



Frontiers of QCD: from Puzzles to Discoveries

14th EDS Blois Workshop (EDS'11)

Quy Nhon (VN), 20th December 2011

David d'Enterria

CERN

Disclaimer

- This is not a summary of all EDS'11 experimental (~30) & theoretical (~25) talks !
- This is a (subjective) selection of a few new results: mostly experimental and mostly from the LHC.
- So, my apologies in advance if you don't find your “favourite” result or plot covered ...

9 QCD topics for EDS'11 ...

- Elastic & total x-sections
- Diffractive scattering
- DPE & central-exclusive production
- Photon-induced collisions
- Hard parton-parton scatterings
- Polarized parton scatterings
- Semi-hard & soft scatterings: UE, MPIs, MB
- Hadronic collisions of UHE cosmic-rays
- Heavy-ion collisions

EDS'11 theoretical developments ...

■ Effective field theories :

- Linear σ + chiral-bag models [M.M. Islam]

■ Regge-type & Regge-Gribov Field Theory approaches :

- Scatt. amplitudes [J. Soffer, L. Jenkovszky, Keiji Igi, A. Godizov]
- Updated (multi-)Pomeron scattering models [Uri Maor]
- Cosmic-rays collision MCs [Tanguy Pierog]

■ Perturbative QCD :

- Central exclusive $|P/\gamma$ -induced production [Szczurek/Luszczak] [L.Harland-Lang]
- NLO+extra wide-angle radiation for N-jets [Jeppe Andersen]
- NLO+PS for $V(V)$ +jets [Y. Kurihara]
- Resummations for jet-shapes [Hsiang-nan Li]

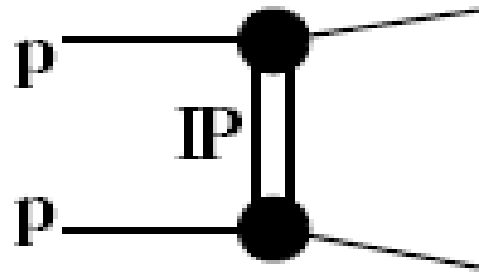
■ Non-linear QCD :

- rc-BK for nuclear DIS [Guilherme Milhano], k_T -factorization [Kazunori Itakura]

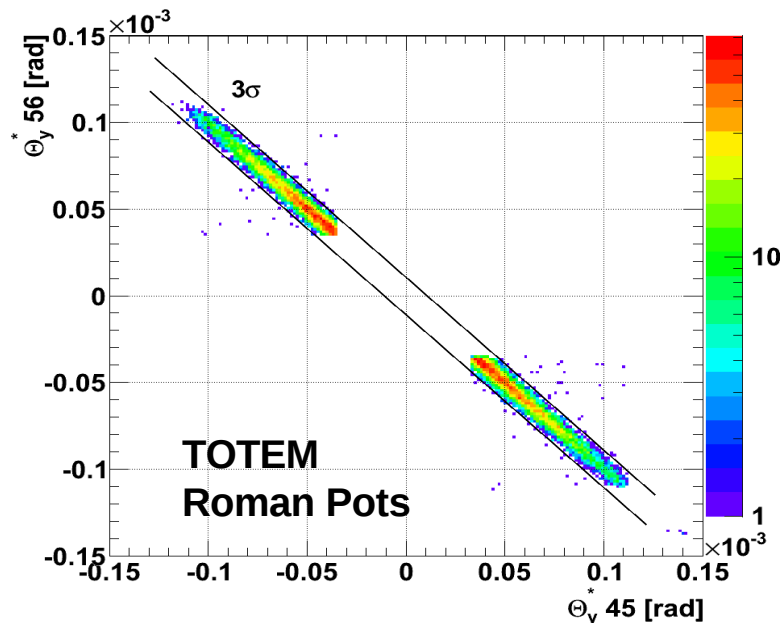
■ AdS/CFT applications:

- Diffractive Higgs production & small-x DIS [Chung-I Tan]
- Hydrodynamics of strongly-interacting fluids [Dam T. Son]
- Quantum phase transitions [Sumit R. Das]
- Generalized PDFs [Taizan Watari]
- Q - Q bar dipole [Antal Jevicki]
- Nucleus (baryons) as D-branes [Koji Hashimoto]

Elastic & total cross-sections



[Mario Deile (TOTEM)]
[Marcello Bindi (LHC)]
[Christophe Royon (D0)]
[I.G. Alekseev (ITEP)]



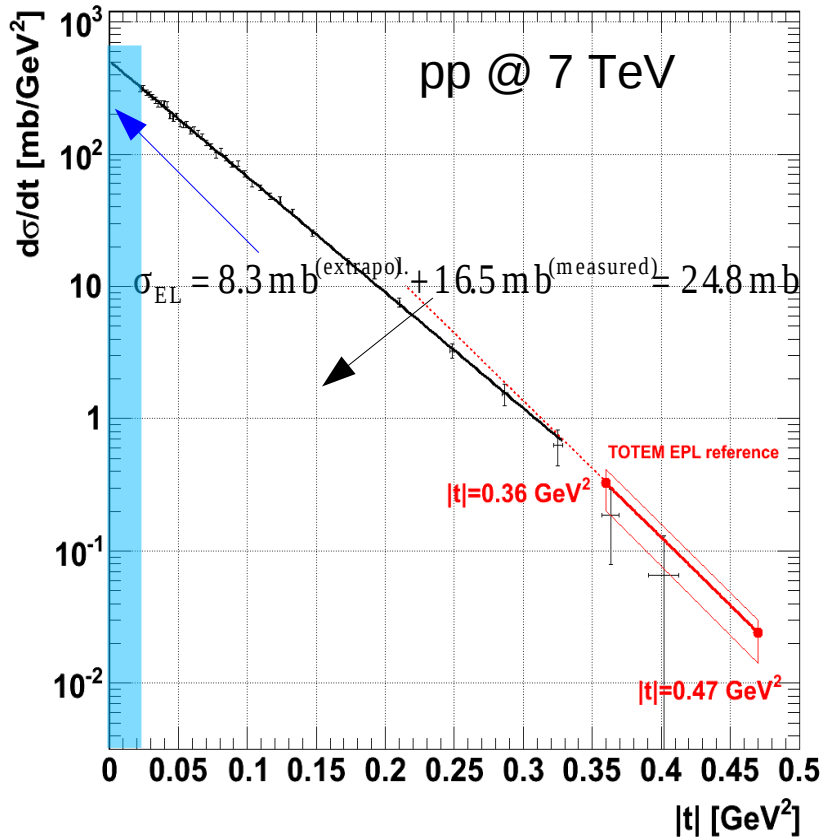
[Jacques Soffer]
[M.M. Islam]
[Uri Maor]
[L. Jenkovszky]
[Keiji Igi]
[A. Godizov]
[Igor Dremin]

Total & elastic cross sections (LHC)

[M. Deile (TOTEM)]

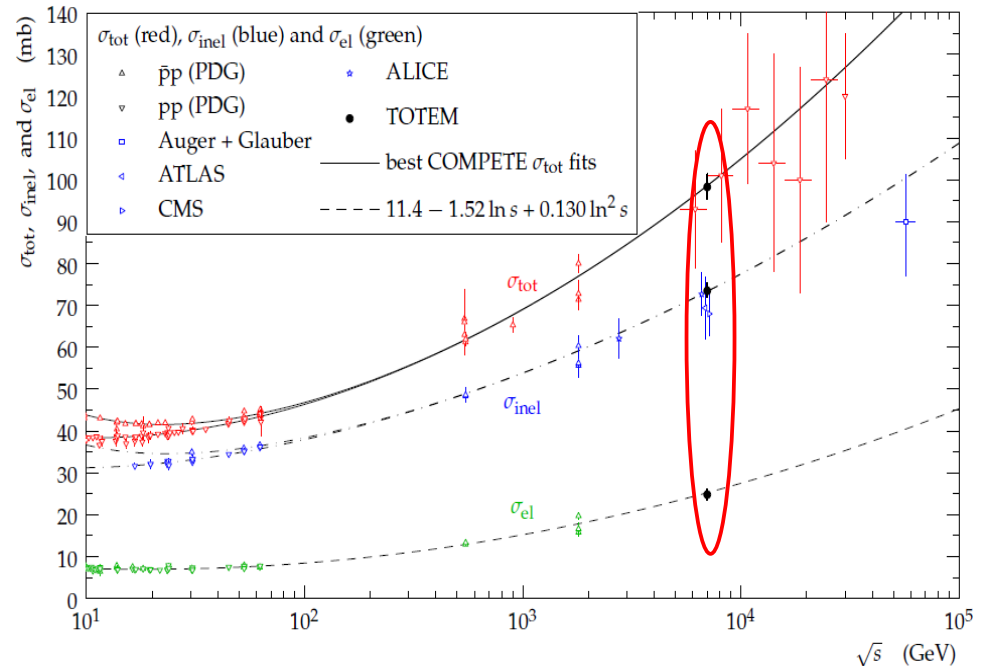
■ **Optical Theorem:** $\sigma_{TOT}^2 = \frac{16\pi(\hbar c)^2}{1+\rho^2} \cdot \frac{d\sigma_{EL}}{dt} \Big|_{t=0}$ $\rho = 0.14^{+0.01}_{-0.08}$ (from COMPETE Collab. world-fit)

$\frac{d\sigma_{EL}}{dt} = \frac{1}{L} \cdot \frac{dN_{EL}}{dt}$ (lumi from CMS, uncertainty $\pm 4\%$)



$$\sigma_T = \left(98.3 \pm 0.2^{(stat)} \pm 2.7^{(syst)} \left[\begin{matrix} +0.8 \\ -0.2 \end{matrix} \right]^{(syst \text{ from } \rho)} \right) \text{ mb}$$

$$\sigma_{inel} = \sigma_{tot} - \sigma_{el} = \left(73.5 \pm 0.6^{(stat)} \left[\begin{matrix} +1.8 \\ -1.3 \end{matrix} \right]^{(syst)} \right) \text{ mb}$$

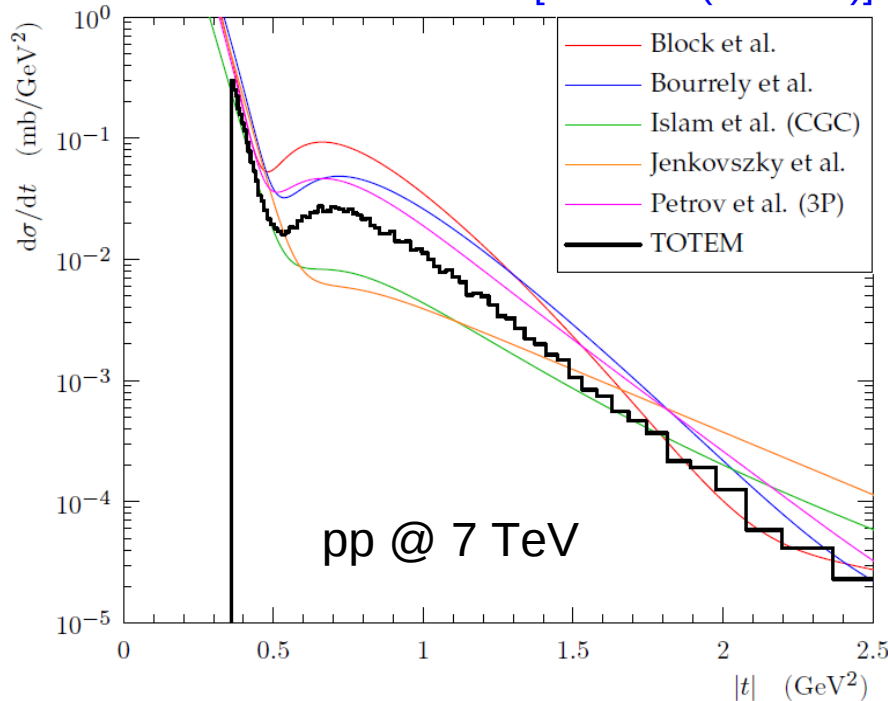


■ σ_{tot} follows closely the value predicted by the **COMPETE fit**.

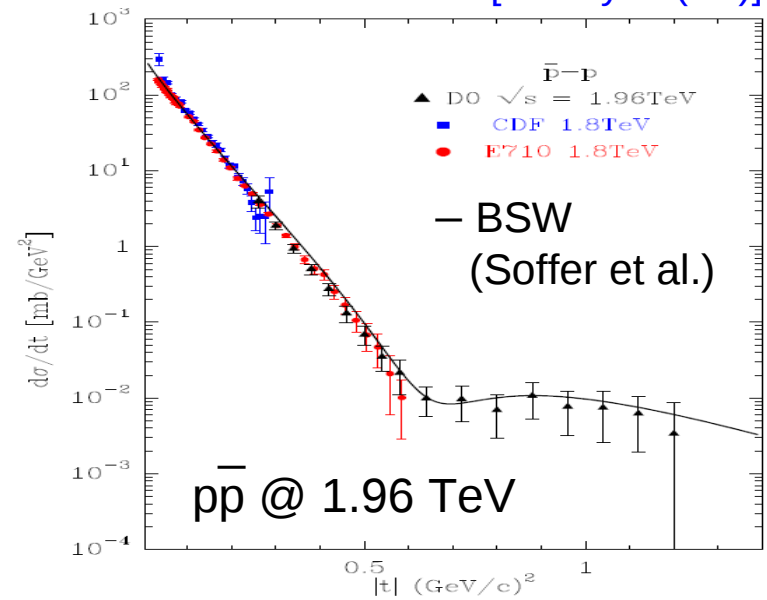
■ TOTEM σ_{inel} slightly larger than ATLAS/CMS. Relevant for cosmic-rays MCs.

Differential elastic scattering (LHC, Tevatron)

[M. Deile (TOTEM)]



[C. Royon (D0)]

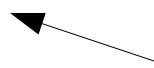


■ TOTEM has confirmed :

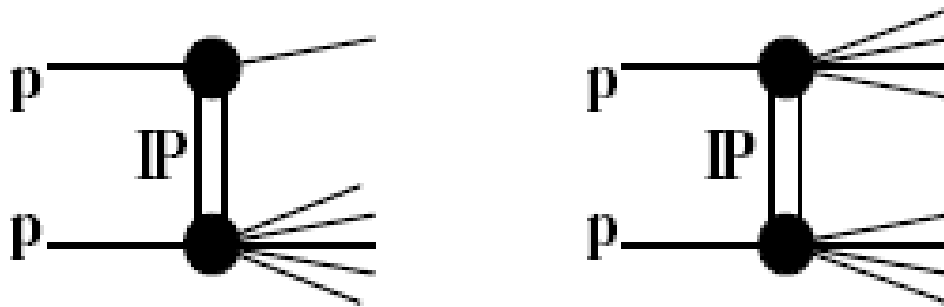
- Increase of σ_{el}/σ_{tot}
- Decrease of inverse expo slope
- Shrinkage of diffraction peak
- Decrease of dip t-position

■ But so far **only partial quantitative agreement** with model predictions.
Can this be improved ?

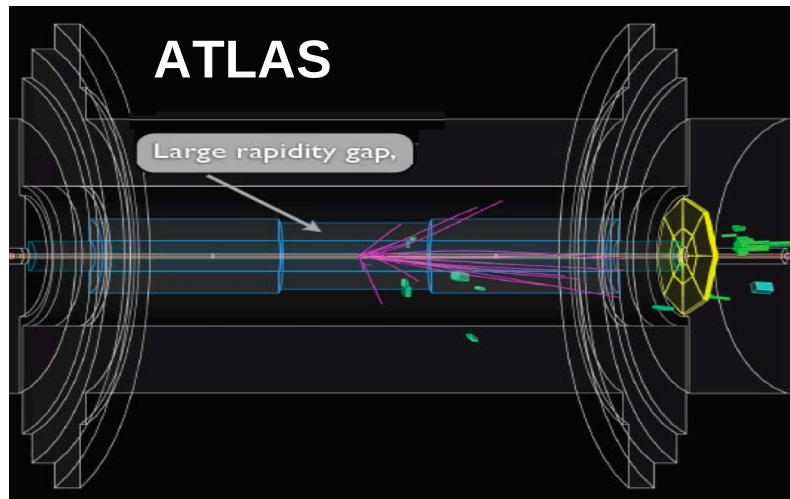
	B (t=-0.4 GeV ²)	t_{DIP}	n in t⁻ⁿ [1.5-2.5 GeV ²]
Block et al.	24.4	0.48	10.4
Bourrely et al.	21.7	0.54	8.4
Islam et al.	19.9	0.65	5.0
Jenkovszky et al.	20.1	0.72	4.2
Petrov et al.	22.7	0.52	7.0
TOTEM	23.6	0.53	7.8
	±0.5±0.4	±0.01±0.01	±0.3±0.3



Diffractive scattering



[Alessia Bruni (ATLAS)]
[Albert Knutsson (CMS)]
[M. Poghosyan (ALICE)]
[Dino Goulianos (CDF)]
[Christophe Royon (D0)]
[Alice Valkarova (HERA)]



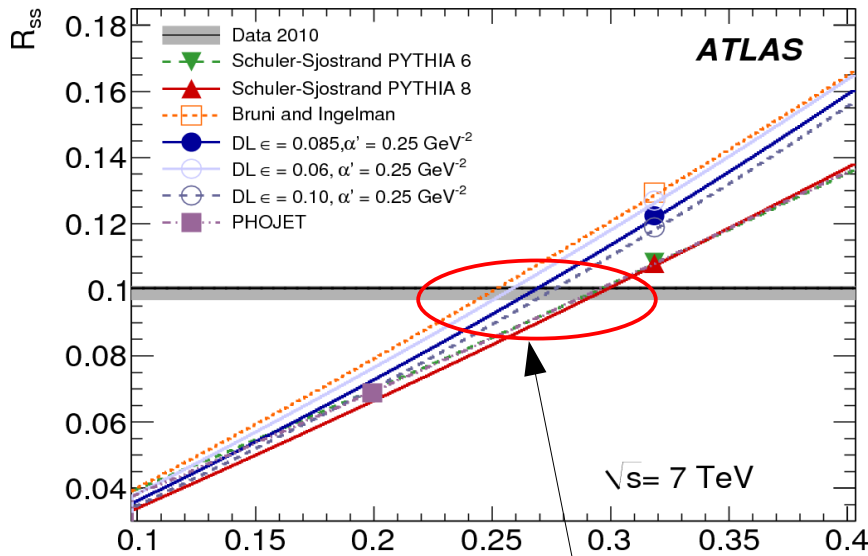
[Jacques Soffer]
[M.M. Islam]
[Uri Maor]

Soft & hard diffraction (LHC)

- 1st attempts at extracting the **inclusive diffractive x-section**:

[M. Pogosyan (ALICE)]

Ratios of single/double-side triggers



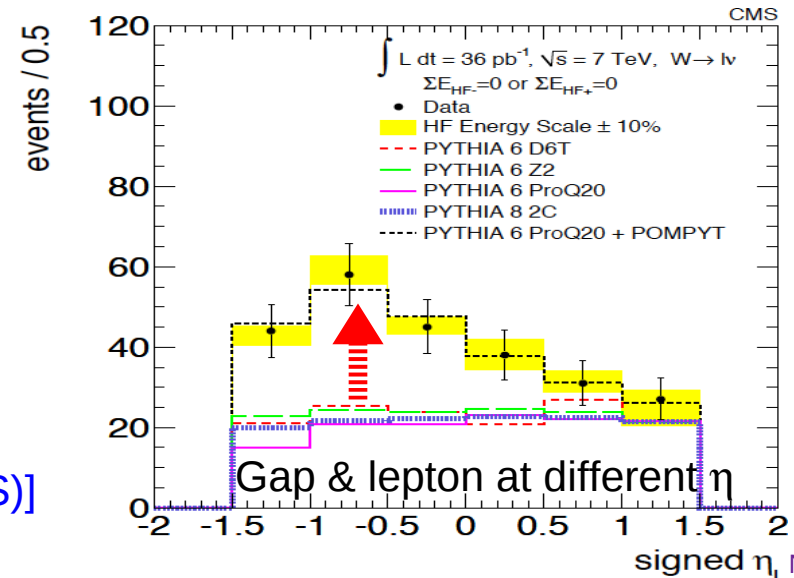
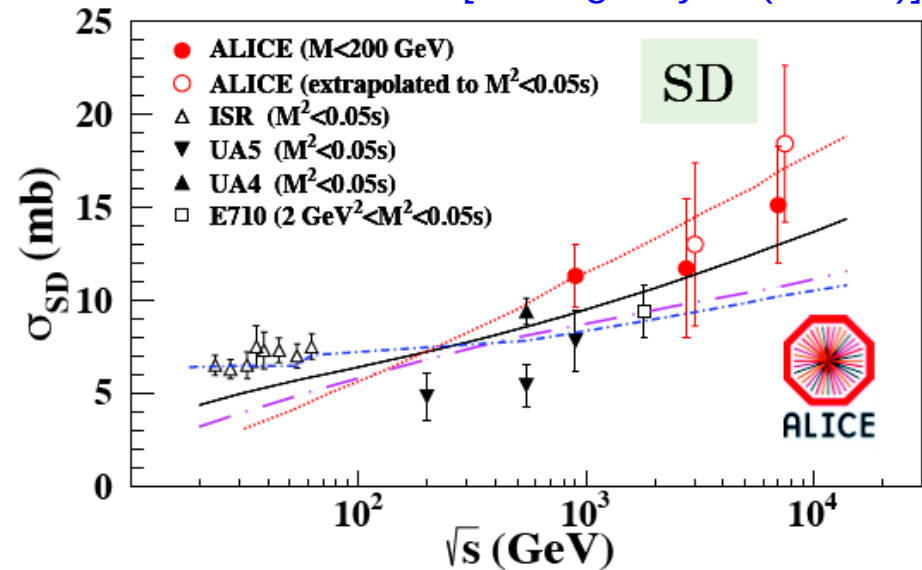
$$R_{SS} = 10.0 \pm 0.4\% \rightarrow f_D \sim 25-30\%$$

($\sigma_{diff} \sim 17-21$ mb) depending on models

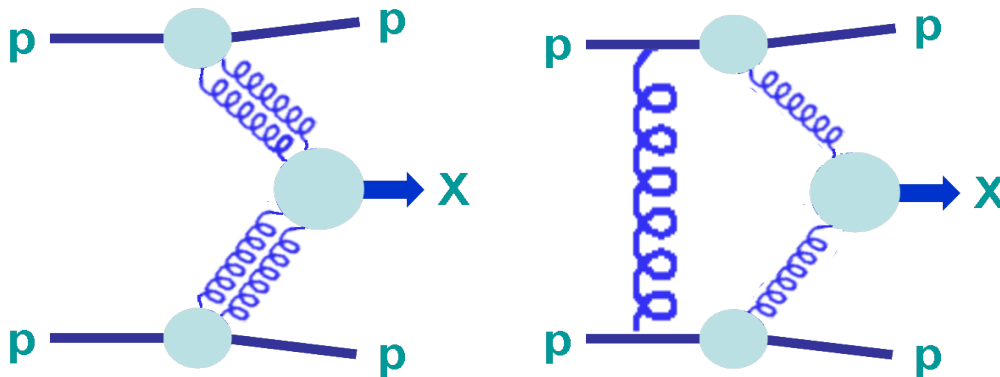
[Alessia Bruni (ATLAS)]

- First observations of **hard diffractive processes** (e.g. **W+rap-gap**):

[Albert Knutsson (CMS)]

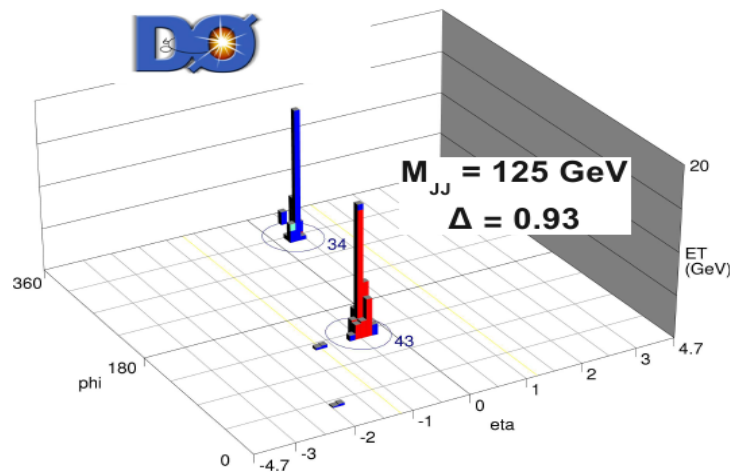


CEP & DPE (IP IP) production



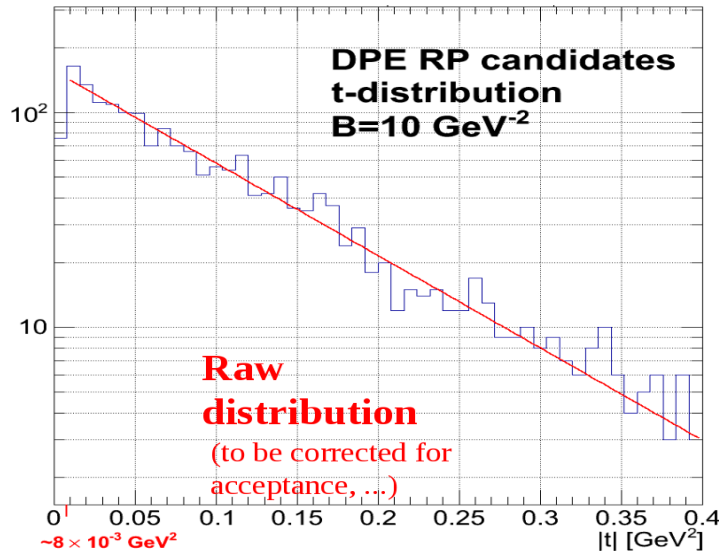
[Mario Deile (TOTEM)]
[R. Schicker (ALICE)]
[Dino Goulianos (CDF)]
[Christophe Royon (D0)]
[Achim Geiser (HERA)]

[A. Szczurek]
[L. Harland-Lang]
[Marta Luszczak]
[Chun-I Tan]

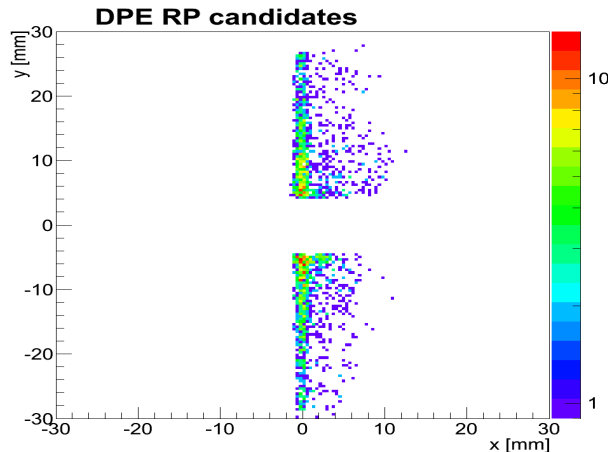


Double Pomeron production (LHC)

- First attempts at measuring the inclusive **DPE** x-section:

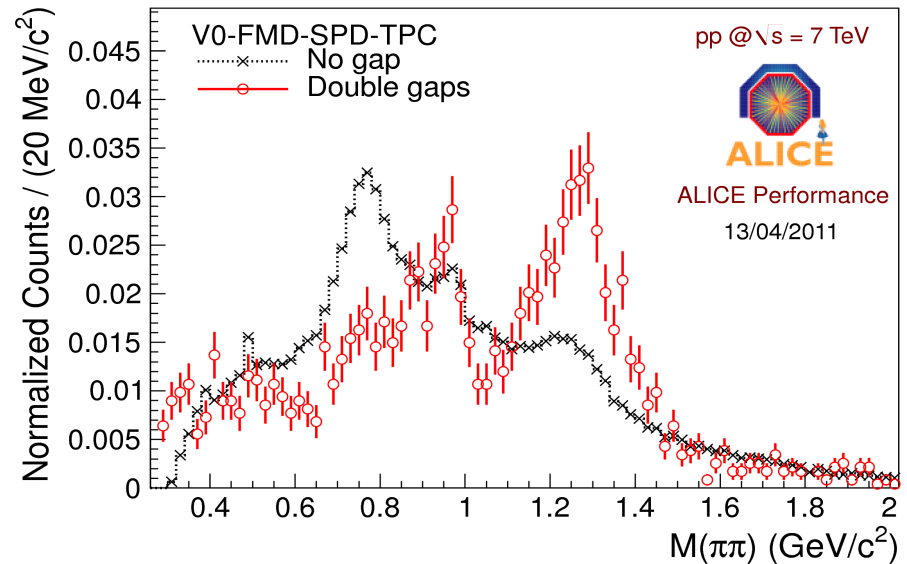
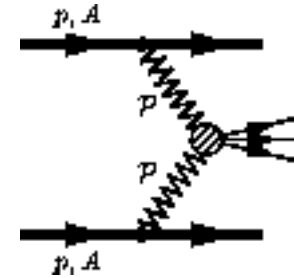


[Mario Deile (TOTEM)]



- Enhanced $f_0(980)$ & $f_2(1270)$ production in double-gap events ($\Delta\eta_{\text{gaps}} = 3,4$):

$$J^{PC} = (0,2)^{++}$$

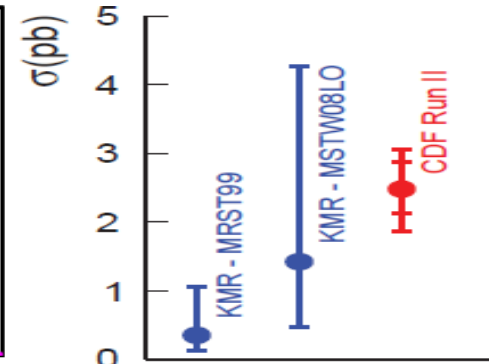
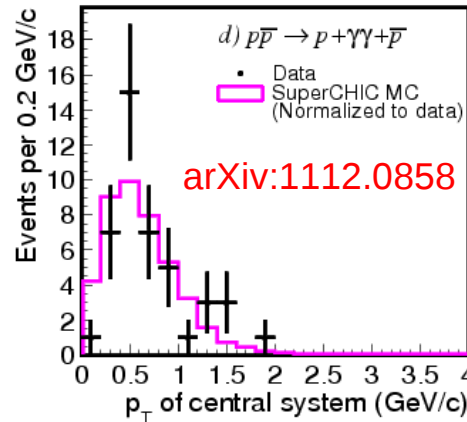
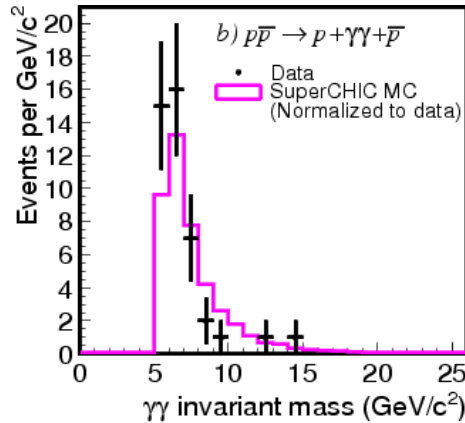
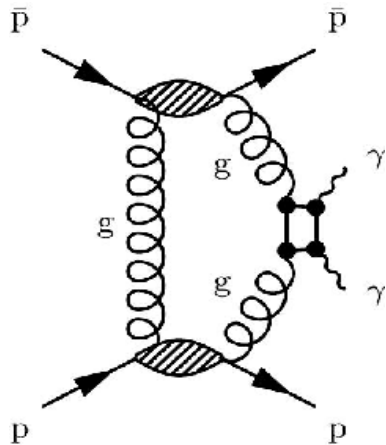


[R. Schicker (ALICE)]

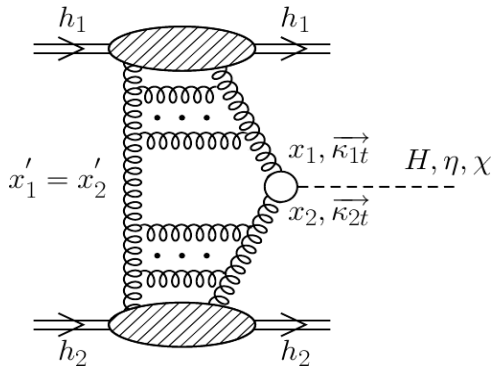
Central exclusive production (Tevatron, LHC)

■ 1st observation of exclusive $|P|P \rightarrow \gamma\gamma$ ($p\bar{p}$ @ 1.96 TeV):

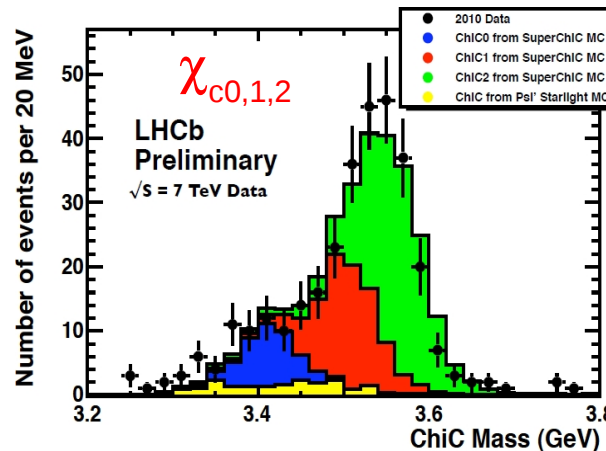
[Dino Goulianos (CDF)]



■ Many theoretical studies for exclusive χ_c, H, \dots production at the LHC:



[Szczurek/Luszczak]
[Chun-I Tan]

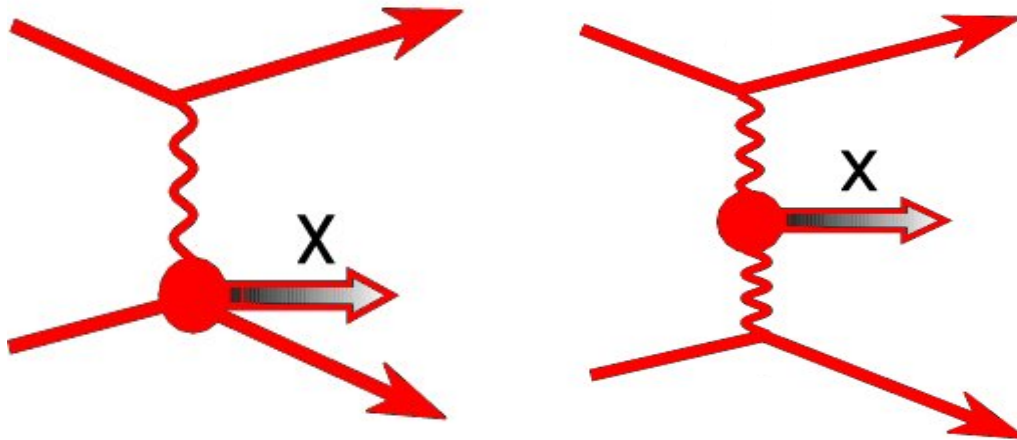


[L. Harland-Lang]

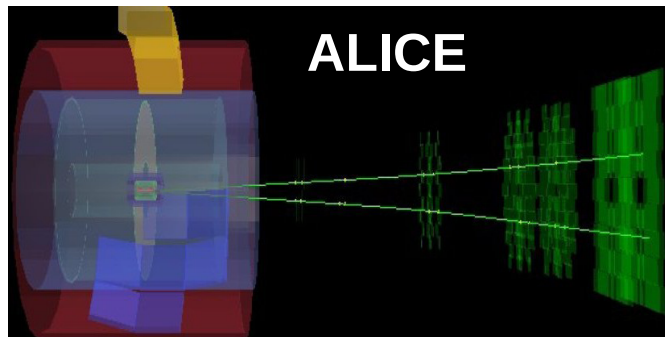
	$\sigma(pp \rightarrow pp(J/\psi + \gamma))$ LHCb (pb)	SuperCHIC prediction (pb)
χ_{c0}	9.3 ± 4.5	14
χ_{c1}	16.4 ± 7.1	10
χ_{c2}	28 ± 12.3	3

➡ Important constraints for gap-survival-probab. & backgds for new excl. physics

Photon-induced collisions



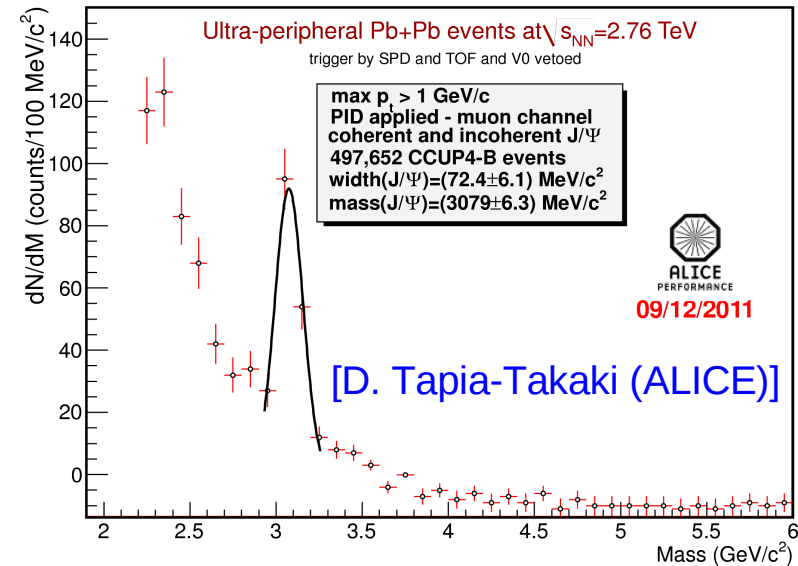
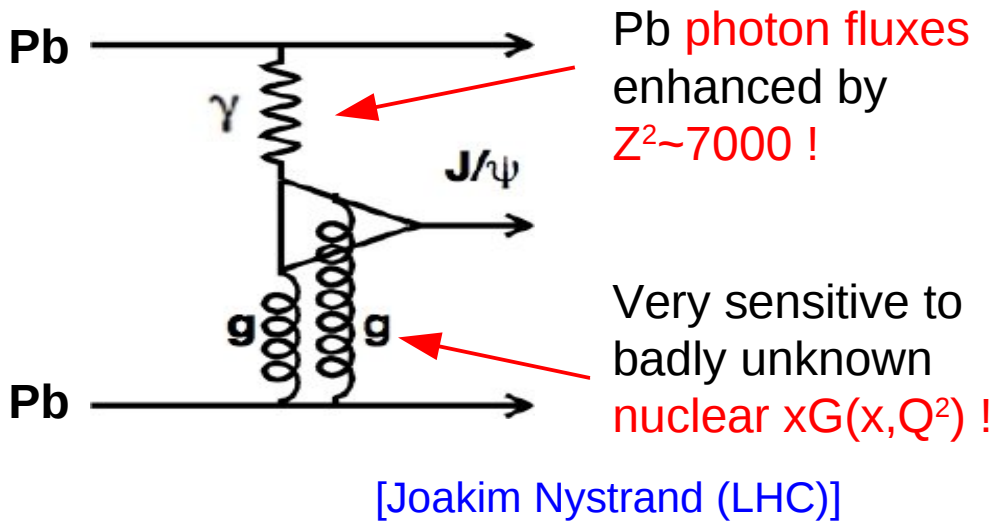
[Laurent Favart (HERA)]
[Joakim Nystrand (LHC)]
[D. Tapia-Takaki (ALICE)]
[Herve Grabas (ATLAS)]



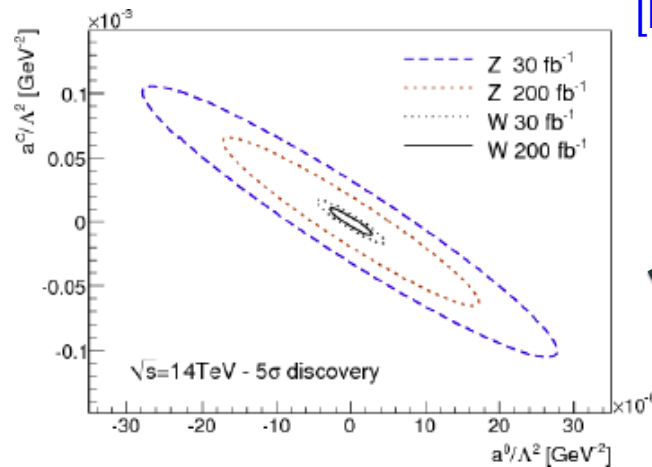
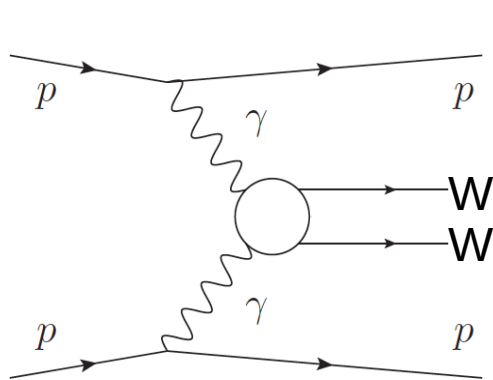
[Szczurek/Luszczak]

γ -A and γ - γ collisions (LHC)

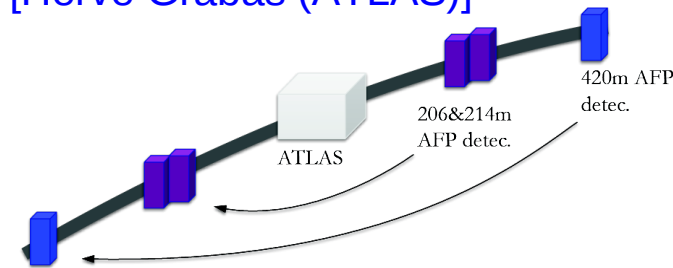
- Observation of **exclusive PbPb \rightarrow Pb J/ Ψ Pb** photoproduction:



- Study of **pp \rightarrow pWWp**: 10^4 times larger sensitivity to **anomalous QGC**

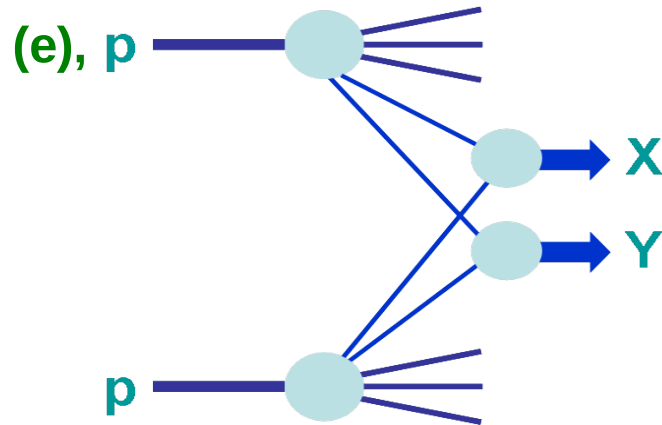


[Herve Grabas (ATLAS)]

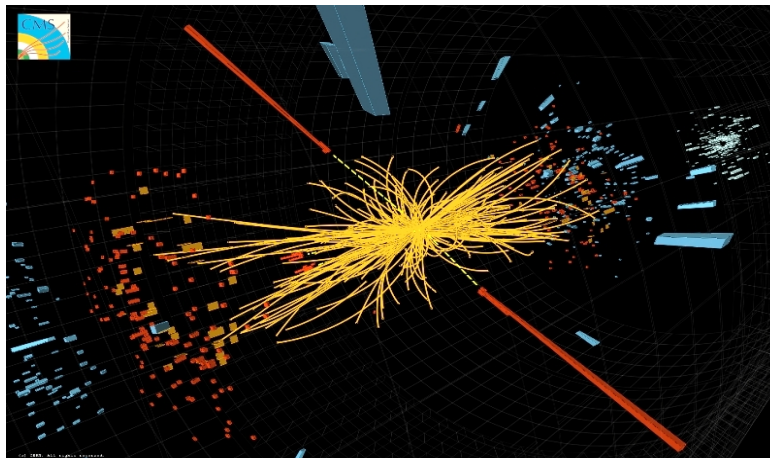


ATLAS AFP p spectrometer+ timing project (206-214m)

Hard parton-parton scatterings



[Achim Geiser (HERA)]
[C. Mesropian (Tevatron)]
[Mikko Voutilainen (LHC)]
[M. Sutton (LHC)]
[Alessia Bruni (ATLAS)]
[Matt Nguyen (CMS)]



[Jeppe Andersen]
[Guilherme Milhano]
[Y. Kurihara]
[Hsiang-nan Li]
[Chun-I Tan]

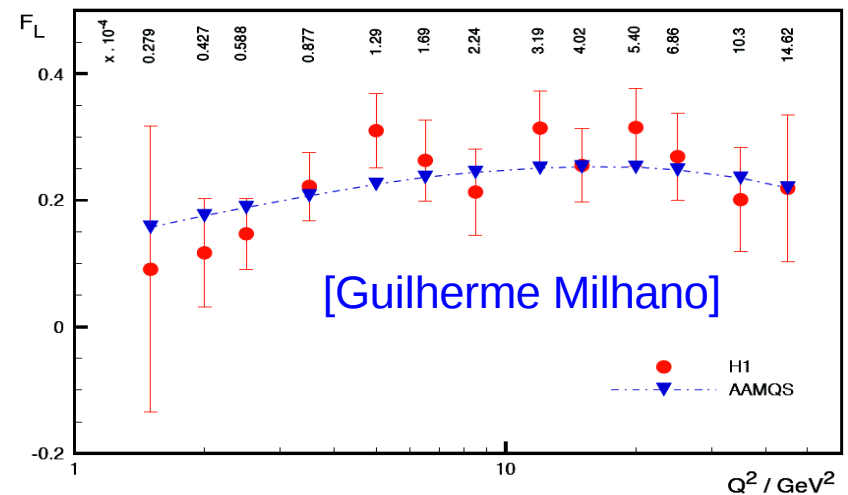
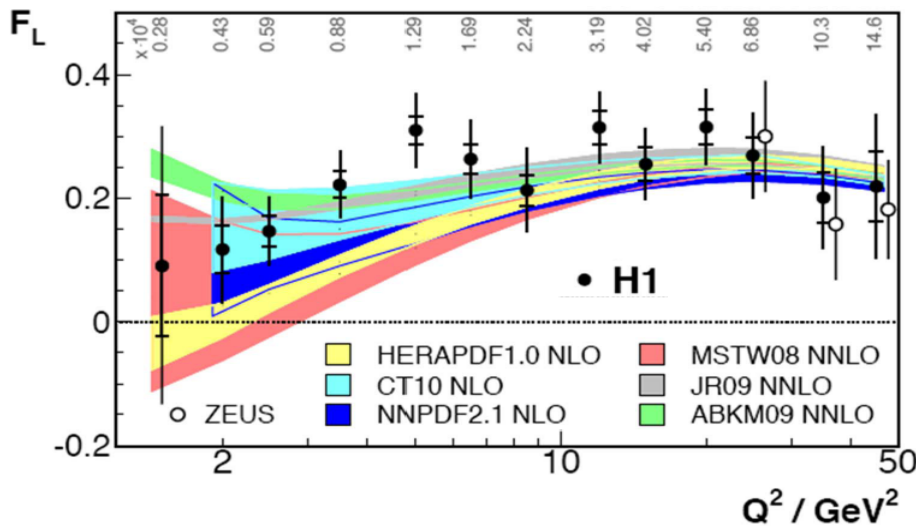
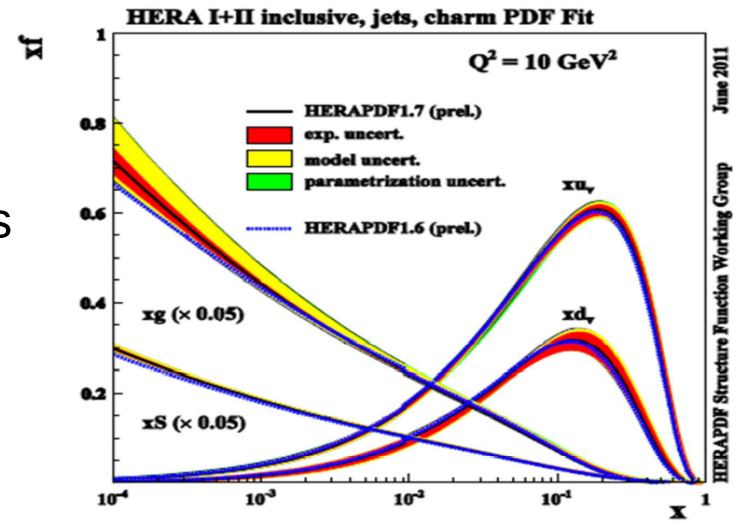
Parton distribution functions (HERA)

- Updated H1+ZEUS HERAPDF sets:
 - Accurate combination of exp. errors.
 - Realistic separation of PDF uncertainties

[Achim Geiser (HERA)]

- F_L (\propto gluon) vs PDF fits:

- Good agreement for DGLAP fits but **large spread at $Q^2 < 10 \text{ GeV}^2$** .
- Excellent agreement of **non-linear QCD** fits (AAMQS: 4 parameters !)

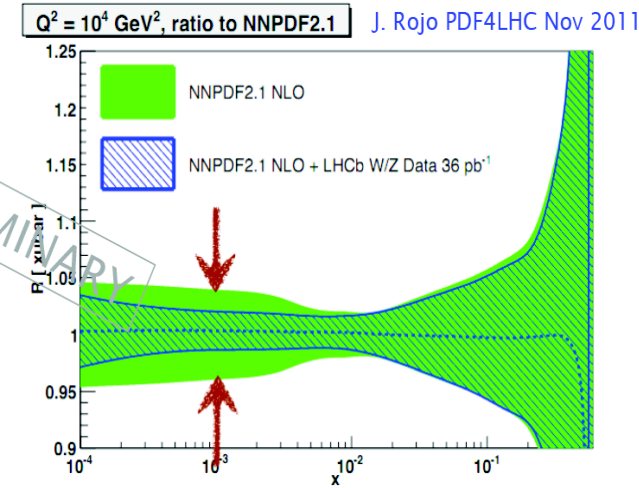
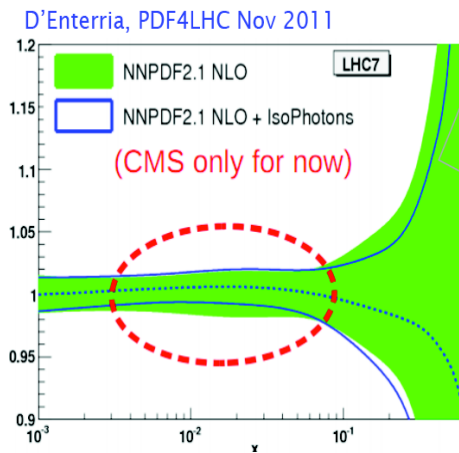
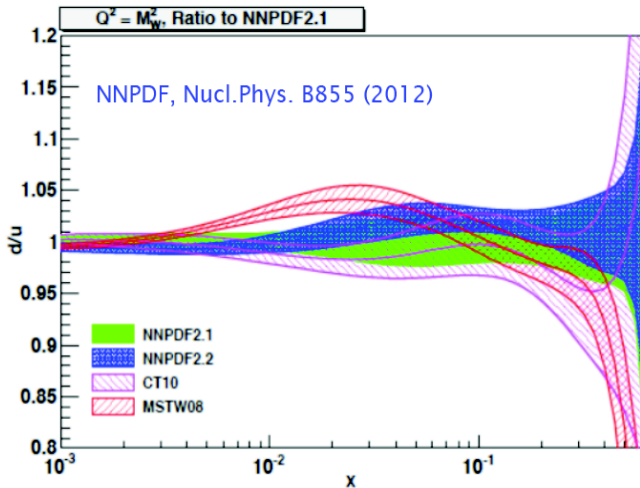
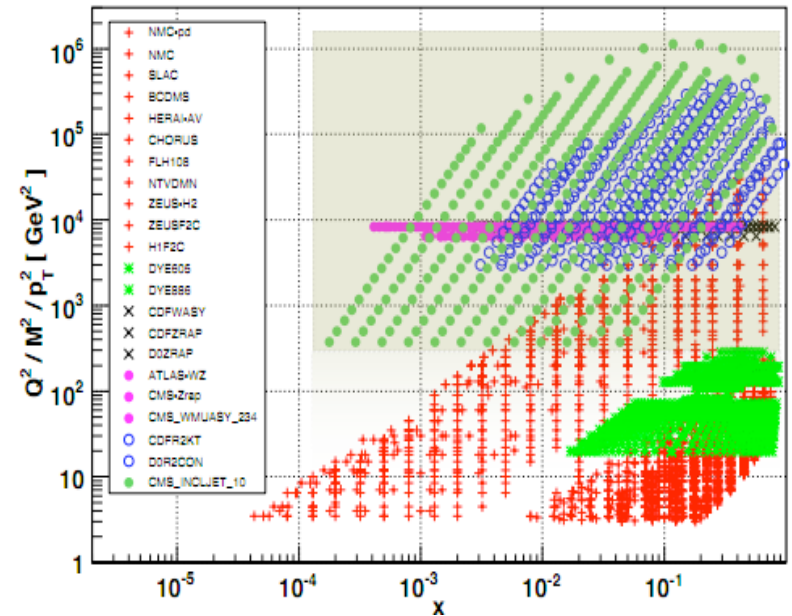


Parton distribution functions (LHC)

- Lots of new data ! [Mikko Voutilainen] [M. Sutton]
 - Medium & large-x gluon: **precision jets, prompt γ , top pairs.**
 - Light-flavors at medium & small x: **low-mass DY, Z vs y , W asymm.**
 - Strangeness & heavy-flavors: **W+c for s; Z, γ +c for charm; Z+b for bottom.**

- New **fast reweighting techniques** (NNPDF2.1) for NLO PDFs:

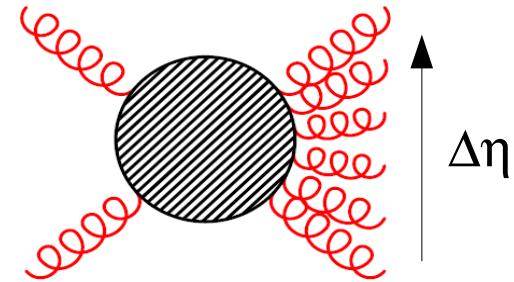
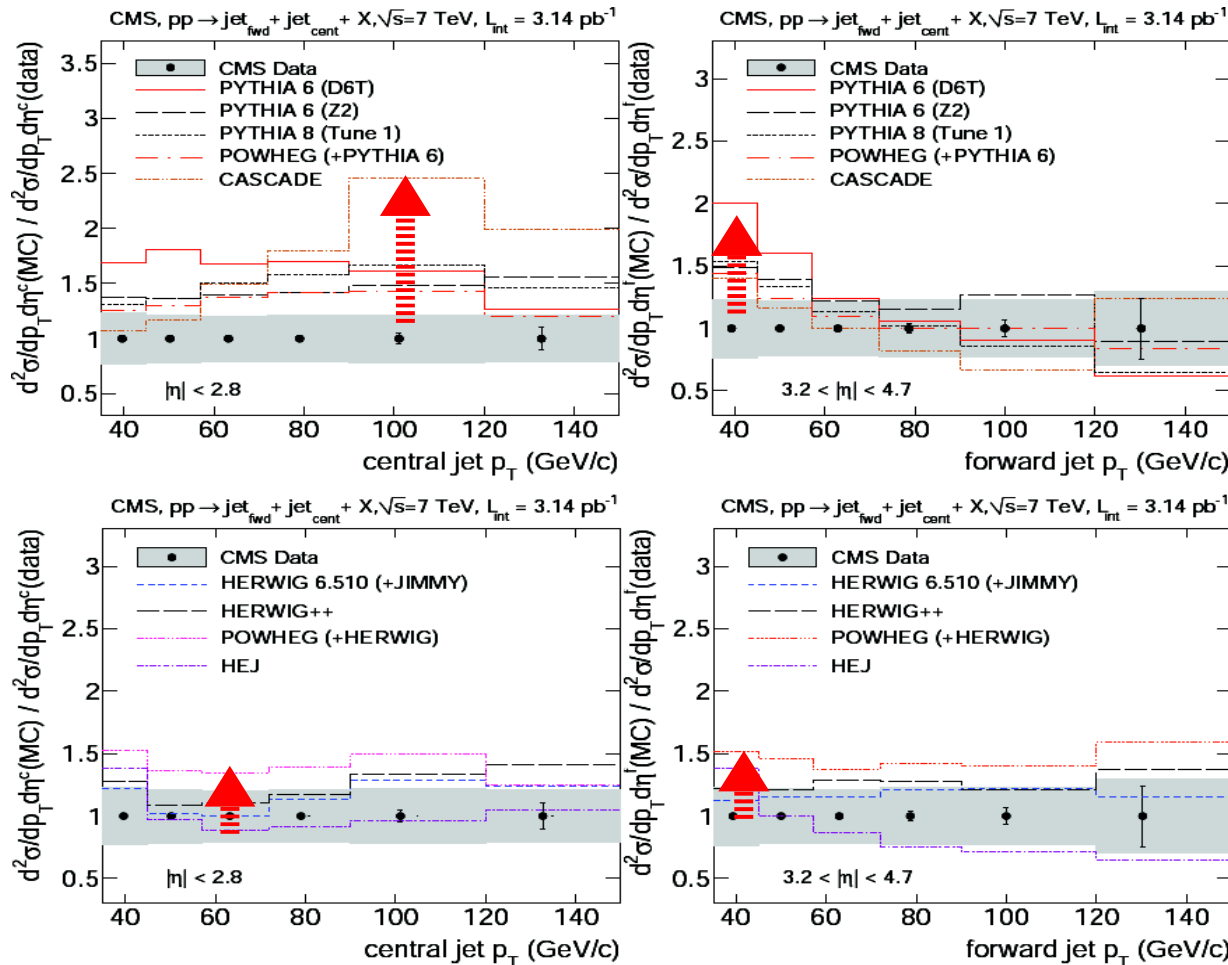
NNPDF2.1 dataset + LHC data



Beyond DGLAP dynamics at the LHC ?

- **Fwd-cent. dijets** or **dijets+central-veto** (p-p at 7 TeV) with large $\Delta\eta$ separations access **BFKL-type** topologies

[A. Bruni (ATLAS)]
[M. Nguyen (CMS)]



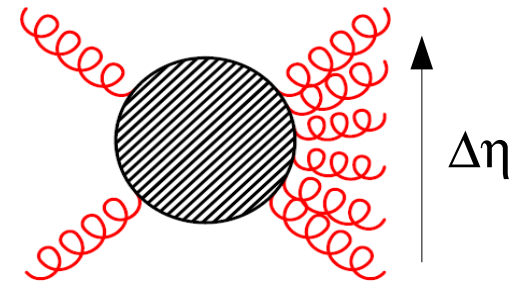
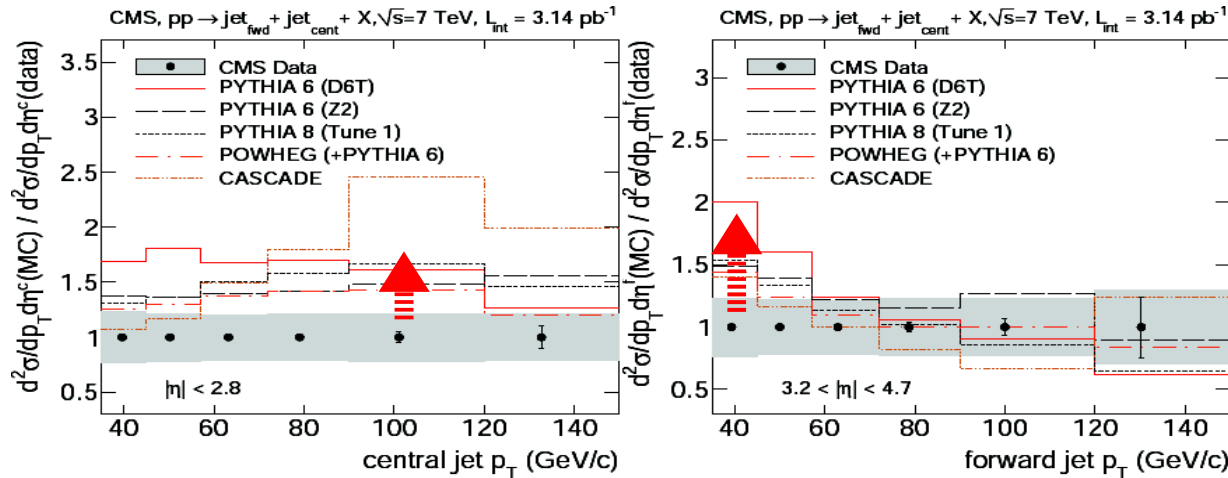
[Jeppe Andersen]

- **PYTHIA & NLO miss** the jet p_T distributions (UE model not relevant).
- Calculations with **wide-angle radiation (HEJ)** show better agreement

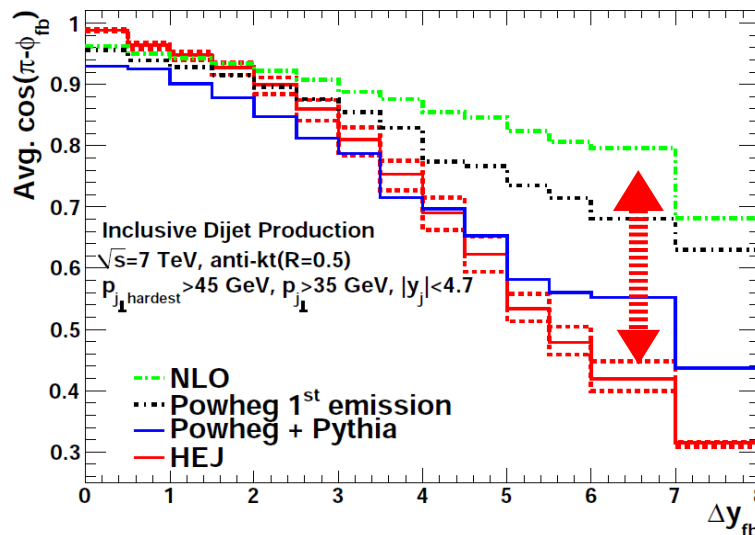
Beyond DGLAP dynamics at the LHC ?

- Fwd-cent. dijets or dijets+central-veto (p-p at 7 TeV) with large $\Delta\eta$ separations access BFKL-type topologies

[A. Bruni (ATLAS)]
[M. Nguyen (CMS)]

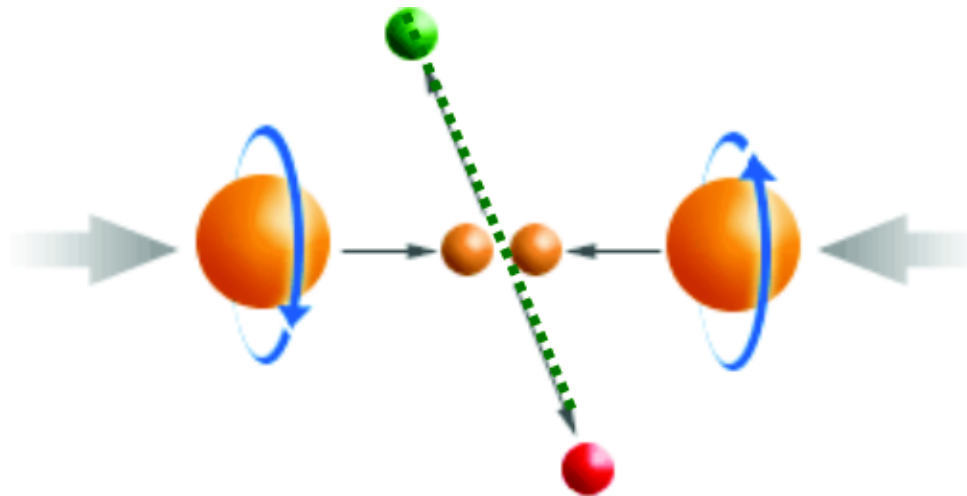


[Jeppe Andersen]



- Calculations with wide-angle radiation (HEJ) show better agreement.
- New observables (Mueller-Navelet dijets) to be studied soon.

Polarized parton scattering

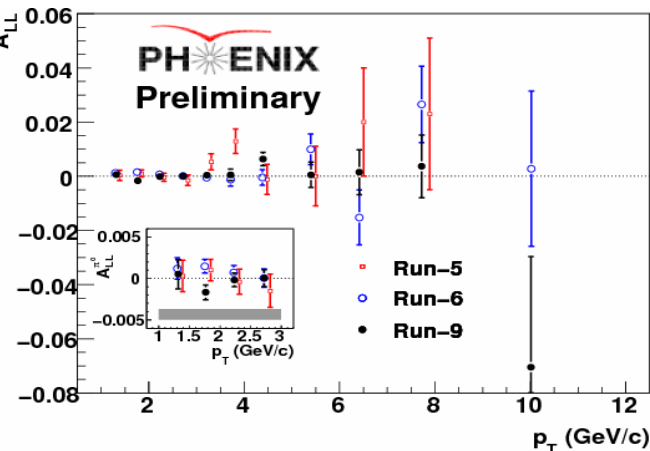
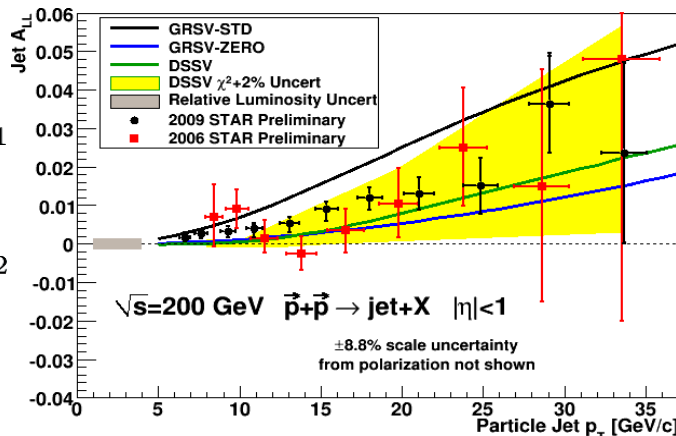
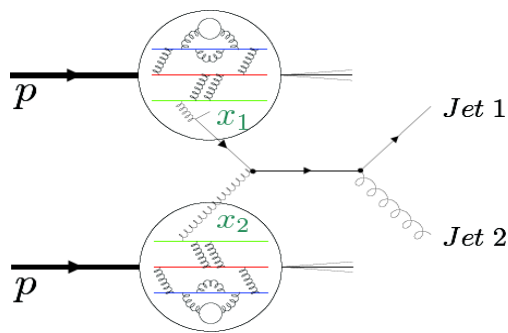


[Bernd Surrow (RHIC)]
[D. Svirida (STAR)]
[Y. Miyachi (HERMES)]

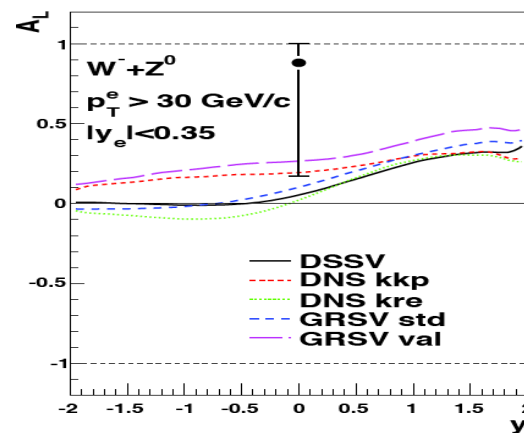
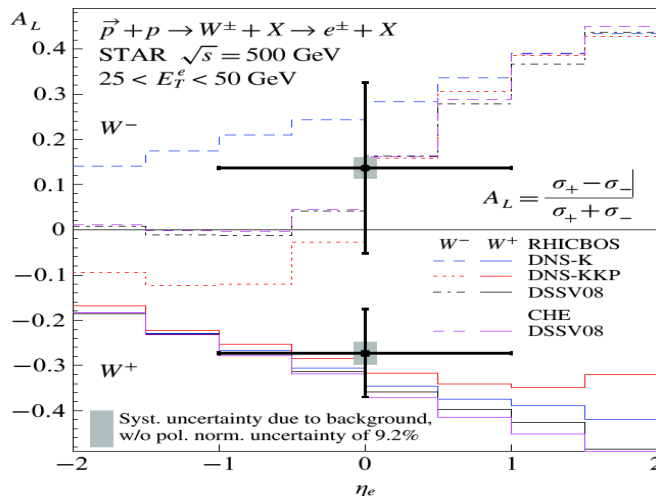
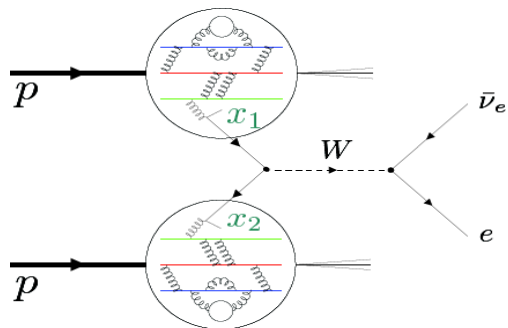
[Jacques Soffer]

q,g polarizations do not explain proton spin !

■ Gluon polarization via A_{LL} in high- p_T π^0 & (di)jet production at RHIC:



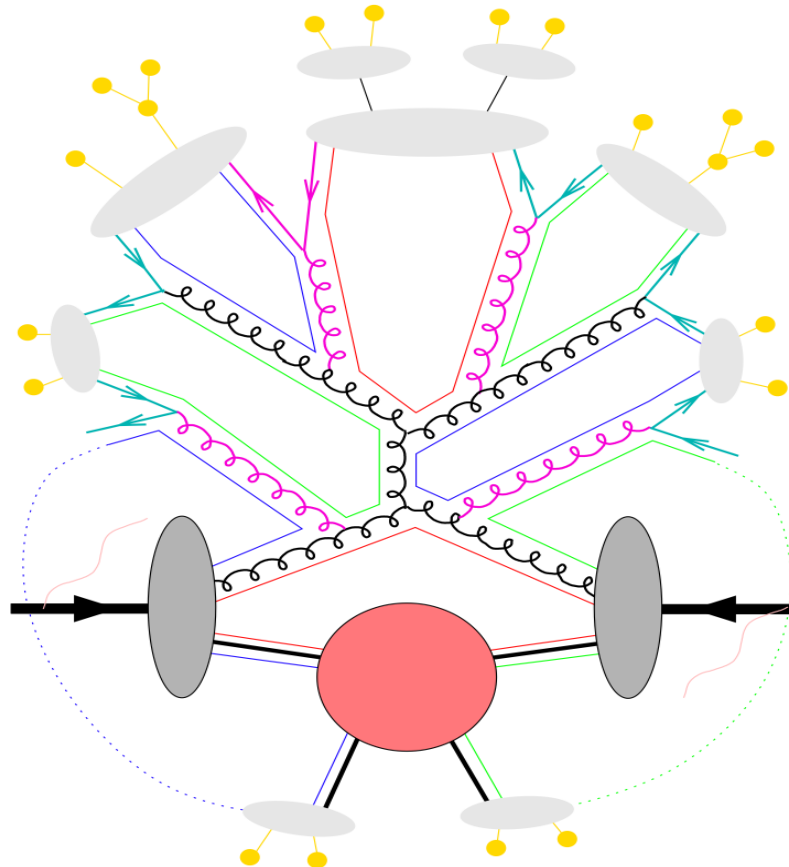
■ q,qbar polarization via A_L in W production at RHIC: [Bernd Surrow (RHIC)]



■ Results prove small (non-null?) G polarization:

$$\frac{1}{2} = \underbrace{\langle S_q \rangle}_{\frac{1}{2} \Delta \Sigma} + \underbrace{\langle S_g \rangle}_{\Delta G} + \underbrace{\langle L_q \rangle + \langle L_g \rangle}_{\text{(spin from ang.mom.)}}$$

Semi-hard & soft processes



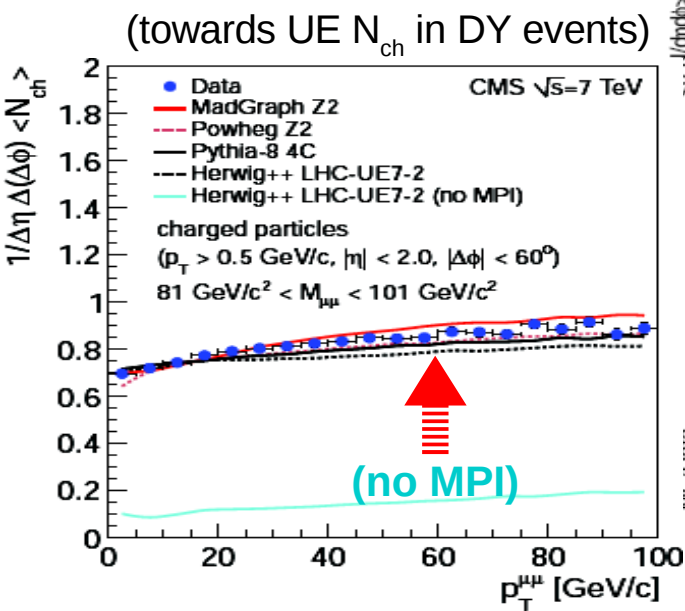
[Nick Brook (LHC)]
[M. Heinrich (LHC)]
[Tomas Hreus (LHC)]

[Tanguy Pierog]
[Igor Dremin]

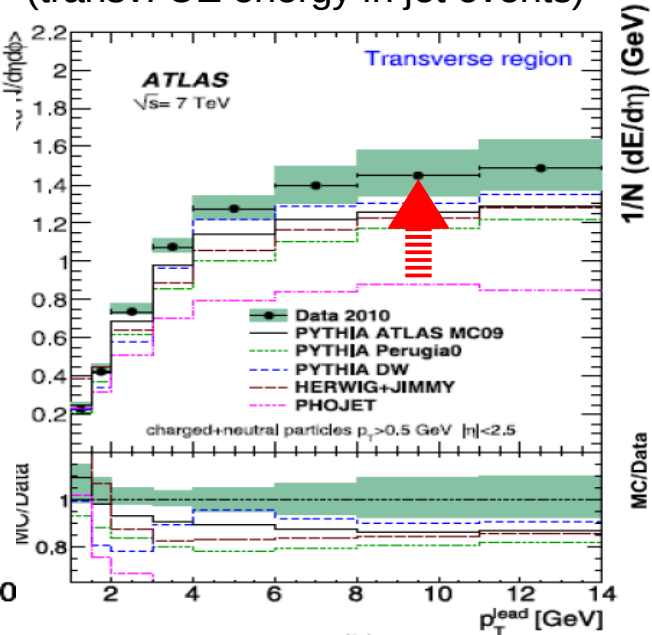
Multi-parton interactions at the LHC

- Underlying event & min-bias distributions clearly require MPIs:

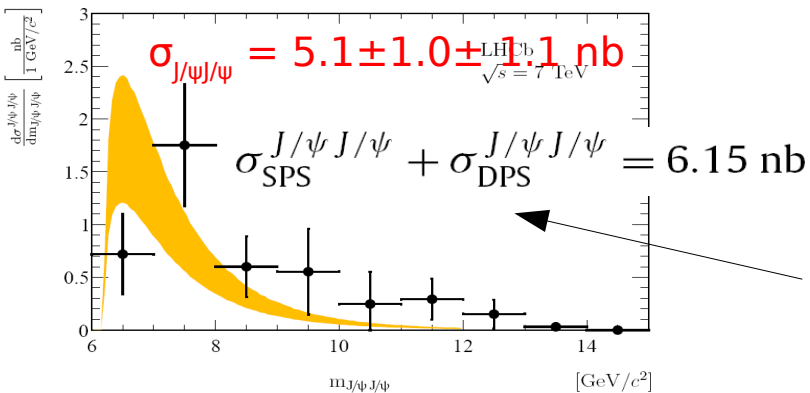
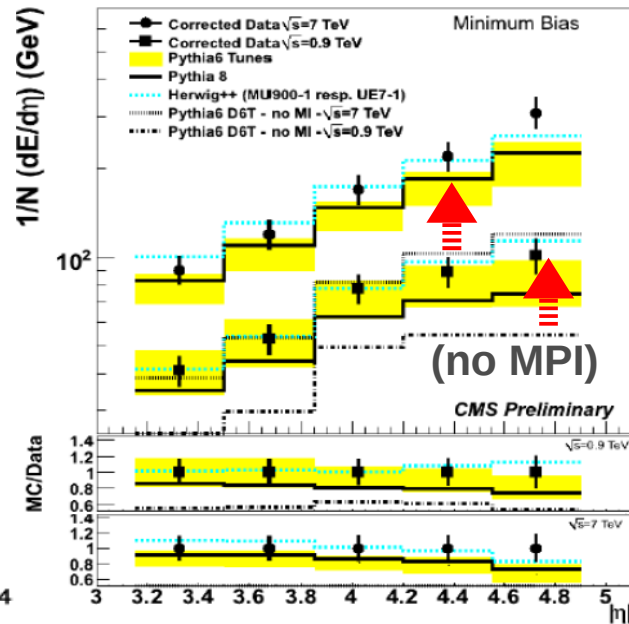
[M. Heinrich (LHC)]



(transv. UE energy in jet events)



(forward energy flow)



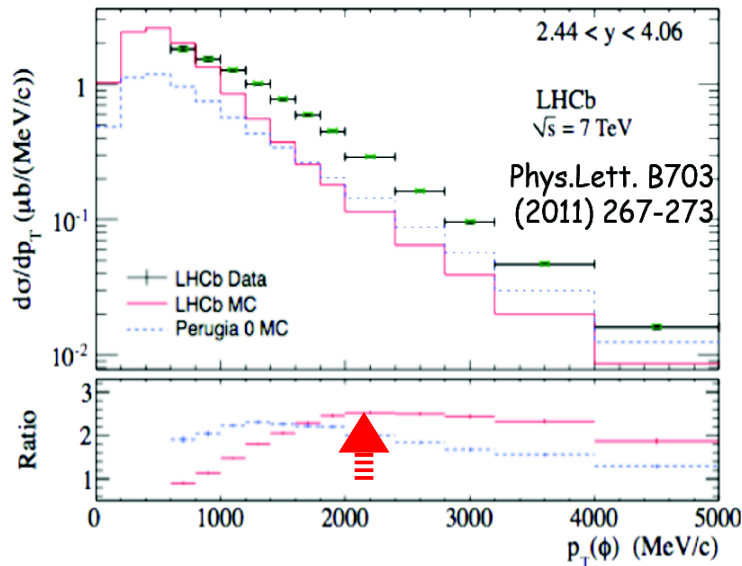
- But yet no clear-cut observation of double hard parton-parton scattering: Ongoing searches on W+jets, 4- μ , ...

Maybe first hint on double J/Ψ prod. ?

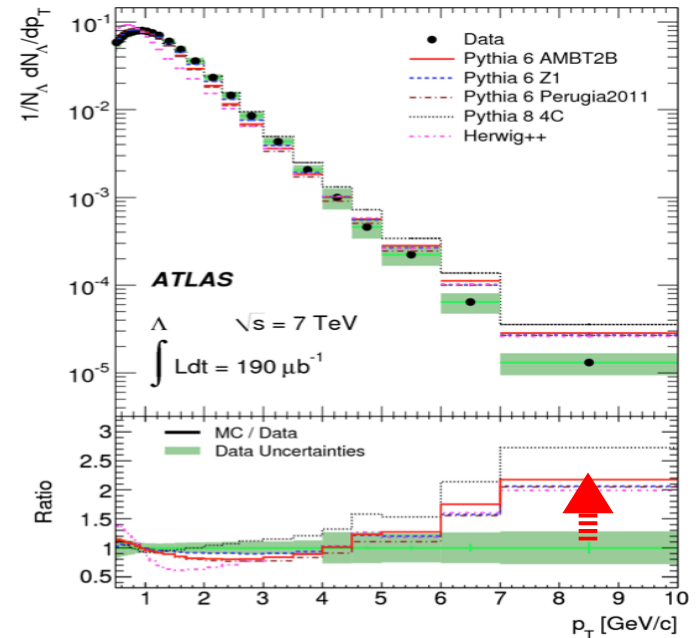
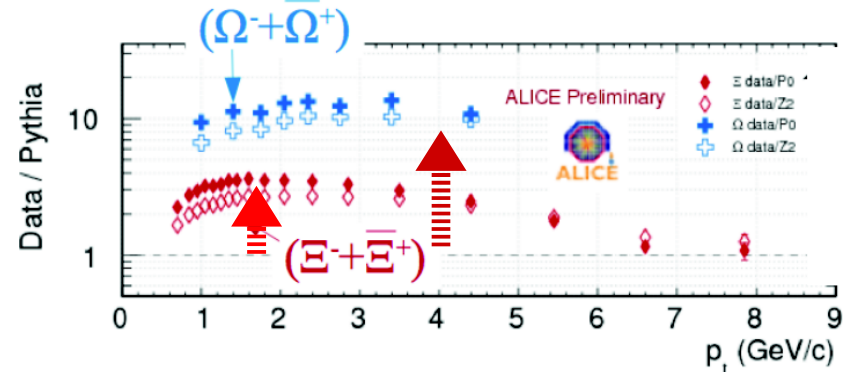
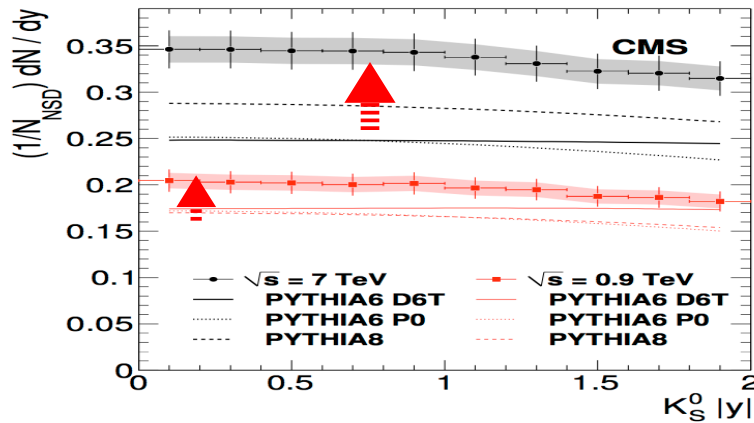
[Tomas Hreus (LHC)]

“Minimum-bias” LHC hadron production

- LEP-tuned MCs ~OK for π, p but not for most strangeness & baryons:

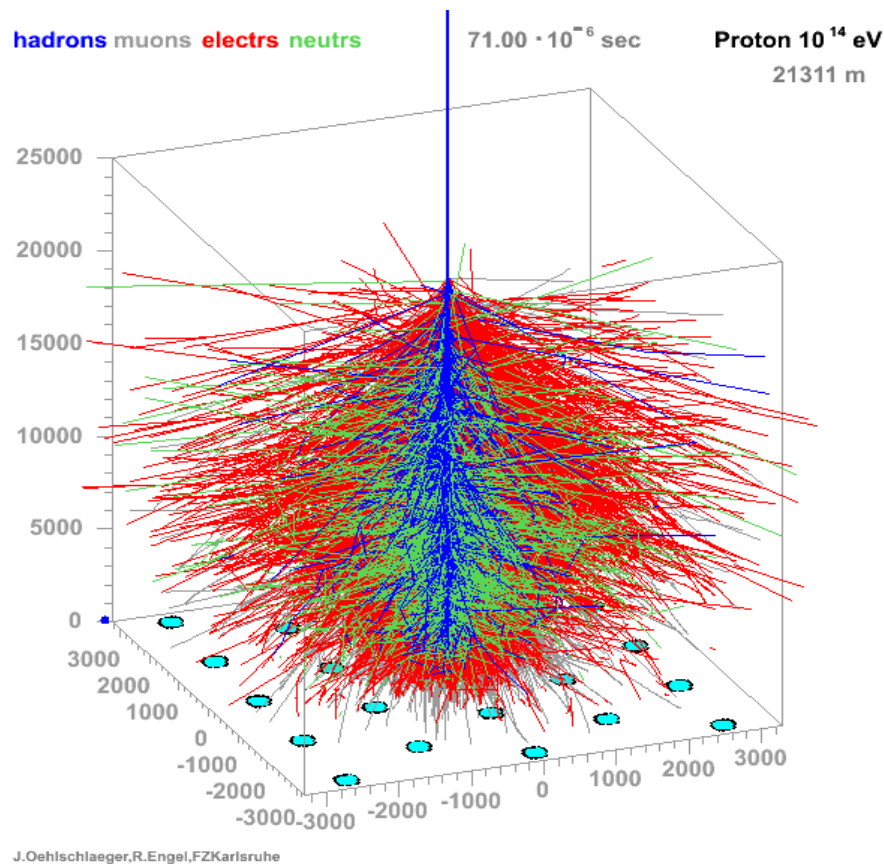


[N. Brook (LHC)]



- Extra final-state effects in p-p ? Is hadronization “universal” ?

Hadronic collisions & UHECR

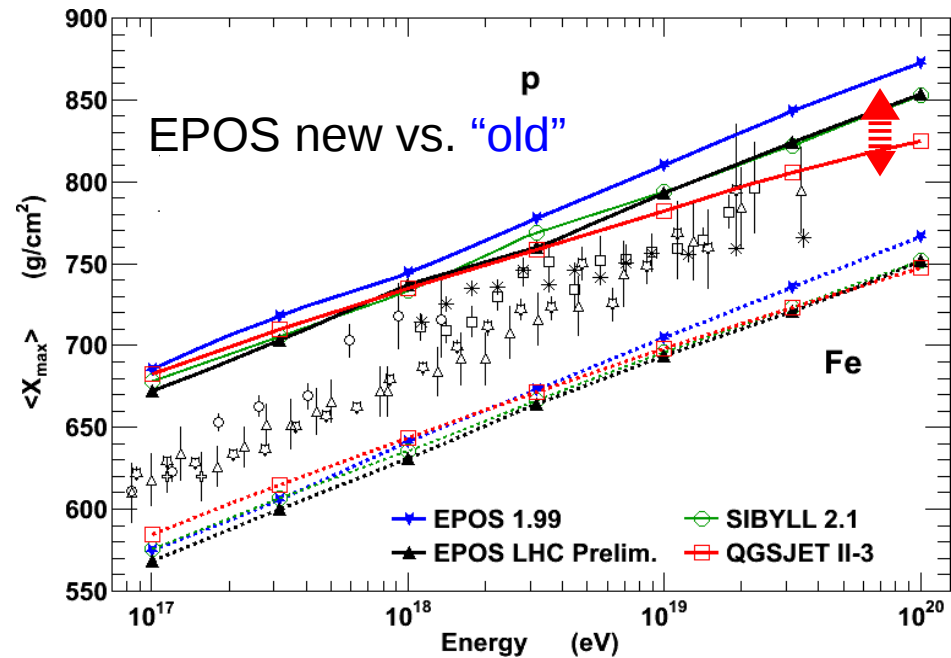
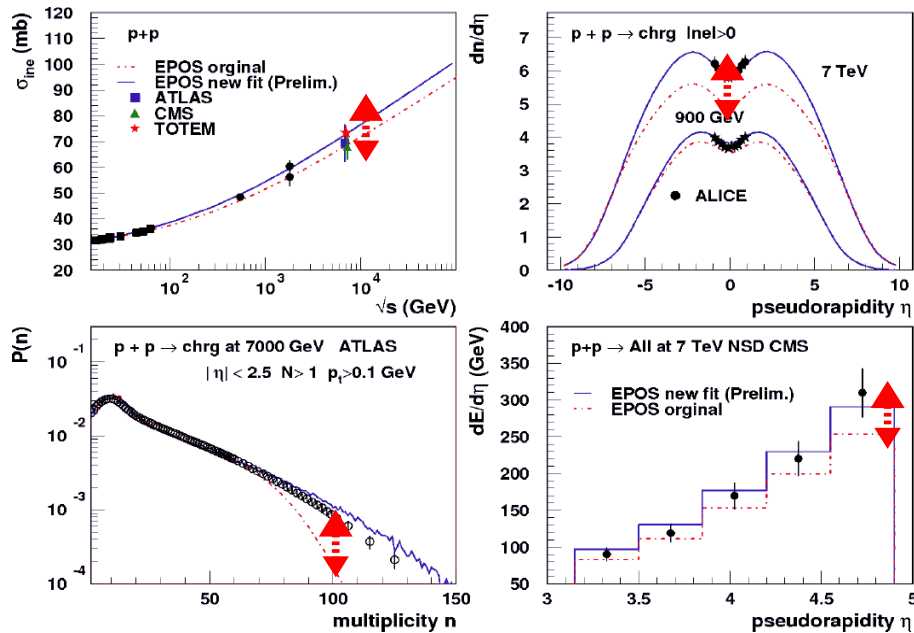


[H. Dembinski]
[M. Shibata]
[G. Mitsuka]
[V. Van Elewyck]

[Tanguy Pierog]
[K. Itakura]
[H. Takami]
[M. Honda]

Cosmic-ray composition at $\sim 10^{20}$ eV

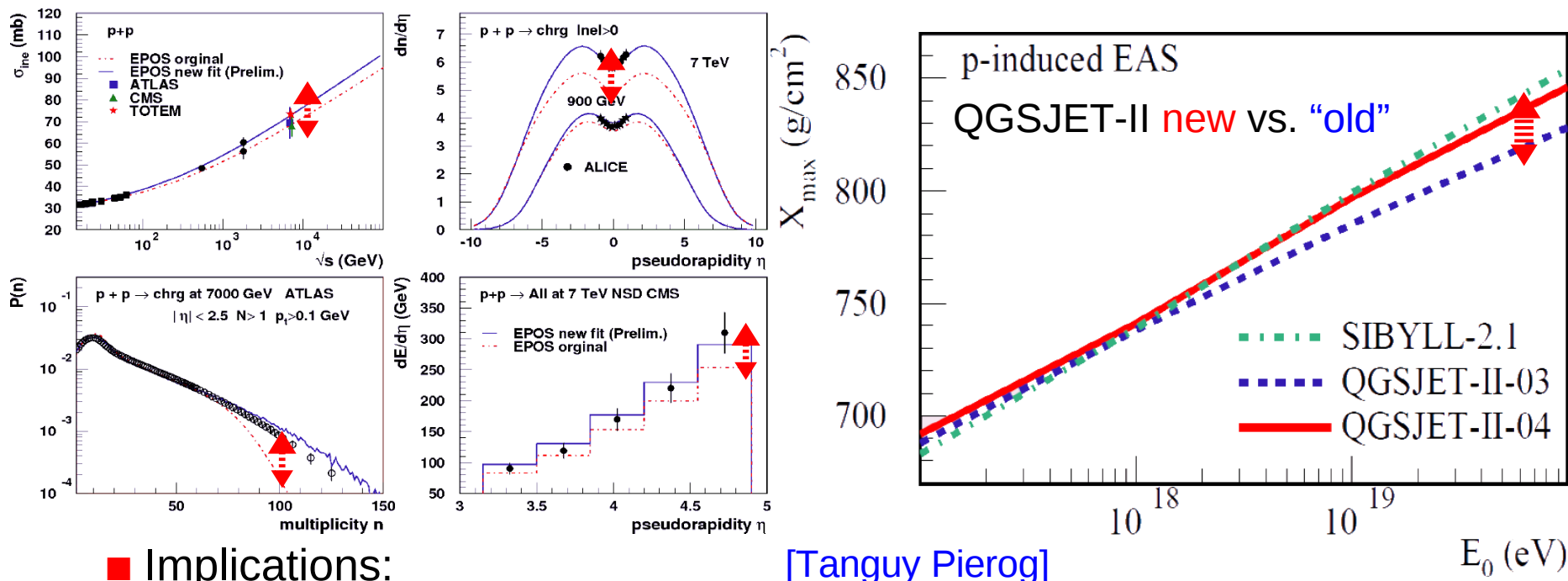
- CR hadronic MCs based on **Regge-Gribov Field Theory** (extension to pQCD regime via “cut Pomerons”).
- **Retuning** of parameters to describe **new LHC data (in particular LHCf !)**:
Ex.: EPOS higher cross section & multiplicity than predicted by 1.99



[Tanguy Pierog]

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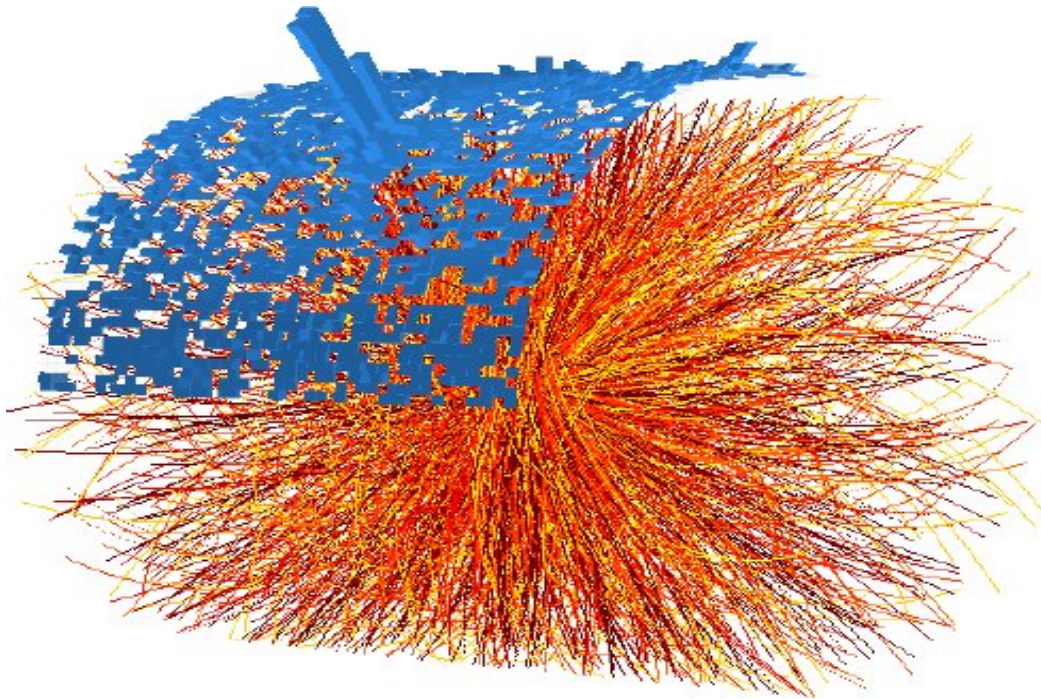
■ Implications:

- EPOS & QGSJET-II predictions **similar now to (older) SIBYLL**:
change in $\langle X_{\text{max}} \rangle$ (reduced uncertainty ~ 60 g/cm² to ~ 10 g/cm²).
- Composition of CRs **closer now to proton-line** for all MCs.

[Tanguy Pierog]

E_0 (eV)

Collisions with heavy-ions

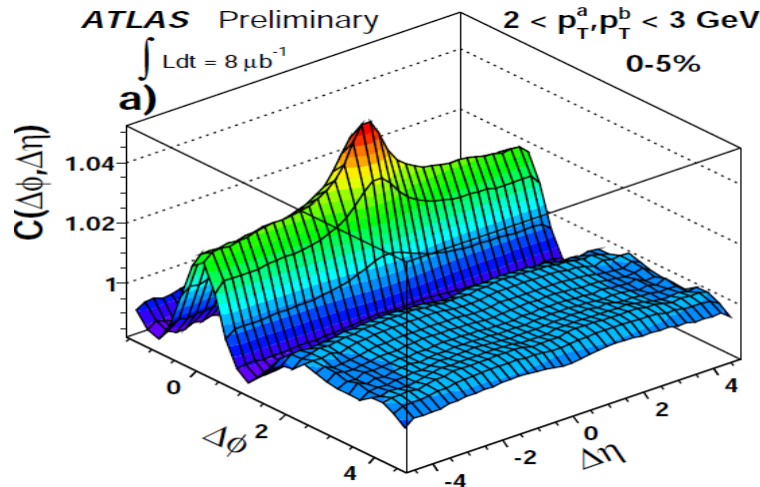


[S. Chattopadhyay (ALICE)]
[Matt Nguyen (CMS)]
[R. Snellings (LHC)]
[Nicola Bianchi (HERMES)]

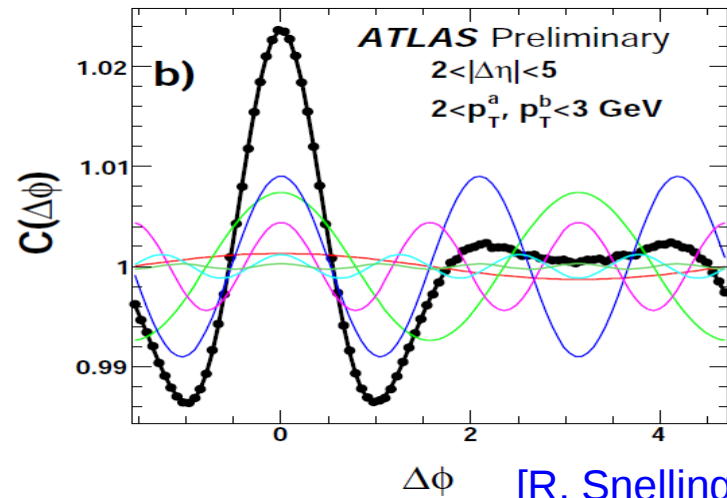
[Jean-Paul Blaizot]

New collective QCD phenomena

- **Strong $\Delta\phi$ - $\Delta\eta$ correlations** found in PbPb collisions. Matter behaves hydrodynamically: **sensitivity to QGP viscosity**, exp. testbed for **AdS/CFT**



[S. Chattopadhyay (ALICE)]



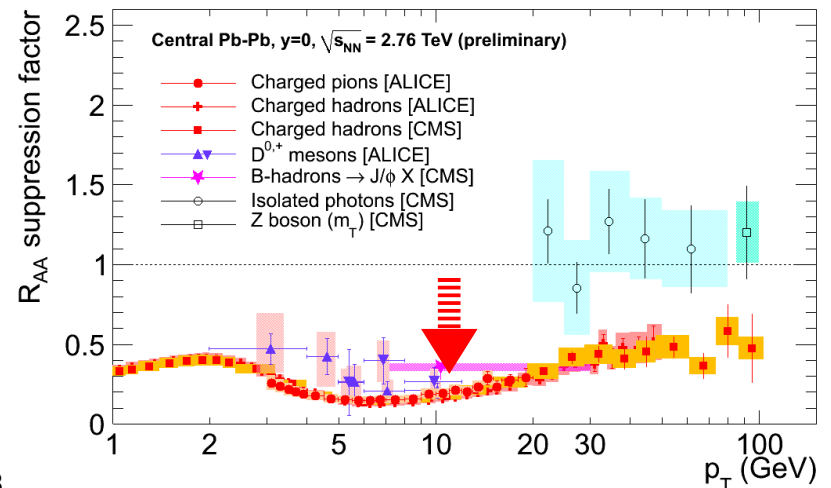
[R. Snellings (LHC)]

(“Ridge” structures **also found in high-multiplicity p-p**: same phenomenon ?)

- Large **high- p_T hadron suppression** in the strongly-interacting medium: **sensitivity to QGP transport coeff.**

[Matt Nguyen (CMS)]

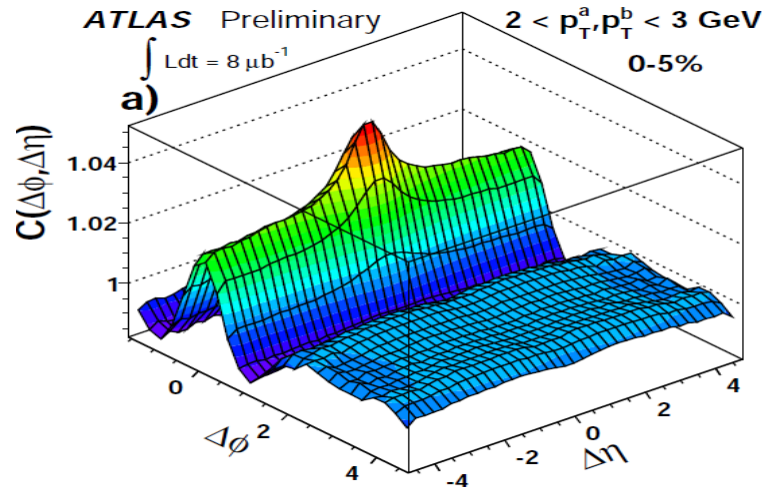
[S. Chattopadhyay (ALICE)]



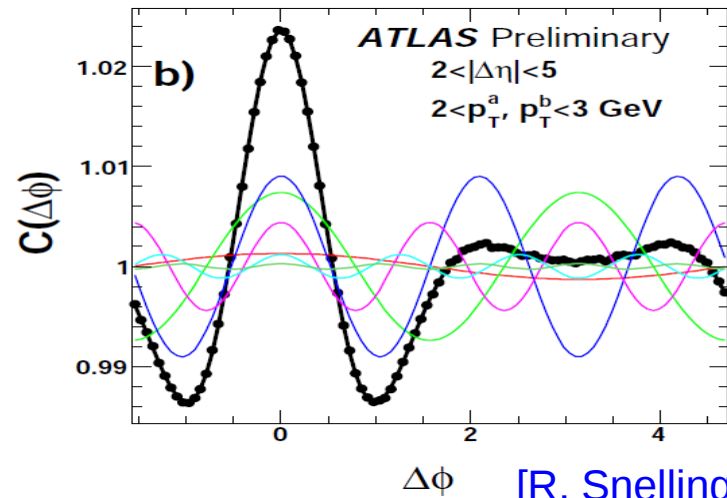
(CERN)

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[S. Chattopadhyay (ALICE)]

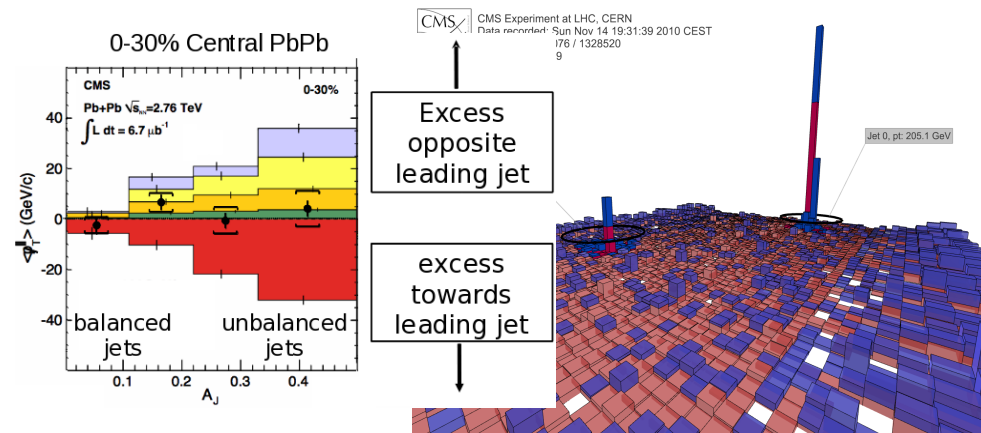


[R. Snellings (LHC)]

(“Ridge” structures also found in high-multiplicity p-p: same phenomenon ?)

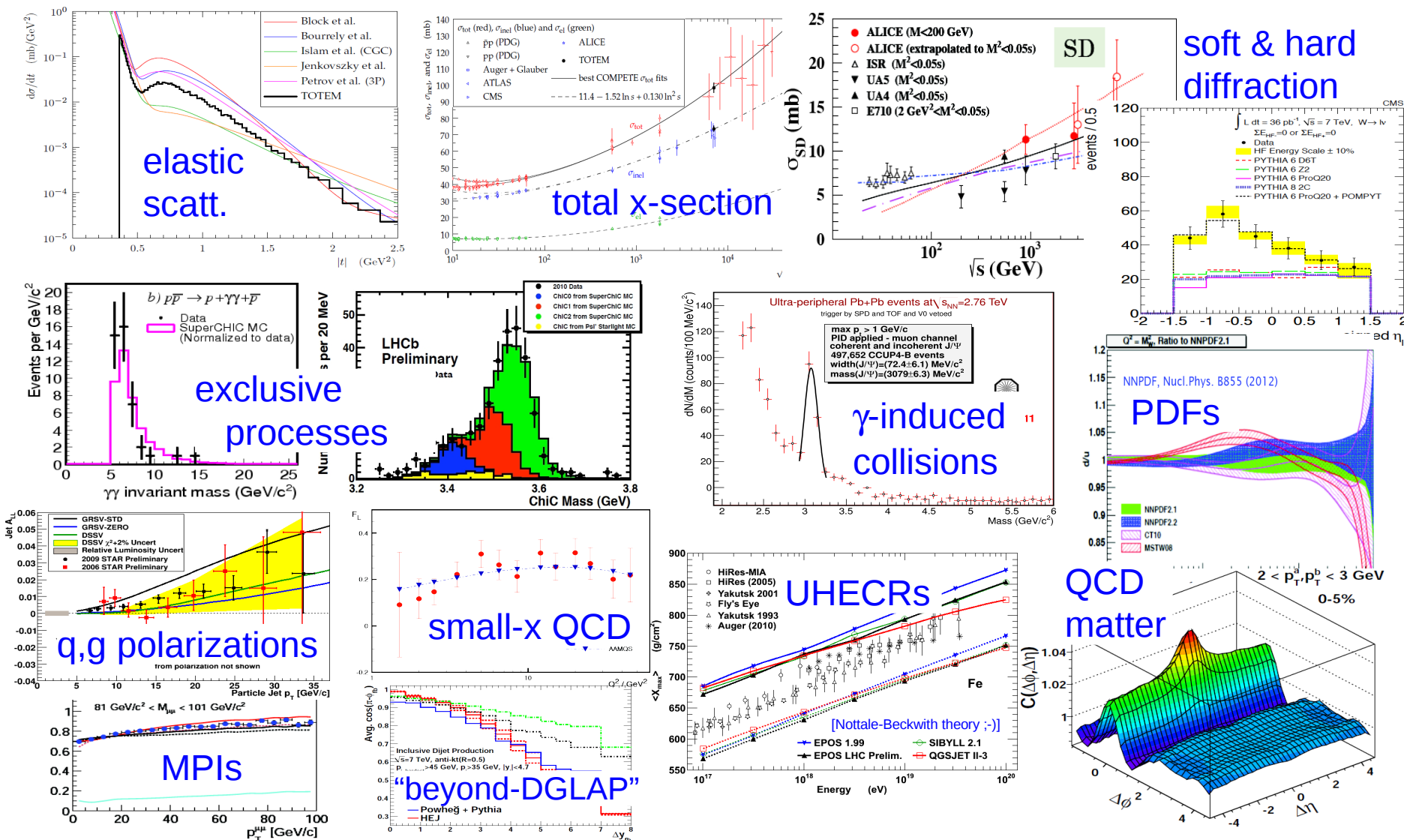
- Large jet energy quenching in the strongly-interacting medium: sensitivity to QGP transport coeff. (but we need 1st to confirm the jet energy loss mechanism)

[Matt Nguyen (CMS)]



Summary

■ The LHC is providing a **wealth of new QCD data** open to study !



■ **Exciting** experimental/theoretical QCD physics for the years to come !

Backup slides