Diffractive Physics

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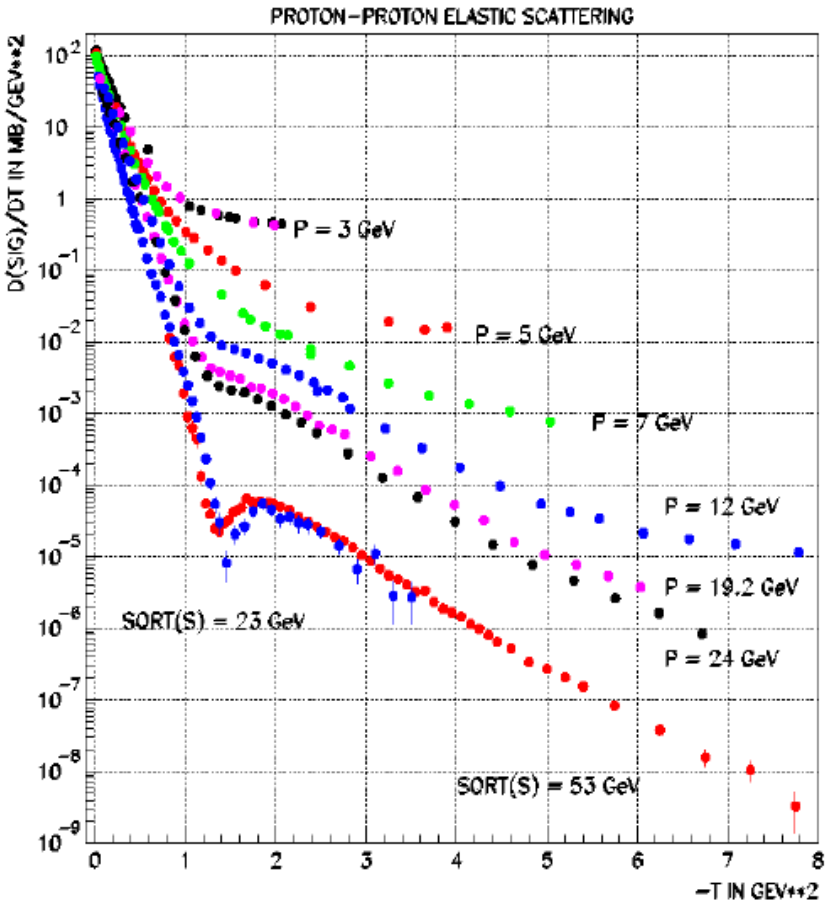
First Sapore Gravis Workshop
Nantes, France, 2-5 December 2013

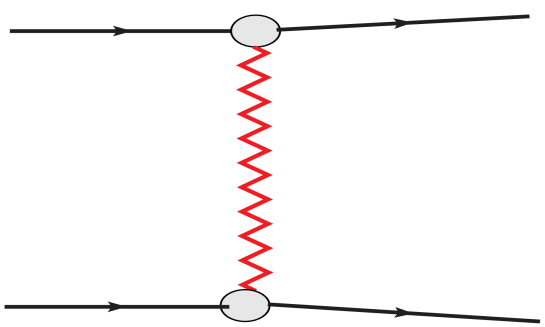
Outline

- Introduction to diffractive processes
- **Elastic scattering** & single-inclusive diffraction (mainly Totem)
- **Exclusive diffraction**: from COMPASS to LHC
- **Diffractive photoproduction of J/ψ and ψ(2s)** in pp, pA and AA collisions (LHCb and ALICE)
- An outlook on selected future perspectives

Note: concentrate on recent results from CERN (LHC & COMPASS), ongoing activity also from experiments at HERA, Tevatron and RHIC !

Elastic scattering and the “diffraction cone”





- Elastic hadron-hadron scattering at high energies reminds of Fraunhofer diffraction
- Black disc of size R, q^2=-t:

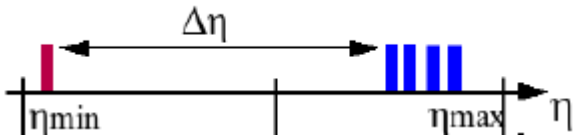
$$f(q) = ikR^2 \frac{J_1(qR)}{qR}$$

- *Optical theorem:*

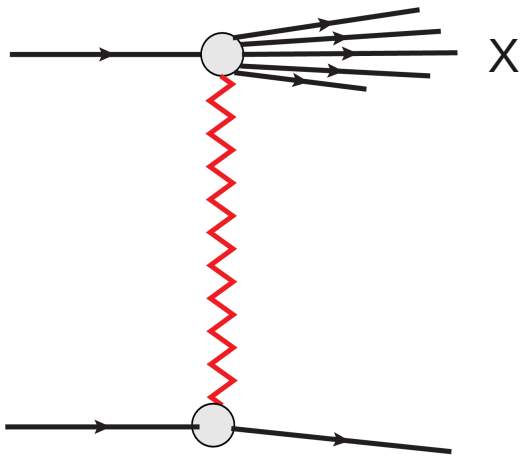
  $4\pi/k \;\; Im\, f(0) = \sigma(tot)$

- Elastic scattering is *unitarity/absorption driven*.
- For the black disc:

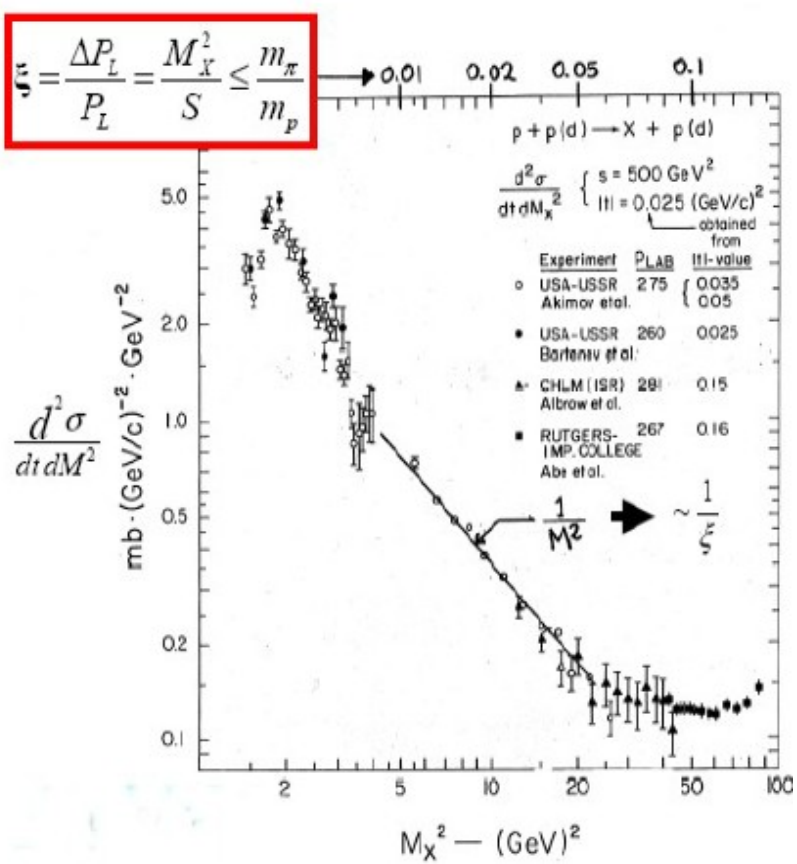
  σ(el) = 0.5 σ(tot)



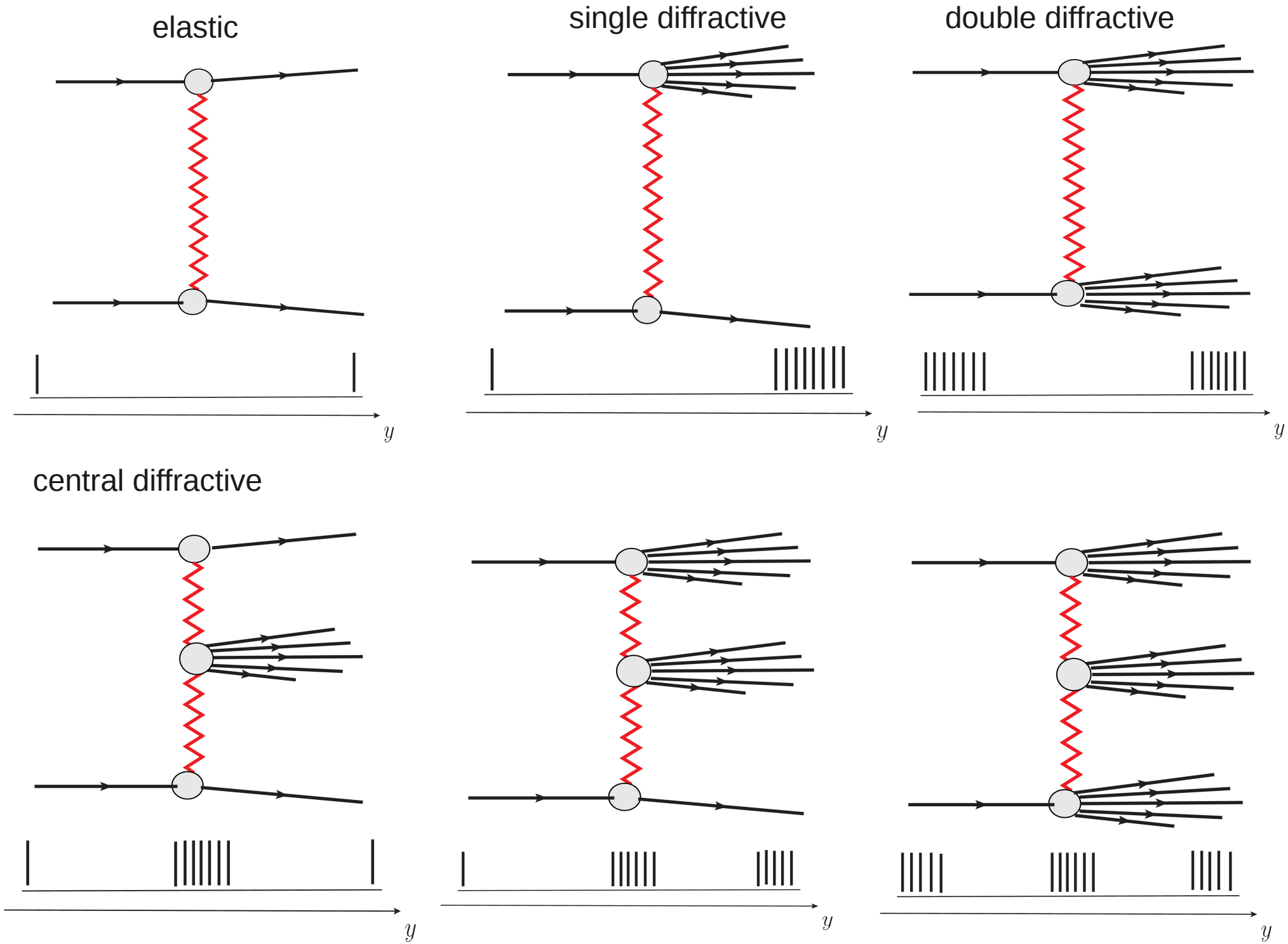
Diffraction dissociation



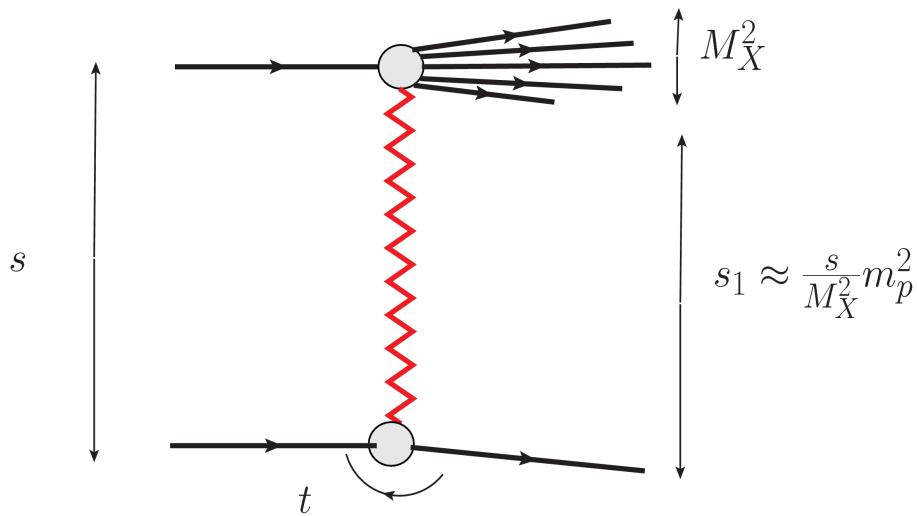
- Above $p_{lab} \geq 5$ GeV diffractive transitions become important
- Proton loses small fraction $\xi = M_X^2/s$ of its momentum, ***large rapidity gap*** between outgoing proton & X



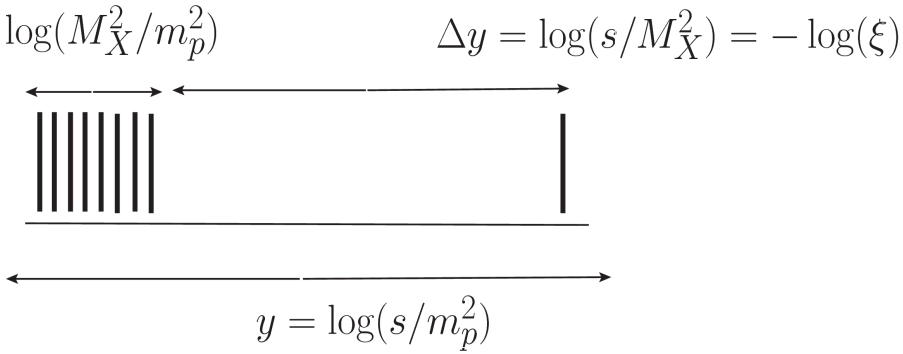
- Shares many properties with elastic scattering: *sharp forward peak, dominance of vacuum quantum number exchange, imaginary amplitude …*
- Another optical analogy: different absorption strength for different components of the beam's wavefunction imply the presence of diffraction dissociation (Glauber, Landau & Pomeranchuk, Akhiezer & Sitenko,...)


elastic
single diffractive
double diffractive
central diffractive
y
y
y
y
y
y

Inelastic diffraction: kinematics & t-channel exchanges



$$\frac{\Delta p_L}{p_L} \equiv \xi \sim \frac{M_X^2}{s} \ll 1$$



$$A(s_1, M_X^2, t) \propto \left(\frac{s_1}{m_p^2}\right)^{\alpha(t)} \propto \left(\frac{1}{\xi}\right)^{\alpha(t)} \implies \sigma \propto \exp[2(\alpha(0)-1)\cdot\Delta y]$$

- **To bridge a gap (say Δy ≥ 3) : α(0) ≥ 1** (Pomeron, C= +1; Odderon(??), C = -1).
- Exchange of secondary Reggeons: α(0)=0.5 for ρ,ω,f2,a1; α(0)=0 for pions **dies out exponentially with the gap size** (no exchange of color or charge over a large gap!)**.**
- **Pomeron/Odderon**: ***multigluon exchanges***; **Reggeons**: ***q $\bar{q}$ - exchange***
- **Photons (J=1, C=-1) also qualify!**

(soft) diffractive phenomena occur frequently !

- Elastic scattering is **about 25 % of the total cross section** at the LHC.
- Inelastic diffraction/gap events (mainly single and double diffraction) make up for about 30 % of the total inelastic cross section.
- Important phenomena of QCD...
- ... which can be a **unique tool** in the investigation of many fundamental QCD problems (spectroscopy/glueballs, jet physics, charmonium states...)

- Single Diffraction (SD) [a]

  $\sigma_{SD}/\sigma_{INEL} = 0.21 \pm 0.03$ (@900 GeV)

- Double Diffraction (DD) [a]

  $\sigma_{DD}/\sigma_{INEL} = 0.11 \pm 0.03$ (@900 GeV)

- Central Diffraction (CD) (a few % of σ_{INEL})

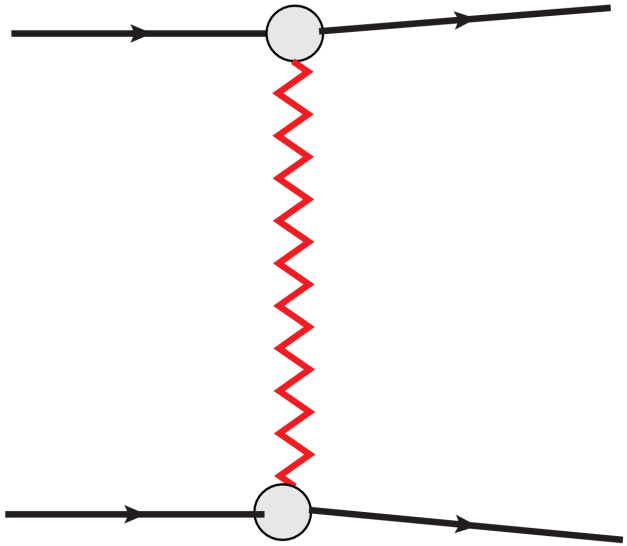
Christoph Mayer

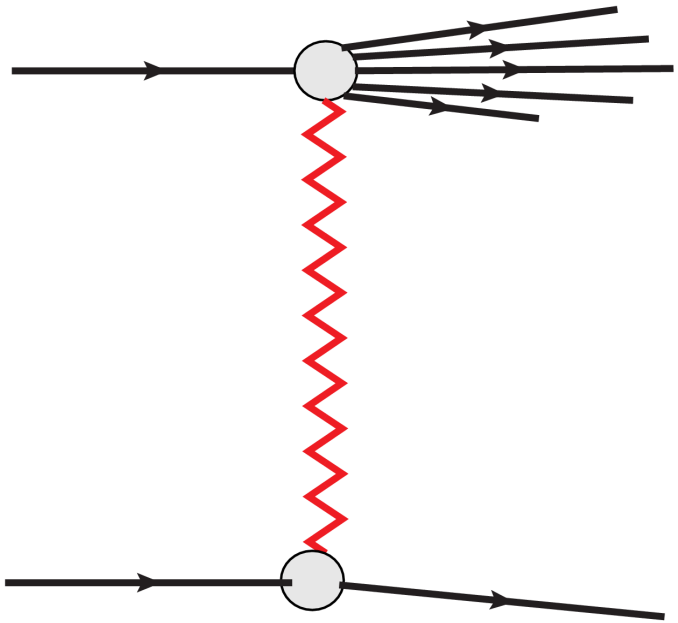
(most of) diffraction: low to medium luminosity physics

- Many of the interesting cross sections are large.
- High lumi environment makes measurement of gap cross sections very challenging: ***multiple inelastic collisions*** in a beam crossing will fill the gaps in the calorimeters (***pileup problem***).
- Need special low lumi run, ideally proton tagging.

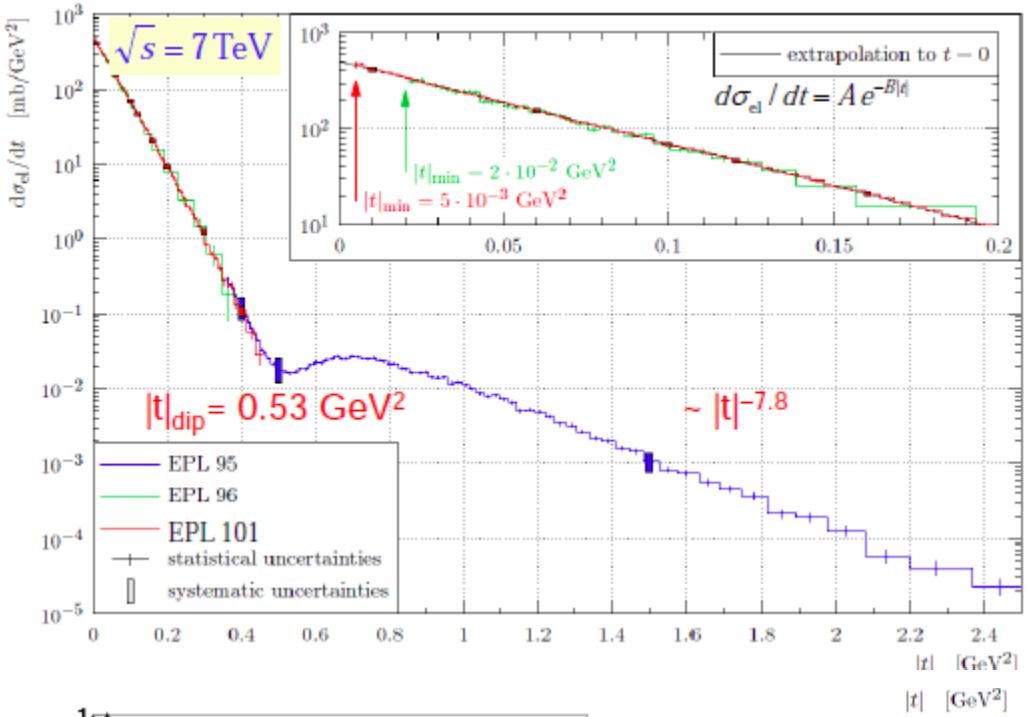
Recent results:

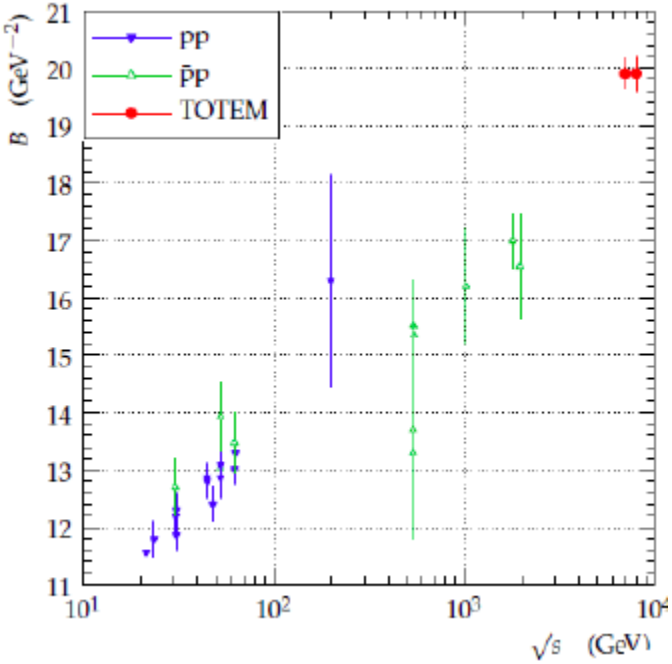
1. elastic scattering and single diffraction

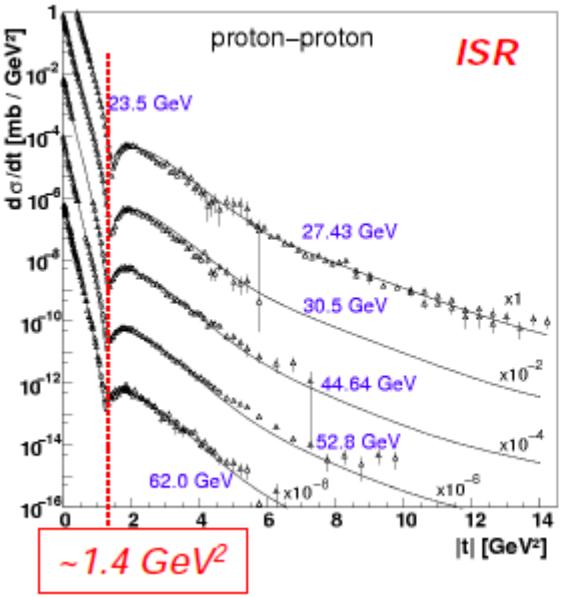




Totem results, elastic scattering:







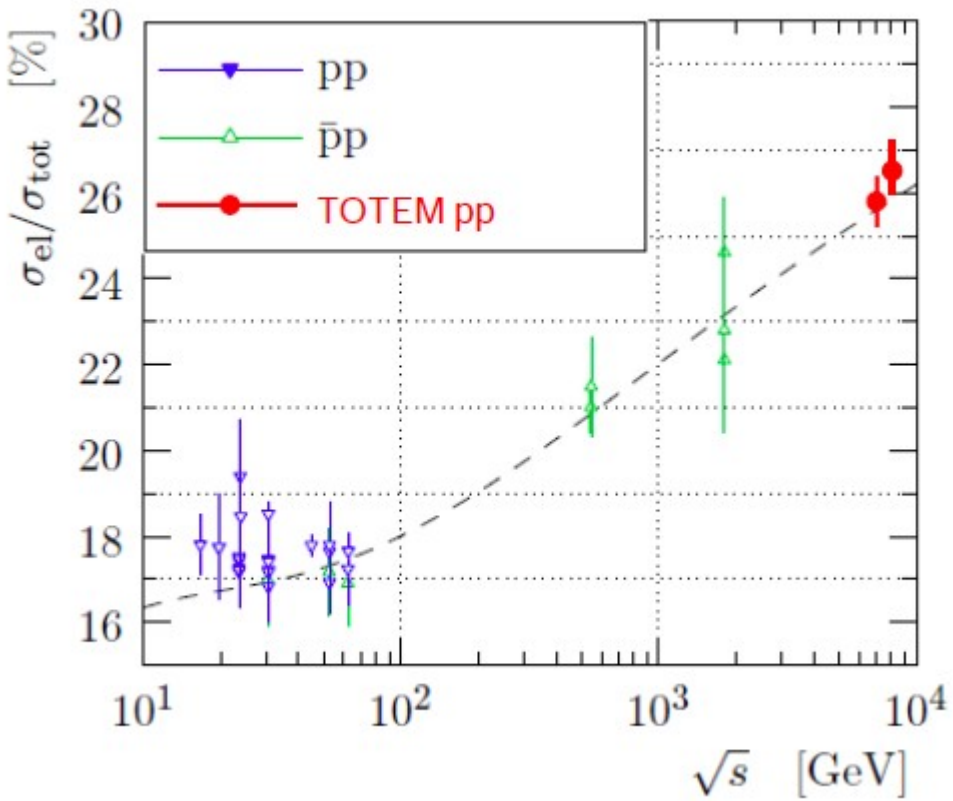
At low |t|: nearly exponential decrease:

$B_{7TeV} = (19.89 \pm 0.27)$ GeV^{-2}

$B_{8TeV} = (19.90 \pm 0.30)$ GeV^{-2}

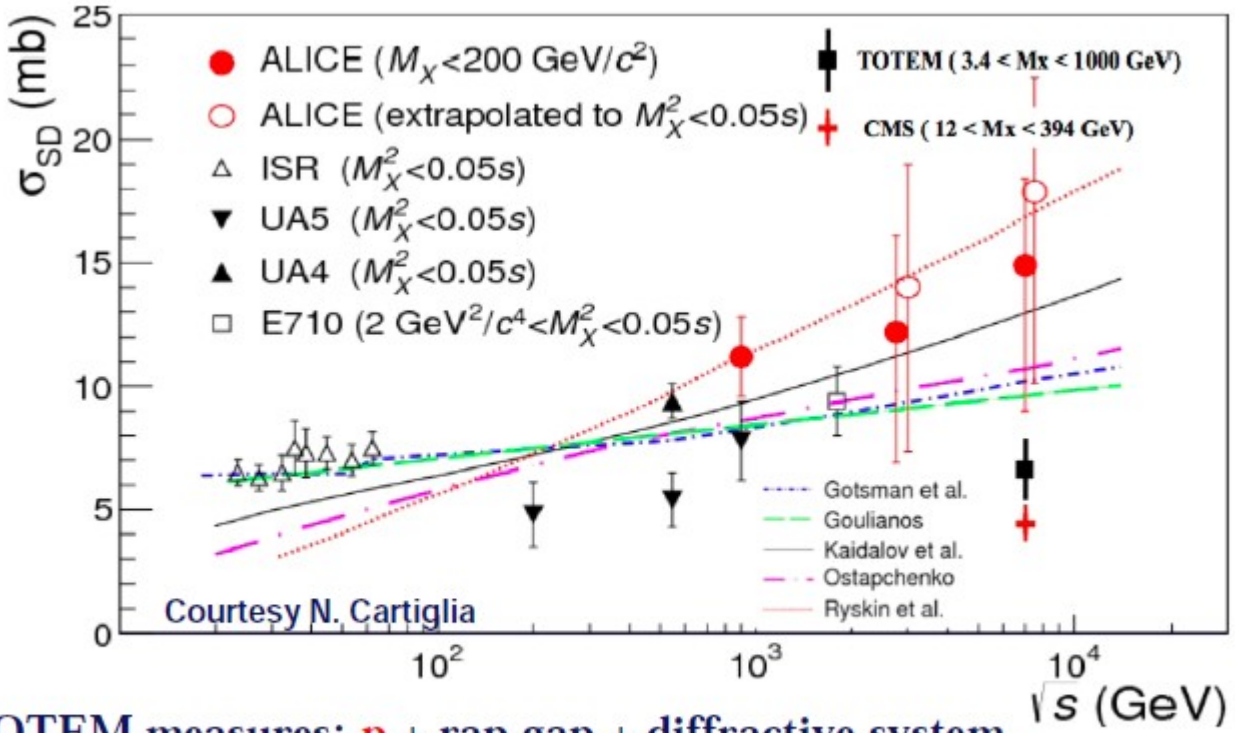
Old trends for increasing s are confirmed:

- "shrinkage of the forward peak": minimum moves to lower |t|
- forward exponential slope B increases



- elastic/total continues to rise.
- Indicative of a “blacker” interaction region. (Recall elastic/total = 0.5 for the black disc).

Inclusive single diffractive cross section



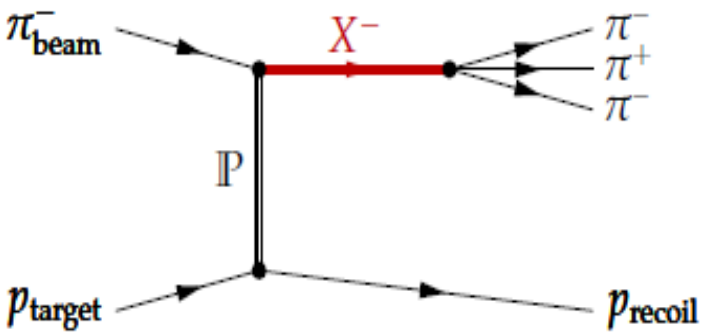
TOTEM measures: p + rap gap + diffractive system,
ALICE & CMS: "rap gap + diffractive system"

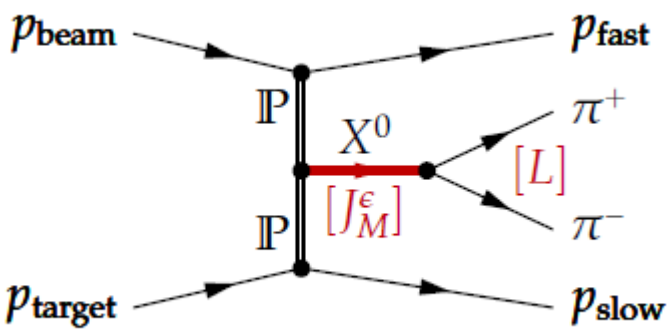
Note: $M_X^2 < 0.05\ s$ → gap size $\Delta y > 3$

At ISR energies secondary reggeons cannot be neglected!

Recent results:

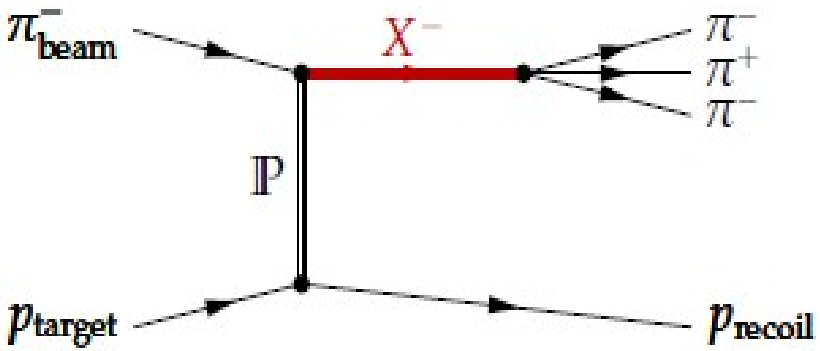
2. exclusive diffraction





COMPASS: light hadron hadron spectroscopy with diffractive processes

A. Austregesilo



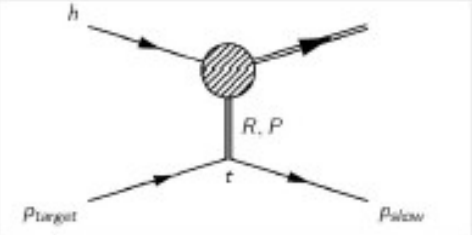
$\pi^- p \to \pi^- \pi^+ \pi^- p$

- 190 GeV/c π^- on lH_2 target
- $\approx$ 50M exclusive events
  $\to$ unprecedented precision
- Squared 4-momentum transfer
  $0.1 < t' < 1(\mathrm{GeV}/c)^2$

Light Meson Spectroscopy

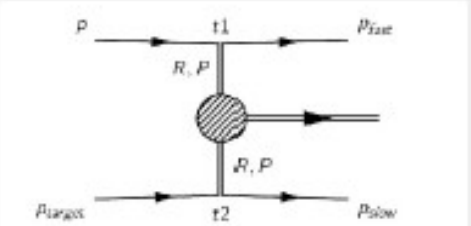
- Many missing and disputed states
- Broad and overlapping resonances
- Exotic quantum numbers
  $(0^{--}, 0^{+-}, 1^{-+}, \ldots)$

Diffractive Dissociation:



- Explore light meson spectrum
- Evidence for spin-exotic mesons

Central Production:

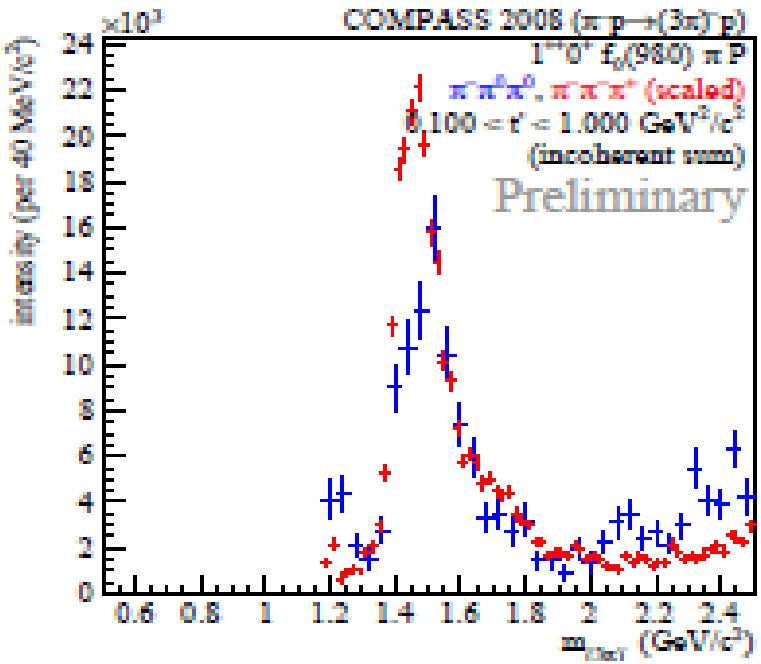


- Glue-rich environment (DPE)
- Supernumurous scalar resonances

COMPASS results:

- don't just measure invariant mass distributions, the huge statistics allows for ***partial wave analysis, study of phase motion of amplitudes...***

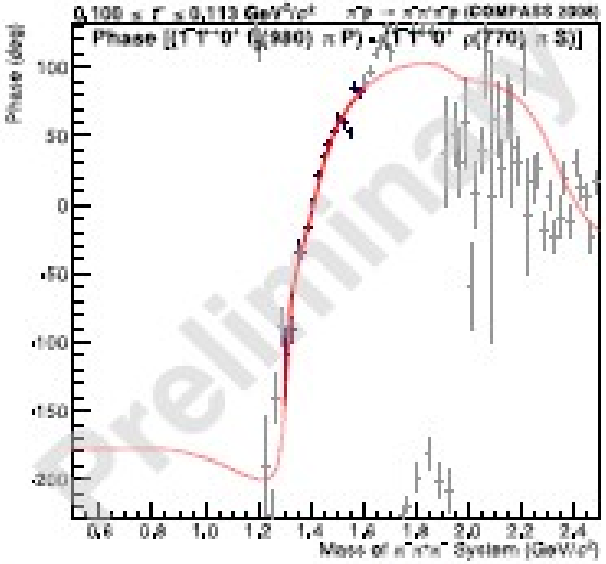
- Example: a new 1(++) state a1(1420) in the (f0(980) π) p-wave.



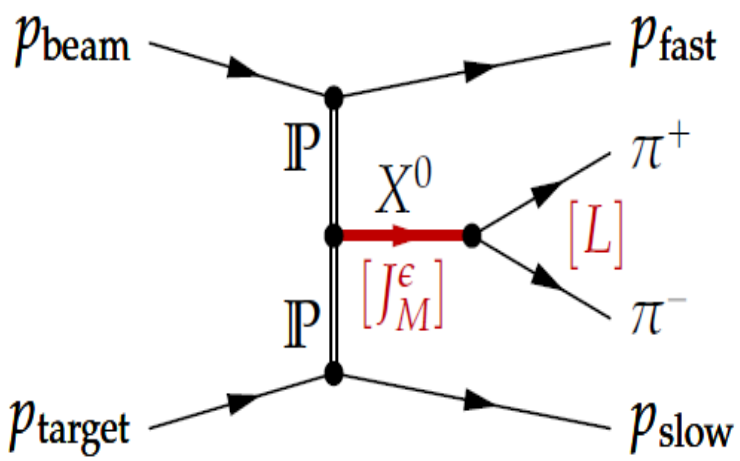
$a_1(1420)$ parameters

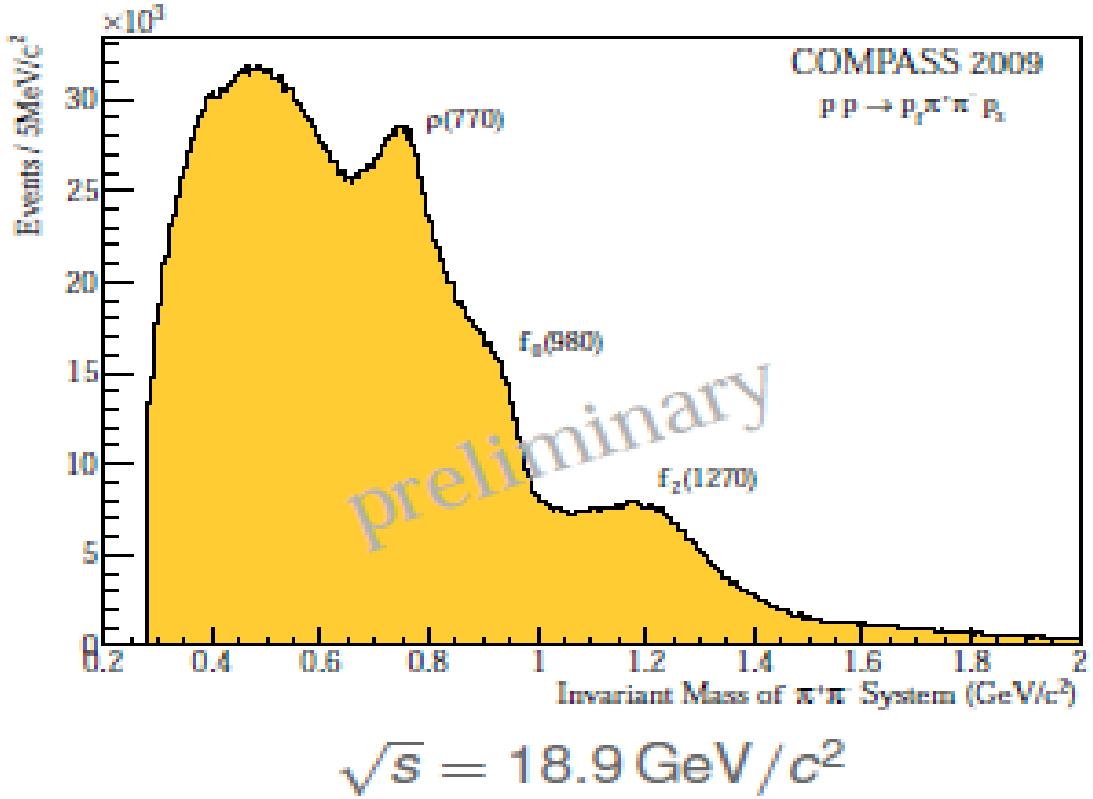
- $M = 1412\text{-}1422\,\mathrm{MeV}/c^2$
- $\Gamma = 130\text{-}150\,\mathrm{MeV}/c^2$

- No entry in PDG 2012
- Significant phase motion w.r.t. all other waves



- Consistent with BW resonance



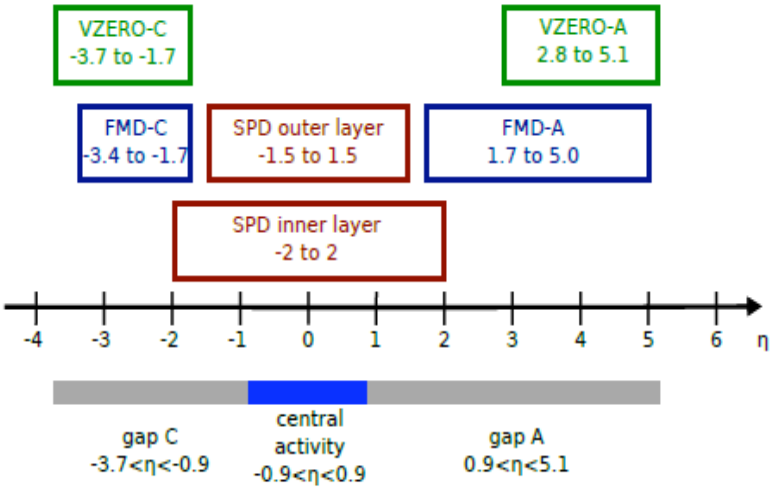


- 2-pion invariant mass spectrum extends out to ~ 2 GeV
- Clear rho-peak indicates presence of ***secondary Reggeon exchanges.***
- Total span in rapidity of only six units. ***Need higher cms-energy to ensure Pomeron-Pomeron dominance.***

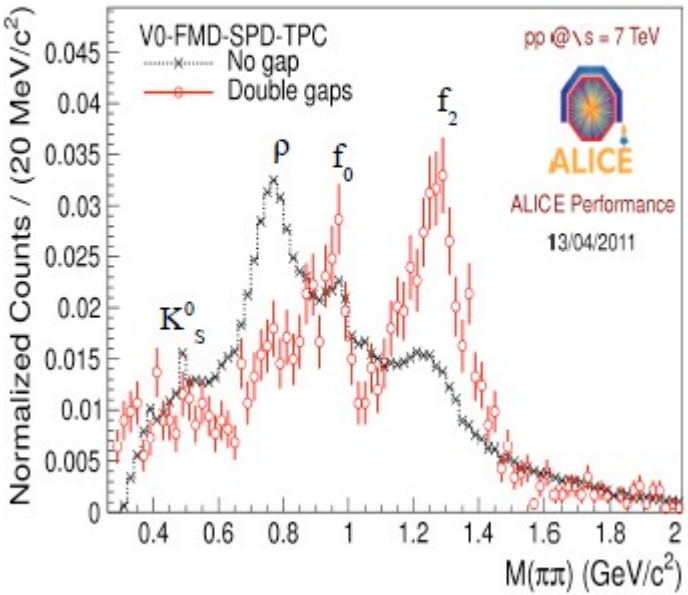
Double gap events: towards exclusive central diffraction in ALICE

Christoph Mayer

qualitative only



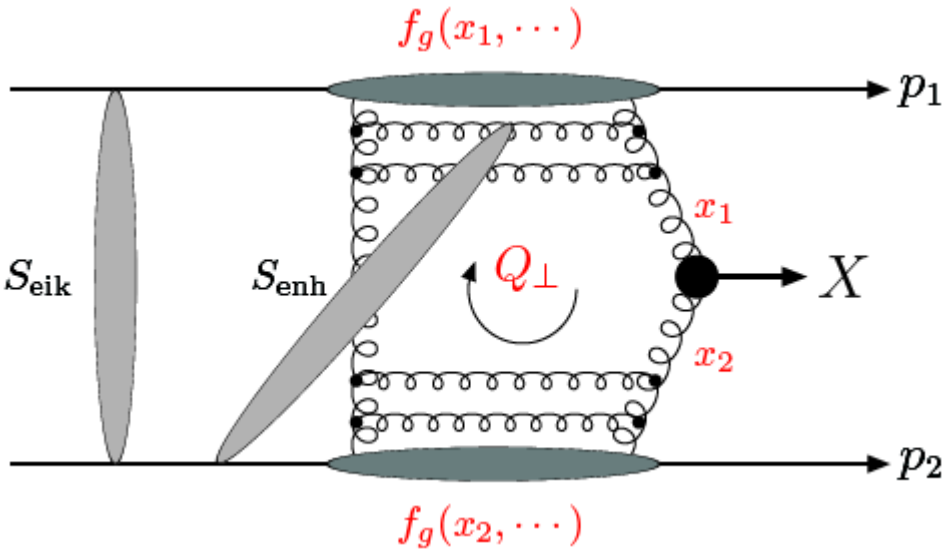
continuous coverage for charged particles $-3.7 < \eta < 5.1$, track $p_T > 20$ MeV/c



- Clear sign of Pomeron-fusion dominance!
- Much larger central masses kinematically accessible,
  - ► *meson spectroscopy in the charm sector*
- Special low pileup run(s) and/or roman pots needed

Central exclusive diffraction with a hard scale – the "Durham approach"

Lucian Harland-Lang



- Large mass of the central system X provides a hard scale. Pomeron exchange described by pQCD gluon ladders.
- *Fusing gluons are correlated!* C-even, P-even color singlet state.

$$J_z^P = 0^+$$

- Large variety of final states X: *dijets (dominantly gluons!), diphotons, light meson pairs, p-wave quarkonia...*
- Extension beyond J_z=0 for $\chi_c(1)$, $\chi_c(2)$ by Szczurek, Pasechnik & Teryaev.
- Original motivation: central exclusive Higgs production. Strong sensitivity on spin/parity of produced system which can be studied in a very clean environment.

Central exclusive diffraction with a hard scale – the "Durham approach"

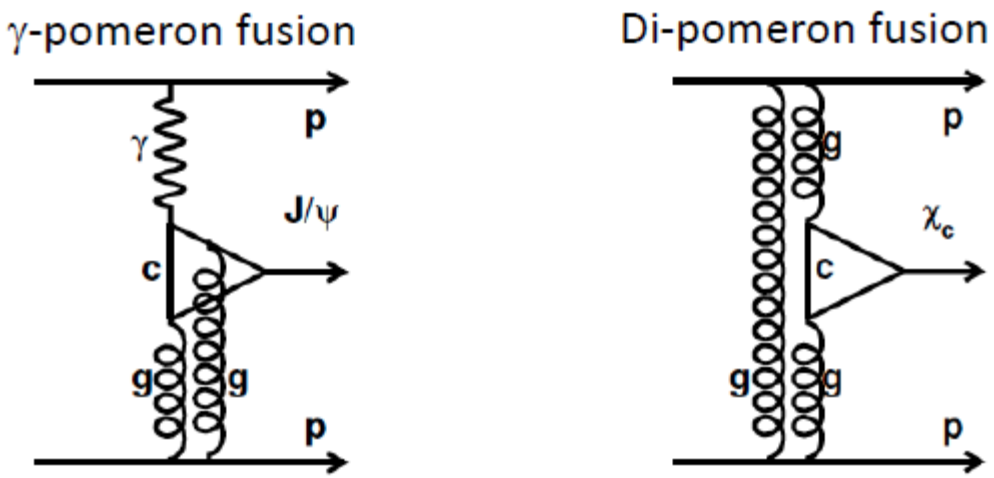
Lucian Harland-Lang

What about the abundant "exotic charmonium states" (XYZ mesons...) ?

- Central exclusive mechanism ***prefers "direct" production*** through the meson's lowest quark/gluon Fock state.
- e.g. exotic meson X(3872) would be produced through a possible $c\bar{c}$ component. ***A dominant "molecular" state would be disfavoured if observed in central exclusive production.***

Recent results:

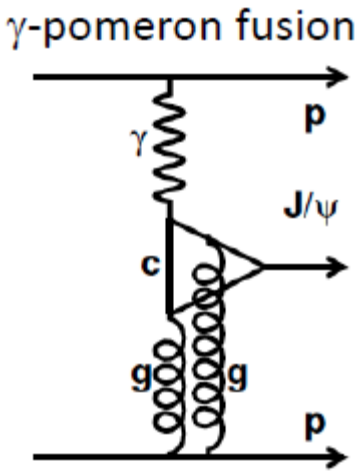
2. exclusive diffraction and diffractive photoproduction (photon-Pomeron fusion)

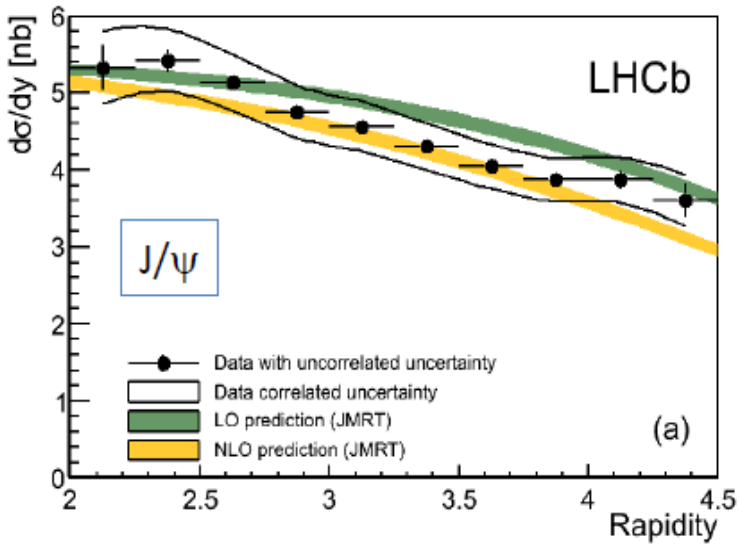


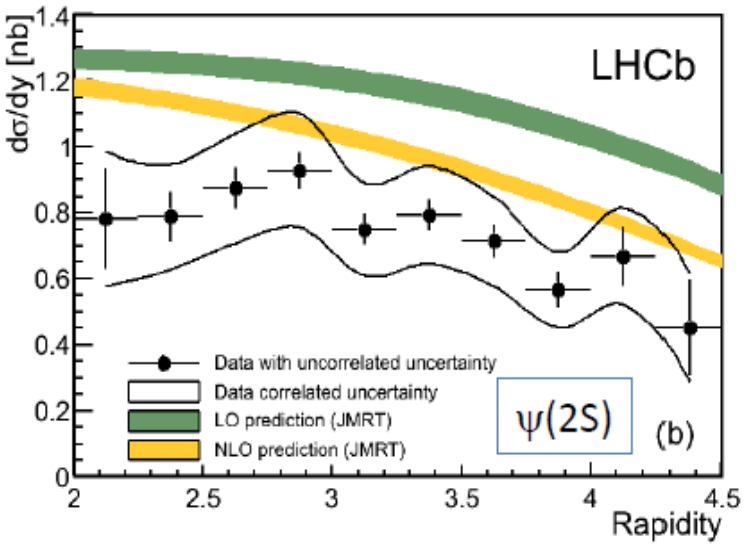
Patrick Robbe

Exclusive photoproduction of J/ψ and ψ(2S)

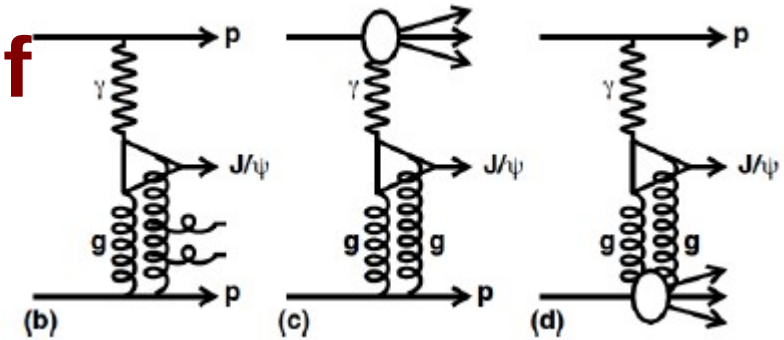
- Two identified muons in $2<\eta<4.5$
- No photons, no other forward tracks: $\Delta y=3.5$
- No backward tracks: $\Delta y=1.7$
- Dimuon mass in 65 MeV mass window of the J/ψ and ψ(2S) masses.



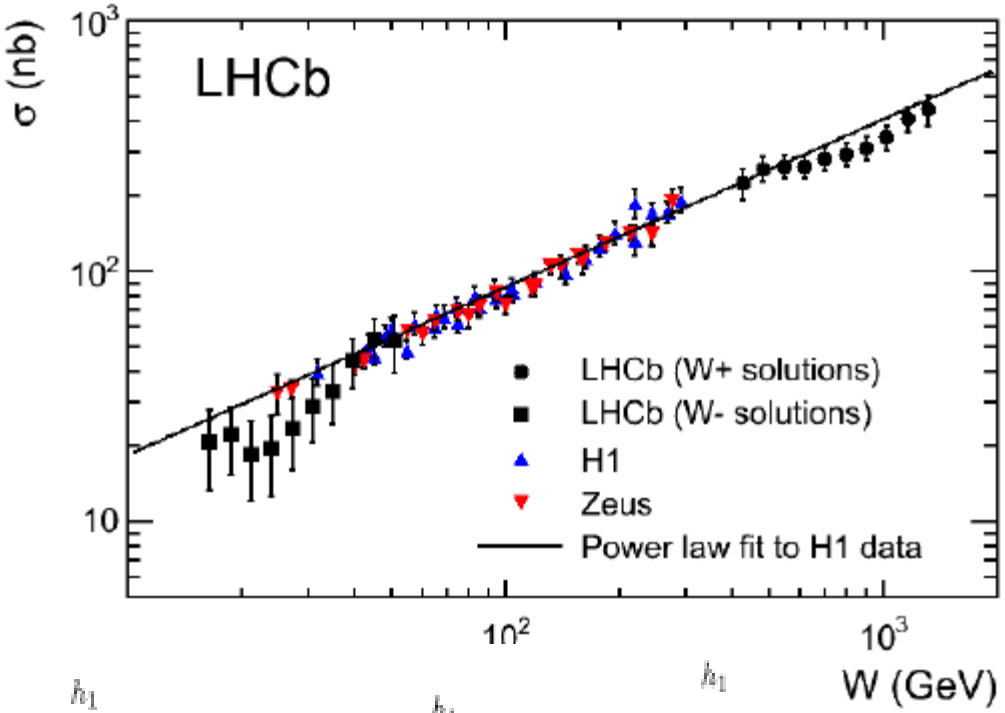




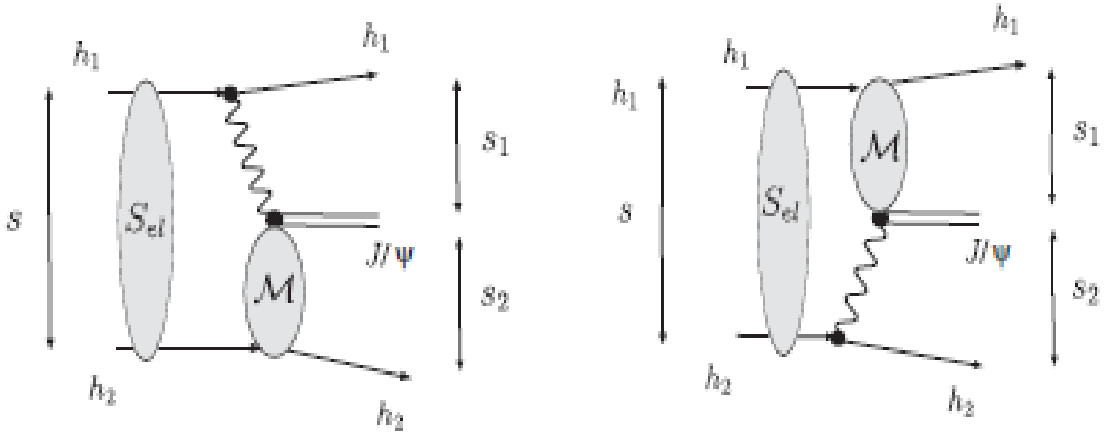
Exclusive photoproduction of J/ψ and ψ(2S)



- Main uncertainty in exctracting the photoproduction cross section: inelastic contributions. *Analysis assumes factorization of inelastic vertices taken from HERA.*



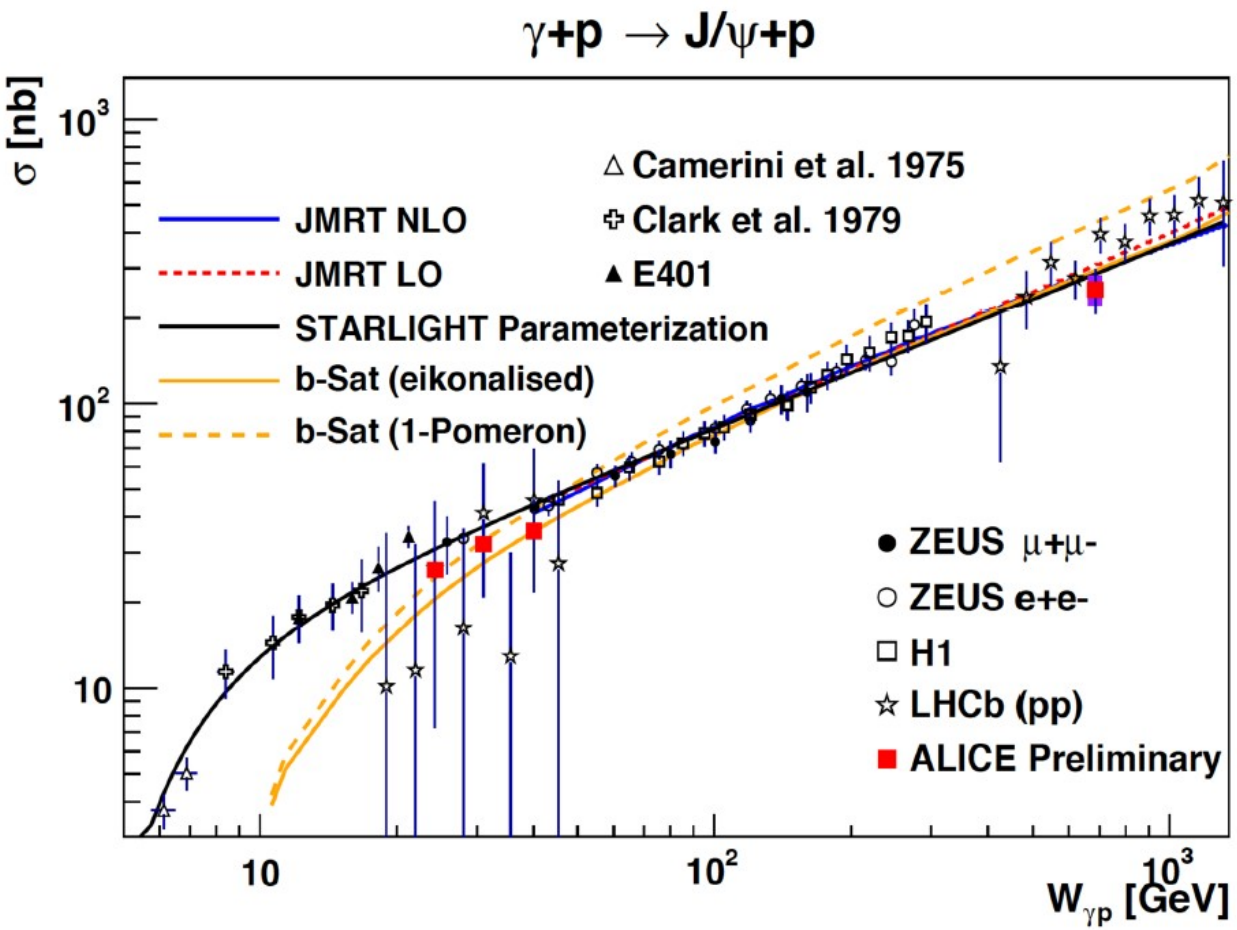
- Probes the glue at *very small x* $= M^2_{J/\psi}/W^2$, but smallish scale $\mu^2 \approx M^2_{J/\psi}/4$
- *Each proton can be the photon emitter !*



Exclusive photoproduction of J/ψ in p Pb collisions

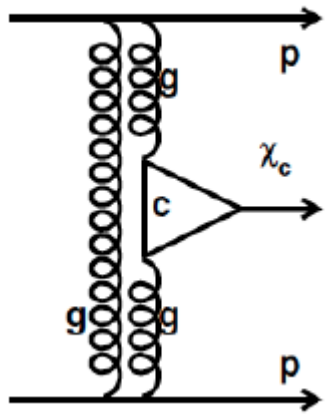
Evgeny Kryshen

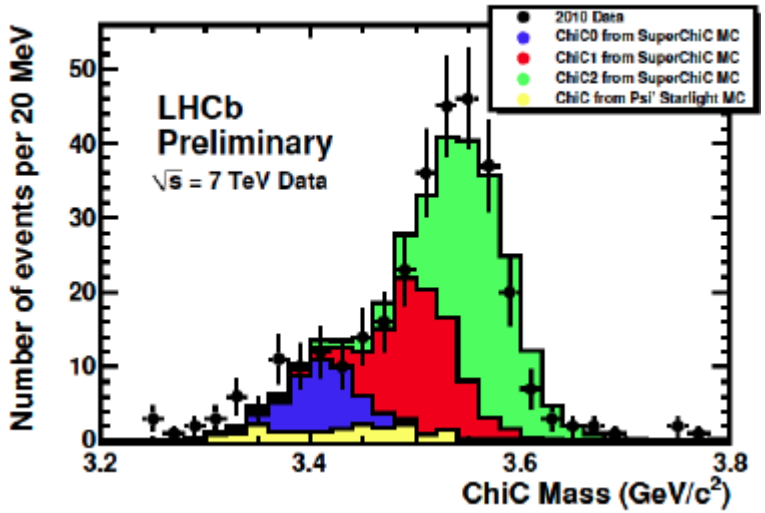
- Photon flux in nucleus enhanced by Z^2 → nucleus is the photon source and proton the "target".
- *Note: on this plot comparison to old LHCb data*



Central exclusive p-wave charmonia

Di-pomeron fusion





Mode	LHCb measured (pb)	SuperCHIC (pb)
$\sigma_{\chi_{c0}\to J/\psi\gamma\to\mu\mu}$	$9.3 \pm 2.2 \pm 3.5 \pm 1.8$	14
$\sigma_{\chi_{c1}\to J/\psi\gamma\to\mu\mu}$	$16.4 \pm 5.3 \pm 5.8 \pm 3.2$	10
$\sigma_{\chi_{c2}\to J/\psi\gamma\to\mu\mu}$	$28.0 \pm 5.4 \pm 9.7 \pm 5.4$	3

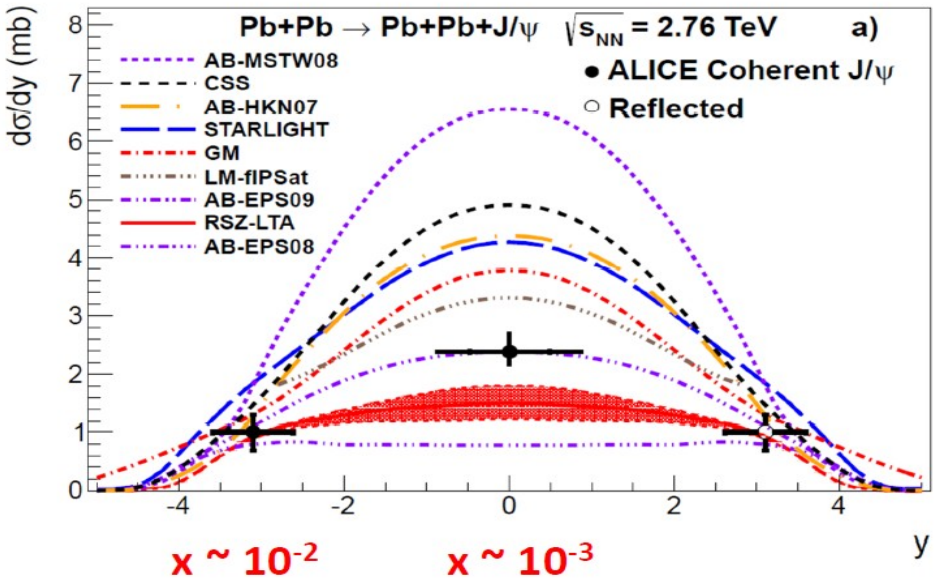
- Measurement of χ(0) in ππ channel possible? (See e.g. Lebiedowicz, Pasechnik & Szczurek)

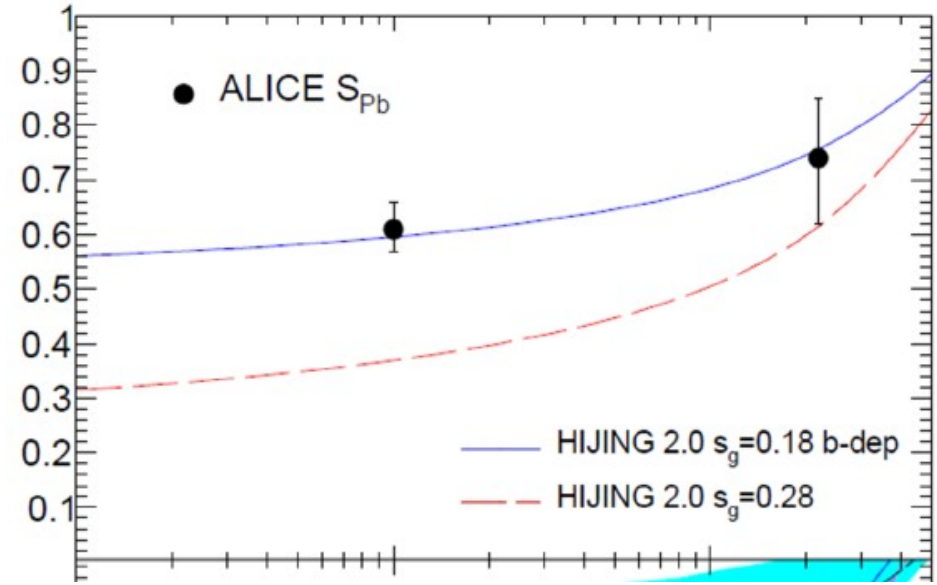
Exclusive photoproduction of J/ψ in ultraperipheral Pb Pb collisions

Evgeny Kryshen

- Sharp coherent peak in the $p_t(\mu\ \mu)$ distribution
- Interpretation in terms of shadowing of a DGLAP evolving nuclear glue must be met with some caution (*scale dependence, inherent theoretical uncertainty of "leading twist" approx...*)
- *Extension to ψ(2S), Υ very much desired.*

$$S(W_{\gamma p}) \equiv \left[\frac{\sigma^{\exp}_{\gamma \mathrm{Pb} \to J/\psi \mathrm{Pb}}(W_{\gamma p})}{\sigma^{\mathrm{IA}}_{\gamma \mathrm{Pb} \to J/\psi \mathrm{Pb}}(W_{\gamma p})}\right]^{1/2}$$





The future: diffractive processes (beyond elastic scattering) with proton tagging

- **Totem + CMS**
- ATLAS: ALFA station, PPS project
- Roman pots for LHCb & ALICE?

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More information: LHC Forward Physics WG:

http://lpcc.web.cern.ch/lpcc/index.php?page=fwd_wg

CERN Yellow Report in preparation

Charge exchange reactions at high energies

Rainer Schicker

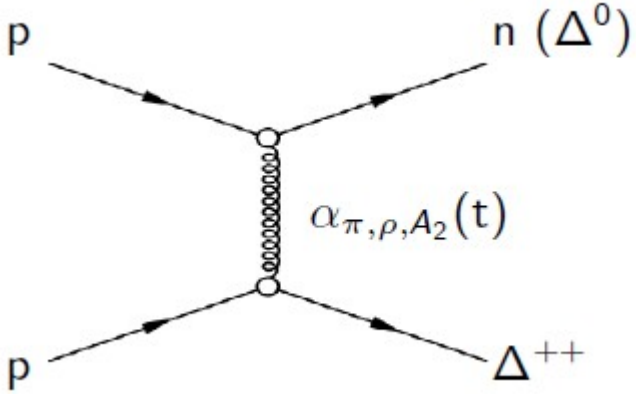
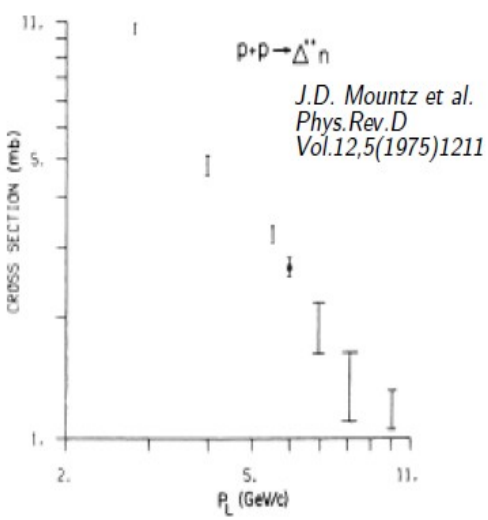
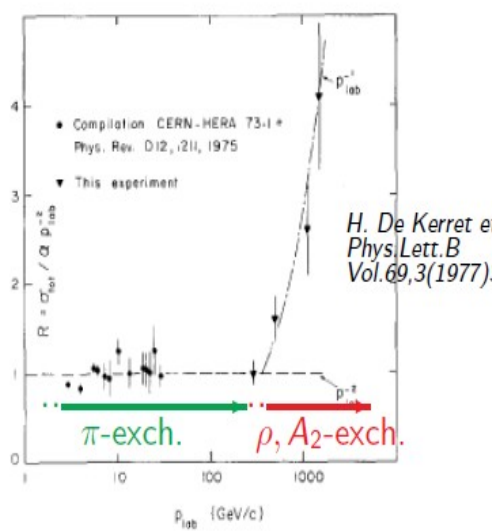


Table: Cross section $pp \to n\Delta^{++}$

	$\sqrt{s}$ (GeV)	σ (nb)
ISR	31	580 $\pm$90
	45	210$\pm$40
	53	170$\pm$40
RHIC	100	48.5$\pm$5.5
	200	12.2$\pm$1.3
LHC	7×10^3	(10.0$\pm$1.1) $\times10^{-3}$
	14×10^3	(2.4$\pm$0.3) $\times10^{-3}$

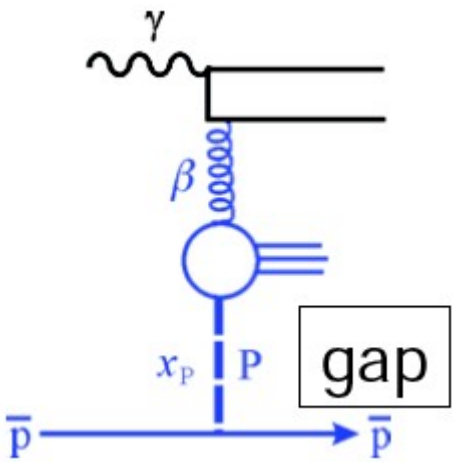


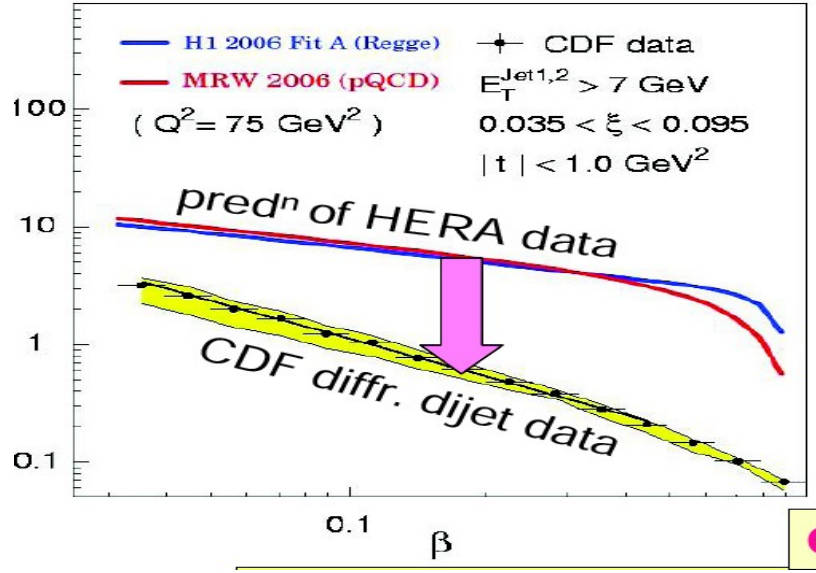


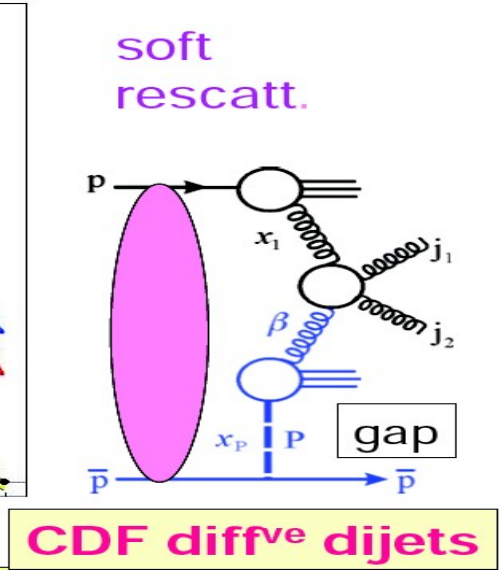
- need zero degree calorimeters
  + tagging of forward proton,pions
- need good pseudorapidity coverage of detectors

if Regge exchange due to pion: $\sigma \sim s^{-2}$, due to ρ, A_2: $\sigma \sim s^{-1}$

Hard inclusive diffraction-Pomeron parton structure?







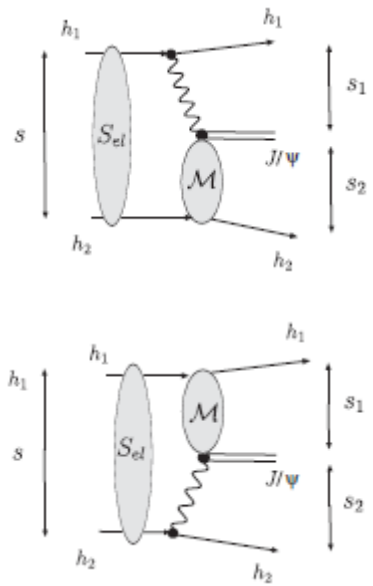
- Hard scattering in *Pomeron-proton and Pomeron-Pomeron collisions*: inclusive diffractive dijets, heavy quarks, high pt-photons...
- Fundamental theory problem: *factorization breaking and gap survival* (Bjorken '92) and its kinematic dependence. Relation to multiparton interactions. Repercussions on inclusive factorization thm's.?
- Related observables: jet-gap-jet...

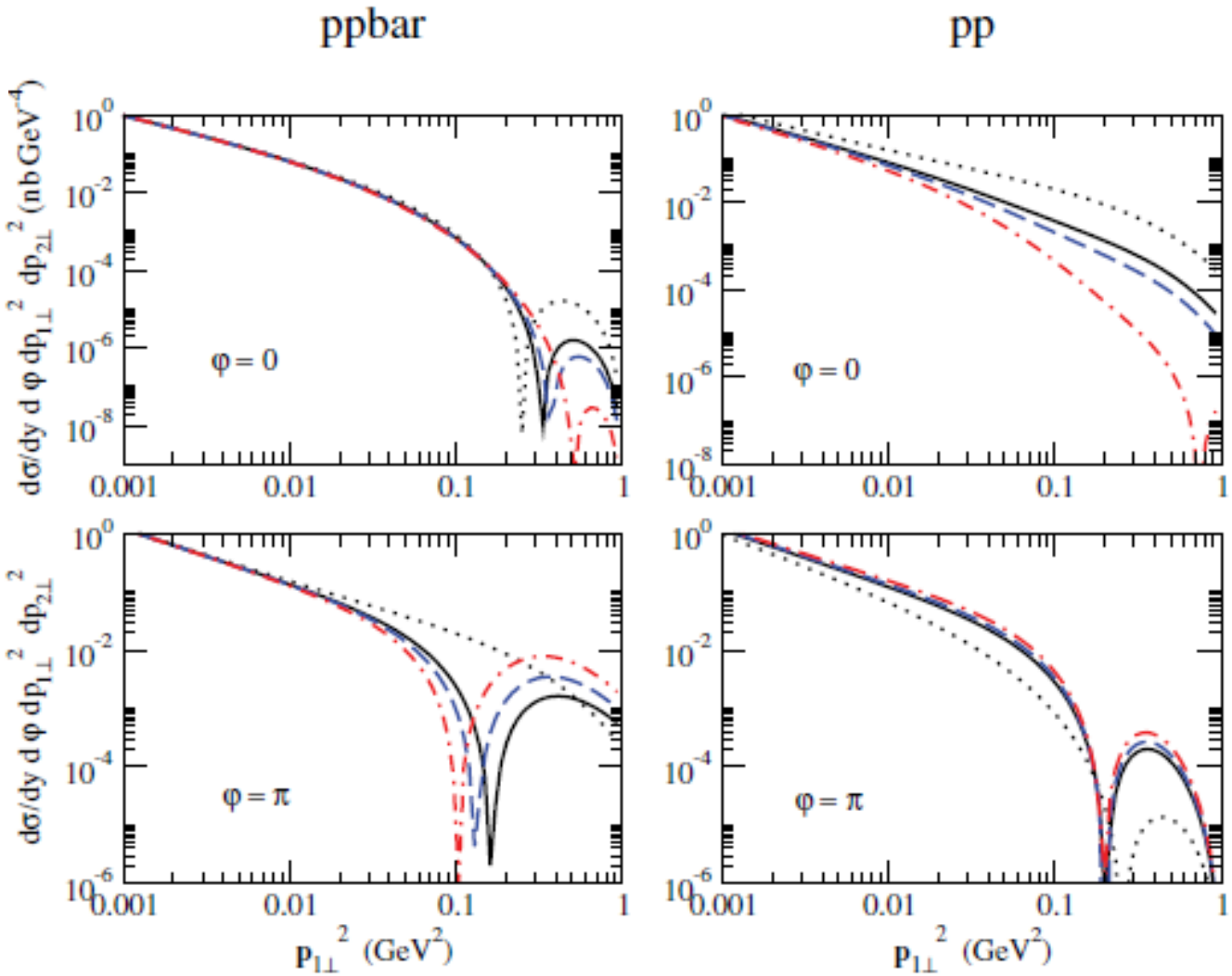
Figures from Alan Martin's Heidelberg lectures

Exclusive photoproduction of J/ψ in proton-proton and proton-antiproton scattering

W. SCHÄFER AND A. SZCZUREK

PHYSICAL REVIEW D **76**, 094014 (2007)





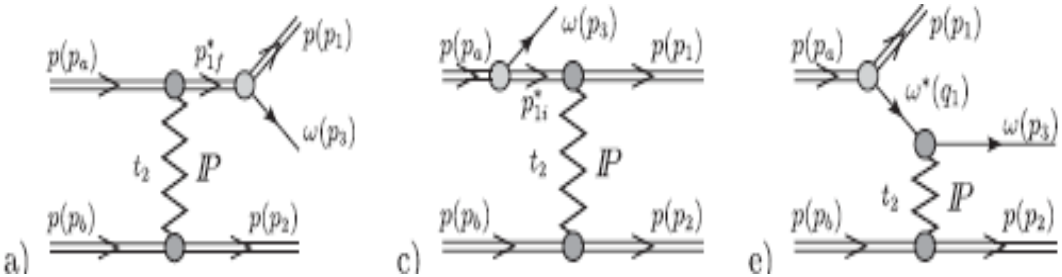
$d\sigma/dy\,dp_1^2\,dp_2^2\,d\phi$ as a function of p_1^2 at $y = 0$ and $p_2^2 = 1$ GeV^2

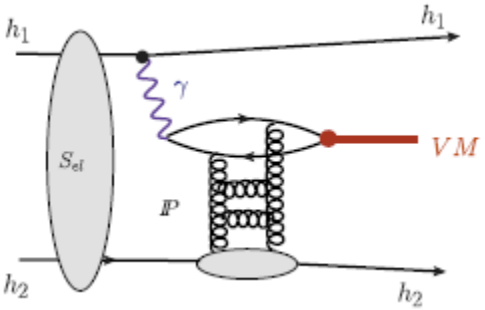
Different curves vary in *strength of absorption.* "Survival factor" is a ***lively function over phase space!***

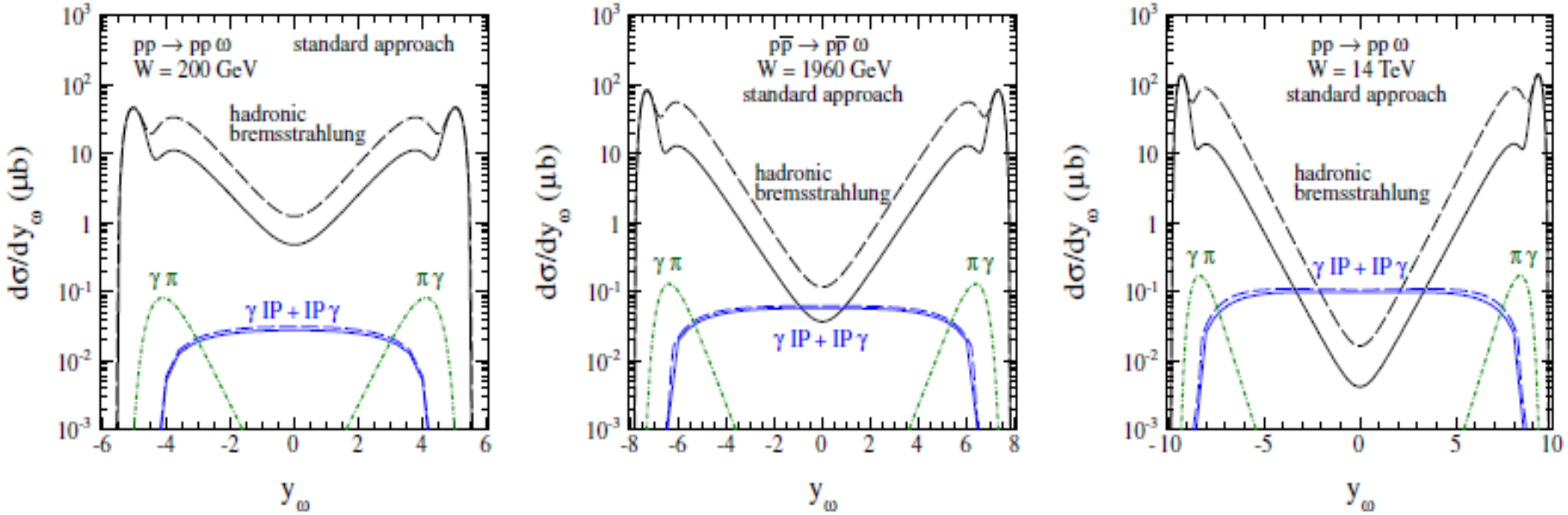
Exclusive production of ω meson in proton-proton collisions at high energies

Anna Cisek,[1,*] Piotr Lebiedowicz,[1,†] Wolfgang Schäfer,[1,‡] and Antoni Szczurek[1,2,§]

PHYSICAL REVIEW D 83, 114004 (2011)



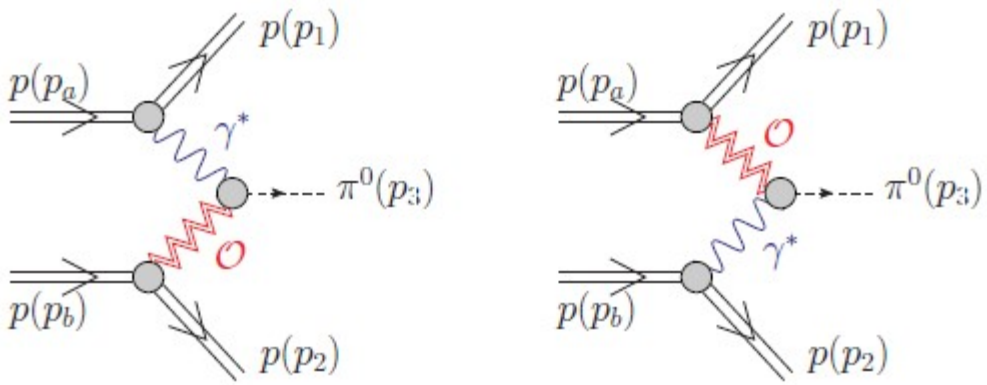




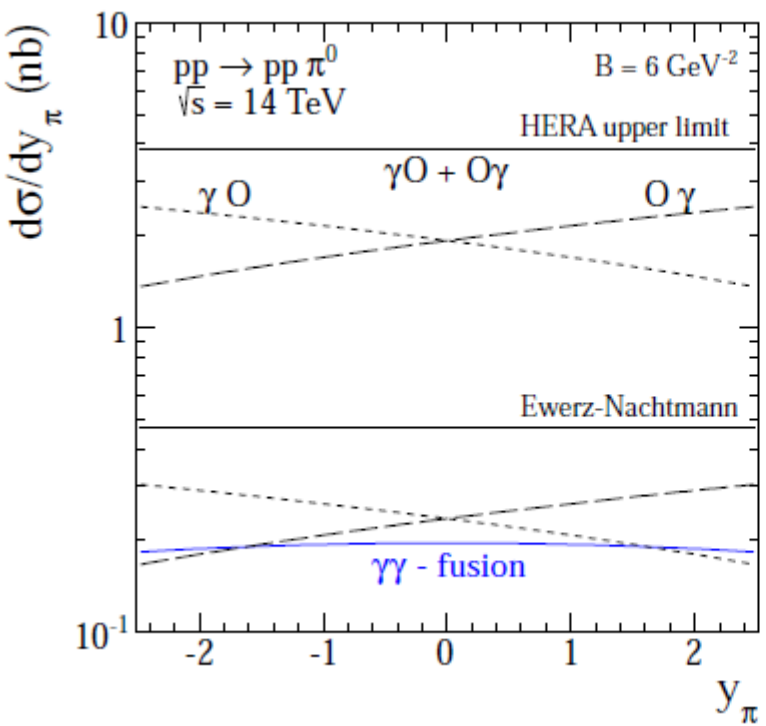
A caveat: a secondary exchange can survive surprisingly long, if its coupling to the Proton is large enough!

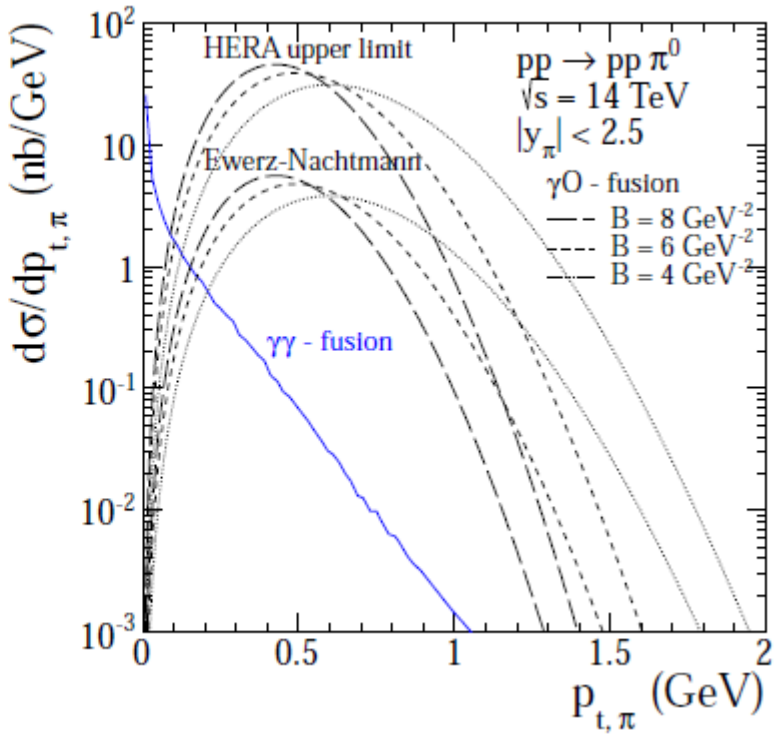
Exclusive $pp \to pp\pi^0$ reaction at high energies

Piotr Lebiedowicz[1,*] and Antoni Szczurek[1,2,†] PHYSICAL REVIEW D 87, 074037 (2013)



A similar analysis for the Odderon contribution to ***central J/ψ production via Pomeron-Odderon fusion*** is called for!





- Diffractive processes are *important QCD phenomena* at collider energies
- Gluon-rich environment provides a tool for many interesting studies: *from hadron spectroscopy to the investigation of gluon jet properties.*
- Central exclusive diffraction offers a particularly clean way to study *spin/parity properties* of the produced system.
- Central diffractive photoproduction allows us to study diffractive photon-proton/nucleus scattering at previously unaccessible energies. Especially production of quarkonia provides us with *constraints on the gluon distribution in proton/nucleus at very small x*
- Photon-photon physics in AA collisions: *QED at high field strengths.* In pp collisions: anomalous gauge boson couplings (first CMS data on excl. WW!).