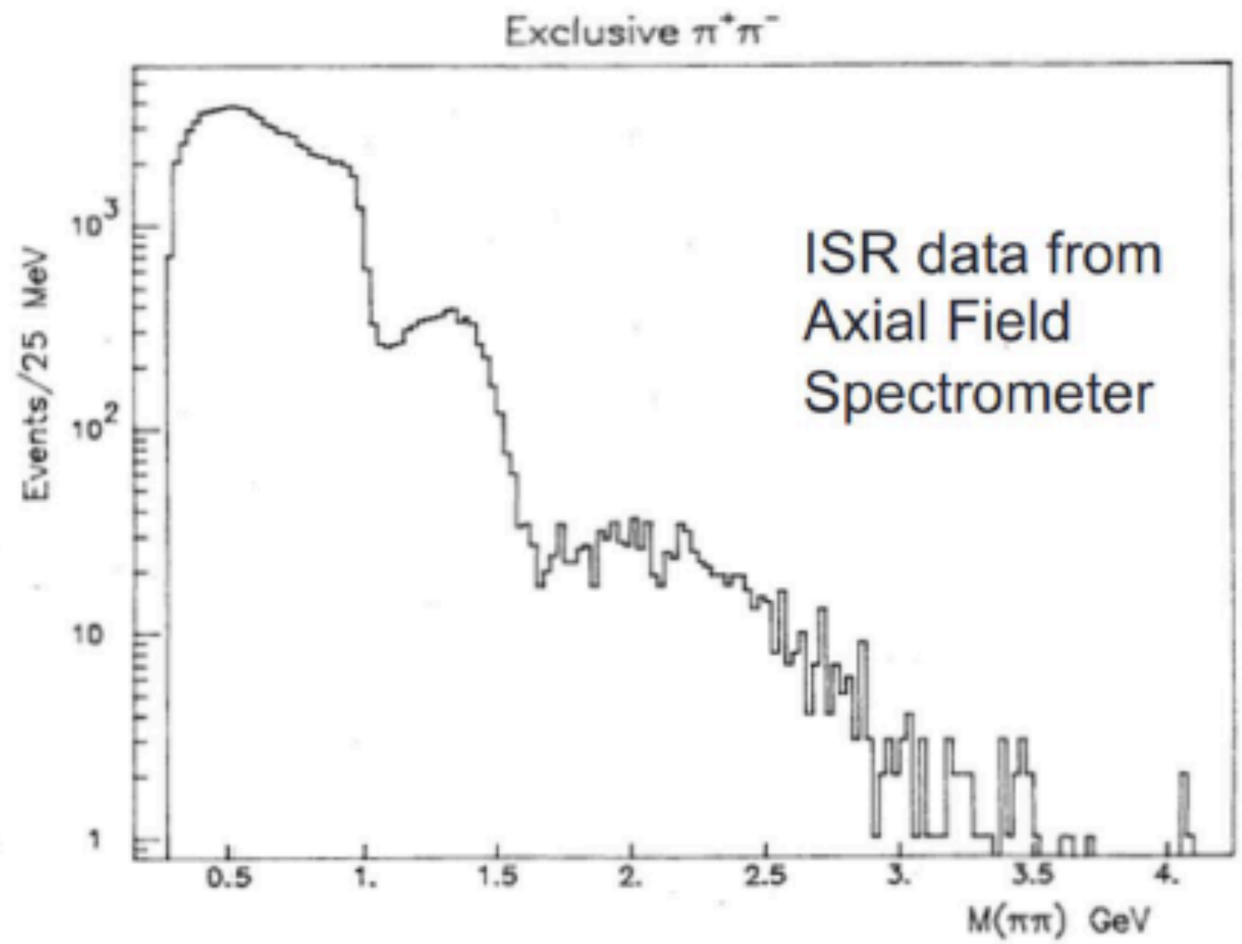

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Open questions: total, elastic and diffractive cross-section

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
Universitá di Pisa

- 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
  It may also be a paradigm for possible BSM 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.

The physics of the early Universe and of compact astrophysical objects may be described by states of matter completely away from our common experience.

Understanding how quarks and gluon deconfine, and what is the nature of the deconfined phase, may give us insight into confinement itself.

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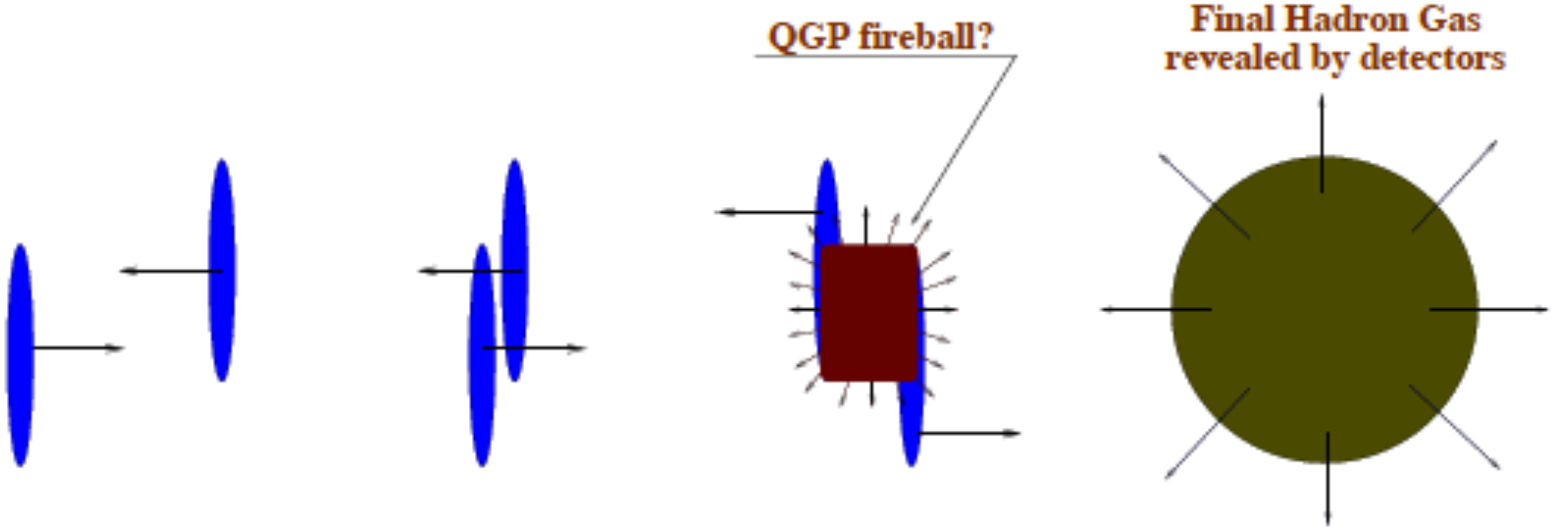
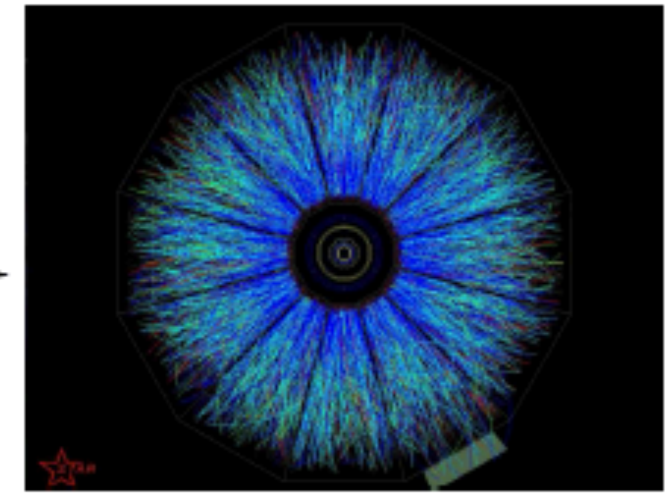
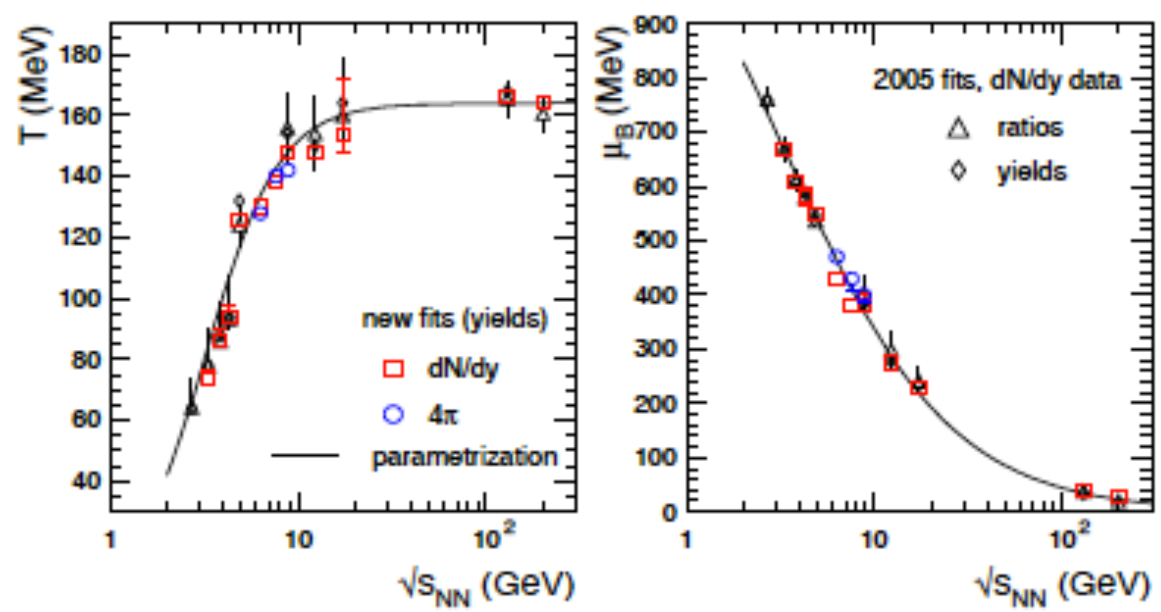
Experimental input? Heavy Ion Collisions (SPS, RHIC, LHC, ... FAIR)





- 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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a comment:

in the italian language trying to translate "New Physics"

one may say, with an appreciably different meaning, :

"Nuova Fisica" meaning

new and unexpected phenomena or facts

but also

"Fisica Nuova"

a "new way of seeing or describing" already known facts

hopefully we are looking for both

and, more important, we should consider both as equally remarkable and striking