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Europe/Athens timezone

Forward and Central Exclusive Production processes at the LHC

V.A. Khoze (IPPP, Durham & PNPI)

(Based on works with Lucian Harland-Lang, Alan Martin and Misha Ryskin)

Outline

- Forward and Diffractive Physics at the LHC
- LHC as a High Energy $\gamma\gamma$ Collider
- "The $\gamma\gamma$-Resonance that Stole Christmas"
- Summary and Outlook.

WITH A BIT OF PERSONAL FLAVOUR

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.

→ 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

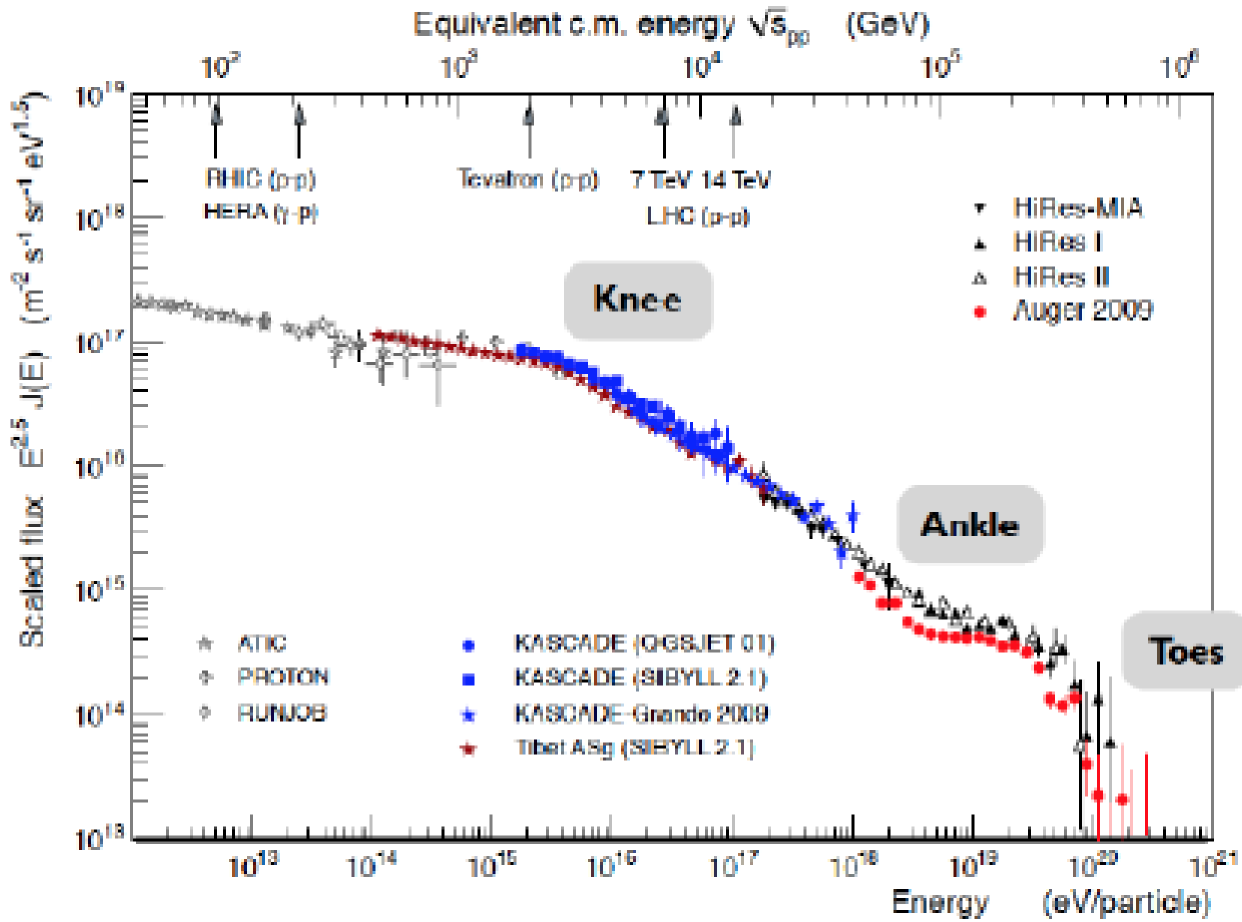
Editors: N. Cartiglia, C. Royon
The LHC Forward Physics Working Group

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

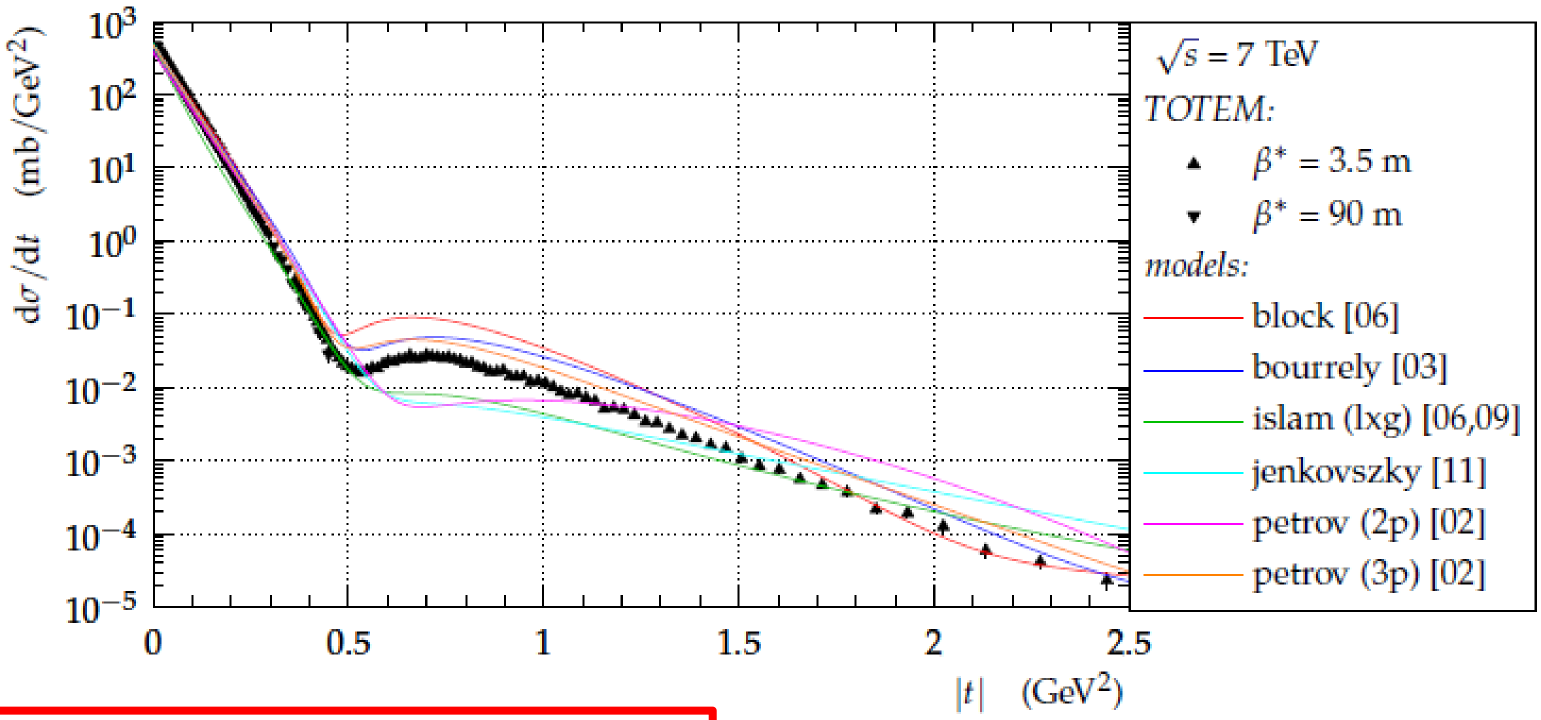
Total Inelastic Cross Section

- Crucial quantity for understanding cosmic ray air showers

- Ingredient for modelling pile-up (and lumi) at LHC



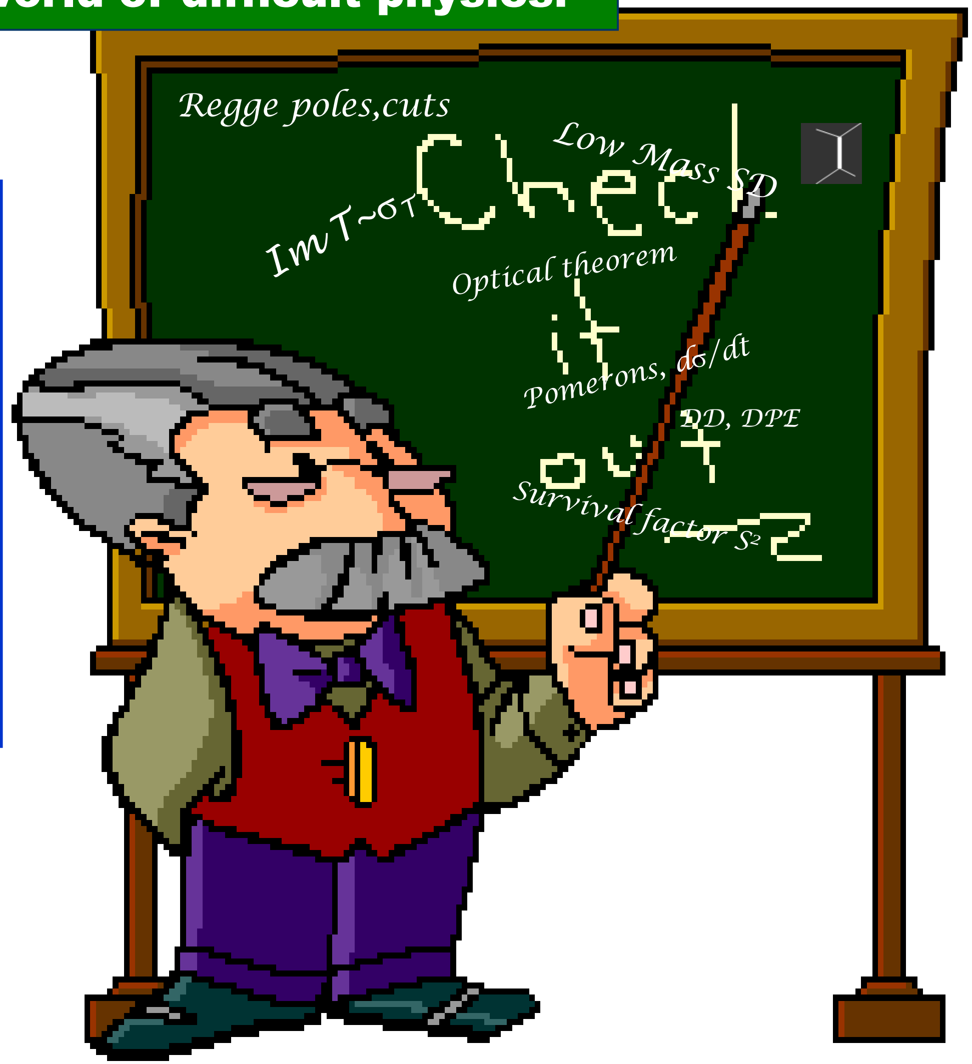
- model predictions (prior to Run I) vs. TOTEM data at $\sqrt{s}$ = 7 TeV:



- *no model compatible with data!*

Welcome to the world of difficult physics!

(talks by Asher, Dino ,Evgeny)

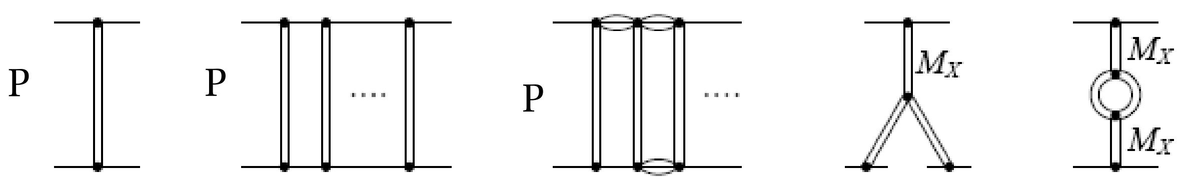


- Current theoretical models for soft hadron interactions are still incomplete, and their parameters are not fully fixed.

- Four (ideologically close) MP- models allowed good description of the data in the ISR-Tevatron range:
  KMR , GLM, Ostapchenko, KP, also BK et al

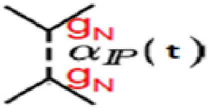
Differences/**Devil**  – in details

Reggeon Field Theory, Gribov- 1986



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 σ_{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 $\alpha'_P = 0.25\ \mathrm{GeV}^{-2}$

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

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

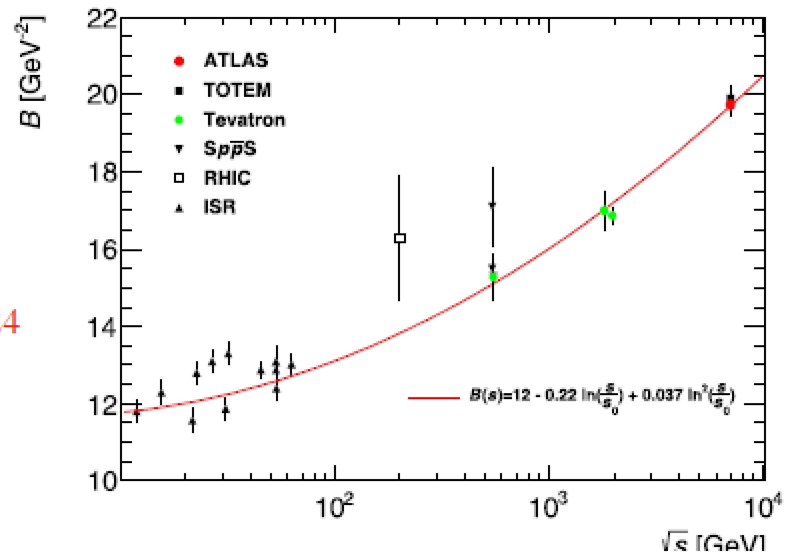
$$B_{el} = 16.98 + 4 \times 0.25 \times \ln(7/1.8) = 18.34\ \text{GeV}^{-2}$$

$\longrightarrow$ 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.

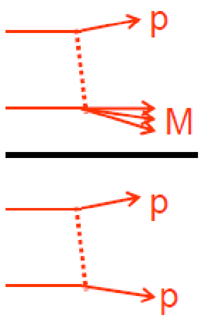
V. A. Schegelsky, M.G. Ryskin, Phys. Rev. D85 (2012) 094024

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



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)

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

Unexpectedly small

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

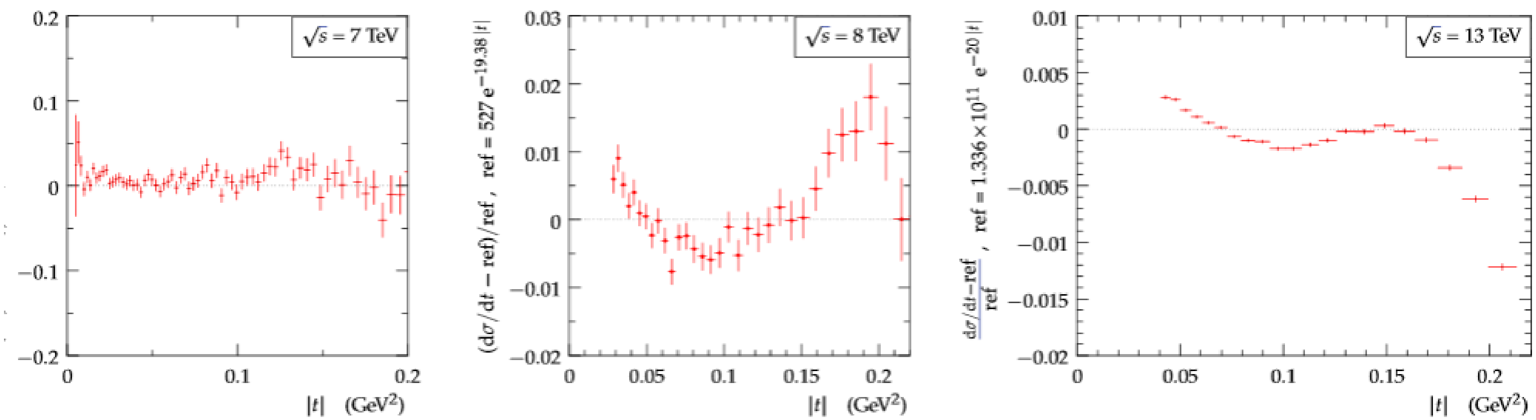
Lesson 4.

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

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

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

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



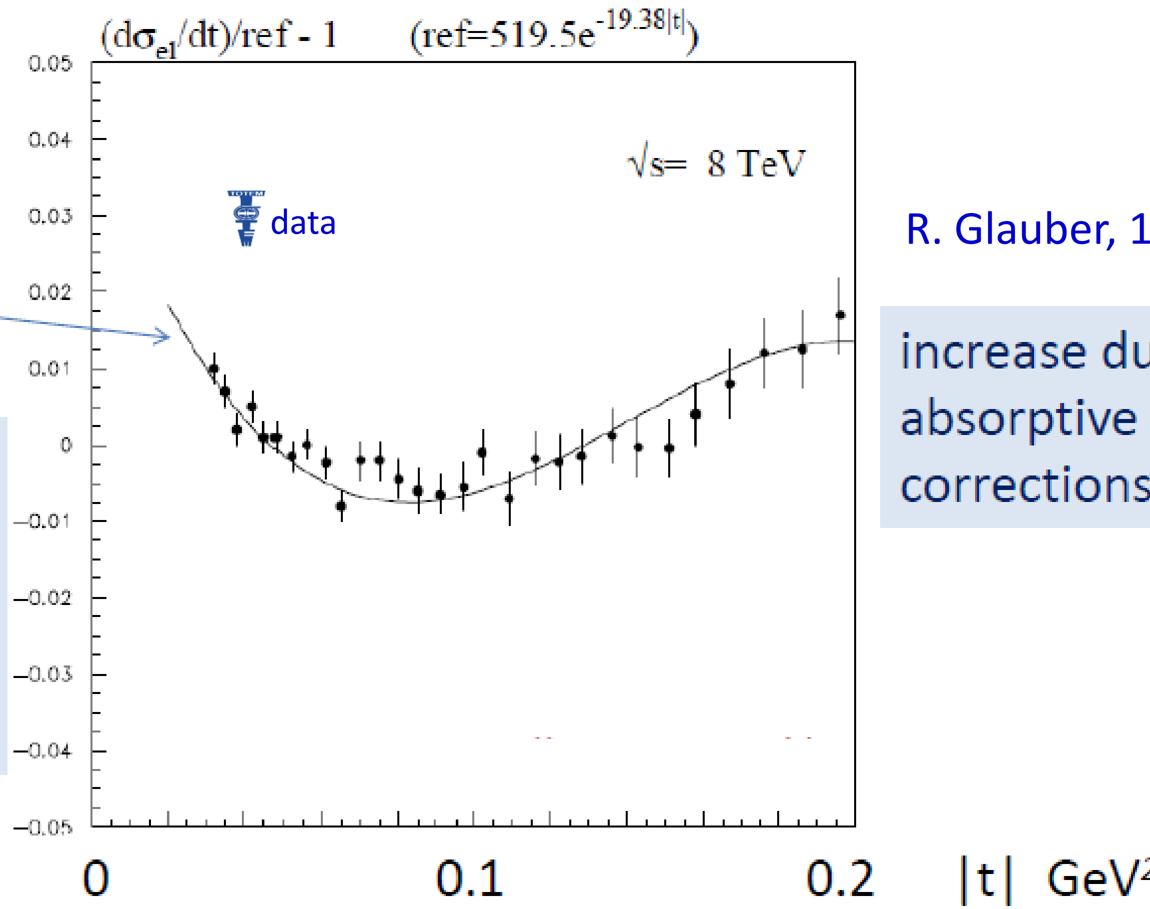
- non-exponentiality observed at 8 and 13 TeV!
  - non-exponentiality of the observed cross-section:

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

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



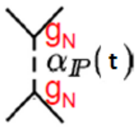
R. Glauber, 1955

increase due absorptive corrections

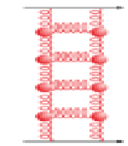
IMPLICATIONS OF THE LHC RUN I DATA
(exemplified in terms of Durham model)

(GLM approach- Asher)

(KMR, 2011-2015)



(Gribov-1961)



(BFKL-1975-78)

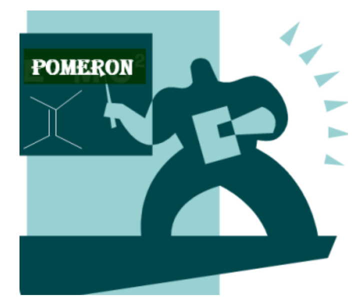
Yes, it is possible to describe all "soft" HE data

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

from CERN-ISR → Tevatron → LHC

in terms of a single "effective" pomeron

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 resumation of the main HO effects- the intercept weakly depends on the scale,

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

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

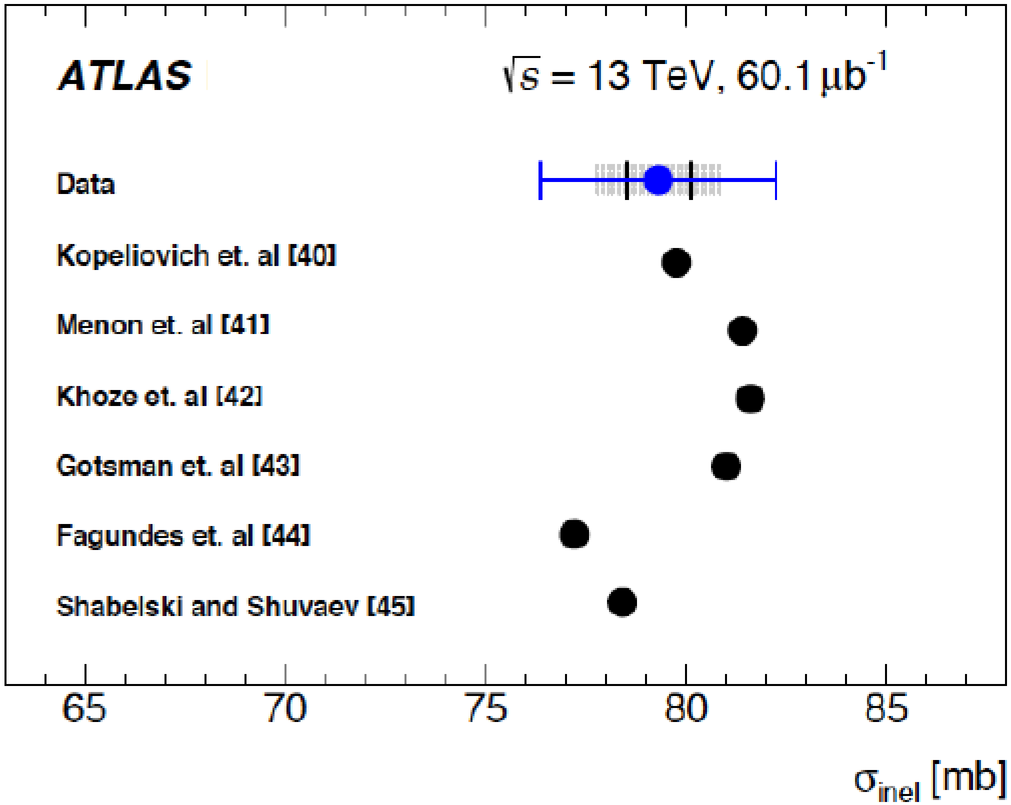
(ALFA +ATLAS/LHCf data are needed)

$\sqrt{s}$	$\sigma_{\rm tot}$	$\sigma_{\rm el}$	$B_{\rm el}(0)$	$\sigma_{\rm SD}^{{\rm low}M}$	$\sigma_{\rm DD}^{{\rm low}M}$	$\sigma_{\rm SD}^{\Delta\eta_1}$	$\sigma_{\rm SD}^{\Delta\eta_2}$	$\sigma_{\rm SD}^{\Delta\eta_3}$	$\sigma_{\rm DD}^{\Delta\eta}$
(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,

$$\sigma_{\text{inel}} = 79.3 \pm 0.8\ (\text{exp.})\ \pm 1.3\ (\text{lum.})\ \pm 2.5\ (\text{extrap.})\ \text{mb.}$$

Total Inelastic Cross Section v Models



arXiv:1606.02625 [hep-ex]

agreement with CMS (within errors)

Within current uncertainties, result is consistent with indicative selection of models based on Regge phenomenology, eikonal approaches and other models of non-perturbative strong interactions

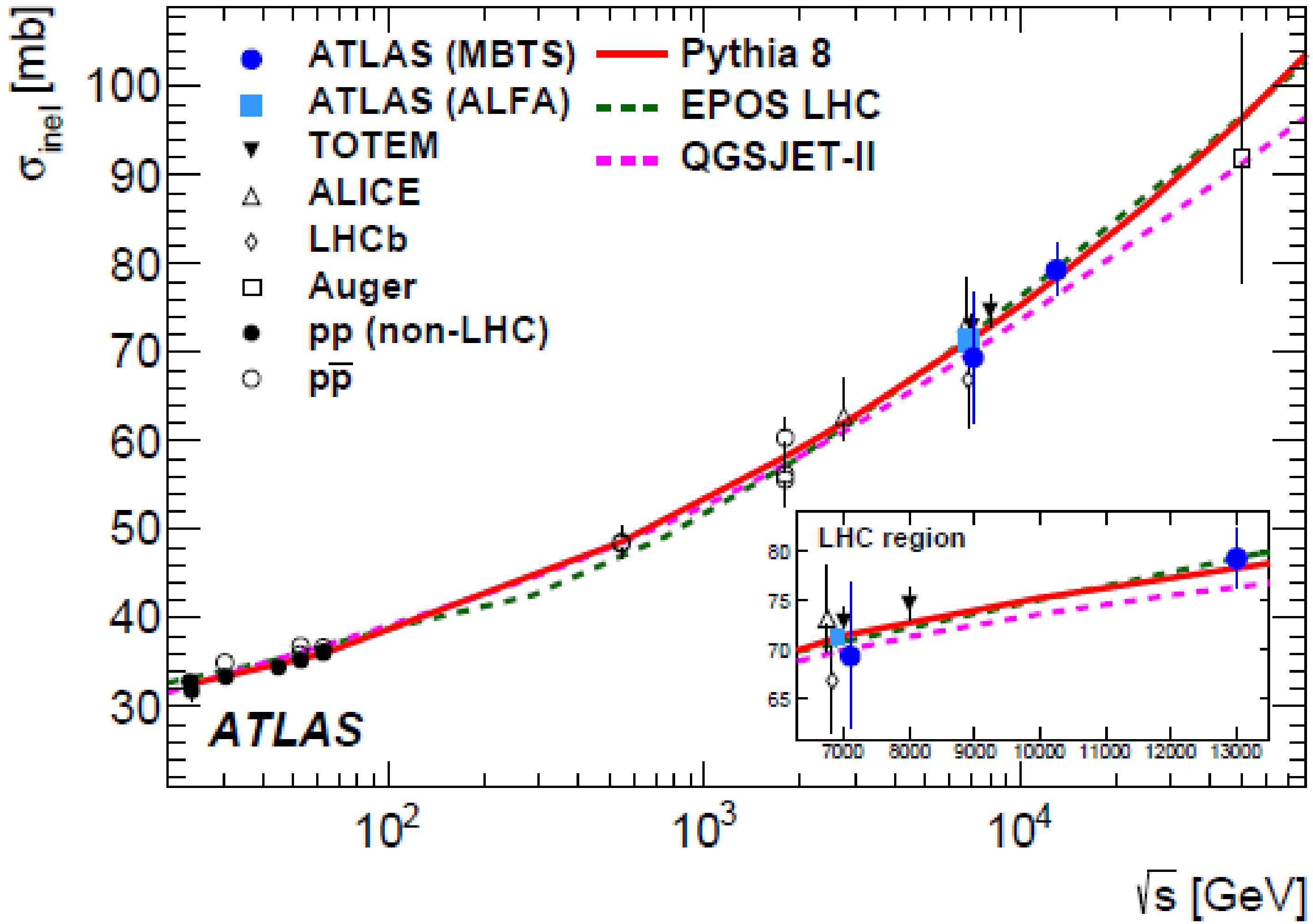
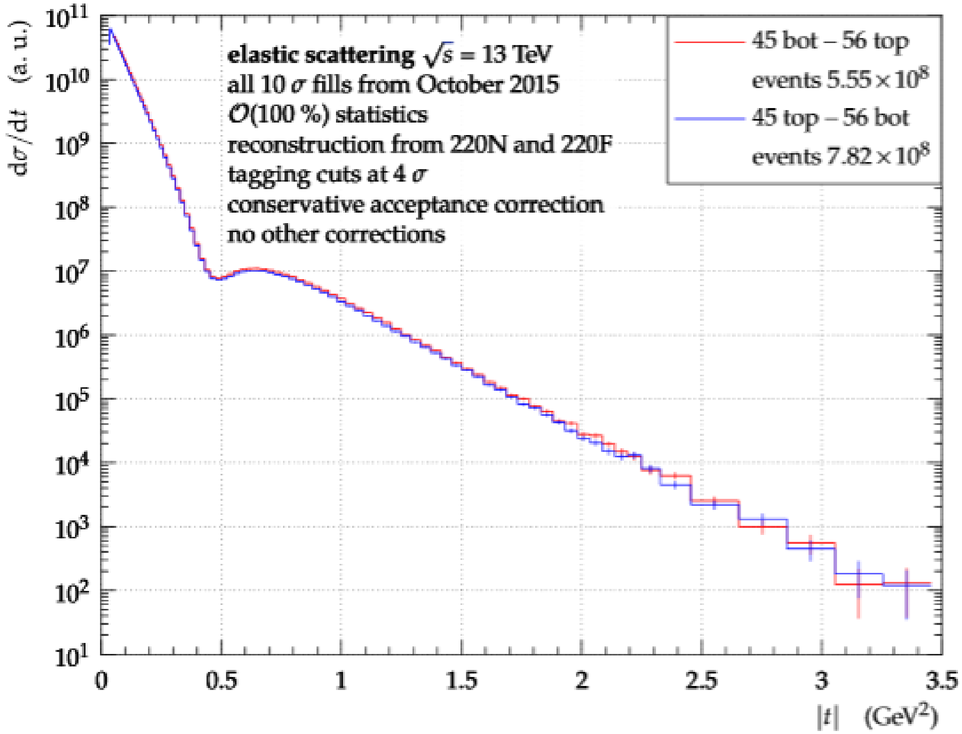


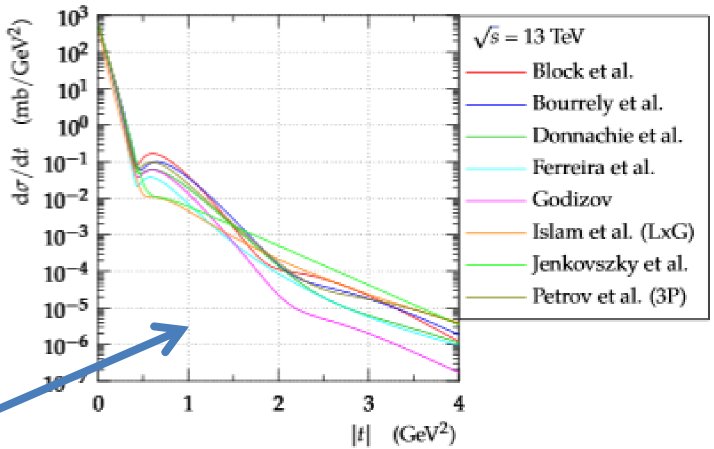
Figure 3: The inelastic proton-proton cross section versus $\sqrt{s}$. Measurements from other hadron collider experiments [6, 8, 10, 13, 14] and the Pierre Auger experiment [15] are also shown. Some of the LHC data points have been slightly shifted in the horizontal position for display purposes. The data are compared to the Pythia8, Epos LHC and QGSJet-II MC generator predictions. The uncertainty in the ATLAS ALFA measurement is smaller than the size of the marker.

very preliminary, but already very strong results

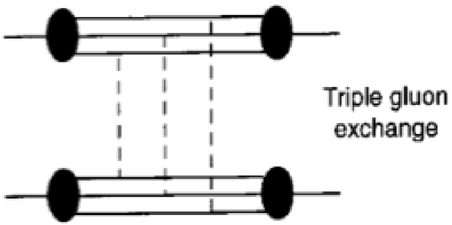
(ALFA data are very welcome)

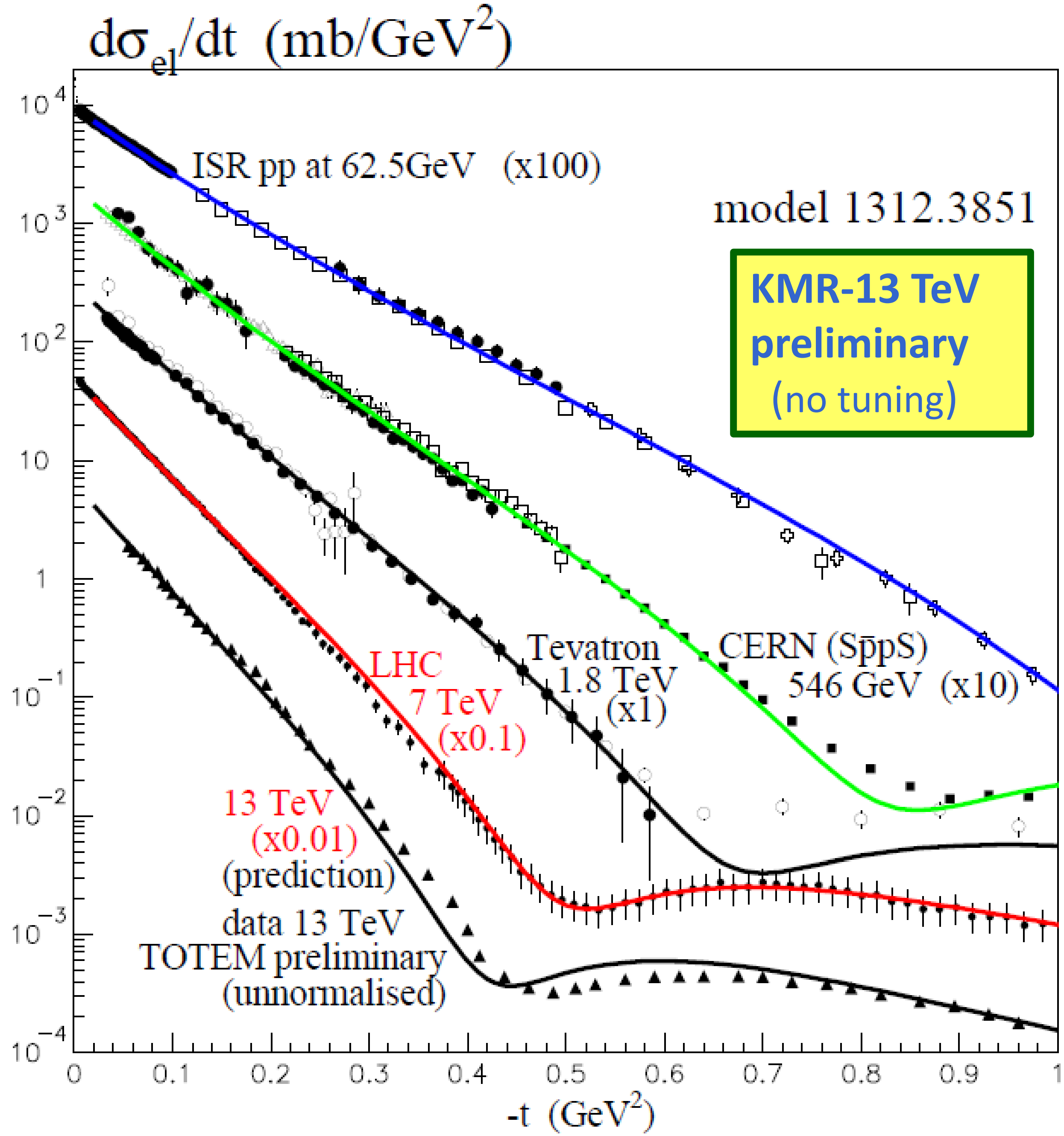


further trial by TOTEM fire



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





dσel/dt (mb/GeV²)
ISR pp at 62.5GeV (x100)
model 1312.3851
KMR-13 TeV
preliminary
(no tuning)
Tevatron
1.8 TeV
(x1)
CERN (Sp̄pS)
546 GeV (x10)
LHC
7 TeV
(x0.1)
13 TeV
(x0.01)
(prediction)
data 13 TeV
TOTEM preliminary
(unnormalised)
-t (GeV²)

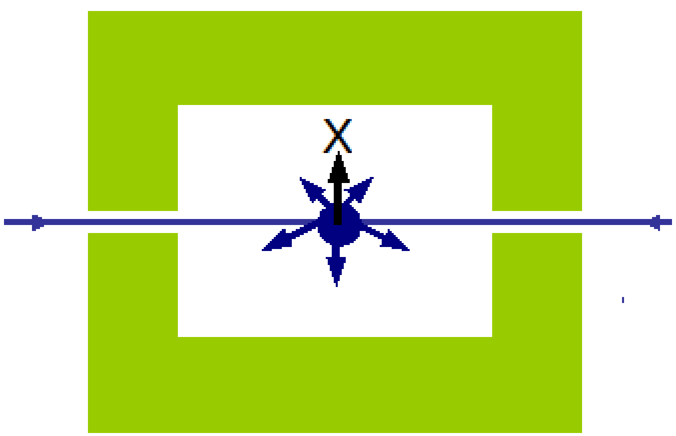
CENTRAL EXCLUSIVE PRODUCTION PROCESSES

What is it?

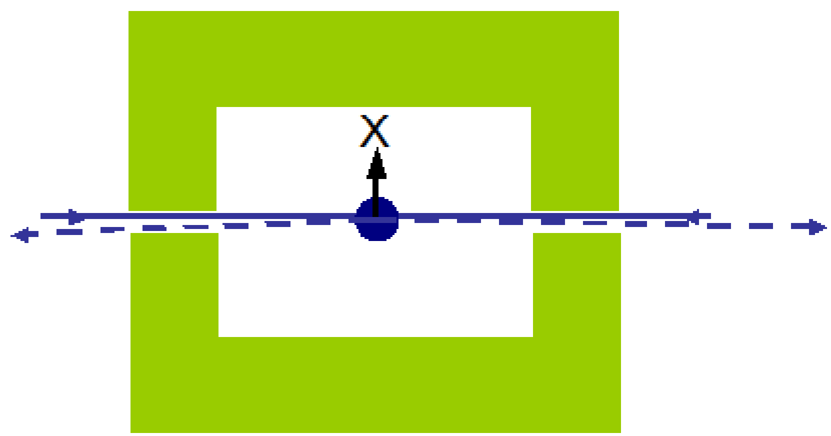
Central Exclusive Production (CEP) is the interaction:

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

- **CEP** 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.

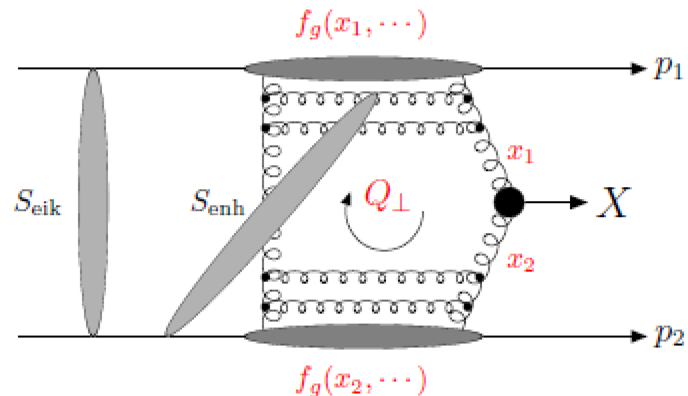


Production mechanisms

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

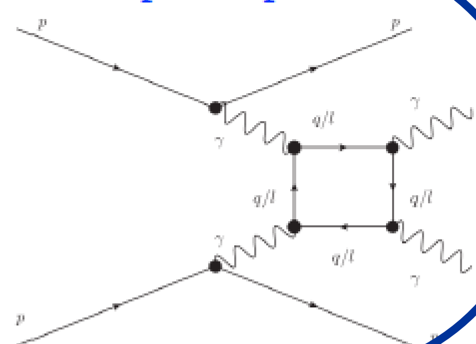
Gluon-induced
(double pomeron exchange):

C-even, couples to gluons



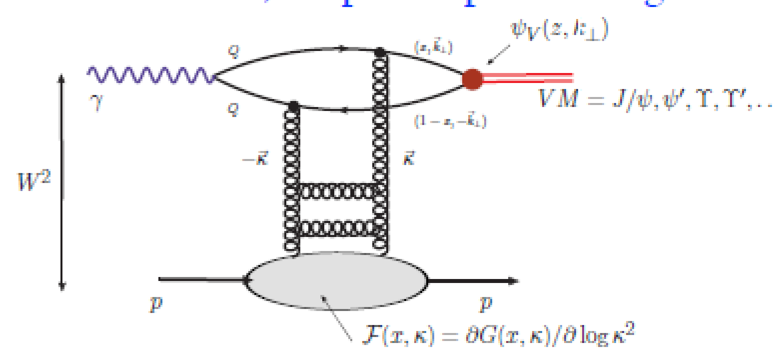
Photon-induced

Couples to photons



Photoproduction

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. (gg)
- 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.

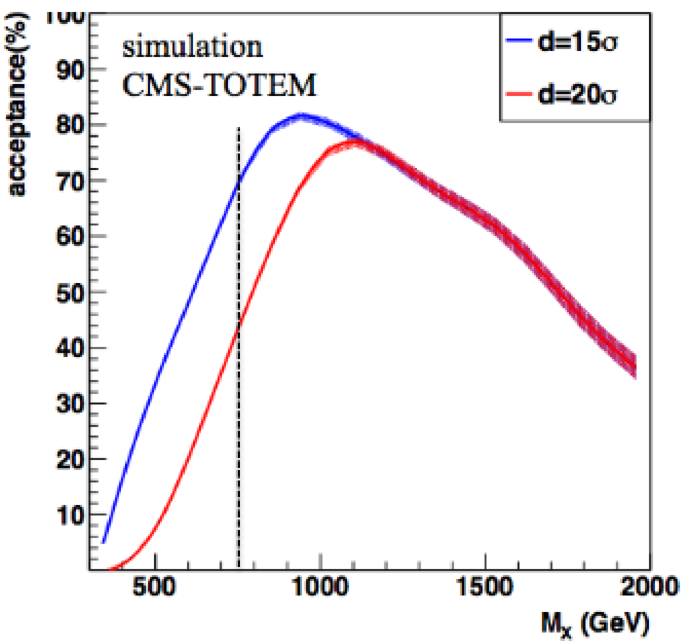
CT-PPS potential

- Expected LHC luminosity in 2016 is around 30 fb^{-1}

Acceptance depends on distance of approach to the beam

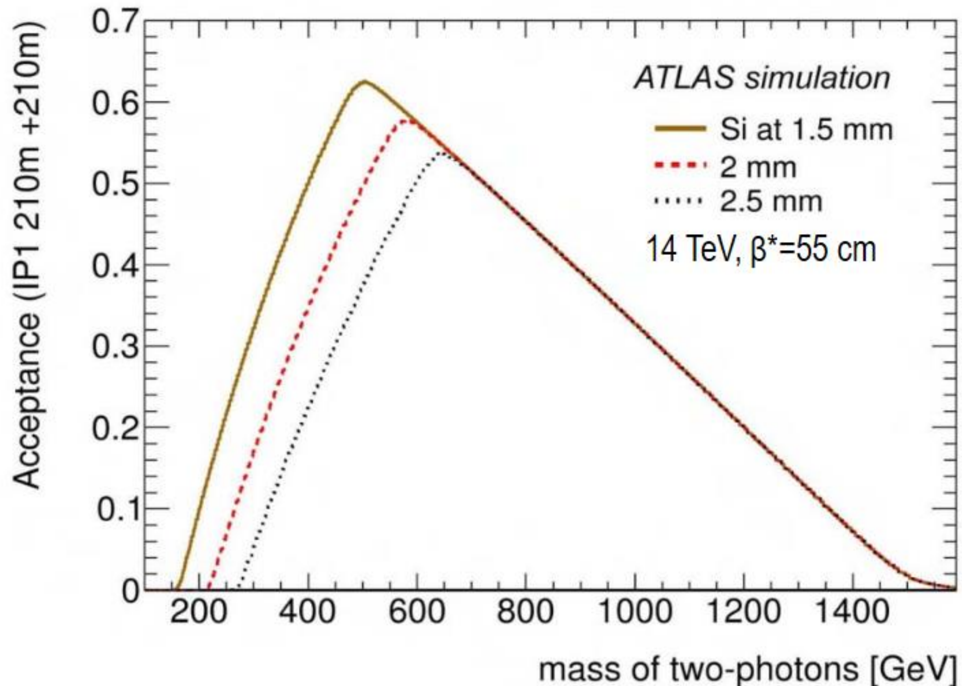
from CT-PPS TDR

LHC optics β^*=0.6m (2014)



Preparing for the 2nd AFP Arm

- AFP has excellent two-proton missing mass acceptance:
  - e.g. for an object produced by $pp \rightarrow p+X+p$, $X \rightarrow \gamma\gamma$:



how close the RPs can safely approach the beam ?

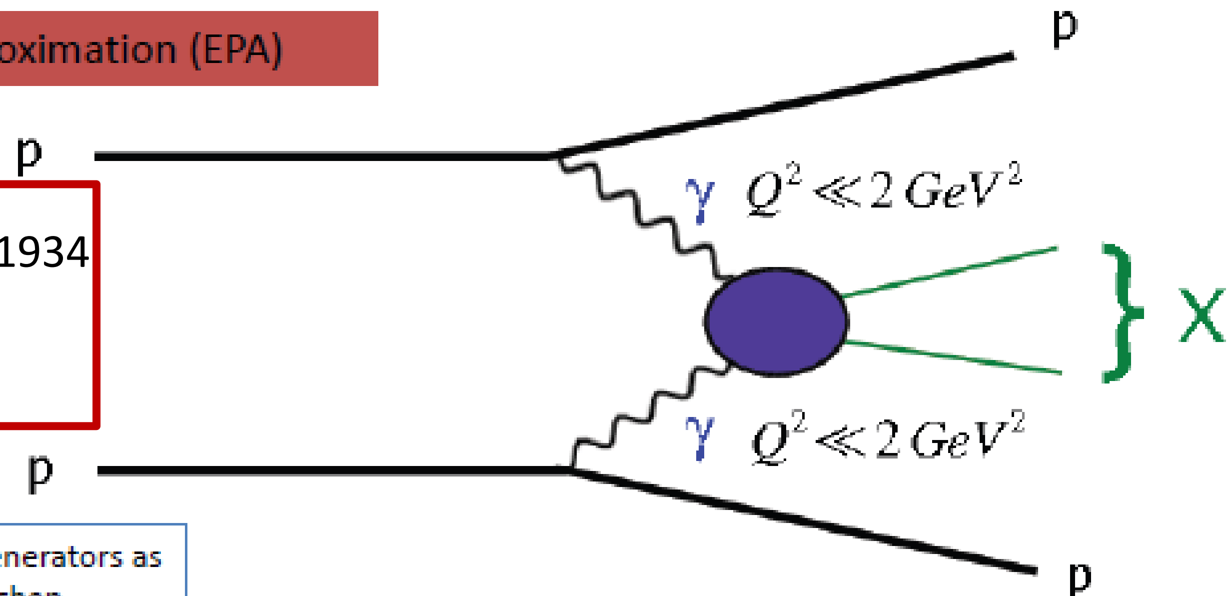
LHC as a $\gamma\gamma$ collider

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

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

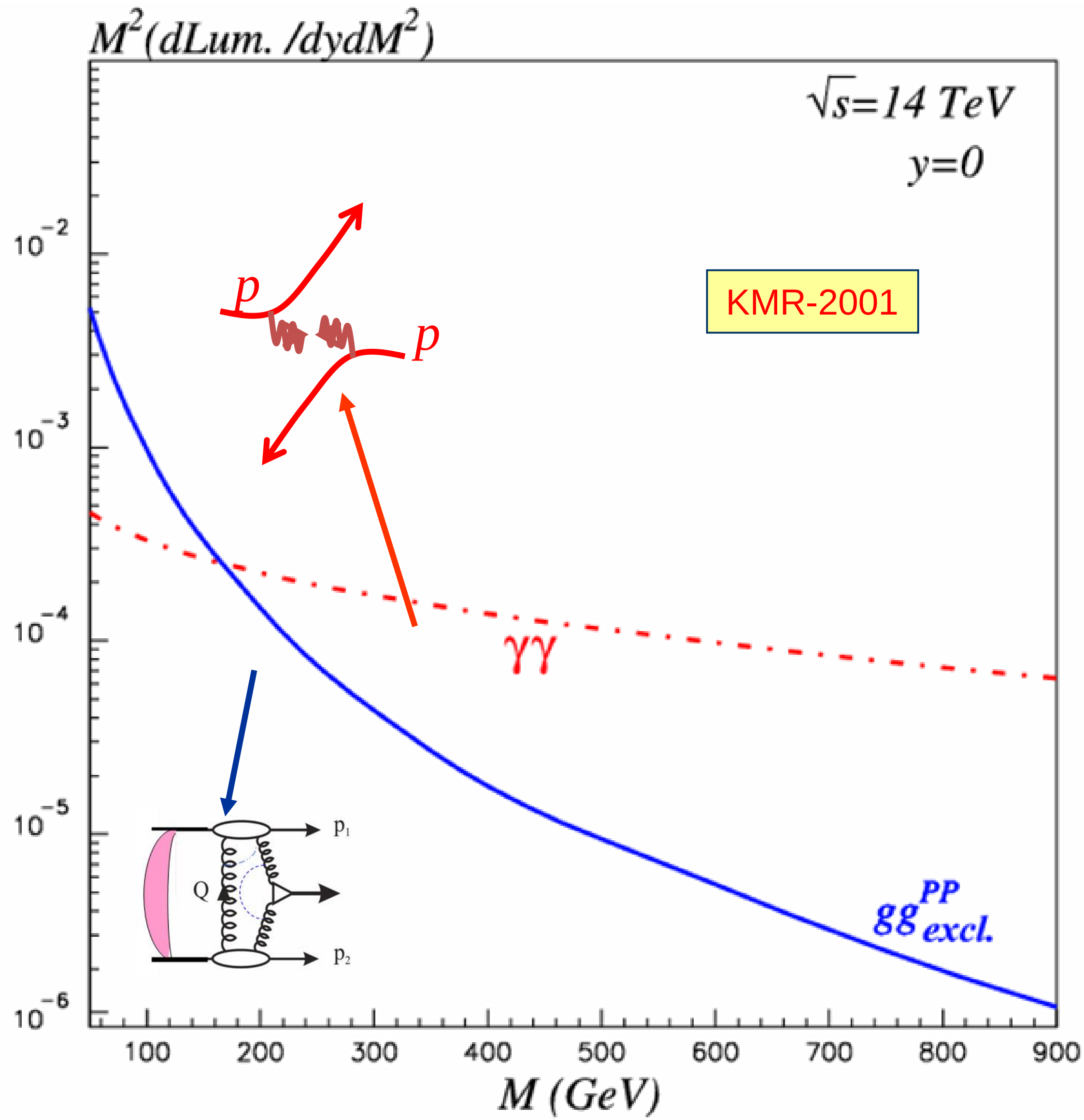
(absorption effects) 

(SuperChic 2 HKR-1508.02718)

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

$$\alpha_S{}^2/8 \rightarrow \alpha^2$$

QCD 'radiation damage' in action

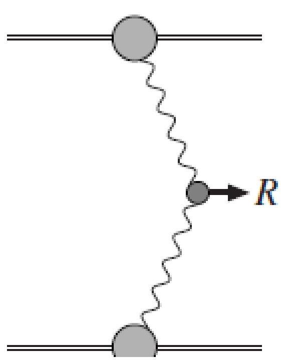


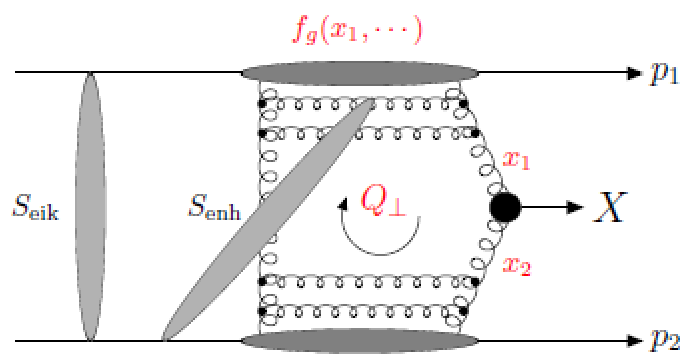
- Exclusive production via QCD-mediated process strongly suppressed at such higher masses. Gluons like to radiate!

$\longrightarrow$ Observing R production exclusively guarantees $\gamma\gamma$ coupling.

- Can measure protons! A $M_R = 750\,\mathrm{GeV}$ 'resonance' is perfectly placed in terms of the mass acceptance of the AFP and CT-PPS detectors.

- Such a measurement would probe only the $\gamma\gamma$-initiated process, and measurements of the proton momenta provide additional insight…

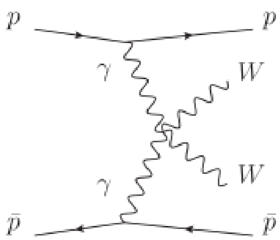


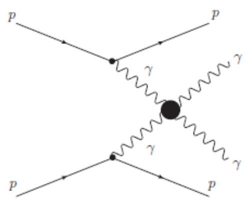


(C.Royon et al, K. Piotrzkowski et al)

Reach at LHC

Reach at high luminosity on quartic anomalous coupling using fast simulation (study other anomalous couplings such as $\gamma\gamma ZZ$...)





Couplings	OPAL limits $[\mathrm{GeV}^{-2}]$	Sensitivity @ $\mathcal{L} = 30$ (200) fb^{-1} 5σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10^{-6} (2.7 10^{-6})	2.6 10^{-6} (1.4 10^{-6})
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10^{-5} (9.6 10^{-6})	9.4 10^{-6} (5.2 10^{-6})
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10^{-5} (5.5 10^{-6})	6.4 10^{-6} (2.5 10^{-6})
a_C^Z/Λ^2	[-0.029, 0.029]	5.2 10^{-5} (2.0 10^{-5})	2.4 10^{-5} (9.2 10^{-6})

- Improvement of LEP sensitivity by more than 4 orders of magnitude with 30/200 fb^{-1} at LHC, and of D0/CMS results by ~two orders of magnitude (only $\gamma\gamma WW$ couplings)
- Reaches the values predicted by extra-dimension models

- Rich $\gamma\gamma$ physics at LHC: see E. Chapon, O. Kepka, C. Royon, Phys. Rev. D78 (2008) 073005; Phys. Rev. D81 (2010) 074003; S.Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon, M. Saimpert, Phys.Rev. D89 (2014) 114004 ; S.Fichet, G. von Gersdorff, B. Lenzi, C. Royon, M. Saimpert, JHEP 1502 (2015) 165

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS
CERNCOURIER
VOLUME 53 NUMBER 6 JULY/AUGUST 2013

LHC PHYSICS

CMS sees first direct evidence for $\gamma\gamma \rightarrow WW$

In a small fraction of proton collisions at the LHC, the two colliding protons interact only electromagnetically, radiating high-energy photons that subsequently interact or "fuse" to produce a pair of heavy charged particles. Fully exclusive production of such pairs takes place when quasi-real photons are emitted coherently by the protons rather than by their quarks, which survive the interaction. The ability to select such events opens up the exciting possibility of transforming the LHC into a high-energy photon–photon collider and of performing complementary or unique studies of the Standard Model and its possible extensions.

The CMS collaboration has made use of this opportunity by employing a novel method to select "exclusive" events based only on tracking information. The selection is made by requesting that two – and only two – tracks originate from a candidate vertex for the exclusive two-photon production. The power of this method, which was first developed for the pioneering measurement of exclusive production of muon and electron pairs, lies in its effectiveness even in difficult high-luminosity conditions with large event pile-up at the LHC.

The collaboration has recently used this approach to analyse the full data sample collected at $\sqrt{s}$=7 TeV and to obtain the first direct evidence of the $\gamma\gamma \rightarrow WW$ process. Fully leptonic W-boson decays have been measured in final states characterized by opposite-sign and opposite-flavour lepton pairs where one W decays into an electron and a neutrino, the other into a muon and a

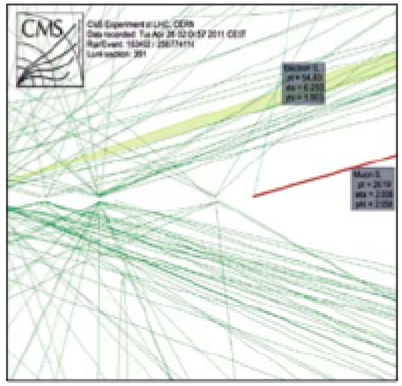
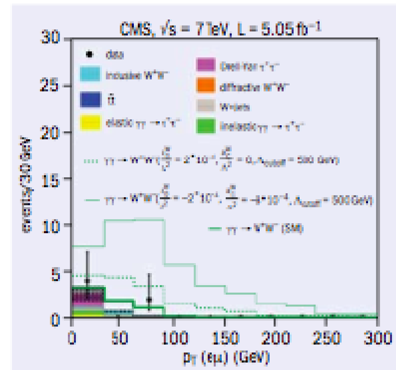


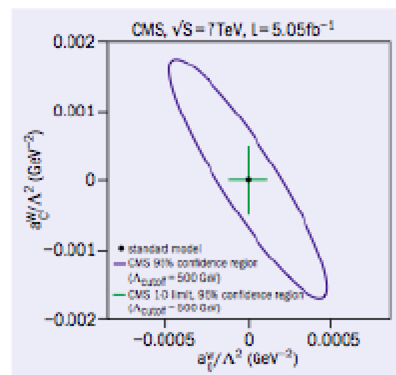
Fig. 1. Above: Proton–proton collisions recorded by CMS at $\sqrt{s}$=7 TeV, featuring candidates for the exclusive two-photon production of a W^+W^- pair, where one W boson has decayed into an electron and a neutrino, the other into a muon and a neutrino.

Fig. 2. Top right: The p_T distribution of $e\mu$ pairs in events with no extra tracks compared with the Standard Model expectation (thick green line) and predictions for anomalous quartic gauge couplings (dashed green histograms).

Fig. 3. Right: Limits on anomalous quartic $\gamma\gamma WW$ couplings.

$|\eta|<2.1$; no extra track associated with their vertex; and for the pair, a total p_T>30 GeV/c. After applying all selection criteria, only two events remained – compared with an expectation of 3.2 events: 2.2 from $\gamma\gamma \rightarrow WW$ and 1 from background (figure 2).





Model, allows stringent limits on anomalous quartic $\gamma\gamma WW$ couplings to be derived. These surpass the previous best limits, set at the Large Electron–Positron collider and at the Tevatron, by up to two orders of magnitude (figure 3).

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:

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

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

$$\frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{\mathrm{EPA}}}{\mathrm{d}M_X^2\,\mathrm{d}y_X} = \frac{1}{s}\,n(x_1)\,n(x_2)$$

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

$$\frac{\mathrm{d}\sigma^{pp\to pXp}}{\mathrm{d}M_X^2\mathrm{d}y_X} = \langle S_{\mathrm{eik}}^2\rangle \frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{\mathrm{EPA}}}{\mathrm{d}M_X^2}\mathrm{d}y_X\,\hat{\sigma}(\gamma\gamma\to X)$$

$\langle S_{\mathrm{eik}}^2\rangle = 0.72 \quad : \quad J_P = 0^+$

$\langle S_{\mathrm{eik}}^2\rangle = 0.77 \quad : \quad J_P = 0^-$

In fact, the situation is more complicated due to the effects caused by the polarization structure of the production amplitude.

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

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 $S^2_{\rm eik}$

- Not a constant: depends sensitively on the outgoing proton $\mathbf{p}_\perp$ vectors.

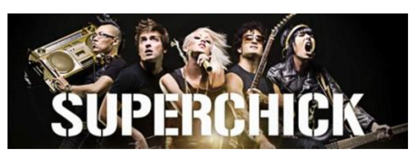
Physically- survival probability will depend on impact parameter of colliding protons. Further apart $\longrightarrow$ less interaction, and $S^2_{\rm eik} \to 1$.

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



“The $\gamma\gamma$- 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.

EW Moriond, 17.03.2016

Theoretical community –frenzy of model building: >150 papers within a month.

Unprecedented explosion in the number of exploratory papers.

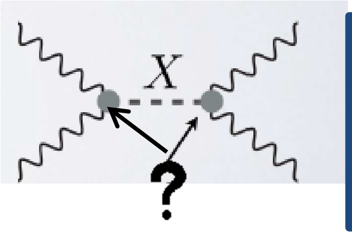
So far ‘most statistically significant’ deviation from SM at the LHC.

(More than 450 papers currently)

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.+ many more

ATLAS ; arXiv:1606.03833; CMS: arXiv:1606.04093 mid June 2016

(CMS, ATLAS talks)

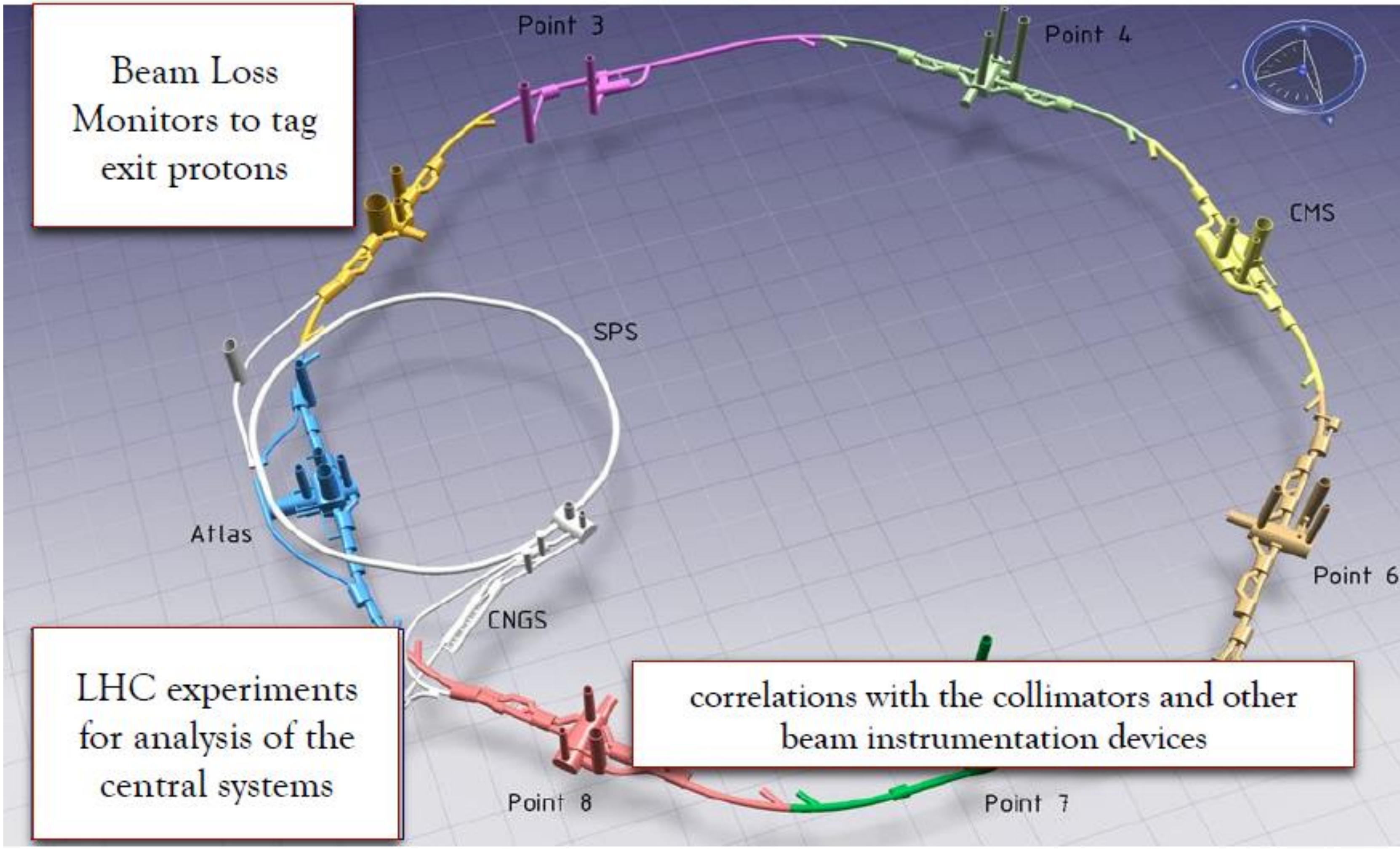
What if this is due to a new state R which couples dominantly to photons ?

- The simplest model.
- Allows the most precise theoretical predictions.
- Provides strong motivations for the CT-PPS and AFP projects.
- ‘Easier’ scenario experimentally

and ‘easier’ to shoot down experimentally.

Brand new idea of combining BLM with LHC detectors for CEP physics searches.
Risto Orava et al 1604.05778

LHC RING AS A NEW PHYSICS SEARCH MACHINE



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.

The production of a diphoton resonance via photon–photon fusion

L. A. Harland–Lang[1], V. A. Khoze[2,3], M. G. Ryskin[3]

[1]Department of Physics and Astronomy, University College London, WC1E 6BT, UK
[2]Institute for Particle Physics Phenomenology, University of Durham, Durham, DH1 3LE
[3]Petersburg Nuclear Physics Institute, NRC Kurchatov Institute, Gatchina, St. Petersburg, 188300, Russia

Abstract

Motivated by the recent LHC observation of an excess of diphoton events around an invariant mass of 750 GeV, we discuss the possibility that this is due to the decay of a new scalar or pseudoscalar resonance dominantly produced via photon–photon fusion. We present a precise calculation of the corresponding photon–photon luminosity in the inclusive and exclusive scenarios, and demonstrate that the theoretical uncertainties associated with these are small. In the inclusive channel, we show how simple cuts on the final state may help to isolate the photon–photon induced cross section from any gluon–gluon or vector boson fusion induced contribution. In the exclusive case, that is where both protons remain intact after the collision, we present a precise cross section evaluation and show how this mode is sensitive to the parity of the object, as well as potential *CP*–violating effects. We also comment on the case of heavy–ion collisions and consider the production of new heavy colourless fermions, which may couple to such a resonance.

'Today the diphoton excess could be everything including nothing'.

(CMS, ATLAS talks)

Enhancing the $\gamma\gamma$ contribution

- Even if R does not couple to colour, will still expect W, Z couplings

  $\Rightarrow$ Production via VBF. (CMS, ATLAS talks)

- In addition, if it does couple to colour $\Rightarrow gg$ fusion.

- How can we suppress these/determine whether $\gamma\gamma$ fusion is indeed dominant?

- Answer: the $\gamma\gamma$ mechanism leads to unique and distinct predictions for the final state in inclusive events.

gg fusion

- Gluons: carry colour and like to radiate!
- Photons: colour-singlet and less likely to radiate ($\alpha \ll \alpha_S$).

$\longrightarrow$ Natural to consider additional jet activity.

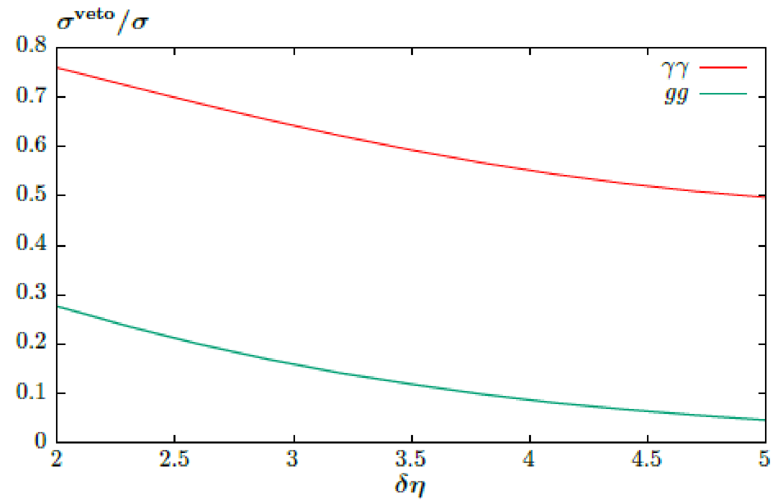
- What is cross section for R + no jets with $k_\perp > k_\perp^c$ and within $\delta\eta$ of R?

  - Gluons: requirement will strongly suppress cross section (double logarithmic 'Sudakov factor' for no parton emission in region).
  - Photons: can readily include veto in DGLAP evolution: suppression much less strong.

HKR 1601.03772

gg fusion

No jets with $k_\perp > 15\,\text{GeV}$ in $\delta\eta$ either side of resonance

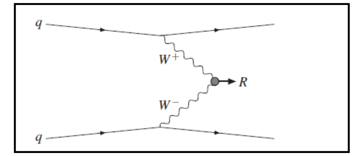


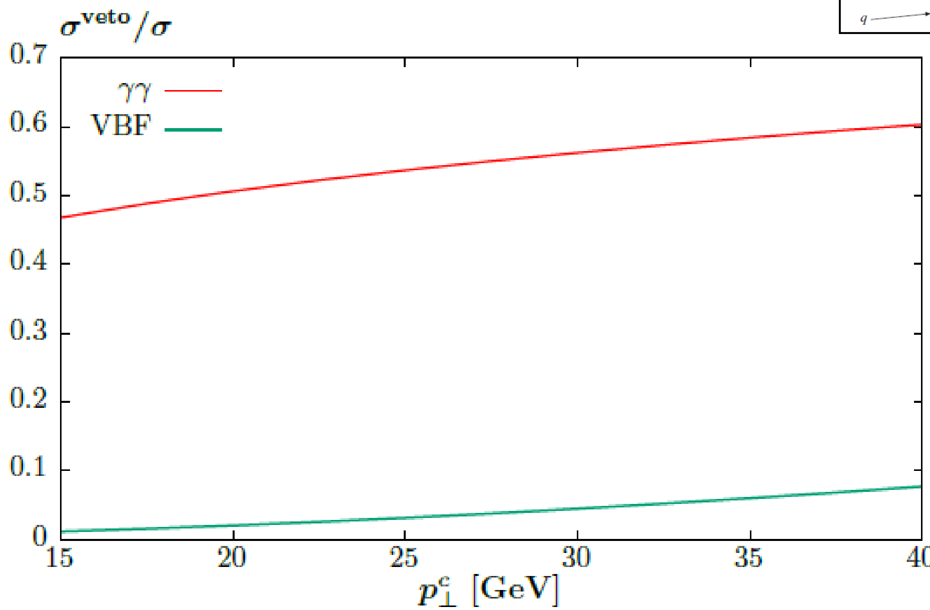
• For $\delta\eta \sim 2-3$ only $\sim 20\%$ of gg-initiated events have no additional jets, whereas for $\gamma\gamma$-initiated events $\sim 70\%$ do.

• For $k_\perp^c = 15(50)$ GeV find $\sim 50(65)\ \%$ of $\gamma\gamma$-events with no jets, while for gg case this is below $\sim 10\%$.

$\longrightarrow$ Clear difference in event topology.

Vector boson fusion





(ZZ, γZ)

- Fraction of VBF contribution with e.g. $p_\perp^R < 20$ GeV is $\sim$ % level, while for $\gamma\gamma$ -initiated production this is $\sim 50\%$.

$\longrightarrow$ Extremely different behaviour under this simple cut.

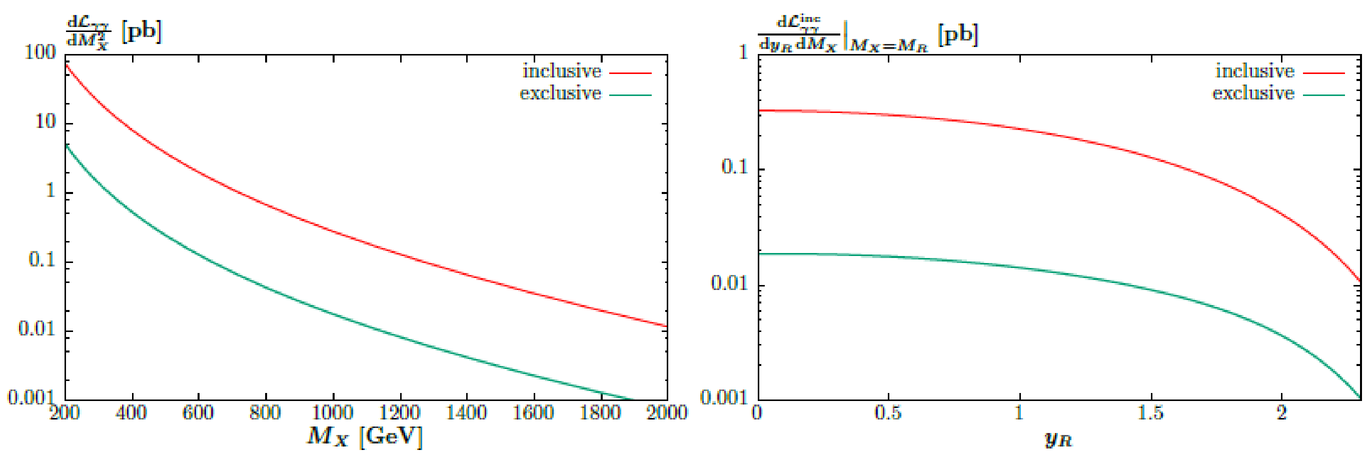
Exclusive resonance cross section

- As with inclusive case, we can consider the $\gamma\gamma$ luminosity, but for exclusive production.

- For R cross section, find:

assumes $\sigma^{\rm inc} = 4 - 8\,{\rm fb}$

$$\sigma^{\rm exc}(pp \to (R \to \gamma\gamma)) = 0.063 \cdot \sigma^{\rm inc}(pp \to (R \to \gamma\gamma)) = 0.25 - 0.50\,{\rm fb}$$



CT-PPS simulation- a few events at $30fb^{-1}$

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

HKR- arXiv:1601.07187

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 $\text{Br}(R \to \gamma\gamma) = 3.1 - 4.4\,\%$.

- $$\frac{\mathcal{L}^{inc}_{\gamma\gamma}(\sqrt{s} = 13\,\text{TeV})}{\mathcal{L}^{inc}_{\gamma\gamma}(\sqrt{s} = 8\,\text{TeV})} = 3.0$$

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…

HKRS- arXiv:1606.04902

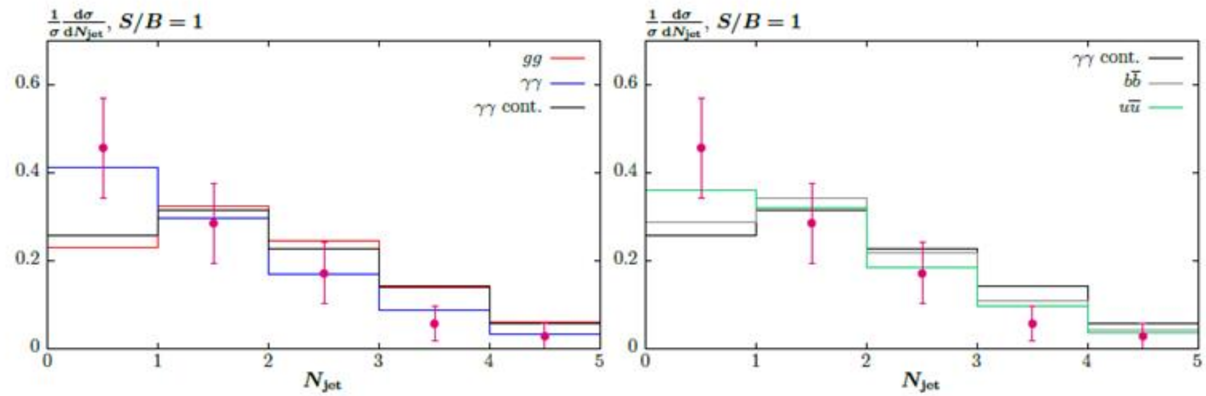


Figure 5: Exclusive jet multiplicities, for different initial–state resonance production processes, and the SM continuum $\gamma\gamma$ production process, compared to ATLAS [1] measurement in the range $700 < M_{\gamma\gamma} < 840$ GeV. The continuum background is taken from [1], and is included in all signal distributions, assuming a S/B ratio of 1.

We perform a Monte Carlo study, and show that the $\gamma\gamma$, gg and light and heavy $q\bar{q}$ initiated cases lead to distinct predictions for the jet multiplicity distributions. We apply this result to the existing ATLAS data for the spin–0 selection, and demonstrate that a dominantly gg–initiated signal hypothesis is already mildly disfavoured, while the $\gamma\gamma$ and light quark cases give good descriptions within the limited statistics.

(but energy dependence )

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 Run II with forward detectors would provide the critical tests of the current theoretical approaches and could be of upmost importance .

- In the forward proton mode the LHC becomes a high energy photon-photon collider. The state-of-the-art results for the photon-photon luminosities are reported.

- Assuming that 750 GeV bump is not a statistical fluctuation it may signal the first hint of physics beyond SM at the LHC.

LOOKING FORWARD TO 2016 ARUN!
RICH PHYSICS PROGRAM ON THE WAY !


THANK YOU


QUESTIONS?

BACKUP

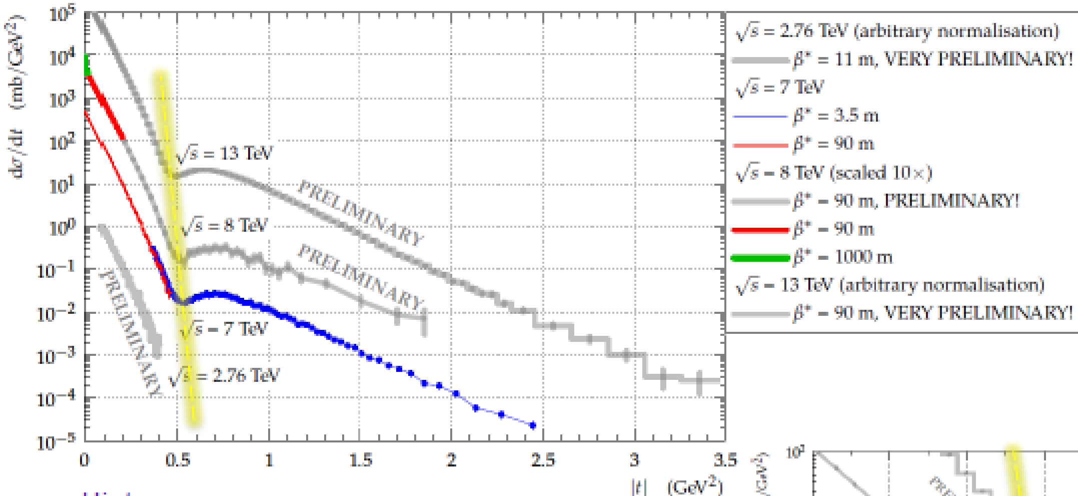
Summary

- presented the search for diphoton resonances with $m_{\gamma\gamma} > 500$ GeV at 8 and 13TeV

- simple and robust analysis strategy
- improved detector calibration @ 3.8 T
- analyzed dataset recorded @ 0T
- compared to previous results in Dec 15, 13TeV analysis improved sensitivity by more than 20%

- results interpreted in terms of scalar resonances & RS gravitons production for different widths
- modest excess of events observed at m_{X}=750(760)GeV for 8+13TeV(13TeV) dataset
- local significance is 3.4(2.9)σ, reduced to 1.6(<1)σ after accounting for look-elsewhere-effect

Preliminary results



Different physics regimes are accessible thanks to different LHC configurations

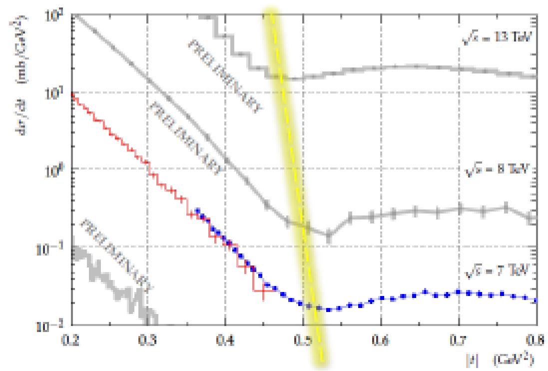
Hints:

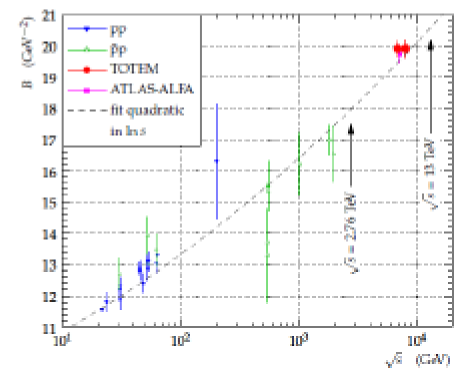
non-exponentiality confirmed at 13 TeV

$\sqrt{s}$ = 7 → 13 TeV: dip moves to lower |t|

Forward slope $B = \frac{d}{dt}\ln(\frac{d\sigma}{dt}|_{t=0})$ increase wrt previous experiments

No structures at high-|t|
(rules out the "optical" models)





13/16

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

- Basic fundamental model-independent relations: unitarity, crossing, analyticity, dispersion relations. The Froissart-Martin **bound**:

$$\sigma_{tot} \leq \text{Const} \ \ln^2 s.$$

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

but not a Must

- Important testable constraints on the cross sections.

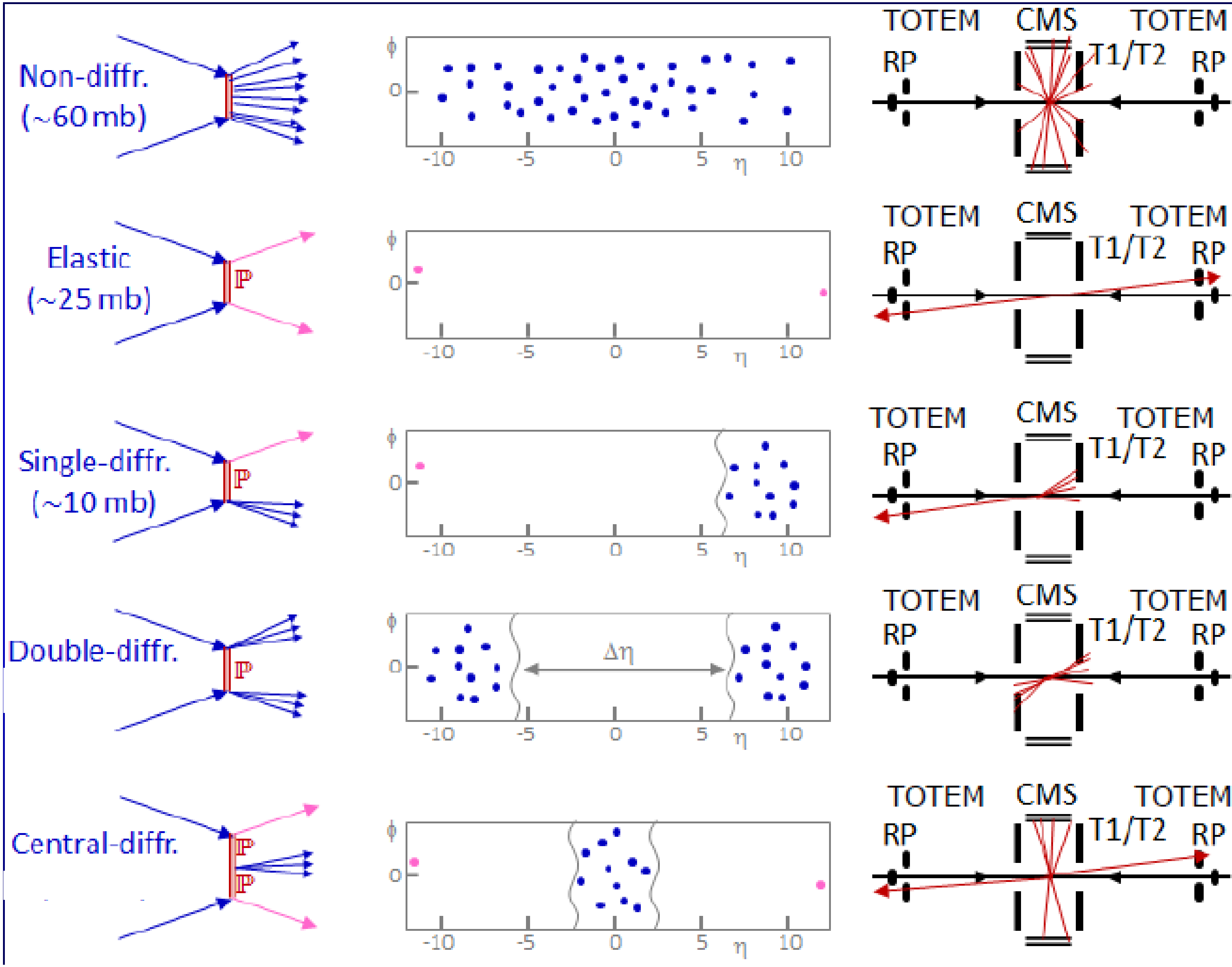
- Phenomenological models- fit the data in the wide energy range and extrapolate to the higher energies. Next step- MC implementations.

- 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: $\mathrm{Im}\, T(s,t=0) = s\sigma_{tot}$

TOTEM –CMS



Non-diffr.
(~60 mb)
Elastic
(~25 mb)
Single-diffr.
(~10 mb)
Double-diffr.
Central-diffr.
ℙ
ϕ
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10
Δη
TOTEM
RP
CMS
T1/T2
TOTEM
RP

Digamma.

arXiv:1604.06446

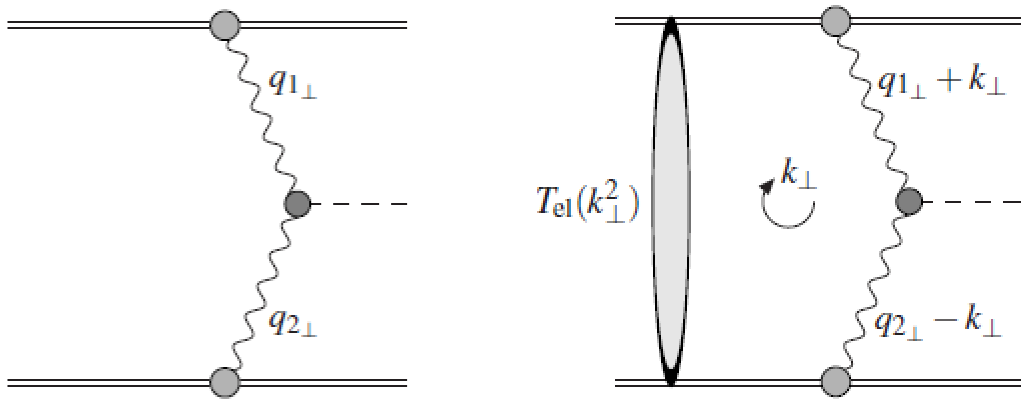
Preliminary LHC data at $\sqrt{s} = 13\,\text{TeV}$ show a hint for a new resonance in $pp \to \gamma\gamma$ (thereby denoted by the letter[1] *digamma*, $\digamma$) at invariant mass of 750 GeV [1], which stimulated intense experimental and theoretical interest. On the experimental side, dedicated analyses strengthen the statistical significance of the excess [2]. New measurements, which are underway, will tell us whether the excess is real and, if so, a thorough exploration of the new particle's properties will start.

Today, with the digamma, we are swimming in deep water. Many key issues related to the new resonance remain obscure. Does it have spin 0, 2, or more? Is it narrow or broad? Or, more generally, how large are its couplings? To which particles can it decay? Do its couplings violate CP? If not, is it CP-even or CP-odd? Is it a weak singlet or a weak doublet or something else? Is it produced through gg, $q\bar{q}$ or weak vector collisions? Is it elementary or composite? Is it a cousin of the Higgs boson? Is it related to the mechanism of electroweak breaking or to the naturalness problem? What is its role in the world of particle physics? Who ordered that?

Soft survival factor

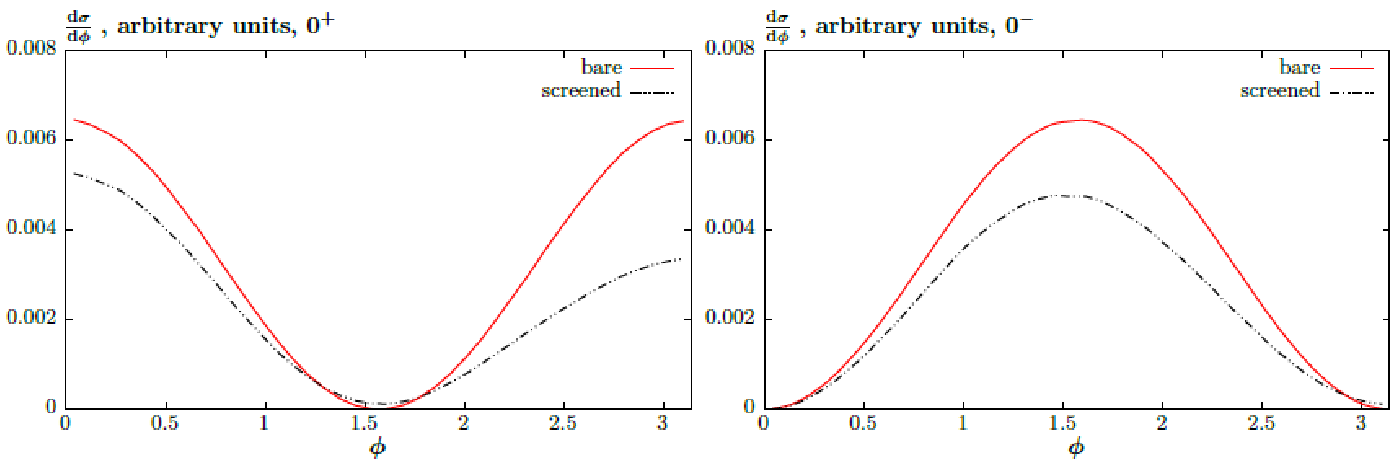
- In any pp collision event, there will in general be 'underlying event' activity, i.e. additional particle production due to pp interactions secondary to the hard process (a.k.a. 'multiparticle interactions', MPI).
- $\gamma\gamma$-initiated interaction is no different, but we are now requiring final state with no additional particle production (X + nothing else).

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



Proton correlations

• Consider distribution with respect to azimuthal angle ϕ between outgoing proton $p_\perp$ vectors.



$\longrightarrow$ With just a handful of events, scalar/pseudoscalar hypotheses distinguishable.

• In addition (not discussed here) these distributions also sensitive to CP-violating effects in production mechanism.

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

750 GeV resonance production

- Easiest to consider the $\gamma\gamma$ 'luminosity' of the colliding protons:

$$\frac{\mathrm{d}\mathcal{L}^{\mathrm{inc}}_{\gamma\gamma}}{\mathrm{d}M_X^2\,\mathrm{d}y_X} = \frac{1}{s}\gamma(x_1,\mu^2)\gamma(x_2,\mu^2) \qquad x_{1,2} = \frac{M_X}{\sqrt{s}}e^{\pm y_X}$$

where $\gamma(x,\mu^2)$ is given by DGLAP evolution from $\gamma(x,Q_0^2)$ given before.

- The resonance R production cross section given by

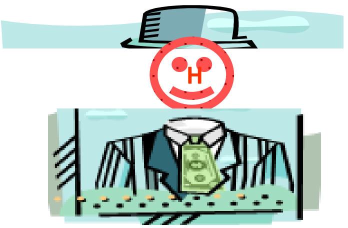
$$\frac{\mathrm{d}\sigma^{\mathrm{inc}}(pp\to R)}{\mathrm{d}y_R} = \frac{8\pi^2\Gamma(R\to\gamma\gamma)}{M_R}\frac{\mathrm{d}\mathcal{L}^{\mathrm{inc}}_{\gamma\gamma}}{\mathrm{d}y_R\,\mathrm{d}M_X^2}\bigg|_{M_X=M_R}$$

- If we are interested in, e.g., ratio of 13 to 8 TeV cross sections, simply consider ratio of corresponding luminosities.

$\longrightarrow$ Conservatively expect $\sim 15-20\,\%$ total uncertainty.

For high total width -sizeable branchings into other SM (or BSM) particles.

In principle: a possibility to search for invisible modes (dark matter particles etc), sharp peak in the missing mass spectrum



CEP as a Dark Matter Factory

but **extremely** challenging if not impossible (in the large pile-up environment)

(BKMR , Eur.Phys.J. C36 (2004) 503-507)

New colourless heavy fermions: the $\gamma\gamma \to F\bar{F}$:

taking $m_F = 360$ GeV and $e_F = 1$, we get $\sigma_{F\overline{F}} = 0.12$ fb at $\sqrt{s} = 13$ TeV.

R production cross section, this will be strongly enhanced in a scenario where the new fermion carry higher electric charge $e_F > 1$. Note that the resonant $R \to F\overline{F}$ cross section may give a comparable contribution to the overall $F\overline{F}$ signal, provided the corresponding branching ratio is not too small.

(still relatively unconstrained, (1512.05327))