ATLAS
EXPERIMENT

Diffractive and Central Processes at the LHC (a theoretical perspective)

V.A. Khoze (IPPP, Durham)

(Based on works with L.Harland-Lang, A.Martin and M.Ryskin)

Outline

- **Forward and Diffractive Physics at the LHC (yesterday, today and tomorrow)**

- **Central Exclusive Production Processes**

- **Selected CEP samples**

- **LHC as a High Energy $\gamma\gamma$ Collider**

WITH A BIT OF PERSONAL FLAVOUR

- **Summary and Outlook.**

Main aim: a brief overview of the current status of forward, exclusive and diffractive physics at the LHC and a discussion of the measurements to be performed in the coming years.

DISCLAIMER

An impressive list of questions from the ATLAS SM group members, some of which I am unable to address due to the lack of time or/and expertise. Please approach me after the talk (breaks/dinner/excursion).

Diffraction at the LHC

- The LHC has allowed measurement of diffraction to be made out to unprecedented collider energies, with broad rapidity coverage and proton tagging. (above the knee in CR)

- Already measurements of the elastic, total and diffractive cross sections in Run I have thrown up some interesting 'surprises' and a hard diffraction program is developing.

$\longrightarrow$ Run II has a lot to offer: discussed in detail in

CERN/LHCC 2013-021
February 28 2015

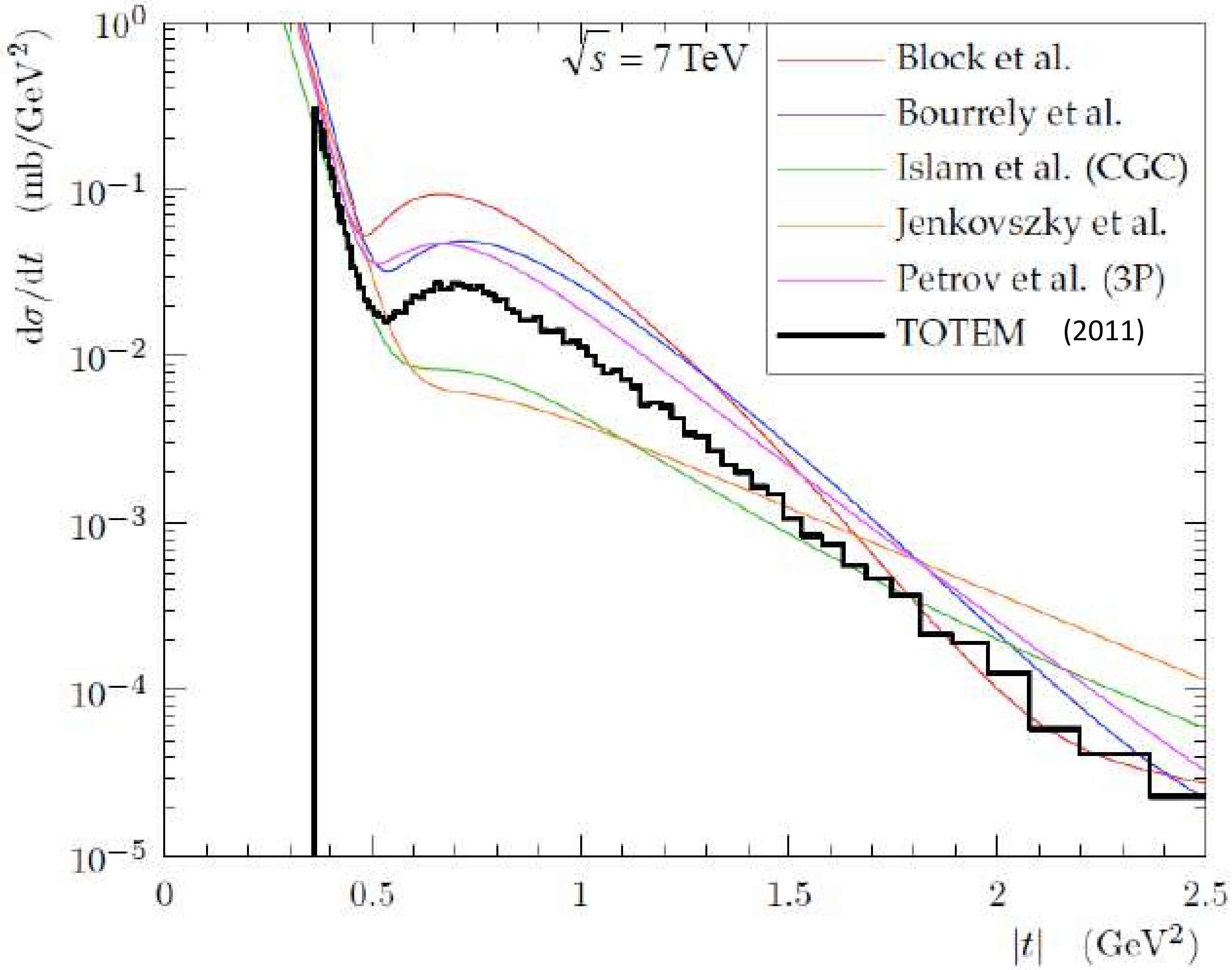
CERN-PH-LPCC-2015-001, SLAC-PUB-16364, DESY 15-167, to be published in Journal of Physics

LHC Forward Physics

Editors: N. Cartiglia, C. Royon
The LHC Forward Physics Working Group

http://www-d0.fnal.gov/Run2Physics/qcd/loi_atlas/fpwg_yellow_report.pdf

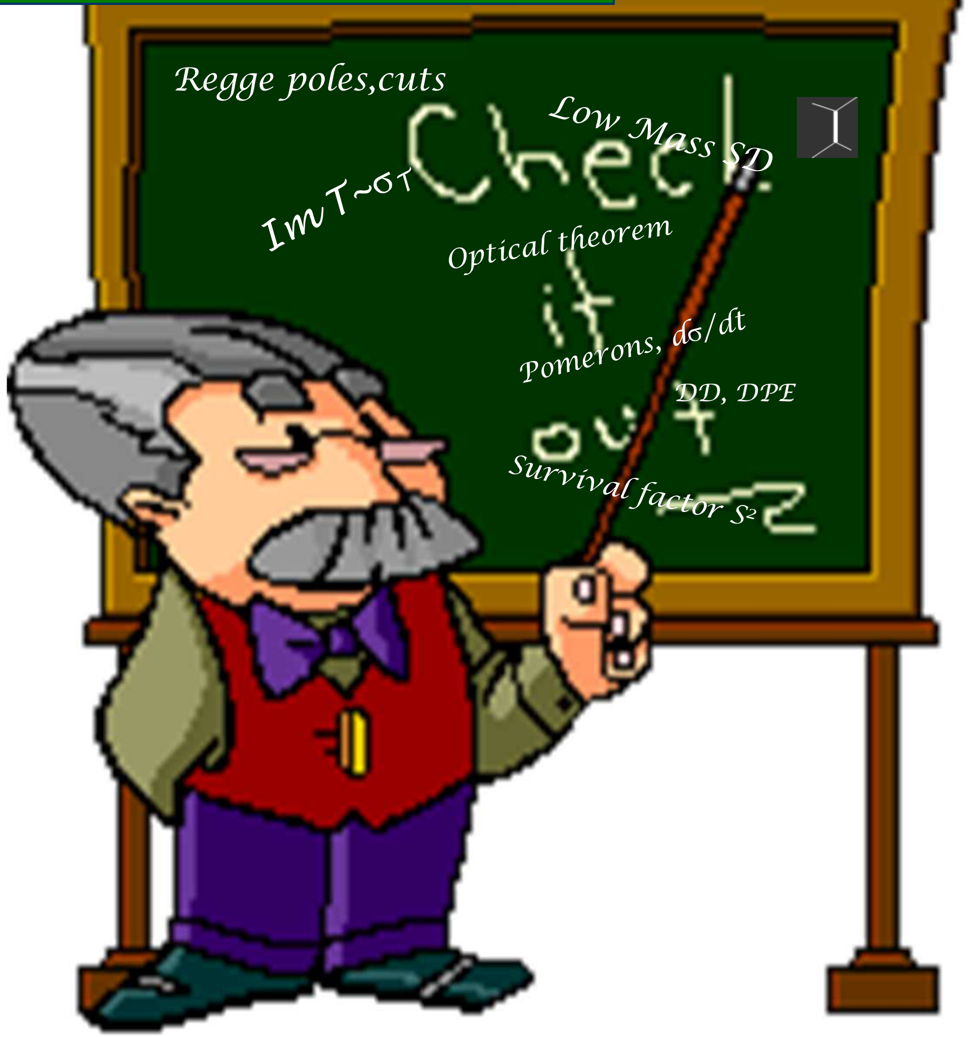
(pre-LHC) Model Comparisons



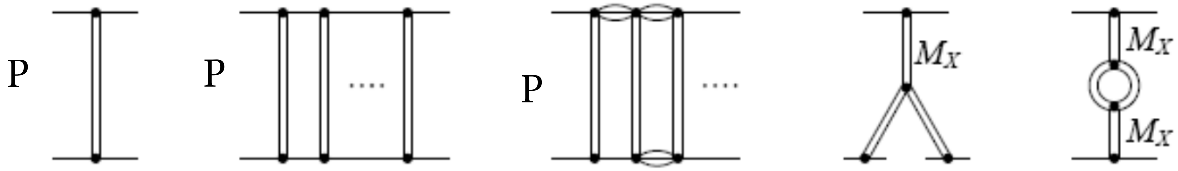
No theoretical / phenomenological model describes the TOTEM data completely.

Welcome to the world of difficult physics!

- Current theoretical models for soft hadron interactions are still incomplete, and their parameters are not fully fixed.
- Four (ideologically close) MP- models allowed good description of the data in the ISR-Tevatron range: KMR ,GLM, Ostapchenko, KP.
- The differences between the results of other models wildly fluctuated.



Reggeon Field Theory, Gribov- 1986



- $\sigma_{\rm tot}$, $\sigma_{\rm inel}$ … could not be calculated from the first principles based on QCD- intimately related to the confinement of quarks and gluons
  (some attempts within N=4 SYM , GLM).

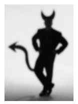
- Basic fundamental model-independent relations:
  unitarity, crossing, analyticity, dispersion relations.
  The Froissart-Martin **bound**: $\sigma_{tot} \leq \text{Const} \ \ln^2 s.$

- Important testable constraints on the cross sections.

most models asympt. ~ $\ln^2 s.$

but not a Must

- Phenomenological models- fit the data in the wide energy range and extrapolate to the higher energies. Next step- MC implementations.

- Well developed approaches based on Reggeon Field Theory with multi-Pomeron exchanges+ Good –Walker formalism to treat low mass diffractive dissociation:
  KMR-Durham, GLM- Tel-Aviv, Kaidalov-Poghosyan, Ostapchenko.
  Differences/**Devil**  – in details

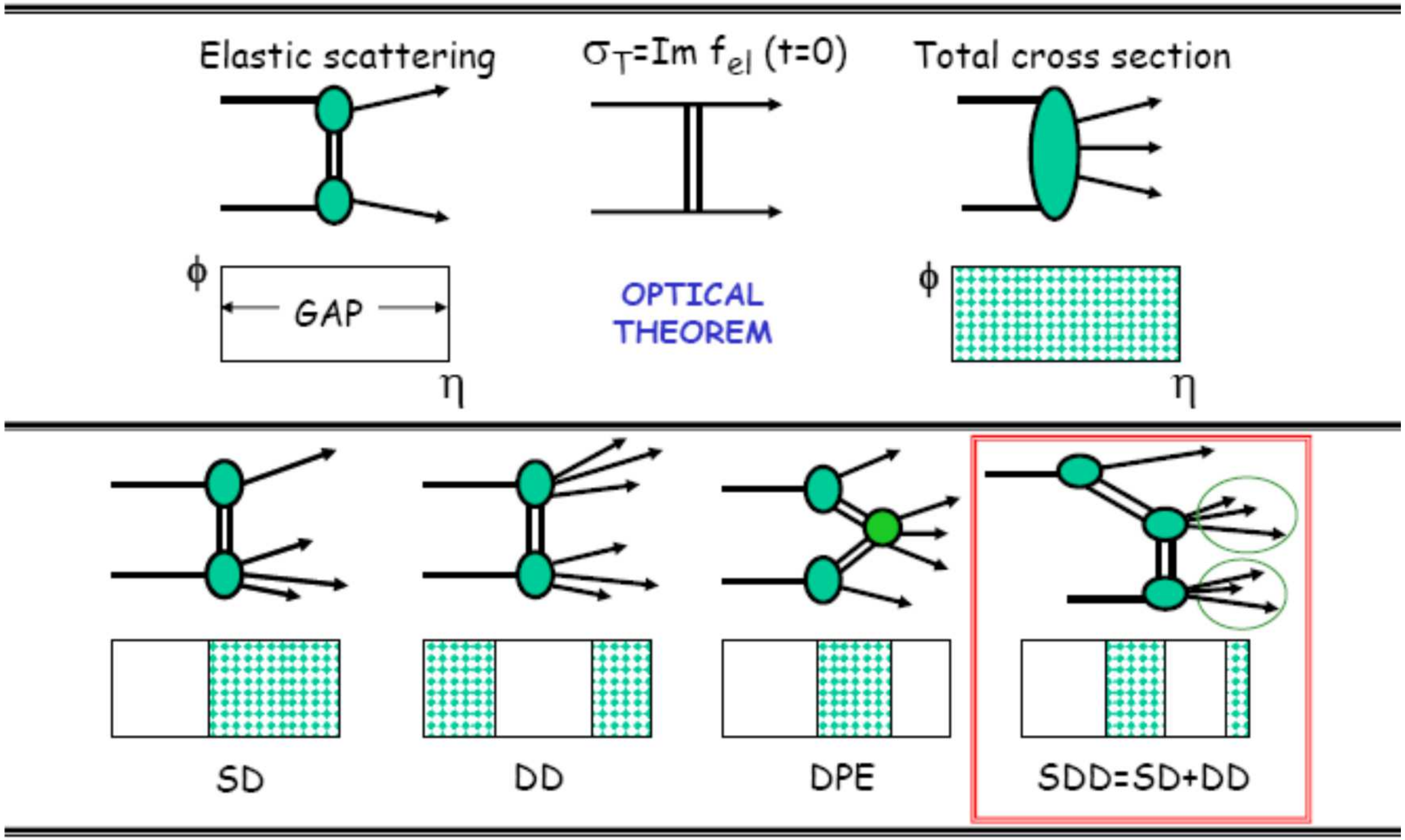
$d\sigma/dt = |T(t)|^2/16\pi s^2 \propto \exp(B_{el}t)$ optical theorem: $\mathrm{Im}\, T(s,t=0) = s\sigma_{tot}$

Diffractive pp Processes

Experimental signature ☞ presence of:

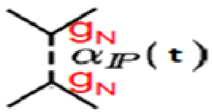
- ❑ intact leading protons
- ❑ Large Rapidity Gaps

(also EW exchanges)



Surprises in the LHC Run I data

Lesson 1.



In the pre-LHC era all data successfully reproduced by DL (1992) fits:

$$\sigma = \sigma_0 \cdot \left(\frac{s}{s_0}\right)^{\alpha_P(0)-1} + \sigma_R \cdot \left(\frac{s}{s_0}\right)^{\alpha_R(0)-1}$$

$$A_{el}(t) = \sigma_0 \cdot F_P(t) \cdot \left(\frac{s}{s_0}\right)^{\alpha_P(t)} + \sigma_R \cdot F_R(t)) \cdot \left(\frac{s}{s_0}\right)^{\alpha_R(t)}$$

$$\alpha_P(t) = 1 + \Delta + \alpha'_P t\ ,$$

with $\Delta = 0.08$ and $\alpha'_P = 0.25\ \mathrm{GeV}^{-2}$

In the Tevatron-LHC energy interval $\sigma_{\rm tot}$ starts to grow faster and the slope of effective P- trajectory α'_P increases.

At 7 TeV

$\sigma_{DL} = 90.7$ mb — Totem - $\sigma = 98.6 \pm 2.2 mb$

ALFA: $95.4 \pm 1.4\ mb$

(faster than predictions of pre-LHC KMR and GLM models)

t-slope: with $\alpha'_P = 0.25\ \mathrm{GeV}^{-2}$

$B_{DL} \le 18.3\ \mathrm{GeV}^{-2}$,

$B_{LHC} = 19.9 \pm 0.3\ \mathrm{GeV}^{-2}$ (TOTEM) ; 19.73 ± 0.24 GeV^{-2} (ALFA)

Lesson 2.

Lessons from LHC run I - elastic slope

- TOTEM and ALFA measurements of elastic slope: $\frac{d\sigma_{el}}{dt} = \left.\frac{d\sigma_{el}}{dt}\right|_{t=0} e^{-B|t|}$

ALFA, Nucl. Phys. B 889 (2014) 486-548

$B = 19.73 \pm 0.14\ \text{(stat.)} \pm 0.26\ \text{(syst.)}\ \text{GeV}^{-2}.$

TOTEM EPL, 95 (2013) 21002

$B = (19.9 \pm 0.3)\ \text{GeV}^{-2}$

- Even taking higher CDF value at 1.8 TeV and $\alpha' = 0.25\,\text{GeV}^{-2}$ DL predicts:

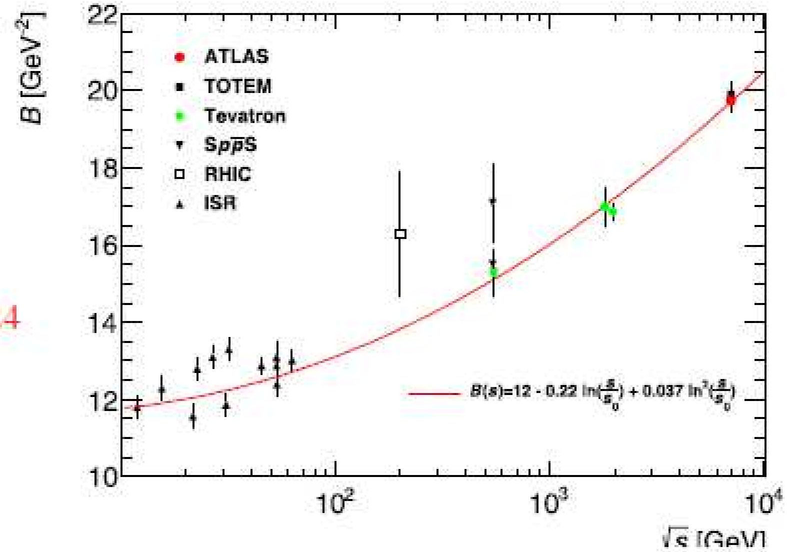
$$B_{el} = 16.98 + 4 \times 0.25 \times \ln(7/1.8) = 18.34\ \text{GeV}^{-2}$$

$\longrightarrow$ Simple linear Regge scaling ruled out: $B_{el} \neq 2b_0 + \alpha' \ln\left(\frac{s}{s_0}\right)$

- Energy dependence fit well by second--order polyn. May be expected from ladder structure of pomeron exchange.

V. A. Schegelsky, M.G. Ryskin, Phys. Rev. D85 (2012) 094024

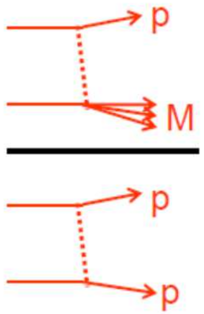
$$2\alpha_P'^{eff} = dB_{el}/d(ln(s/s_0))$$



Lesson 3.

Decrease of $\frac{\sigma_{\text{low M}}}{\sigma_{\text{elastic}}}$ with energy increasing.

	CERN-ISR 62.5 GeV		TOTEM 7 TeV	(M<3.4 GeV)



$$\frac{\sigma_{\text{low M}}}{\sigma_{\text{elastic}}} = \frac{2\text{-}3\ \text{mb}}{7\ \text{mb}} \overset{?}{=} \frac{2.6\ \text{mb}}{25.4\ \text{mb}}$$

Unexpectedly small
Before TOTEM, models predicted $\sigma_{\text{low M}} \sim$ 6-10 mb

Impact on the EAS characteristics : consistency of the current data with almost pure proton composition in the energy range $E_0 = 10^{18} - 10^{20}$ eV

S. Ostapchenko (arXiv:1402.5084

➔ possible long-ranging consequences for astrophysical interpretation of UHECR:

Important for discriminating between models for transition from galactic to extragalactic CR origin in the ultra HE range.

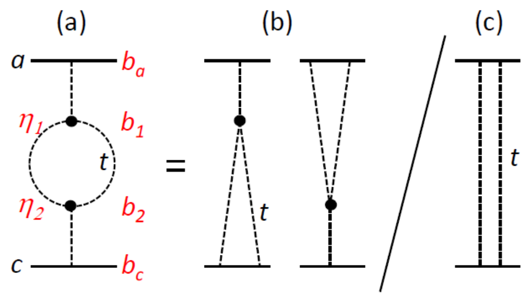
Lesson 4.

Strong violation of 'naïve factorization ' between the observed elastic, SD and DD cross sections.

In the first rapidity/mass interval from the TOTEM 7 TeV results it follows:

$$\frac{\sigma_{\rm DD}\,\sigma_{\rm el}}{(\sigma_{\rm SD})^2} \simeq 3.6,$$

$\sigma_{\rm DD} = 0.116$ mb (TOTEM, arXiv:1308.6722)



$$\frac{d\sigma_{\rm DD}}{dt\,d\eta_1 d\eta_2} = \frac{d\sigma_{\rm SD}}{dt\,d\eta_1}\,\frac{d\sigma_{\rm SD}}{dt\,d\eta_2}\Big/\frac{d\sigma_{\rm el}}{dt}.$$

Lesson 5.

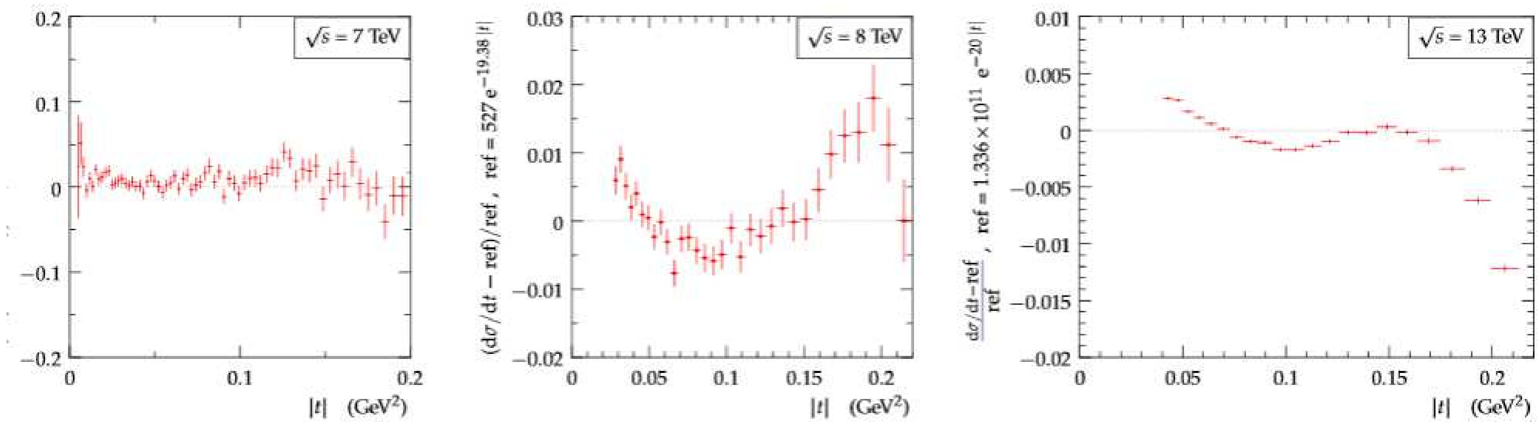
'Slope non-exponentiality ' at low-t –not unexpected, but still impressive

$$B = d[\ln(d\sigma_{el}/dt]/dt$$

15 years back, **KMR, Eur.Phys.J. C18 (2000) 167**

$$\frac{d\sigma/dt - \text{ref}}{\text{ref}}$$

- β^* = 90 m measurements at different energies (stat. unc. only):



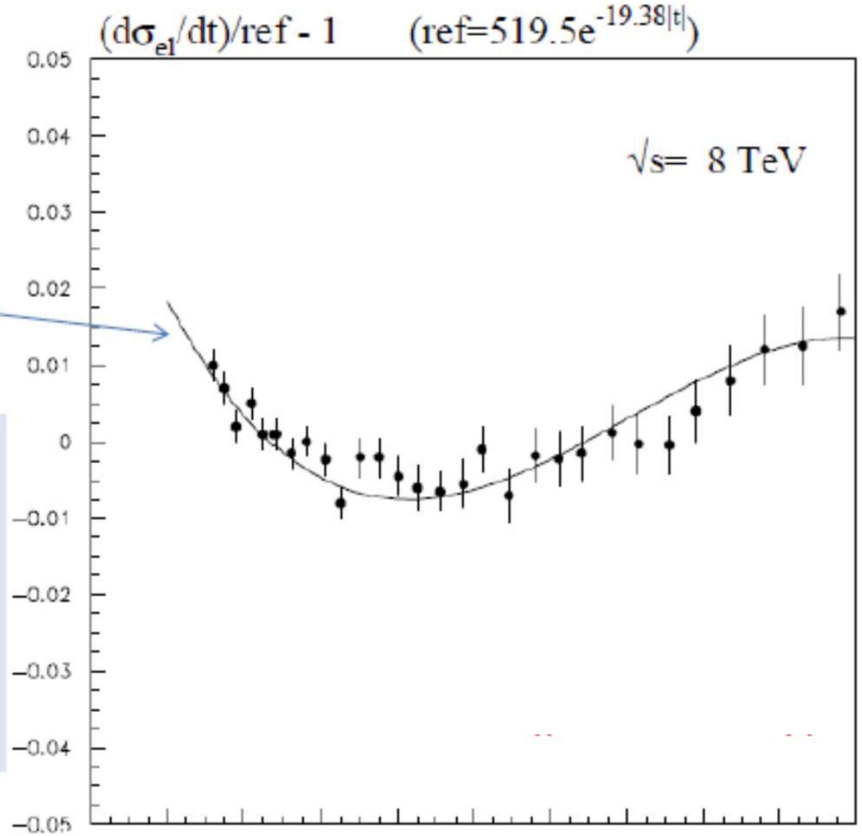
- non-exponentiality observed at 8 and 13 TeV!
  - non-exponentiality of the observed cross-section:

KMR, J.Phys. G42 (2015) no.2, 025003

t dependence of elastic slope shown as deviation from pure exponential   dσ(el)/dt ~ exp(19.38 t)

Anselm-Gribov, 1972

R. Glauber, 1955



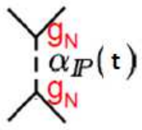
0   0.1   0.2 |t| GeV²

decrease due
(i) pion-loop in pom.traj.
(ii) pomeron-proton ff

increase due absorptive corrections

IMPLICATIONS OF THE LHC RUN I DATA
(exemplified in terms of Durham model)

(KMR, 2011-2015)



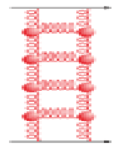
(Gribov-1961)

Yes, it is possible to describe all "soft" HE data

σ_{tot}, $d\sigma_{el}/dt$, $\sigma_{low\ M}$, (+ $\sigma_{high\ M}$)

from CERN-ISR → Tevatron → LHC

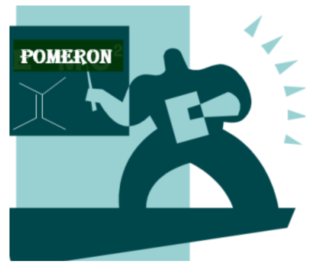
in terms of a single "effective" pomeron



(BFKL-1975-78)

Energy dep. of σ_{el}, σ_{tot} controlled by intercept and slope of "effective" pomeron trajectory

Diffractive dip and $\sigma_{low\ M}$ controlled by properties of GW eigenstates



High-mass diss^n driven by multi-pomeron effects

BFKL Pomeron naturally allows to continue from the 'hard' domain to the 'soft' region: after resummation of the main HO effects- the intercept weakly depends on the scale,

$$\Delta \equiv \alpha_P(0) - 1 \sim 0.3$$

KMR-13

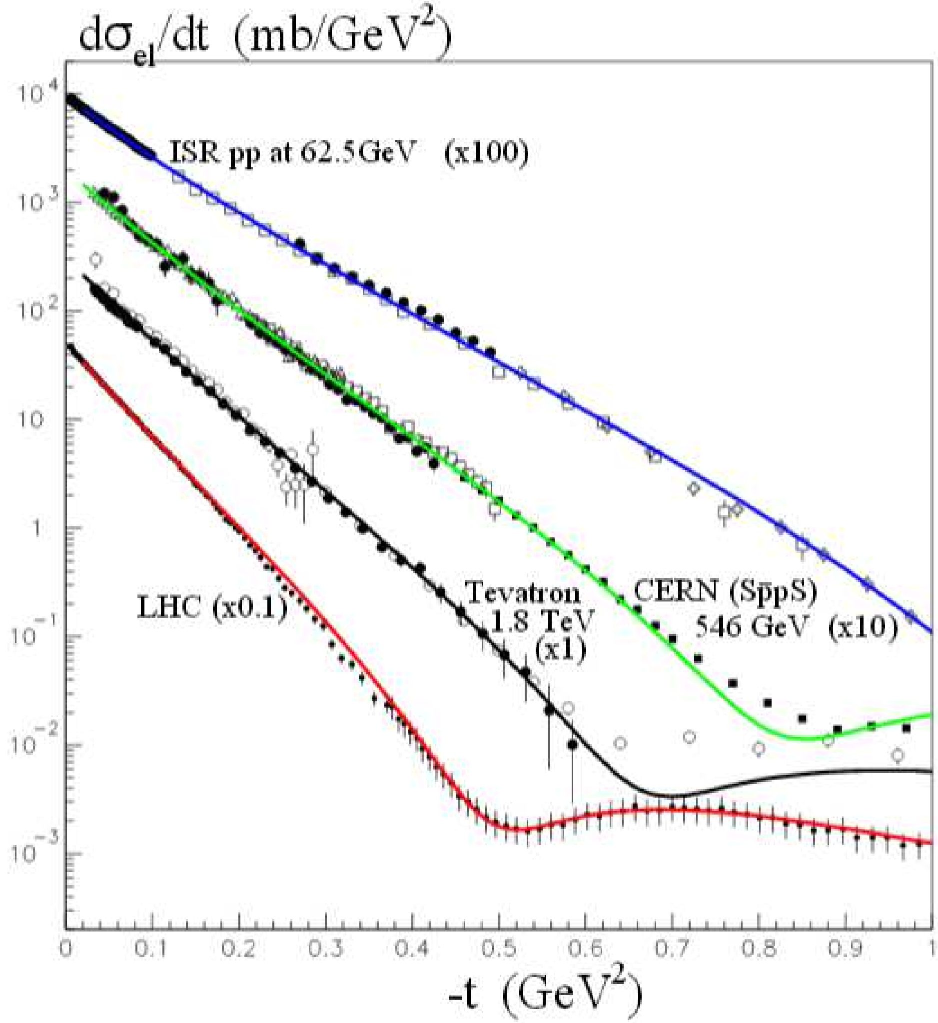
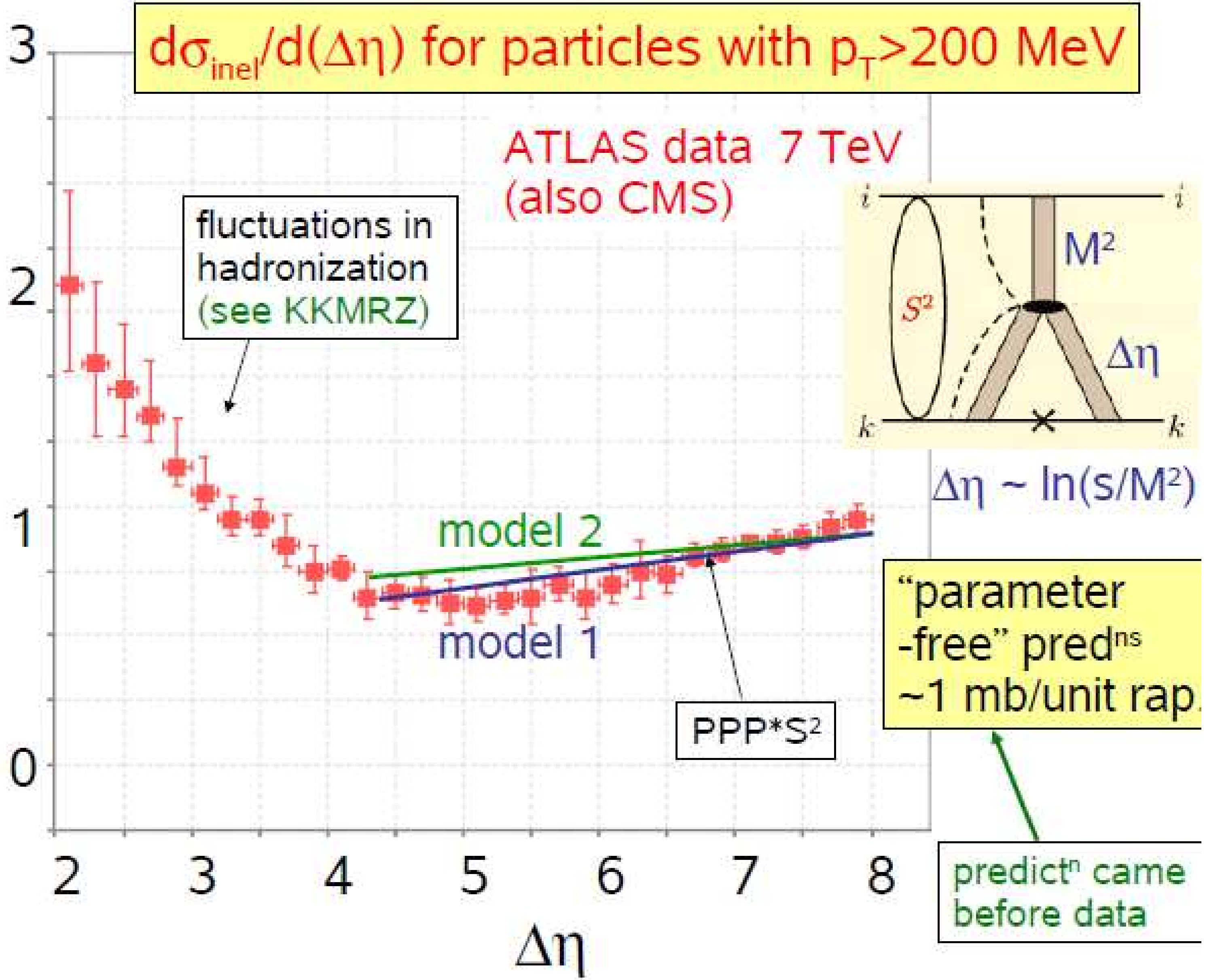


Figure 1: The description of pp or ($p\bar{p}$) elastic data. The references to the pre-LHC elastic data can be found in [18]. Here LHC refers to 7 TeV and the data are from [8, 5]


dσinel/d(Δη) for particles with pT>200 MeV
ATLAS data 7 TeV
(also CMS)
fluctuations in hadronization
(see KKMRZ)
M²
S²
Δη
Δη ~ ln(s/M²)
model 2
model 1
PPP*S²
"parameter -free" predns ~1 mb/unit rap.
predictn came before data
3
2
1
0
2 3 4 5 6 7 8
Δη

KMR 1402.2778

Tension between the TOTEM and the ATLAS/CMS results on LRG results.

ATLAS, 1201.2808

TOTEM, ~20% error bars

WARNING!

still unpublished, conference talks only

Compromise solution

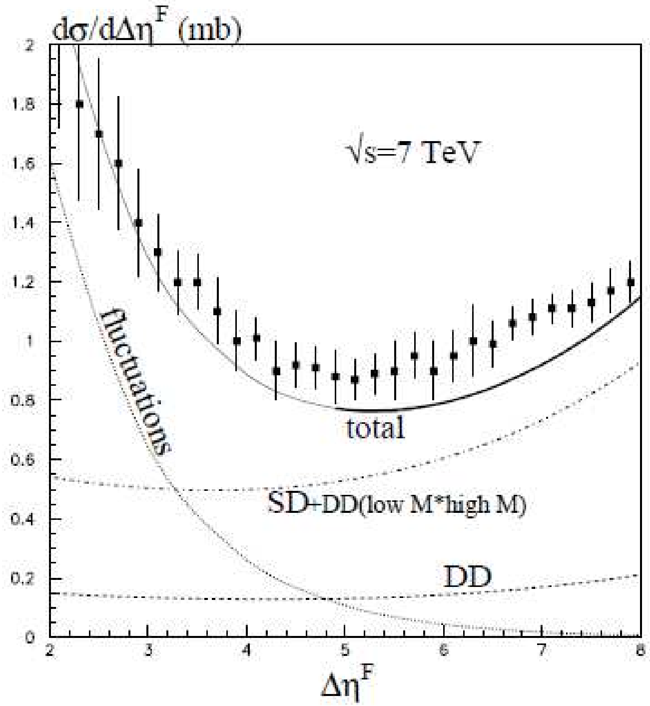


Figure 12: The ATLAS [46] measurements of the inelastic cross section differential in rapidity gap size $\Delta\eta^F$ for particles with $p_T > 200$ MeV. Events with small gap size ($\Delta\eta^F \lesssim 5$) may have a non-diffractive component which arises from fluctuations in the hadronization process [76]. This component increases as $\Delta\eta^F$ decreases (or if a larger p_T cut is used [76, 46]). The data with $\Delta\eta^F \gtrsim 5$ are dominantly of diffractive origin, are compared with the present 'global' diffractive model.

WARNING!

TOTEM data still unpublished, conference talks

Mass interval (GeV)	(3.4, 8)	(8, 350)	(350, 1100)
Prelim. TOTEM data	1.8	3.3	1.4
CMS data (LRG)		4.3	
Present model **KMR**	2.3	4.0	1.4

(ALFA +ATLAS/LHCf data are needed)

$\sqrt{s}$	$\sigma_{\rm tot}$	$\sigma_{\rm el}$	$B_{\rm el}(0)$	$\sigma_{\rm SD}^{{\rm low}M}$	$\sigma_{\rm DD}^{{\rm low}M}$	$\sigma_{\rm SD}^{\Delta\eta_1}$	$\sigma_{\rm SD}^{\Delta\eta_2}$	$\sigma_{\rm SD}^{\Delta\eta_3}$	$\sigma_{\rm DD}^{\Delta\eta}$
(TeV)	(mb)	(mb)	(GeV^{-2})	(mb)	(mb)	(mb)	(mb)	(mb)	(μb)
1.8	77.0	17.4	16.8	3.4	0.2				
7.0	98.7	24.9	19.7	3.6	0.2	2.3	4.0	1.4	145
8.0	101.3	25.8	20.1	3.6	0.2	2.2	3.95	1.4	139
13.0	111.1	29.5	21.4	3.5	0.2	2.1	3.8	1.3	118
14.0	112.7	30.1	21.6	3.5	0.2	2.1	3.8	1.3	115
100.0	166.3	51.5	29.4	2.7	0.1				

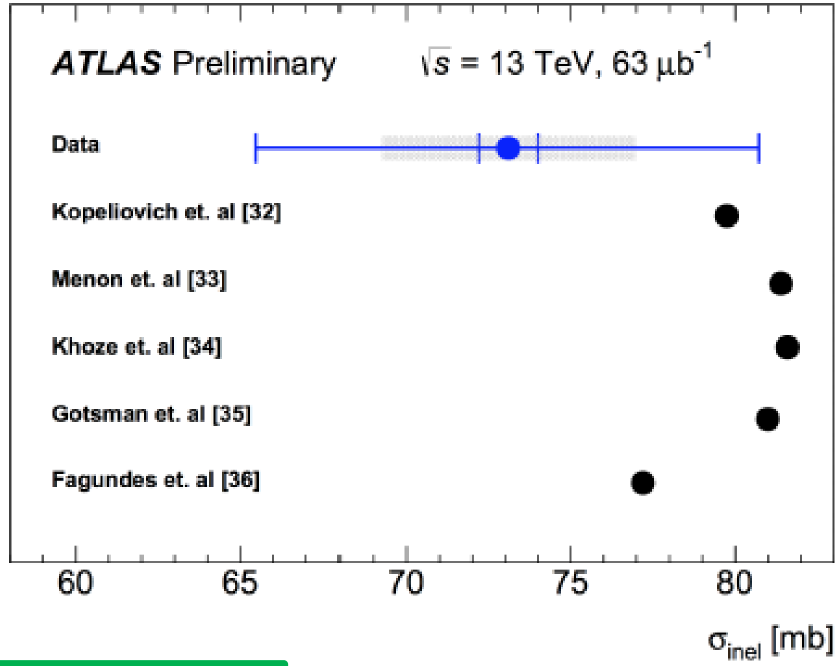
The predictions of the present model for some diffractive observables for high energy pp collisions at $\sqrt{s}$ c.m. energy. $B_{\rm el}(0)$ is the slope of the elastic cross section at $t=0$. Here $\sigma_{\rm SD}$ is the sum of the single dissociative cross section of both protons. The last four columns are the model predictions for the cross sections for high-mass dissociation in the rapidity intervals used by TOTEM at $\sqrt{s}$=7 TeV: that is, $\sigma_{\rm SD}$ for the intervals $\Delta\eta_1=(-6.5,-4.7)$, $\Delta\eta_2=(-4.7,\ 4.7)$, $\Delta\eta_3=(4.7,\ 6.5)$, and $\sigma_{\rm DD}^{\Delta\eta}$ is the double dissociation cross section where the secondaries from the proton dissociations are detected in the rapidity intervals $\Delta\eta_1=(-6.5,-4.7)$ and $\Delta\eta_3=(4.7,\ 6.5)$, At $\sqrt{s}$=7 TeV, the three 'SD' rapidity intervals correspond, respectively, to single proton dissociation in the mass intervals $\Delta M_1=(3.4,8)$ GeV, $\Delta M_2=(8,350)$ GeV, $\Delta M_3=(0.35,1.1)$ TeV,

MBTS: Extrapolation to Total $\sigma_{pp}^{textinel}$

first pp_{inel} cross-section measurement at 13 TeV

- Extrapolation factor obtained from MC (Pythia 8 D-L $\epsilon = 0.085$, as in the 7 TeV measurement).
- The uncertainty is taken as the envelope of the extrapolation factors from the different models.
- Compatible with different theoretical models.
- Luminosity and extrapolation from fiducial region dominate the uncertainty.
- Recent vdM scan luminosity calibration will be used to reduce the former.

Source	Value
This measurement	73.1 ± 0.9 (exp.) ± 6.6 (lum.) ± 3.8 (extr.) mb
Pythia8	78.4 mb
Kopeliovich et al. [33]	79.8 mb
Menon et al. [34]	81.4 ± 2.0 mb
Khoze et al. [35]	81.6 mb
Gotsman [36]	81.0 mb
Fagundes [37]	77.2 mb



ATLAS-CONF-2015-038

Towards a Full Acceptance Detector at the LHC

- A **F**ull **A**cceptance **D**etector for the SSC (J.D. Bjorken, SLAC-PUB-5692, 1991)

- In addition the physics at the very lowest mass scales, the log-s physics, has suffered from lack of attention at energies higher than attained at the CERN ISR.

- The physics of diffractive processes (Pomeron physics) i.e. physics of event structure containing "rapidity gaps" (regions of rapidity into which no particles are produced), **must not be compromised**.

- FELIX proposal for LHC- 1997 (J.Phys.G(28:R117-R215,2002).

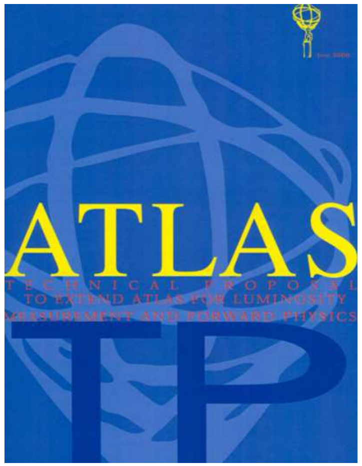
(A Full Acceptance Detector at the LHC (FELIX).)

ALFA

- Proposal to Extend ATLAS for Luminosity Measurement and Forward Physics

June 2000

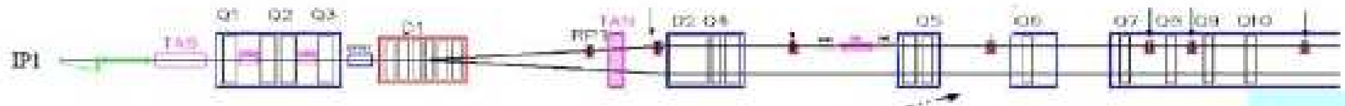
H. Ahola[1], M. Battaglia[2], O. Bouianov[3,4], M. Bouianov[2,3], G. Forconi[4], E. Heijne[5], J. Heino[4], V. Khoze[6], A. Kiiskinen[4,7], K. Kurvinen[4], L. Lahtinen[4], J.W. Lamsa[8], E. Lippmaa[9], T. Meinander[1], V. Nomokonov[4], A. Numminen[4], R. Orava[2,4], K. Piotrzkowski[10], M. White[4], M. Ryynänen[1], L. Salmi[4,7], J. Subbi[9], K. Tammi,[4], S. Tapprogge[4], T. Taylor[5]

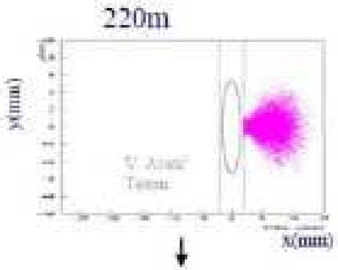


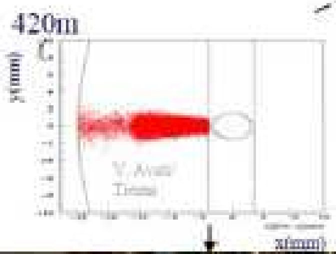
But ATLAS is un-instrumented in rapidity between ~5 and 9.5 @ 13TeV (CMS, ALICE, LHCb have installed FSCs)

AFP = ATLAS Forward Proton

Proton leaves the interaction intact, travels through LHC optics and is detected at ~220 m





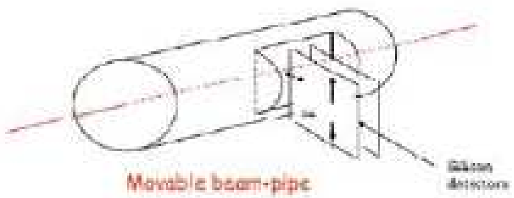


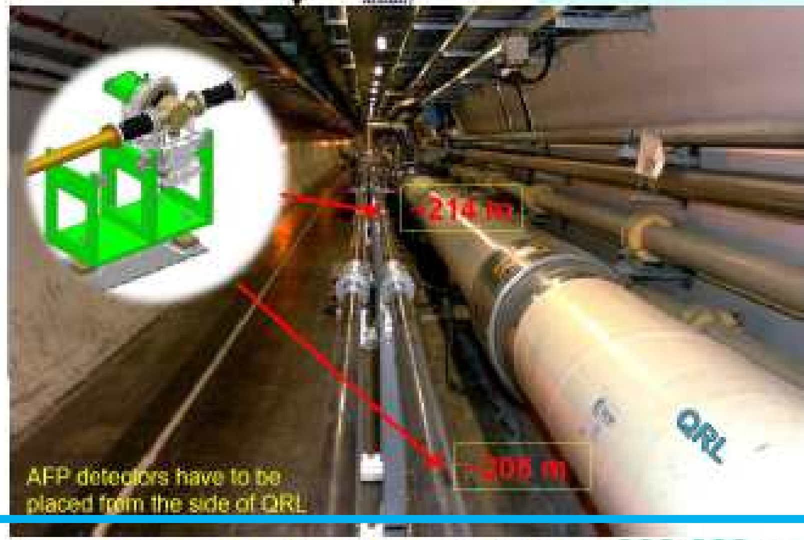
What is AFP?

1) Array of radiation-hard near-beam **Silicon detectors** with resolution ~10 µm, 1µrad
2) **Timing detectors** with up to ~10 ps resolution for overlap background rejection (SD+JJ+SD)
3) **Roman Pots**

Horizontal detectors in a movable beam-pipe at 216 and 224 m on each arm.

Detectors as close as possible to the beam: 10σ = 1mm





AFP: 2 stations on each side of IP with tracking and timing detectors at ~ 220m 200-220m, ATLAS side

3

The AFP Detector for Run 2

- Winter 2015-2016 shutdown – installation of a single AFP 'arm' with two Roman pot stations, the '0+2' AFP configuration (AFP0+2) **DONE!**
- Winter 2016-2017 shutdown – installation of the second detector arm

AFP 0+2:

- two silicon tracking detectors and a Level-1 Trigger
- physics: soft single diffraction, single diffractive jets, W, jet-gap-jet, exclusive jet production (one tag)

AFP 2+2:

- two silicon tracking detectors on second arm and time-of-flight detectors on both far stations
- physics: soft central diffraction, central diffractive jets, jet-gap-jet, γ+jet, exclusive jet production, anomalous couplings, 750 GeV resonance

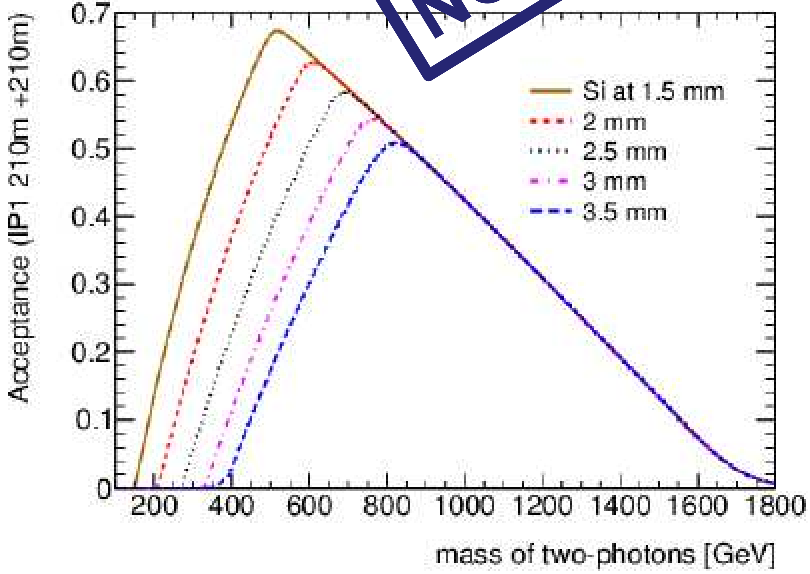
Kinematics

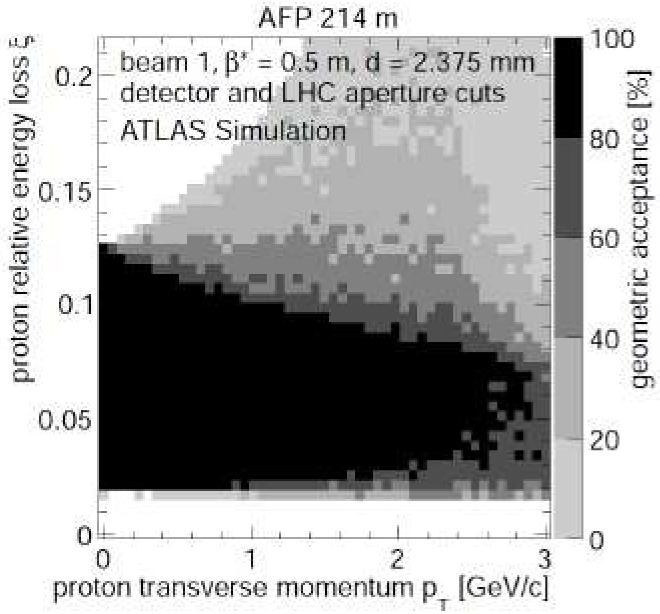
AFP

how close the RPs can safely approach the beam ?

- Acceptance large for 0.015 < ξ< 0.13
- Good resolution in ξ, not so great resolution in p_T
- Tag protons in both stations to reconstruct mass (resolution ~ 1-2% depending on mass)
- Timing detectors, mass trigger at L1 from course bars (quart/diamonds)

NOT UPDATED





PRAGUE FZU

MUCH NEEDED RUN II MEASUREMENTS (1)

- Measurements of $\sigma_{\rm tot}$ and elastic slope B at 13 TeV
  (in particular a confirmation of the rise of effective α'_P).

- Accurate determination of σ^{SD}_{LM}, σ_{SD}, σ_{DD} in different mass intervals
  (ALFA+ ATLAS) (most usual suspects)

  FSCs are very desirable [CMS, LHCb, ALICE all have these installed].

- Detailed comparison of $d\sigma_{el}/dt$, in the wide t-interval with the theory predictions.

- Comparison of particle distributions / compositions and correlations (BEC)
  in the **PP**, **P**p events with those in the pp collisions (ALFA+ ATLAS)
  (sensitivity to the (small) size of the Pomeron).

- $\frac{d\sigma_{\rm SD}}{dt dM^2}(pp \to pX)$, $dN_{DPE} / d\eta dp_t^2$

.

MUCH NEEDED RUN II MEASUREMENTS (2)

- Promising plans of combined ALFA+ LHCf measurements to study SD (n, γ, π0 in final state).

- Special LHC runs with low lumi/ large β^* are badly needed.

  (The cross-sections are (normally) large, and we do not need high luminosity)

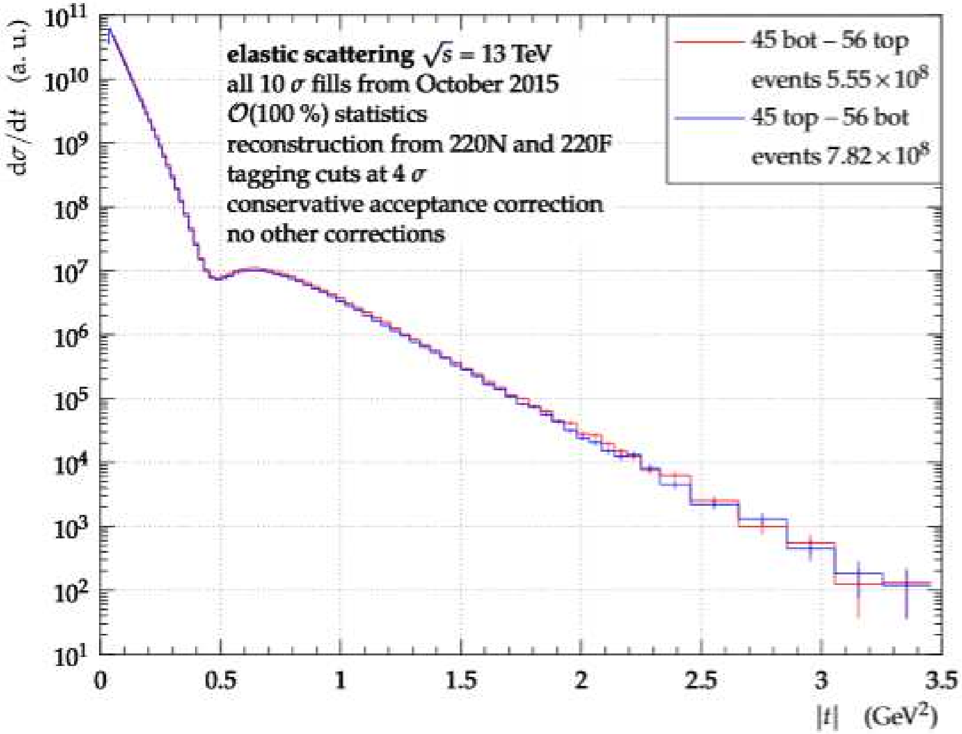
- Runs with very large β^* ~2.5 km

  (ALFA), Coulomb interference region, Re/Im measurements

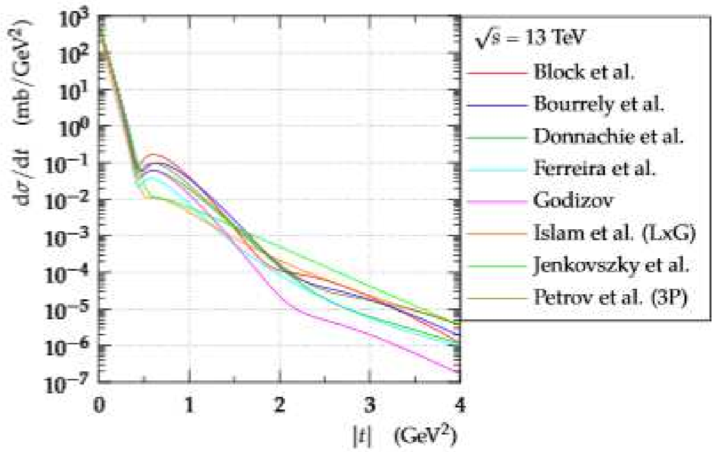
- Odderon = (hypothetical) cross-odd partner of Pomeron

  structures in $d\sigma/dt$:

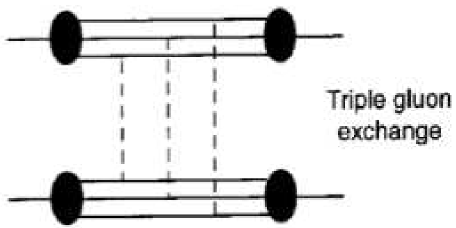
- very preliminary, but already very strong results



(ALFA data are very welcome)

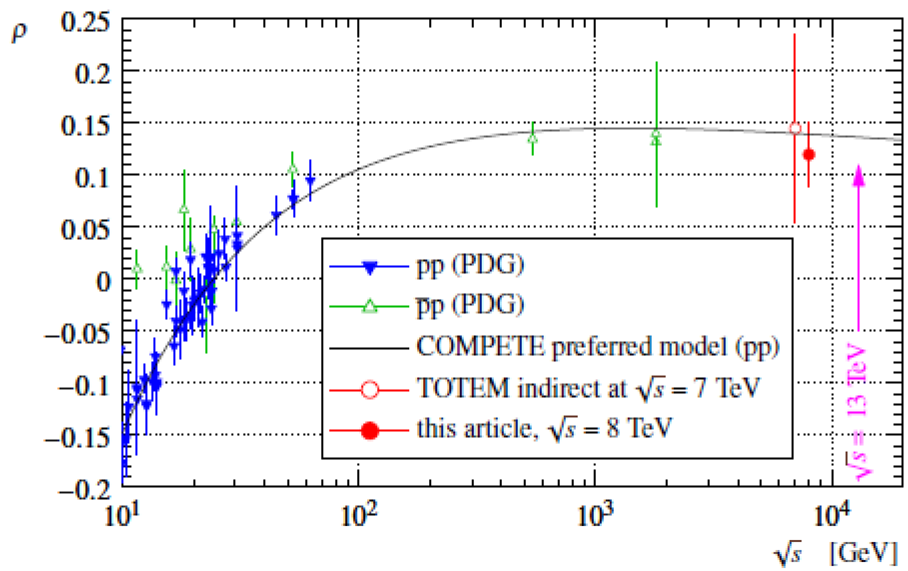


- high-$|t|$ data: no structures!
  - rules out many models
  - rules out physics mechanism: "optical" models
  - physics interpretation: transition between diffraction and pQCD



Outlook: $\beta^* = 2500$ m planned in 2016

- Coulomb-nuclear interference measurement at 13 TeV
  - need larger β^* for low $|t|$ at higher energy $\Rightarrow \beta^* = 2500$ m
  - experimental key improvement: higher statistics at low $|t|$
    - leading source of uncertainty on ρ
    - hardware improvement in Run II: both diagonals can be used $\Rightarrow$ factor 2
    - longer running time: 3 days requested



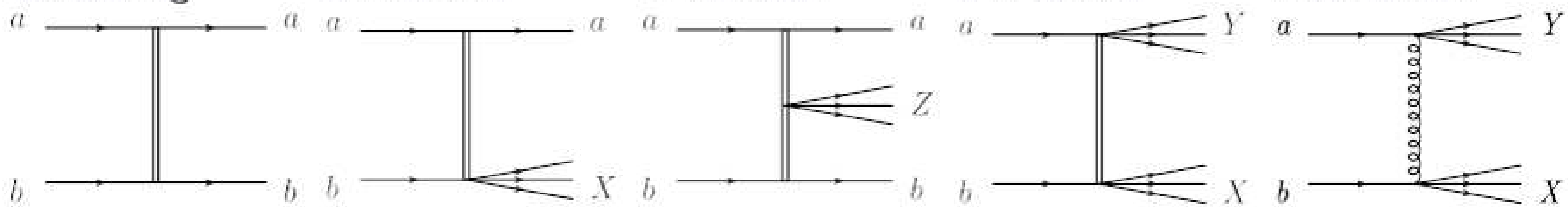
(ALFA data are very welcome)

- theoretical improvements welcome
  - interference formulae
  - constraints on hadronic component (modulus and phase)

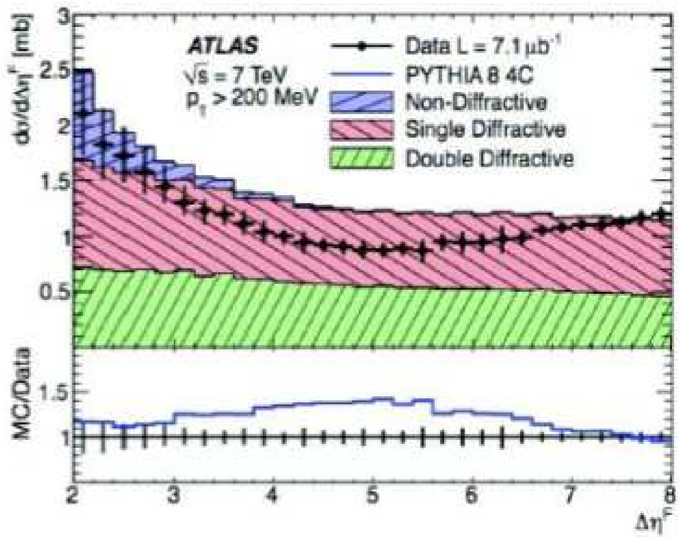
Soft Processes

Physics with AFP0+2 and AFP2+2
Rafał Staszewski
AFP detectors
Soft processes
Jet production
Electroweak bosons
Photon + jet
Jet-gap-jet processes
Exclusive jets
BSM physics
Conclusions
Backup

elastic scattering | single diffraction | central diffraction | double diffraction | non-diffractive interaction



- Gap measurement in ATLAS does not distinguish SD from DD
- More information about events with forward proton tagging
- High cross sections → low lumi needed → possible with lowest pile-up
- AFP 0+2 – single diffraction
  AFP 2+2 – central diffraction
- Goal for 2016 running



Eur. Phys. J. C72 (2012) 1926

2. CENTRAL EXCLUSIVE PRODUCTION PROCESSES

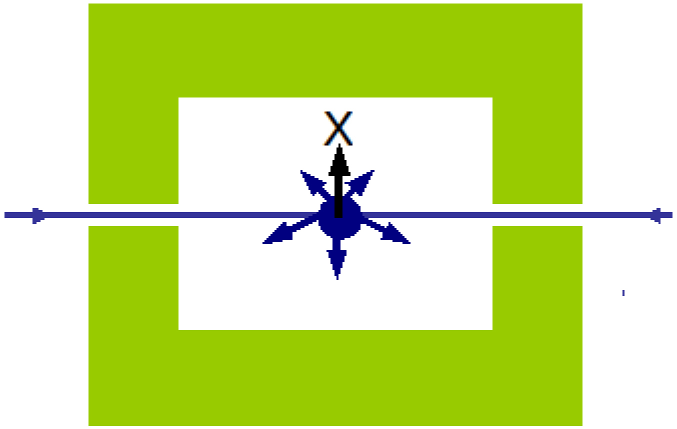
What is it?

MIND THE GAP

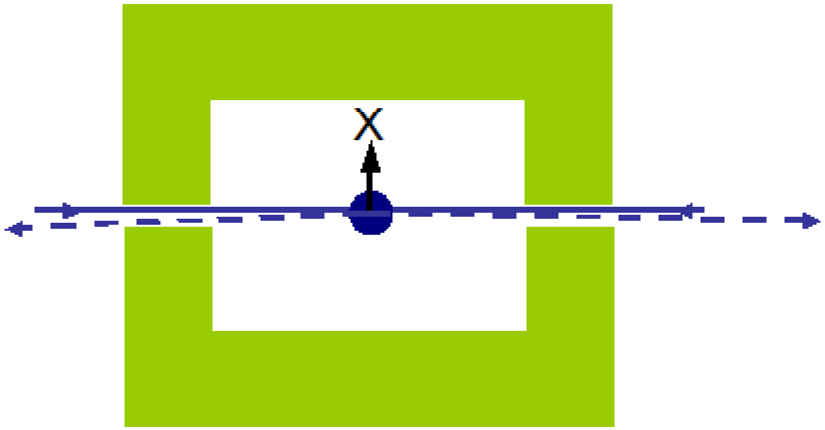
Central Exclusive Production (CEP) is the interaction:

$$pp \rightarrow p + X + p$$

- Diffractive: colour singlet exchange between colliding protons, with large rapidity gaps ('+') in the final state.
- Exclusive: hadron lose energy, but remain intact after the collision.
- Central: a system of mass M_X is produced at the collision point and only its decay products are present in the central detector.



vs.

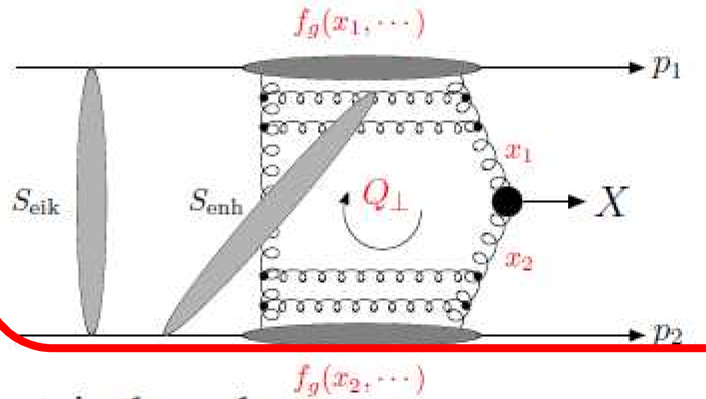


Production mechanisms

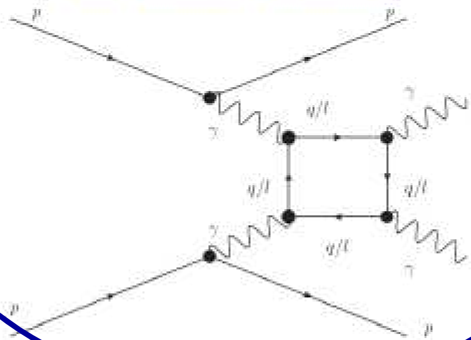
Exclusive final state can be produced via three different mechanisms, depending on quantum numbers of state:

Gluon-induced
(double pomeron exchange):

C-even, couples to gluons



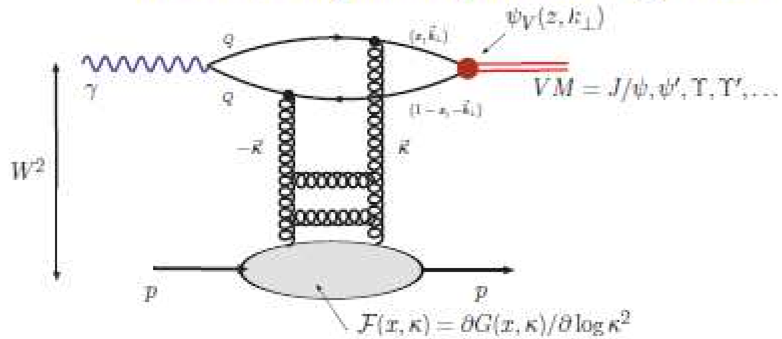
Couples to photons



Photoproduction

Photon-induced

C-odd, couples to photons + gluons



Why is it interesting?

- Clean:
  - Experimentally clean signal: low multiplicity ($\longrightarrow$ low background) process,* not typically seen in hadronic collisions.
  - Theoretically modeling such exclusive processes requires novel application of pQCD, quite different to inclusive case.
- Quantum number selection:
  - Demanding exclusivity strongly selects certain quantum numbers for produced object - the '$J_z^{PC} = 0^{++}$' selection rule for certain processes.
- Proton tagging:
  - Outgoing protons can be measured by tagging detectors installed at CMS (CT-PPS) and **Installed !** ATLAS (AFP). Handle to select events and provides additional event information (missing mass/proton correlations).

$\longrightarrow$ Clean production environment and selection rules provide potentially unique handle on QCD physics, but also BSM objects.

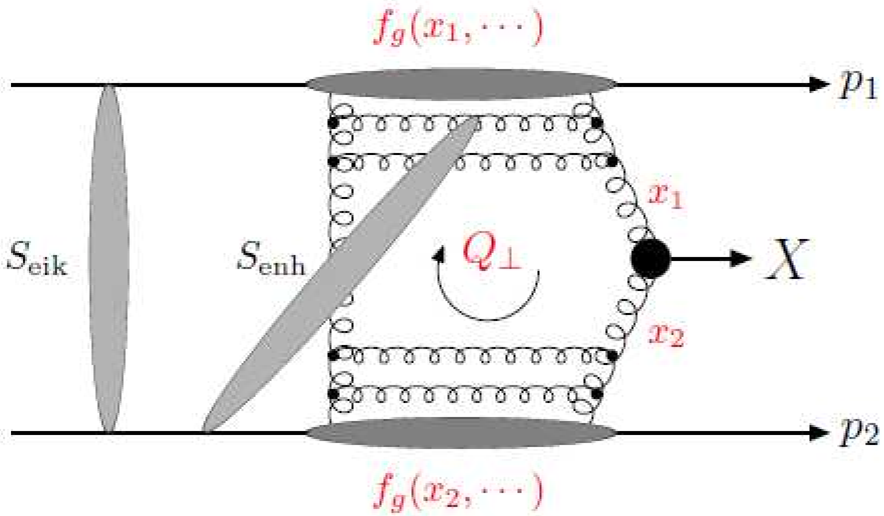
*In absence of pile-up

'Durham Model' of Central Exclusive Production

(QCD mediated)

- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons.
- The use of pQCD is justified by the presence of a hard scale $\sim M_X/2$. This ensures an infrared stable result via the Sudakov factor: the probability of no additional perturbative emission from the hard process.

- The possibility of additional soft rescatterings filling the rapidity gaps is encoded in the 'eikonal' and 'enhanced' survival factors, $S^2_{\rm eik}$ and $S^2_{\rm enh}$.
- In the limit that the outgoing protons scatter at zero angle, the centrally produced state X must have $J_Z^P = 0^+$ quantum numbers.



SURVIVAL GUIDE

Survival factor

- Survival factor, $S^2_{\rm eik}$: probability of no additional soft proton-proton interactions, spoiling exclusivity of final-state.

- Not a constant: depends sensitively on the outgoing proton $\mathbf{p}_\perp$vectors. Physically- survival probability will depend on impact parameter of colliding protons. Further apart $\longrightarrow$ less interaction, and $S^2_{\rm eik} \to 1$.
  b_t and $p_\perp$: Fourier conjugates.

Process dependence

$\longrightarrow$ Need to include survival factor differentially in MC.

First fully differential implementation of soft survival factor – **SuperChic 2** MC event generator- HKR, ArHiv:1508.02718

Some CEP Samples

- CEP of light meson pairs ($\pi\pi, KK, \eta(')\eta(')...$) : predict very different behaviour for singlet vs. non-singlet mesons. Can shed light on the component of the η', η. Interesting theoretical features of Durham + 'hard exclusive' formalism.

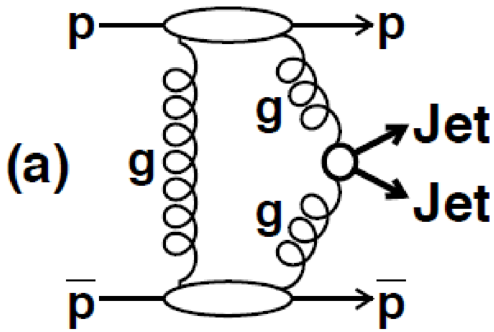
Remarkable theory expectations.

- $\gamma\gamma$ CEP : experimentally clean signal. Further (differential) test of approach. Sensitive to gluon PDF,

- Dijet/3 jet CEP. "Gluon factory"..

- Photoproduction ($J/\psi, \Upsilon, \psi(2S)$), two-photon collisions, BSM objects, glueballs...

EXCLUSIVE JET PRODUCTION



KMR-2000,Jz=0 selection rule

- Taking e.g. $m_b = 4.5$ GeV and $M_X = 40$ GeV we then get

$$\frac{\mathrm{d}\sigma(b\bar{b})/\mathrm{d}t}{\mathrm{d}\sigma(gg)/\mathrm{d}t} \approx 10^{-3}$$

(CDF-2008)

$\longrightarrow$ Huge suppression in b quark jets (increasing with M_X). Completely unlike inclusive case.

$$\frac{\sigma(|J_z|=2)}{\sigma(J_z=0)} \sim \frac{\langle p_\perp^2 \rangle^2}{\langle Q_\perp^2 \rangle^2} \sim 10^{-2}$$

Average outgoing proton transverse momentum (sub-GeV^2)

Average gluon transverse momentum in loop $\sim$ several GeV^2

$$\frac{\mathrm{d}\sigma^{J_z=\pm 2}(q\bar{q})/\mathrm{d}t}{\mathrm{d}\sigma(gg)/\mathrm{d}t} \approx \frac{N_c^2-1}{16N_c^3} \frac{\langle p_\perp^2 \rangle^2}{\langle Q_\perp^2 \rangle^2} \sim 10^{-4}$$

For one flavour $\Rightarrow$ multiply by $n_f = 4$

$\longrightarrow$ Huge suppression in light quark jets

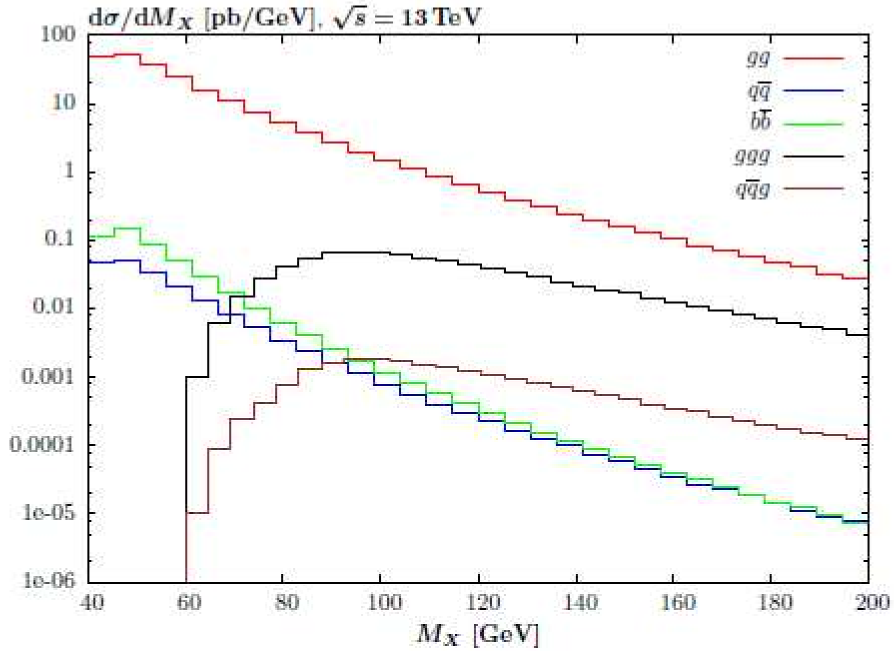
LHC cross sections

- Predictions for $\sqrt{s} = 13\,\text{TeV}$:

σ [pb] $|\eta_j| < 2.5$ anti–k_t, $R = 0.6$

	M_X(min)	gg	$q\bar{q}$	$b\bar{b}$	ggg	$gq\bar{q}$
$|p_{\perp,j}| > 20\,\text{GeV}$ →	75	120	0.073	0.12	6.0	0.14
$|p_{\perp,j}| > 20\,\text{GeV}$ →	150	4.0	1.4×10^{-3}	1.7×10^{-3}	0.78	0.02
$|p_{\perp,j}| > 40\,\text{GeV}$ →	250	0.13	5.2×10^{-5}	5.2×10^{-5}	0.018	5.0×10^{-4}

one flavour MMHT14 LO PDFs

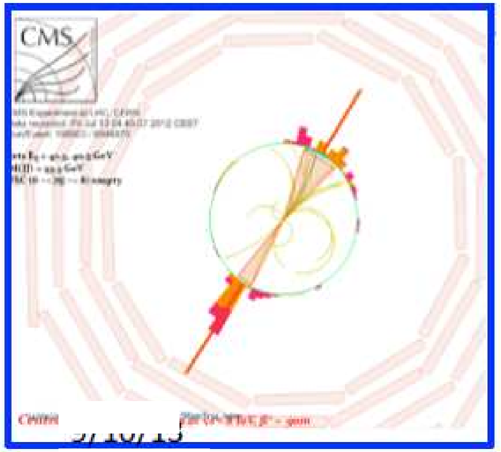


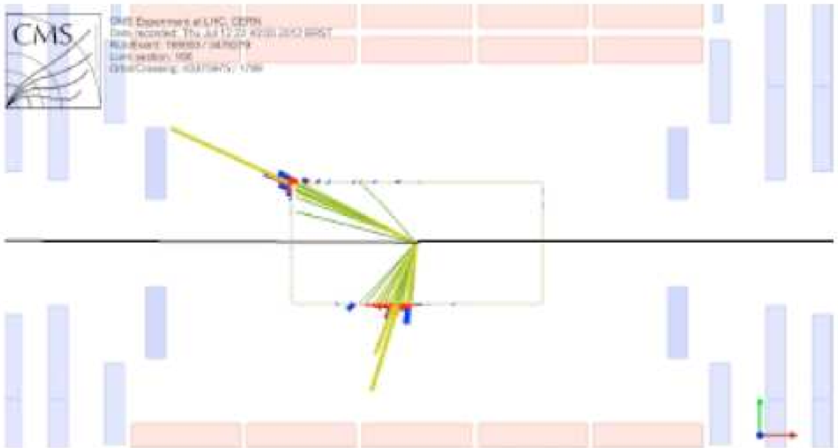
(Very interesting effects in 3jet qqg event)

Gluon jet dominance

From the above considerations, we expect dijet events to be almost entirely (colour singlet) gg

$\longrightarrow$ CEP of dijets offers the possibility of observing the isolated production of gluon jets at the LHC.





CMS + TOTEM event displays (2012)

These dijet and trijet events are the cleanest ever seen at a hadron collider, and remind one of LEP events. But these dijets are nearly all gg, while at LEP there were all $q\bar{q}$.

$\longrightarrow$ Clean probe of properties of gluons jets (multiplicity, particle correlations...)

Dijet CEP as a gluon factory

A MC for CEP : `SuperChic v2`

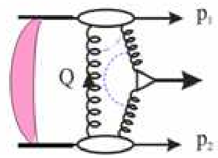
New(ish) MC for CEP released in August. Based on earlier MC, but with significant extensions. See arXiv:1508.02718 for details.

HKR-2015

- Processes generated:
  - SM Higgs boson
  - Jets: gg, heavy/massless $q\bar{q}$, ggg, massless $gq\bar{q}$
  - Double quarkonia: $J/\psi J/\psi$, $J/\psi\psi(2S)$ and $\psi(2S)\psi(2S)$
  - Light meson pairs: $\pi\pi$, KK, $\rho\rho$, $\eta(')\eta(')$, $\phi\phi$
  - $\chi_{c,b}$: two body and J/ψ, $\Upsilon + \gamma$ channels
  - $\eta_{c,b}$
  - Photoproduction: J/ψ, $\psi(2S)$ and Υ
  - Two-photon interactions: W^+W^-, l^+l^- and Higgs
  - Photoproduction: ρ and ϕ
  - Two-photon interactions in electron/positron collisions

The only MC generator which consistently incorporates the calculation of survival factors and Sudakov effects

SELECTED CEP SHOPPING LIST



- Interferometry with outgoing proton momenta in dimeson, dijet , $\gamma\gamma$ CEP.

Deep probe of the model for soft diffraction and absorptive effects..

- $\gamma\gamma$ CEP at E_T in ~ 2.5-10 GeV

Detailed study of perturbative CEP mechanism and the probe of higher order effects , restricting PDF choice.
Comparison with the dipion CEP.

- CEP of the $\chi_b(1P), \chi_b(2P), \chi_b(3P)$ states ($\Upsilon\gamma$ transitions)

(much) better controlled perturbatively, scale issue, quarkonium dynamics

Exclusive dijet production at comparatively large pT.

$$pp \to p + jj + p$$

'Gluon factory'

Comparing soft particle production in pp and PP events :

pT distributions and prompt hadron production ratios

$$\frac{\bar{p}}{p}, \frac{\pi^-}{\pi^+}, \frac{K^-}{K^+}, \frac{p+\bar{p}}{\pi^- + \pi^+}, \frac{K^+ + K^-}{\pi^+ + \pi^-} \quad ....$$

Observation of $\pi\pi, K^+K^- (p\bar{p}, \Lambda\bar{\Lambda})$ CEP in the resonance and non-resonance regions.

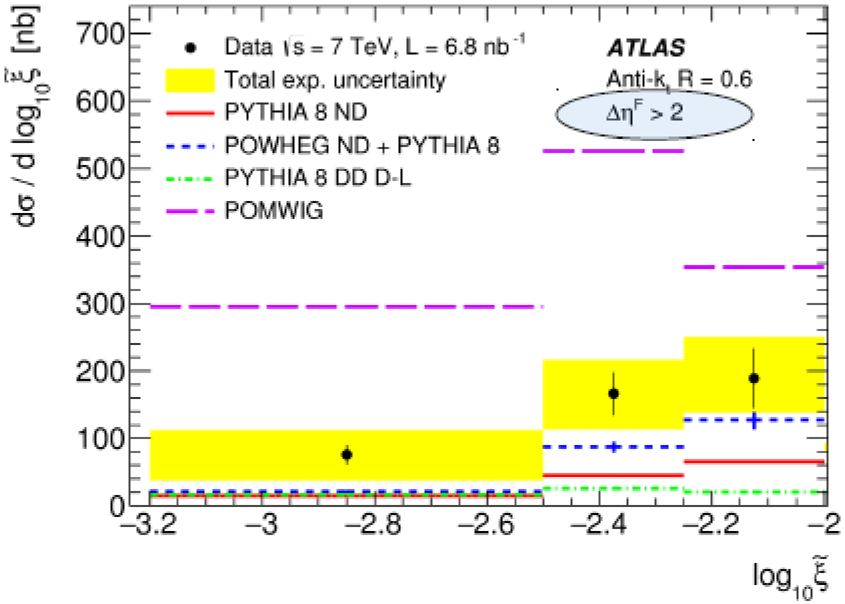
(a very useful additional handle on various ingredients of production mechanism)

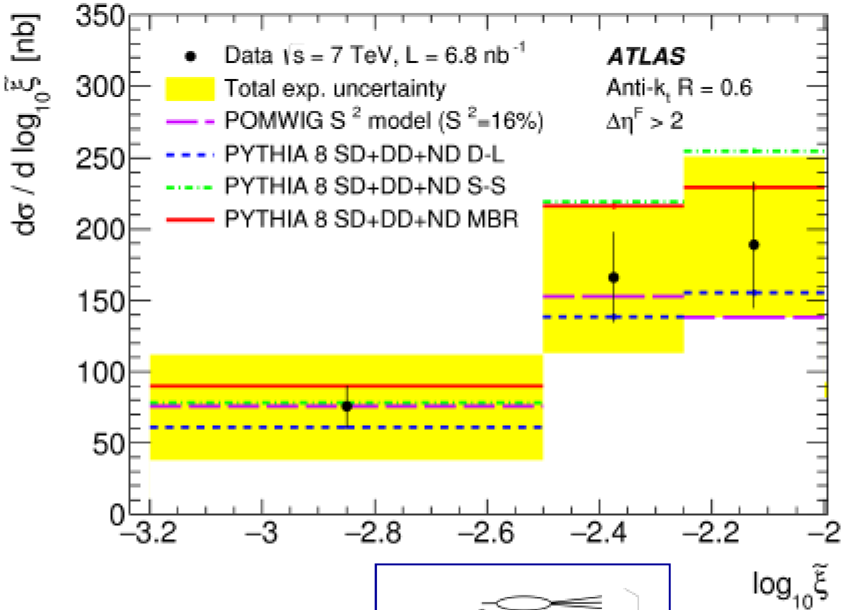
Detailed measurements of the $(\eta'\eta', \eta\eta', \eta\eta)$ CEP.

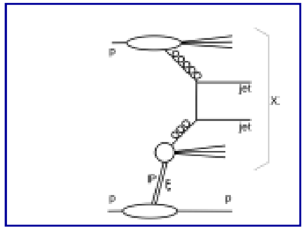
Test of non-trivial theory predictions. Probing the gluon component.

Phys.Lett. B754 (2016) 214

Diffractive dijet production at √s = 7 TeV (cont.)







- Alternative MCs:
  - POMWIG: factorisable pomeron (DPDFs)
  - Pythia 8: soft/hard diffractive models interfaced
- Determine rapidity-gap survival probability to mixed POMWIG/Py8 model:
  - using ratio of data to SD in POMWIG after subtracted ND
  - $S^2 = 0.16 \pm 0.04$ (stat) ± 0.08 (syst)

S^2 is not universal: depends on the process/kinematics/cuts

In a broad agreement with the theory expectations !

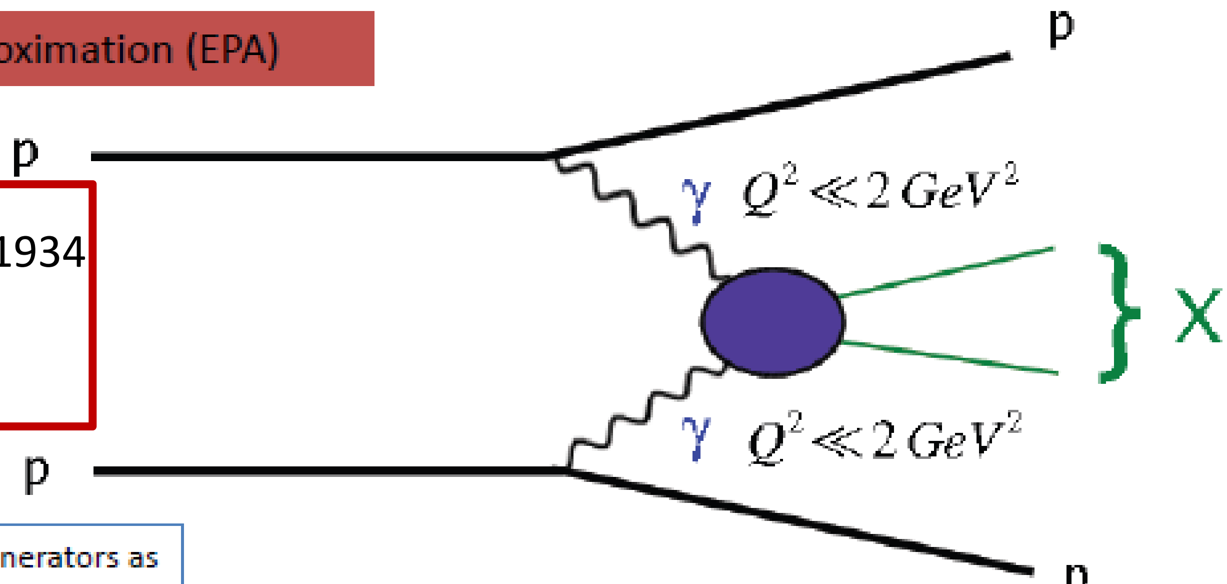
LHC as a $\gamma\gamma$ collider

Equivalent photon approximation (EPA)

C.F. von Weizsacker, 1934

E.J. Williams , 1934

E. Fermi, 1925



...introduced to major event generators as Madgraph, Pythia, Sherpa, Calchep

$$\sigma(\,pp \to (\gamma\gamma \to X)\,pp\,)$$

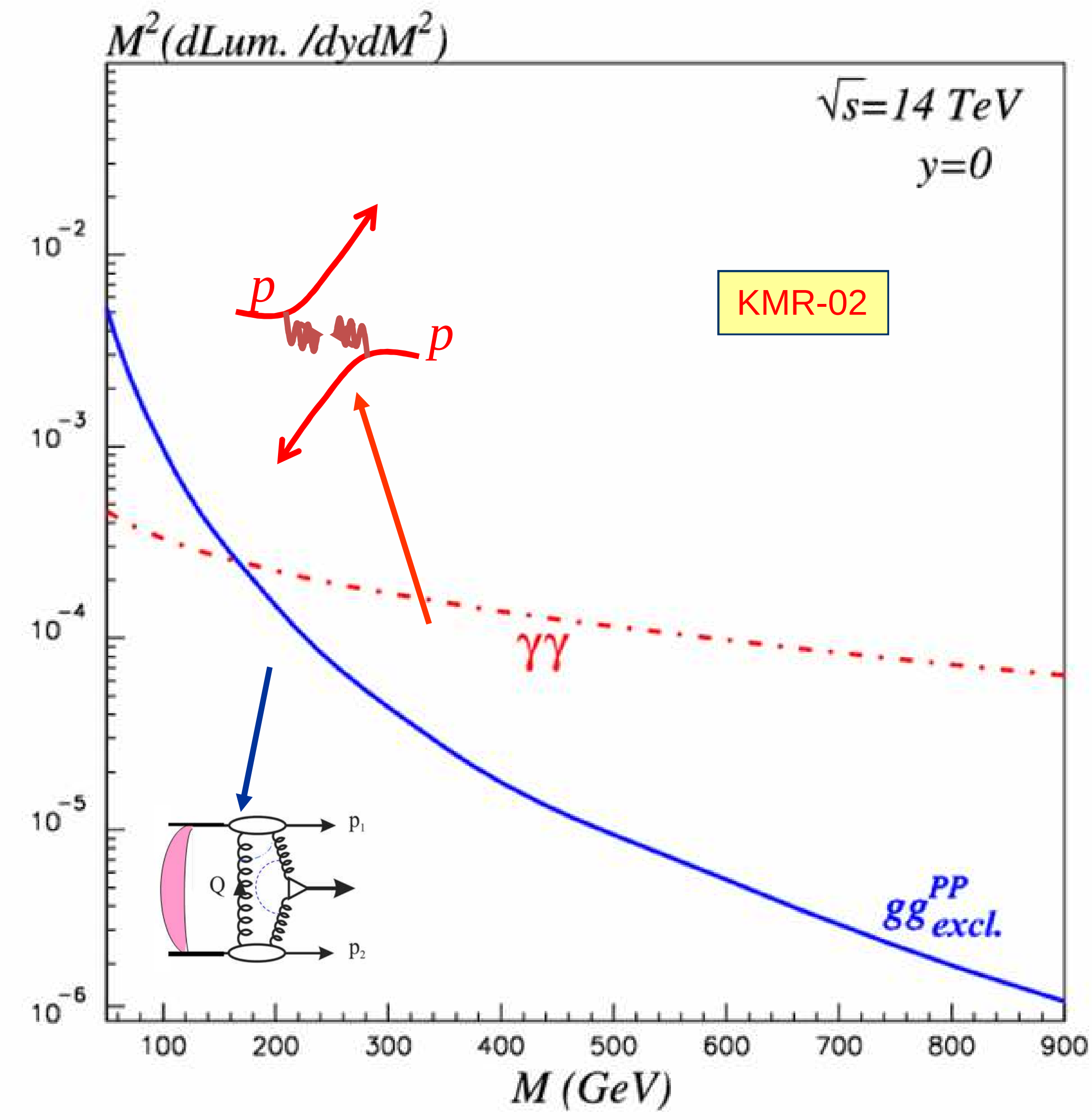
low γ virtuality 

(SuperChic 2 HKR-1508.02718)

- factorization to
  - long distance photon exchange
  - short distance $\gamma\gamma \to$ X interaction

$$\alpha_S^{\,2}/8 \to \alpha^2$$

QCD 'radiation damage' in action



Equivalent photon approximation

- Initial-state $p \to p\gamma$ emission can be to v. good approximation factorized from the $\gamma\gamma \to X$ process in terms of a flux:

$$n(x_i) = \frac{1}{x_i}\frac{\alpha}{\pi^2}\int \frac{d^2 q_{i_\perp}}{q_{i_\perp}^2 + x_i^2 m_p^2}\left(\frac{q_{i_\perp}^2}{q_{i_\perp}^2 + x_i^2 m_p^2}(1-x_i)F_E(Q_i^2) + \frac{x_i^2}{2}F_M(Q_i^2)\right)$$

- Cross section the given in terms of $\gamma\gamma$ `luminosity':

$$\frac{d\mathcal{L}_{\gamma\gamma}^{\rm EPA}}{dM_X^2\, dy_X} = \frac{1}{s}\, n(x_1)\, n(x_2)$$

THE TWO-PHOTON PARTICLE PRODUCTION MECHANISM. PHYSICAL PROBLEMS. APPLICATIONS. EQUIVALENT PHOTON APPROXIMATION

V.M. BUDNEV, I.F. GINZBURG, G.V. MELEDIN and V.G. SERBO

USSR Academy of Science, Siberian Division, Institute for Mathematics, Novosibirsk, USSR

Received 25 April 1974
Revised version received 5 July 1974

$$\frac{d\sigma^{pp\to pXp}}{dM_X^2\, dy_X} \approx S_\gamma^2 \cdot S_{\rm soft}^2 \cdot \frac{d\mathcal{L}_{\gamma\gamma}^{\rm EPA}}{dM_X^2\, dy_X}\hat{\sigma}(\gamma\gamma \to X)$$

Two effects to consider:*

*in fact procedure slightly more complicated, see arXiv:1508.02718

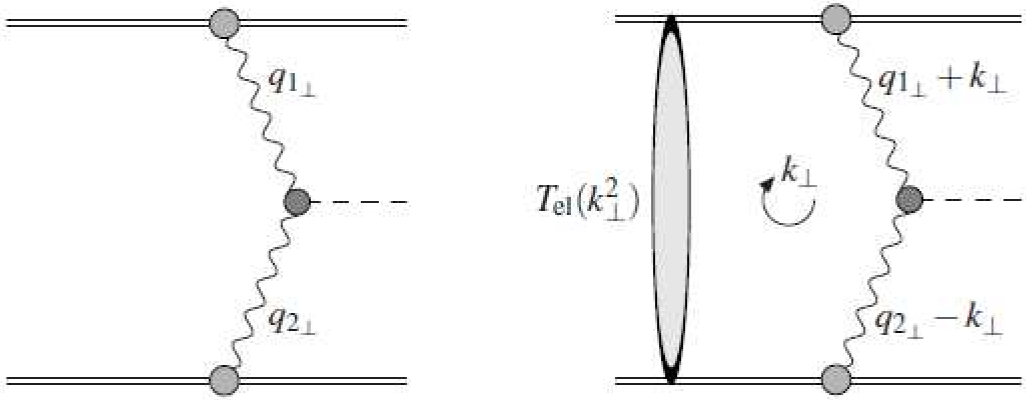
- Emitted photon may split further ($\gamma \to q\overline{q}$, $\gamma \to l^+ l^-$) : `Sudakov factor'.
- Colliding protons may interact independently: 'Survival factor'.

Soft survival factor

• In any pp collision event, there will in general be 'underlying event' activity, i.e. additional particle production due to pp interactions secondary to the hard process (a.k.a. 'multiparticle interactions', MPI).

• Our $\gamma\gamma$-initiated interaction is no different, but we are now requiring final state with no additional particle production (X + nothing else).

→ Must multiply our cross section by probability of no underlying event activity, known as the soft 'survival factor'.



- Photon virtuality has kinematic minimum $Q^2_{1,\text{min}} = \frac{\xi_1^2 m_p^2}{1-\xi_1}$

where $\xi_1 \approx \frac{M_\psi}{\sqrt{s}} e^{y_\psi}$ assuming photon emitted from proton 1 positive z-direction

$\longrightarrow$ Forward production $\Rightarrow$ higher photon Q^2 and less peripheral interaction

$\Rightarrow$ Smaller S^2_{eik}

- Survival factor, S^2_{eik}: probability of no additional soft proton-proton interactions, spoiling exclusivity of final-state.

- Not a constant: depends sensitively on the outgoing proton $\mathbf{p}_\perp$ vectors. Physically- survival probability will depend on impact parameter of colliding protons. Further apart $\longrightarrow$ less interaction, and $S^2_{\text{eik}} \to 1$.
b_t and $p_\perp$: Fourier conjugates.

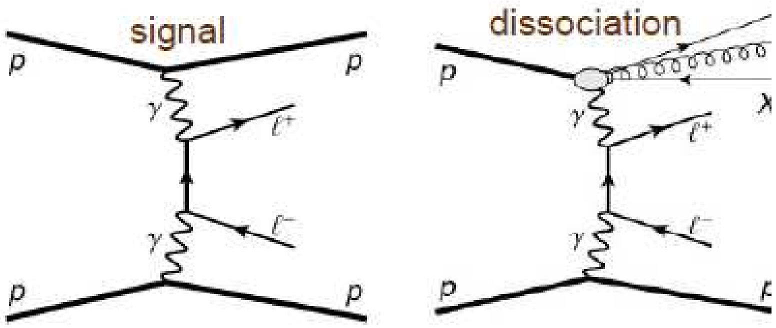
$\longrightarrow$ Need to include survival factor differentially in MC.

First fully differential implementation of soft survival factor – **SuperChic 2** MC event generator- HKR, ArHiv:1508.02718

Exclusive $\gamma\gamma \rightarrow ll$ (l=e,μ) at $\sqrt{s}$ = 7 TeV

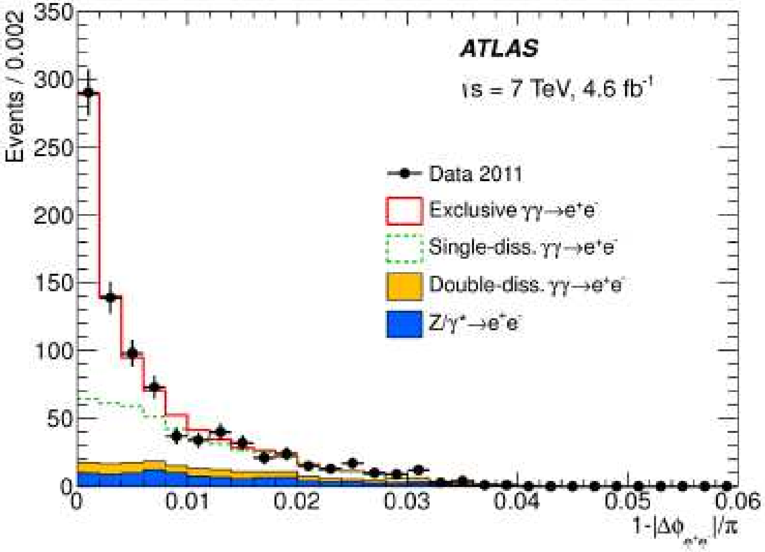
Physics Letters B 749 (2015) 2

- Can be seen as γ-γ collision (QED)
  - predicted with high precision (2%) 
- Simultaneous fit of signal + background to aplanarity: 1 - $|\Delta\phi(ll)|$
  - Discrimination between exclusive production and dissociation

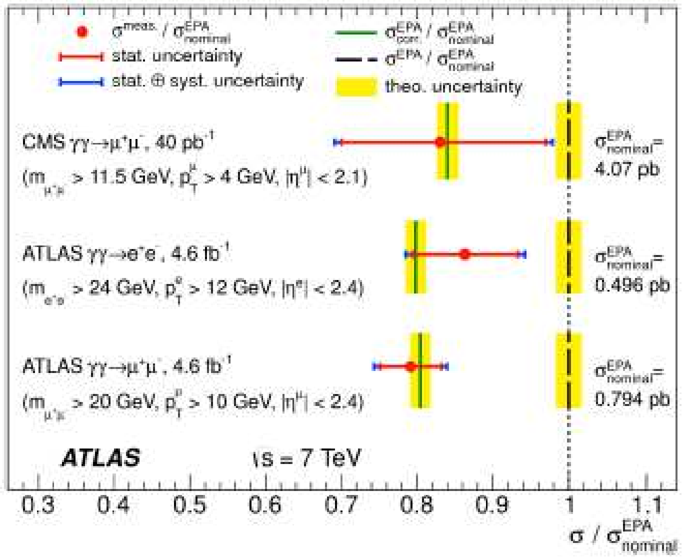


- Have to correct for proton absorptive effects due to final proton size 

$\sigma_{\gamma\gamma\text{->}ee}$ = 0.428 ± 0.035 (stat) ± 0.018 (syst) pb



$\sigma_{\gamma\gamma\text{->}\mu\mu}$ = 0.628 ± 0.032 (stat) ± 0.021 (syst) pb



Comparison to ATLAS

- Using results from above:

Variable	Electron channel	Muon channel
p_T^ℓ	> 12 GeV	> 10 GeV
$\lvert\eta^\ell\rvert$	< 2.4	< 2.4
$m_{\ell^+\ell^-}$	> 24 GeV	> 20 GeV

[pb]	$\mu^+\mu^-$	e^+e^-
σ^{EPA}	0.795	0.497
$S_\gamma^2 \cdot \sigma^{\mathrm{EPA}}$	0.751	0.477
$S_{\mathrm{soft}}^2 \cdot S_\gamma^2 \cdot \sigma^{\mathrm{EPA}}$	0.704	0.444
ATLAS	$0.628 \pm 0.032 \pm 0.021$	$0.428 \pm 0.035 \pm 0.018$

preliminary
work in progress)

$\rightarrow$ After including effects of Sudakov and survival factors find excellent agreement for e^+e^- and reasonable for $\mu^+\mu^-$.

Important: an account of the polarization structure of the production amplitude

ignored in M. Dyndal and L. Schoeffel, Phys. Lett. B741 (2015) 66-70

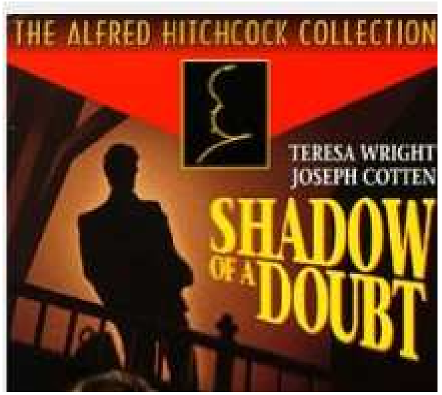
“The γγ- Resonance that Stole Christmas”

ATLAS &CMS seminar on 15 Dec. 2015

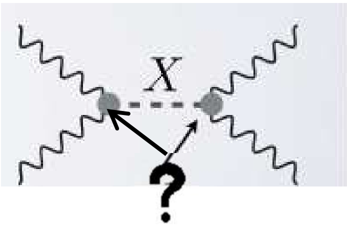
750 GeV

The ATLAS announcement of a 3.6 σ local excess in diphotons with invariant mass ~750 GeV in first batch of LHC Run –II data, combined with CMS announcing 2.6 σ local excess.

Theoretical community –frenzy of model building: >150 papers within a month.
Unprecedented explosion in the number of exploratory papers.
So far most statistically significant deviation from SM at the LHC.



If not a statistical fluctuation,
a natural minimal interpretation:
scalar/pseudoscalar resonance coupling dominantly to photons.



S. Fichet, G. von Gersdorff, and C. Royon, (2015), 1512.05751.
C. Csaki, J. Hubisz, and J. Terning, (2015), 1512.05776. + ~10 more

What if this is due to a new state R which couples dominantly to photons ?

- The simplest model.
- Allows the most precise theoretical predictions.
- Provides strong motivations for the CT-PPS and AFP projects.
- ‘Easier’ scenario experimentally (BG, limit. jet activity or missing Et)
- and ‘easier’ to shoot down experimentally.

Assuming the 750 GeV- resonance survives and couples dominantly to photons :

HKR- arXiv:1601.07187

Main aim: to provide the most precise possible predictions for the $\gamma\gamma$ luminosity, needed to calculate the corresponding resonance production cross sections, in both the inclusive and exclusive cases.

- Simple cuts on the final state can efficiently reduce the relative contribution from gg and VBF resonance production, if such modes are present, relative to the $\gamma\gamma$–initiated case.
- A precise calculation of the exclusive $\gamma\gamma$ luminosity, relevant to the case where both protons remain intact after the interaction, has been presented, with an associated uncertainty that is very small, and does not exceed a few percent.

- Within this scenario if $\Gamma_{\rm tot} = 45\ {\rm GeV}$., then $\mathrm{Br}(R \to \gamma\gamma) = 3.1 - 4.4\,\%$.
- $$\frac{\mathcal{L}^{inc}_{\gamma\gamma}(\sqrt{s} = 13\,\mathrm{TeV})}{\mathcal{L}^{inc}_{\gamma\gamma}(\sqrt{s} = 8\,\mathrm{TeV})} = 3.0$$

Exclusive case

- With good missing mass resolution: separation between resonance states.
- Resonance spin-parity, searches for CP-violating effects via the asymmetry in proton distributions…

- The exclusive channel leads naturally to a strong suppression of the gg and VBF initiated modes. The ratio of inclusive to exclusive $\gamma\gamma$ luminosities is found to be $\sim$ 16 with corresponding exclusive cross section $\sim 0.3 - 0.6$ fb via the $\gamma\gamma$ decay channel, for the current best estimate of the inclusive cross section corresponding to the apparent diphoton excess. Assuming favourable experimental efficiencies and resolution this could therefore be accessible with the hundreds of fb^{-1} of integrated luminosity which can be taken with the AFP [12, 13] and CT–PPS [14] forward proton taggers, associated with the ATLAS and CMS central detectors, respectively. It is in particular worth pointing out that the mass of the potential resonance is precisely in the region of maximum acceptance for these detectors [15].

Important consequences of the $\gamma\gamma$ production:
depletion of multi-jet activity (due to the 'coherent' photon component);

Asymmetric jet distribution;

Comparatively low transverse momentum of the resonance.

CONCLUSION AND OUTLOOK

- The Run I LHC data have already led to important implications for the theoretical models of soft hadron interactions. Allowed to distinguish between previously successful theory scenarios.
- The post-Run I comprehensive models based on RFT+GW allow a fairly good description of the whole range of the HE soft diffractive data.
- The experimental studies in the soft diffraction domain in Run II with forward detectors would provide the critical tests of the current theoretical approaches and could be of upmost importance .
- CEP processes incorporate non-trivial combination of soft and hard QCD LHC Run II has a great potential to improve our understanding of these reactions.
- In the forward proton mode the LHC becomes a high energy photon-photon collider.
- Assuming that 750 GeV bump is not a stat. fluctuation it may signal the first hint of physics beyond SM at the LHC.
  The state-of-the-art results for the photon-photon luminosities are derived.