NANYANG TECHNOLOGICAL UNIVERSITY

Conference on New Physics at the Large Hadron Collider

29 February to 4 March 2016

Nanyang Executive Centre, Nanyang Technological University, Singapore

Diffractive and Central Processes at the LHC (selected topics)

V.A. Khoze (IPPP, Durham and PINP)

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

Outline

- Forward and Diffractive Physics at the LHC (yesterday, today and tomorrow)
- LHC as a High Energy $\gamma\gamma$ Collider
- "The $\gamma\gamma$- Resonance that Stole Christmas" (M. Neubert)

  Central Exclusive Production Processes

  CEP =  series

- Selected CEP samples 
- Summary and Outlook.

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.

• 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 upcoming yellow report...

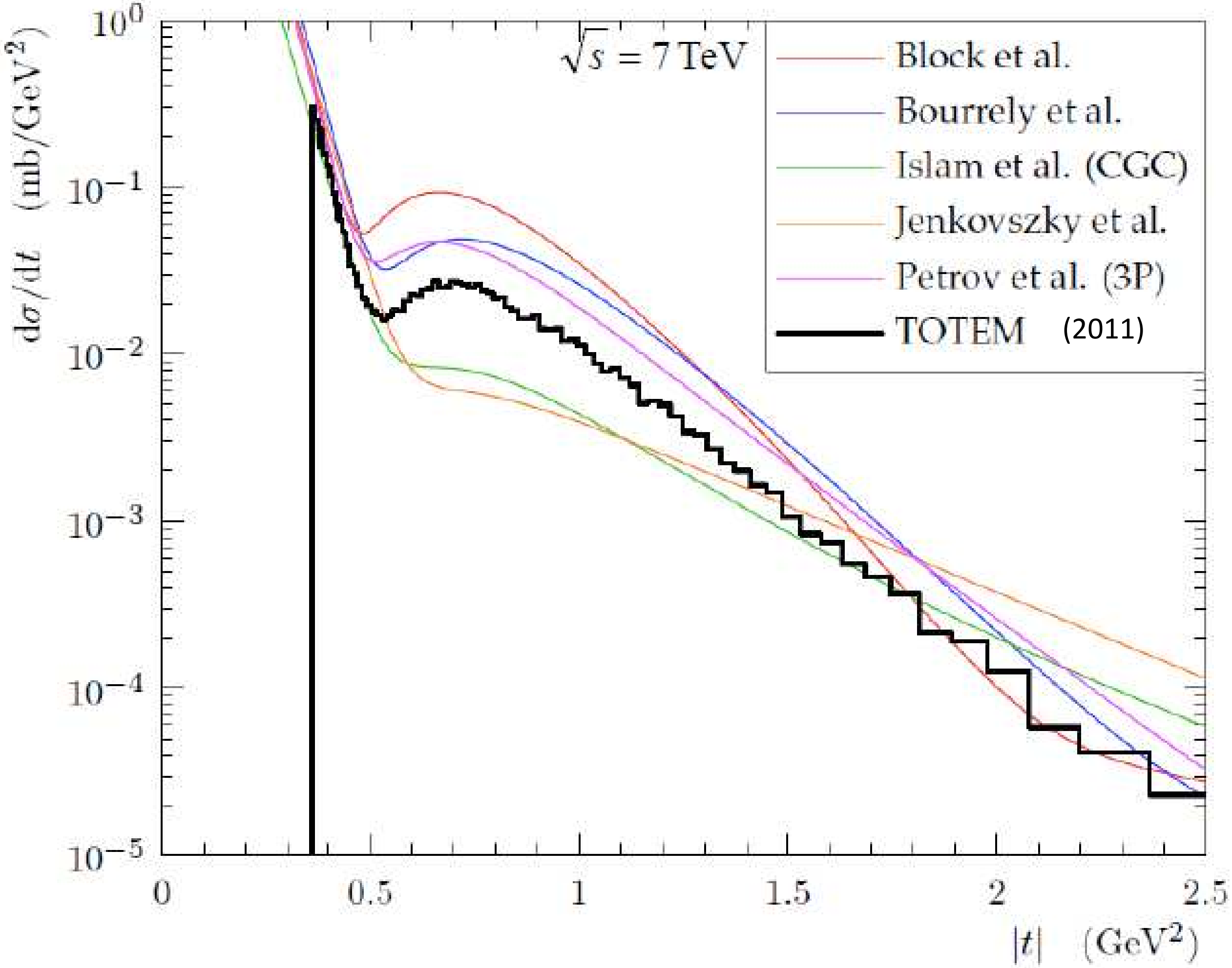
CERN/LHCC 2013-021
February 28 2015

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

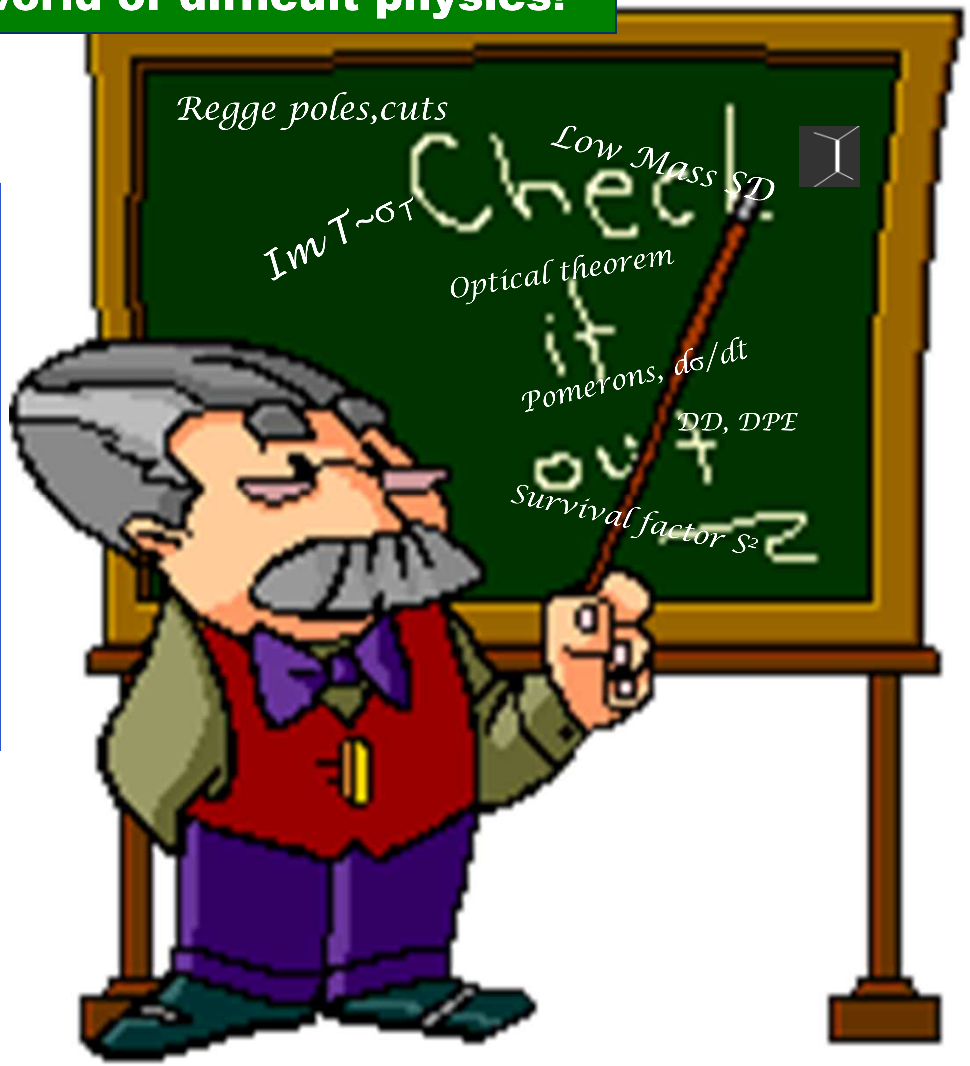
(pre-LHC) Model Comparisons



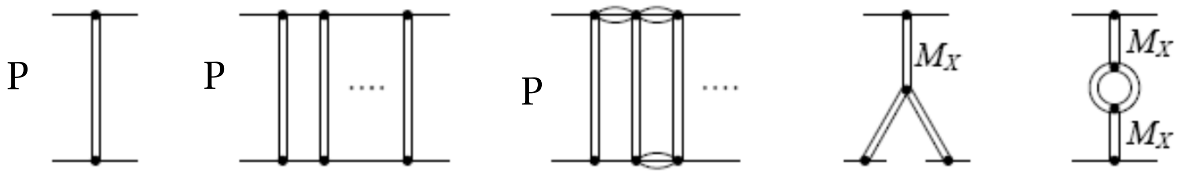
No theoretical / phenomenological model describes the TOTEM data completely.

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).

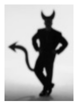
- Basic fundamental model-independent relations: unitarity, crossing, analyticity, dispersion relations. The Froissart-Martin **bound**: $\sigma_{tot} \leq \text{Const} \ \ln^2 s.$

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

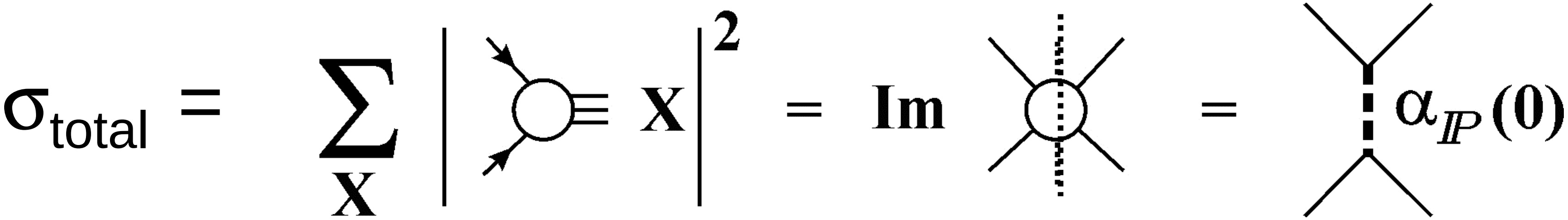
$$d\sigma/dt = |T(t)|^2/16\pi s^2 \propto \exp(B_{el}t)$$

optical theorem: $\operatorname{Im} T(s,t=0) = s\sigma_{tot}$

THEORETICAL BACKGROUND

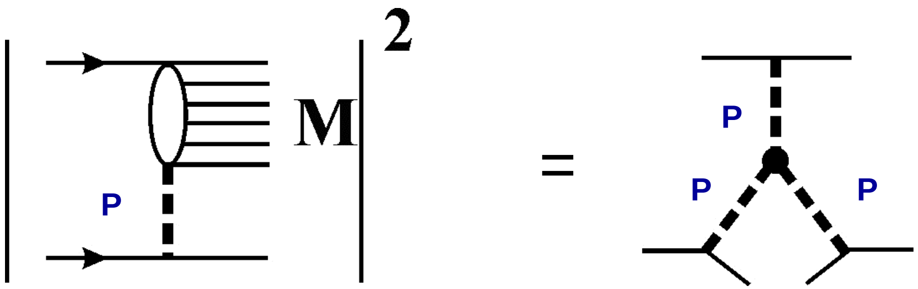
Pomeron (Gribov-1961)

A diffractive process is characterized by a large rapidity gap (LRG), which is caused by t-channel Pomeron exch.



Multi-pomeron contributions

High mass diffractive dissociation



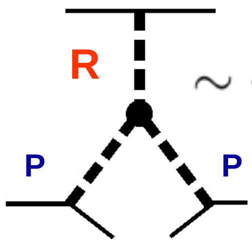
$$d^2\sigma/dM^2dt|_{t=0} \sim \frac{s^{2\epsilon}}{(M^2)^{1+\epsilon}}$$ S^2 $\sim 1/M^2$

PPP-diagram

Low mass diffractive dissociation

introduce diffve estates ϕ_i, ϕ_k (comb^{ns} of p,p*,..) which only undergo "elastic" scattering (Good-Walker)

dual to

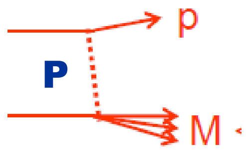


$$\sim \frac{s^{2\epsilon}}{(M^2)^{1.5+2\epsilon}}$$ S^2 $\sim 1/M^3$

PPR-diagram

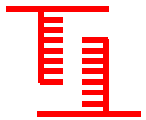
Diffractive Dissociation (of special importance for CR physics)

No unique definition of diffraction



1. Diffraction is elastic (or quasi-elastic) scattering caused, via s-channel unitarity, by the absorption of components of the wave functions of the incoming particles
   e.g. pp→pp,
   pp→pX (single proton dissociation, SD),
   pp→XX (both protons dissociate, DD)

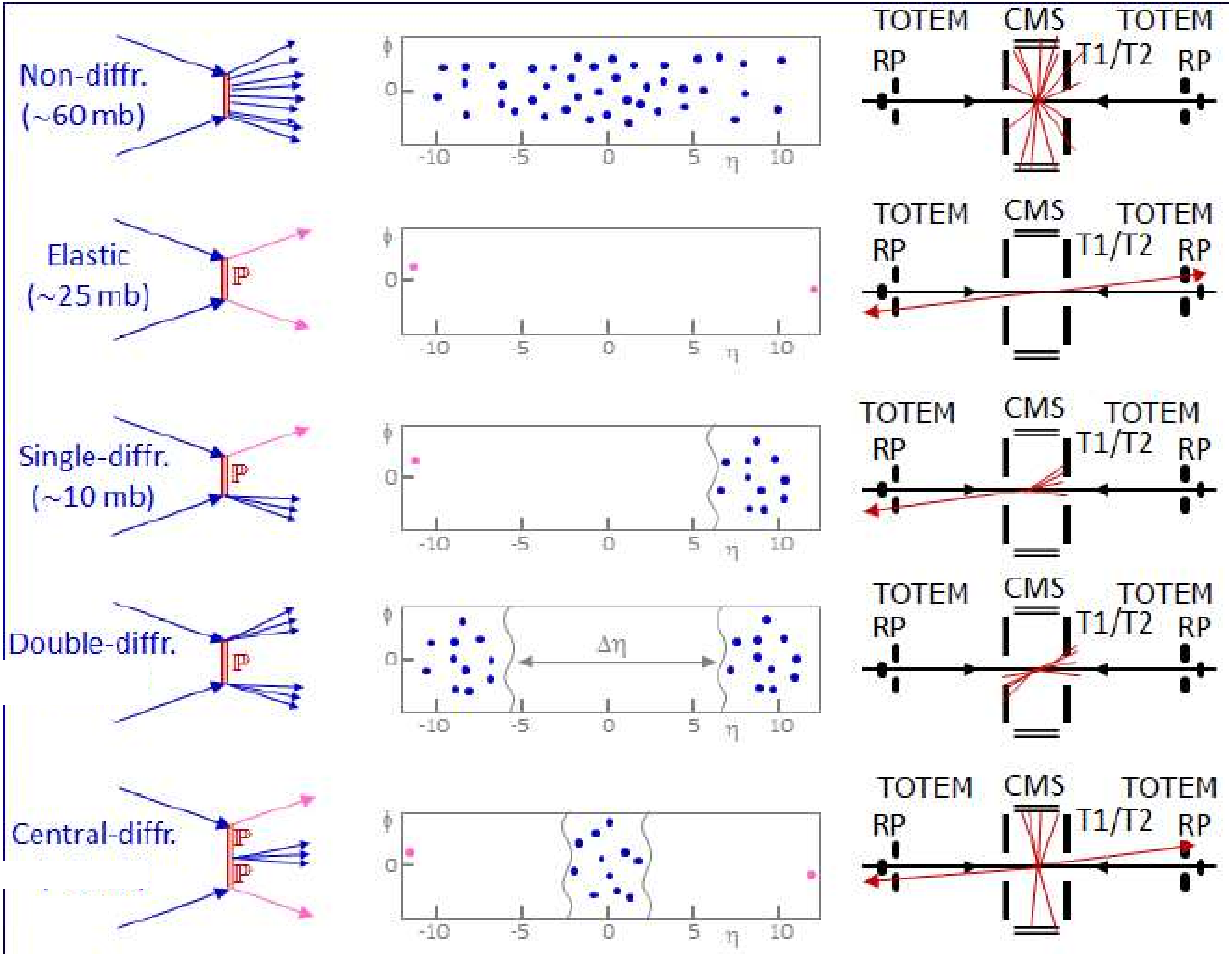
Good for quasi-elastic proc.
– but not high-mass dissoc^n



2. A diffractive process is characterized by a large rapidity gap (LRG), which is caused by t-channel "Pomeron" exch.

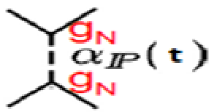
Only good for very LRG events – otherwise Reggeon/fluctuation contaminations

TOTEM –CMS


Non-diffr.
(~60 mb)
Elastic
(~25 mb)
Single-diffr.
(~10 mb)
Double-diffr.
Central-diffr.
ϕ
0
-10
-5
0
5
η
10
Δη
TOTEM
RP
CMS
TOTEM
T1/T2
RP

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 ± 0.24 GeV^{-2} (ALFA)

Lesson 2.

Lessons from LHC run I - elastic slope

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

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:

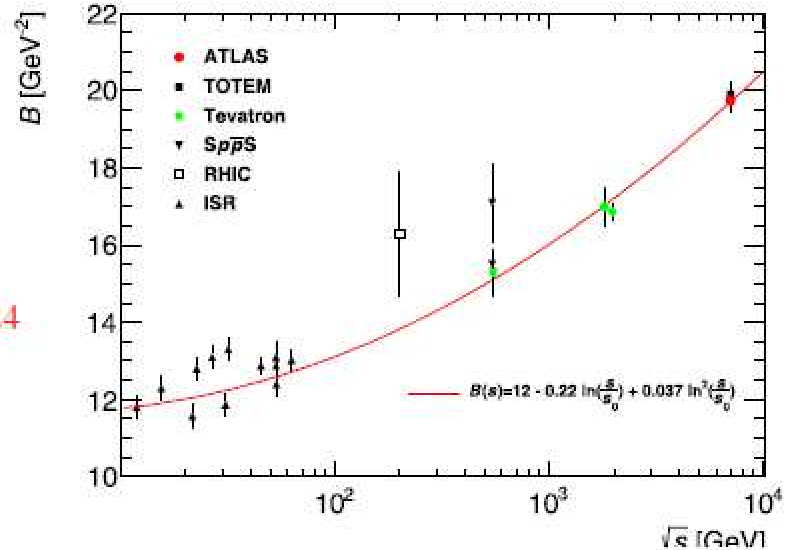
$$B_{\text{el}} = 16.98 + 4 \times 0.25 \times \ln(7/1.8) = 18.34\ \text{GeV}^{-2}$$

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

- 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

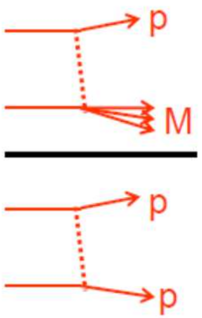
$$2\alpha_P'^{eff} = dB_{el}/d(ln(s/s_0))$$



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)



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

(the end of a simple quasi-eikonal ?)

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.

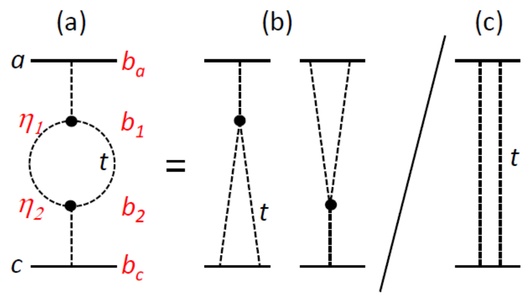
Lesson 4.

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:

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

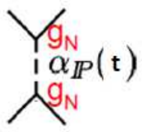
$$\sigma_{\rm DD} = 0.116 \text{ mb}$$ (TOTEM, arXiv:1308.6722)



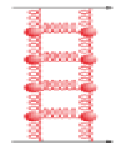
$$\frac{d\sigma_{\rm DD}}{dt\,d\eta_1 d\eta_2} = \frac{d\sigma_{\rm SD}}{dt\,d\eta_1}\frac{d\sigma_{\rm SD}}{dt\,d\eta_2} \Big/ \frac{d\sigma_{\rm el}}{dt}.$$

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

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

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

KMR-13

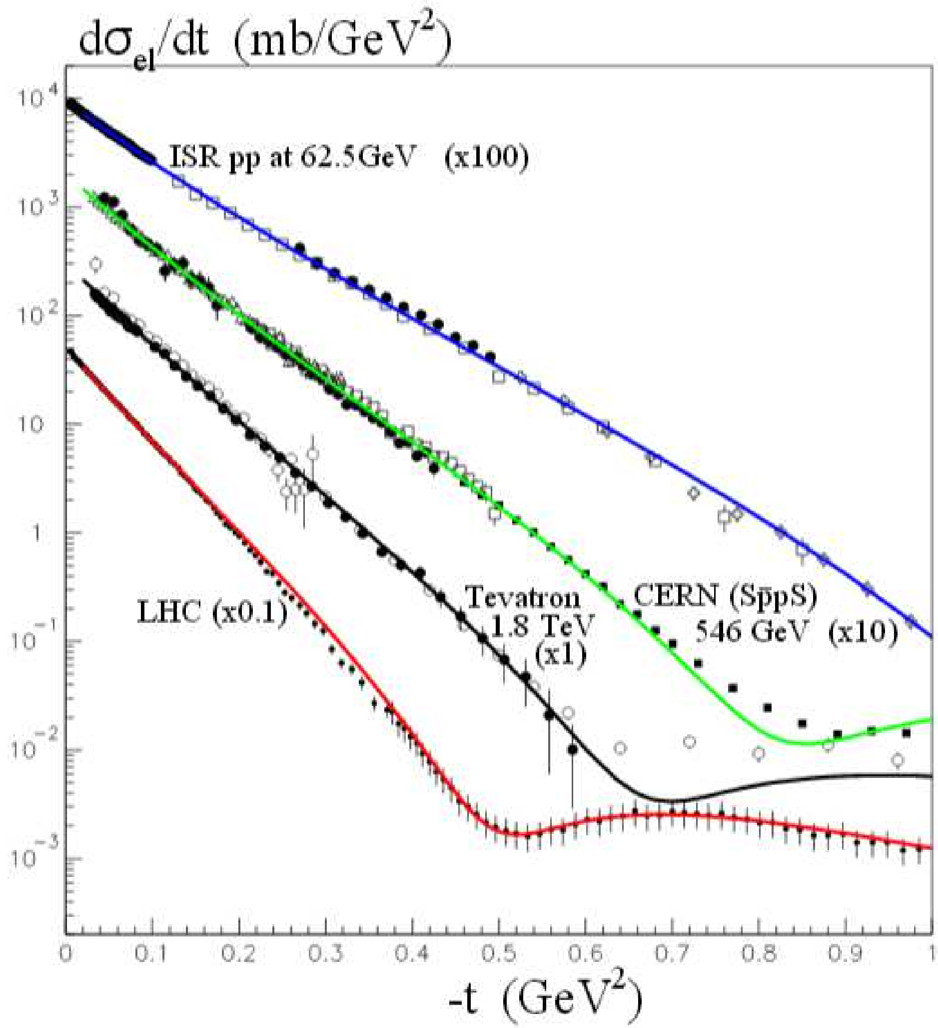


Figure 1: The description of pp or ($p\bar{p}$) elastic data. The references to the pre-LHC elastic data can be found in [18]. Here LHC refers to 7 TeV and the data are from [8, 5]

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

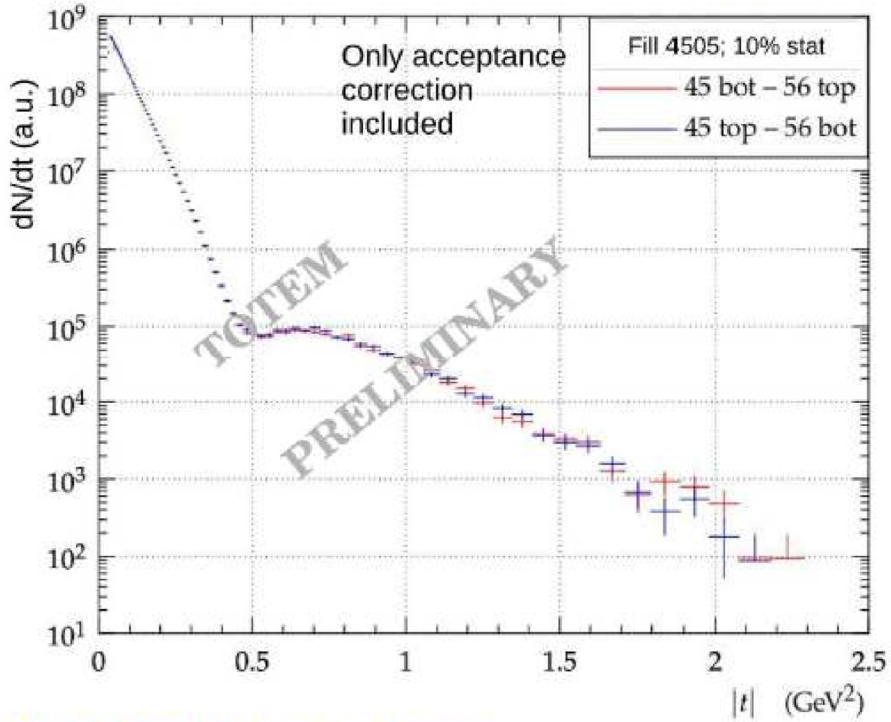
$\sqrt{s}$	$\sigma_{\rm tot}$	$\sigma_{\rm el}$	$B_{\rm el}(0)$	$\sigma_{\rm SD}^{\rm low\,M}$	$\sigma_{\rm DD}^{\rm low\,M}$	$\sigma_{\rm SD}^{\Delta\eta_1}$	$\sigma_{\rm SD}^{\Delta\eta_2}$	$\sigma_{\rm SD}^{\Delta\eta_3}$	$\sigma_{\rm DD}^{\Delta\eta}$
(TeV)	(mb)	(mb)	(GeV^{-2})	(mb)	(mb)	(mb)	(mb)	(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, s

Outlook

Very high statistics β^* = 90 m data at 13 TeV:

~ 3 · 10^9 elastic events ⇒ access higher |t|-values



Common CMS-TOTEM data taking:

8 – 10 kHz @ CMS HLT ⇒ e.g. 100M events of [double arm RP & T2 veto & tracks in CMS tracker] for exclusive low mass resonance studies

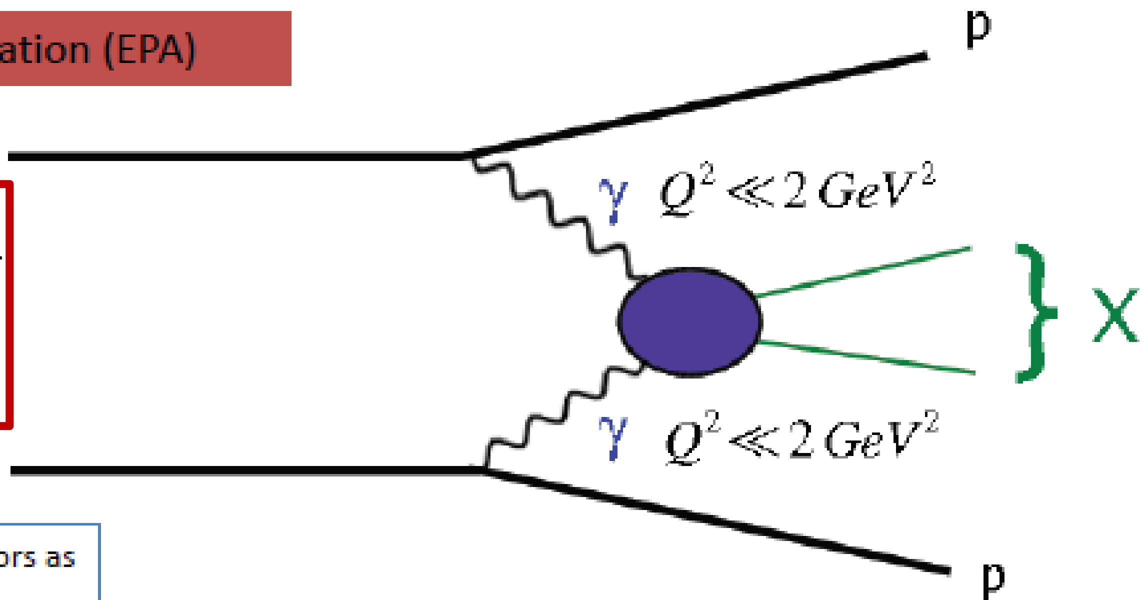
LHC as a $\gamma\gamma$ collider

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

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

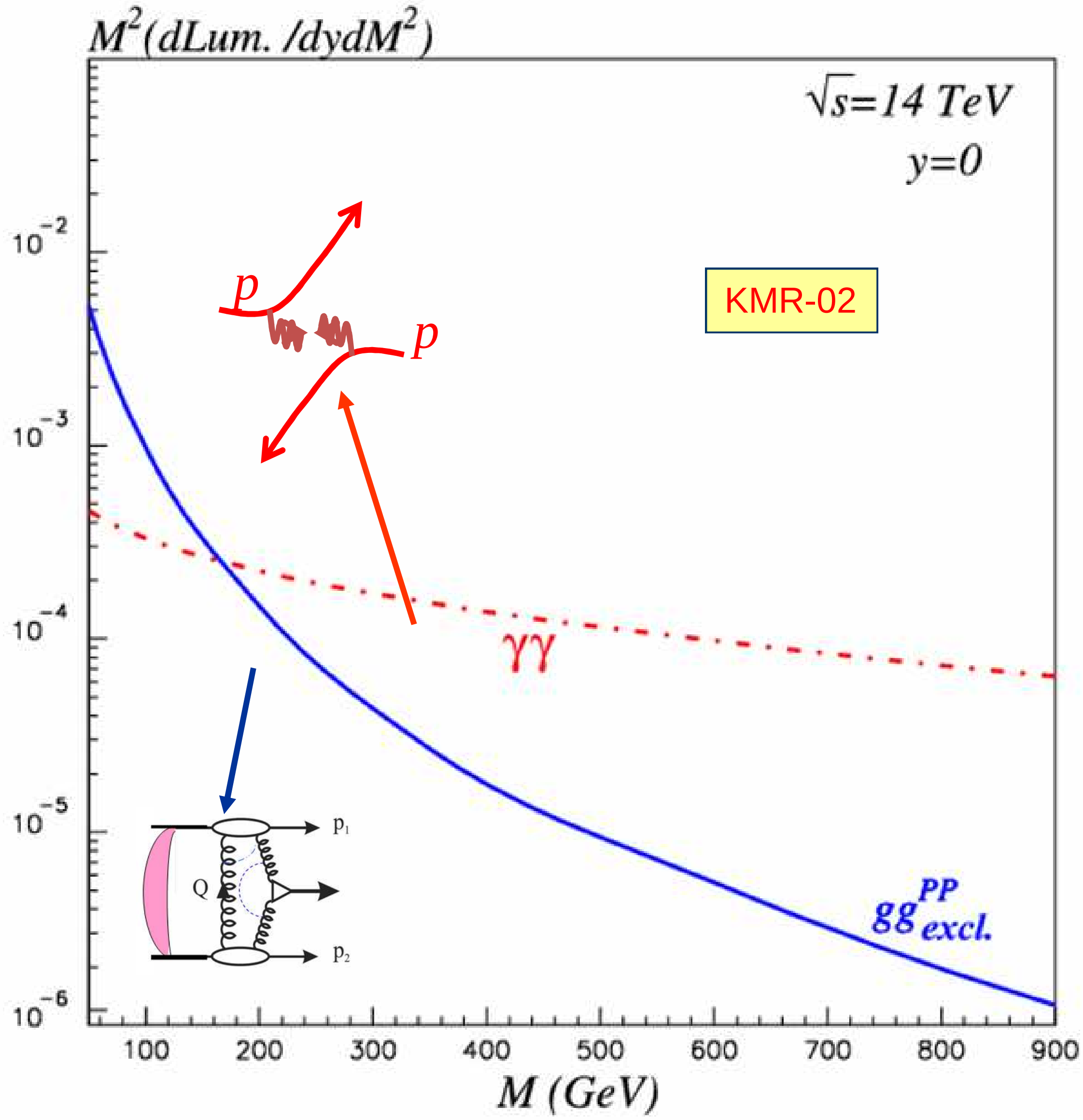
low γ virtuality 

(SuperChic 2 HKR-1508.02718)

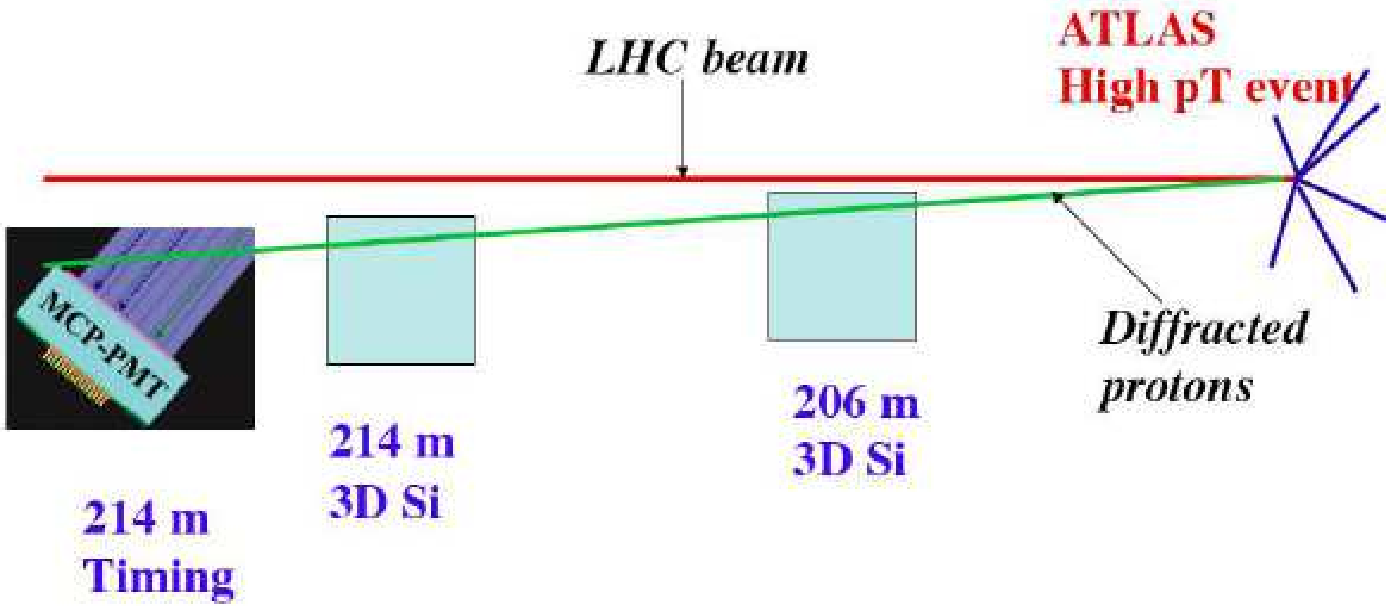
- factorization to
  - long distance photon exchange
  - short distance $\gamma\gamma \to$ X interaction

$$\alpha_S^2/8 \to \alpha^2$$

QCD ‘radiation damage’ in action



AFP and CT-PPS

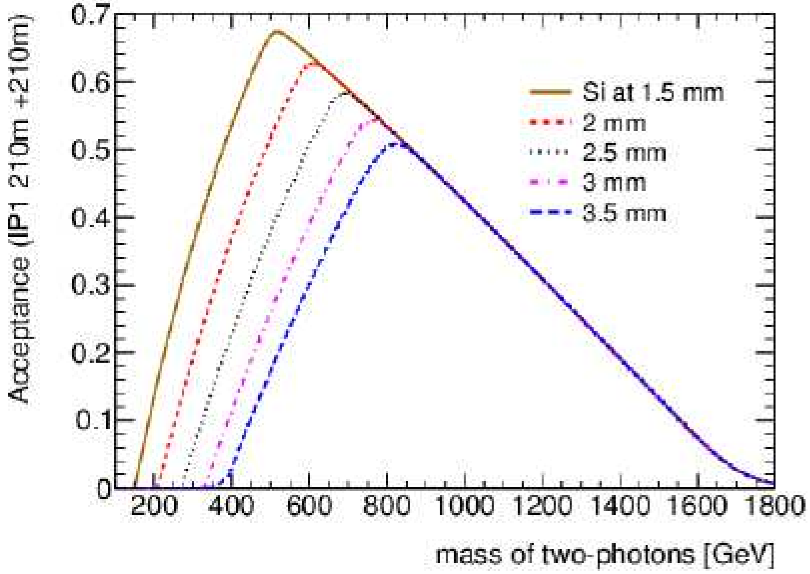


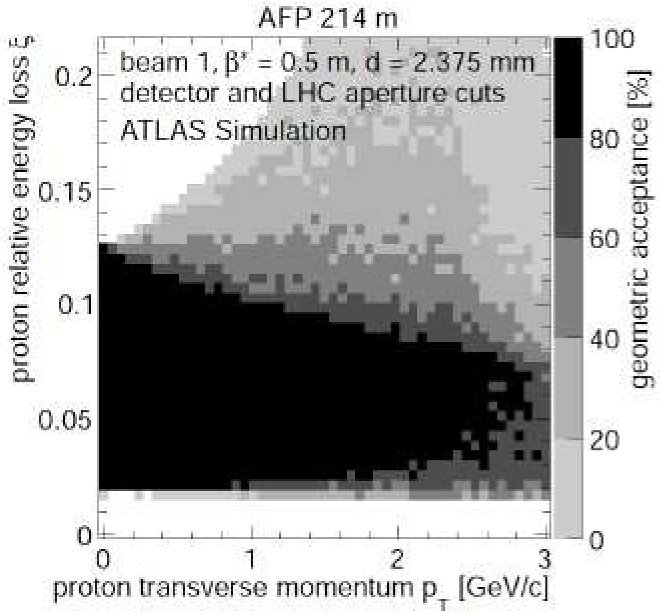
- Tag and measure protons at ±210 m: AFP in ATLAS, CT-PPS in CMS/Totem
- AFP and CT-PPS detectors: measure proton position (Silicon detectors) and time-of-flight (timing detectors)

Kinematics

AFP

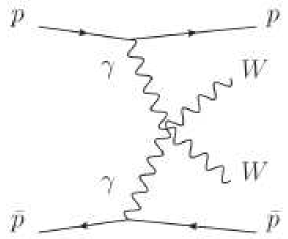
- Acceptance large for 0.015 < ξ< 0.13
- Good resolution in ξ, not so great resolution in p_T
- Tag protons in both stations to reconstruct mass (resolution ~ 1-2% depending on mass)
- Timing detectors, mass trigger at L1 from course bars (quart/diamonds)

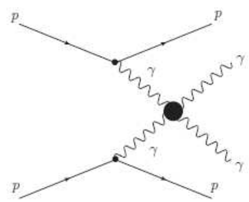




Reach at LHC

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





Couplings	OPAL limits [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

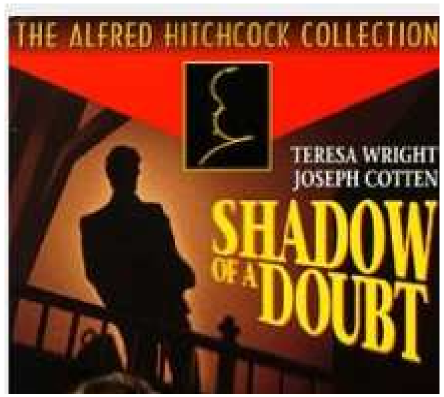
"The γγ- Resonance that Stole Christmas"

ATLAS &CMS seminar on 15 Dec. 2015

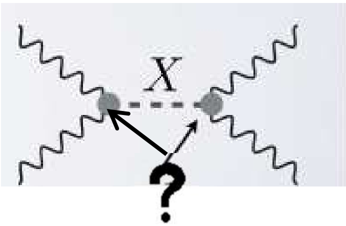
750 GeV

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

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 $\Gamma_{\rm tot} = 45$ 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 ~ 14, 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);

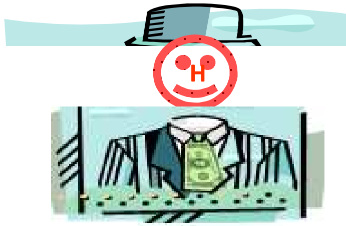
Asymmetric jet distribution;

Comparatively low transverse momentum of the resonance.

- The simplest model.
- Allows very accurate theoretical predictions.
- Provides strong motivations for the CT-PPS and AFP projects.
- ‘Easy’ to shoot down experimentally.

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



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))

(M. Neubert)

with my Durham hat on

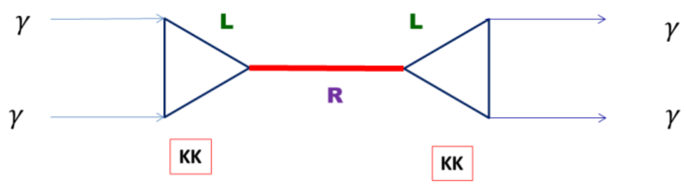
Photo-production of a 750 GeV di-photon resonance mediated by Kaluza-Klein leptons in the loop

Steven Abel and Valentin V. Khoze

arXiv:1601.07167

Abstract

We consider the phenomenology of a 750 GeV resonance X which can be produced at the LHC by only photon fusion and subsequently decay into di-photons. We propose that the spin-zero state X is coupled to a heavy lepton that lives in the bulk of a higher-dimensional theory and interacts only with the photons of the Standard Model. We compute the di-photon rate in these models with two and more compact extra dimensions and demonstrate that they allow for a compelling explanation of the di-photon excess recently observed by the ATLAS and CMS collaborations. The central role in our approach is played by the summation over the Kaluza-Klein modes of the new leptons, thus providing a significant enhancement of the $X \to \gamma\gamma$ loops for the production and decay subprocesses.



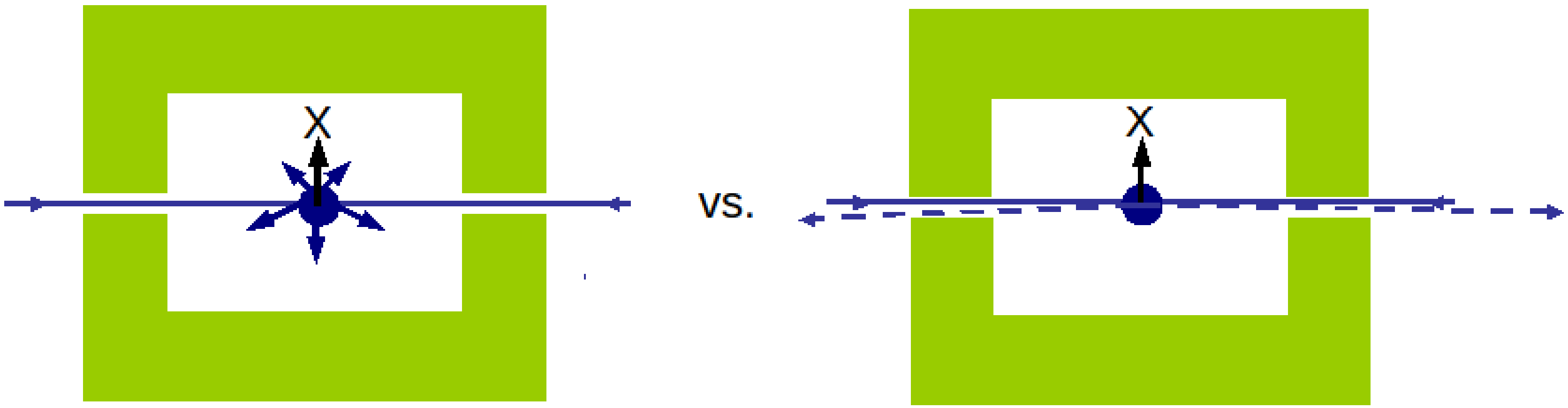
What is it?

MIND THE GAP

Central Exclusive Production (CEP) is the interaction:

$$pp \to p + X + p$$

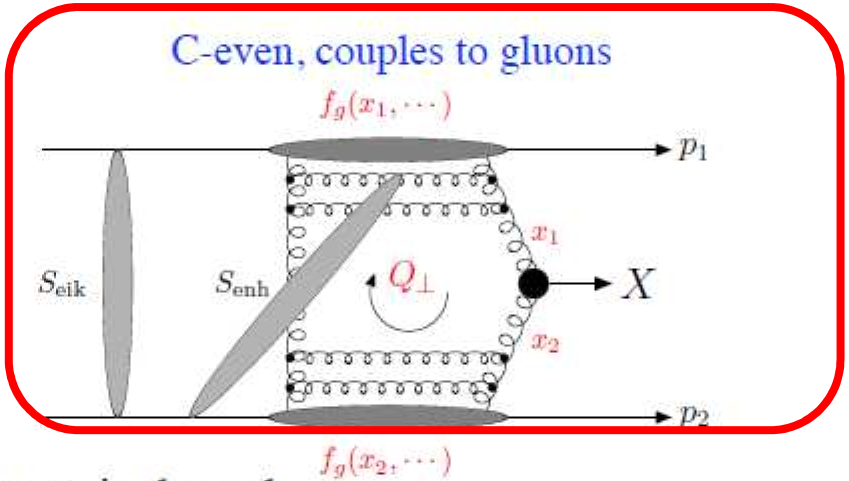
- Diffractive: colour singlet exchange between colliding protons, with large rapidity gaps ('+') in the final state.
- Exclusive: hadron lose energy, but remain intact after the collision.
- Central: a system of mass M_X is produced at the collision point and only its decay products are present in the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

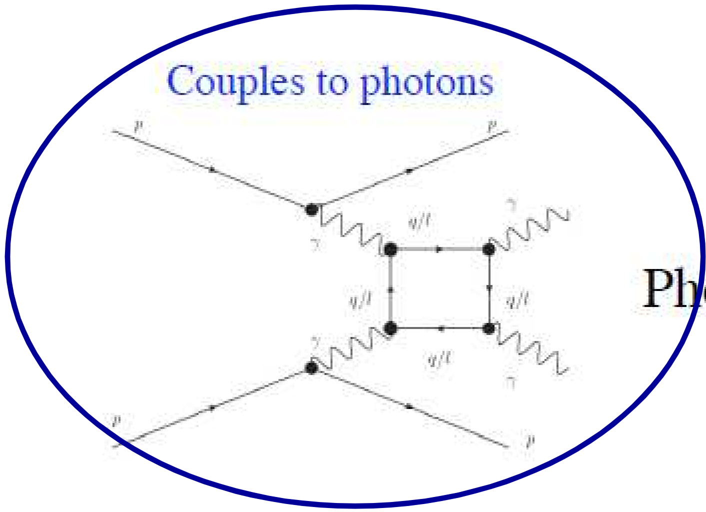


Production mechanisms

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

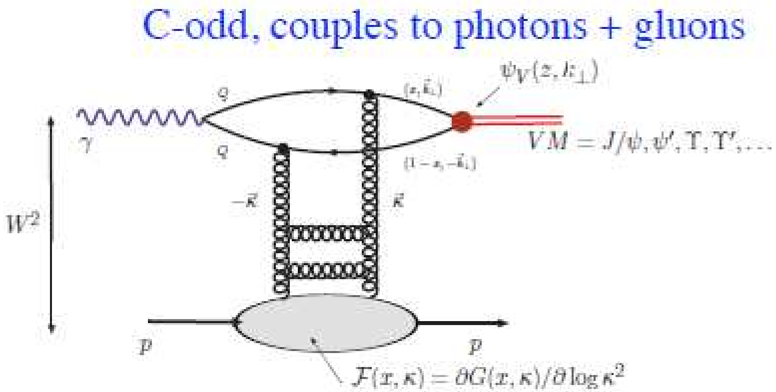
Gluon-induced
(double pomeron exchange):





Photoproduction

Photon-induced



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 approved for 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.

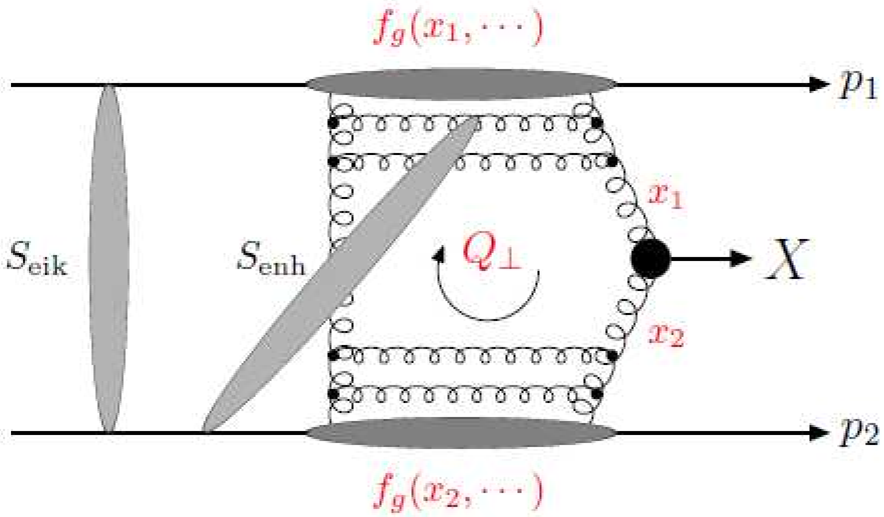
*In absence of pile-up

'Durham Model' of Central Exclusive Production

(QCD mediated)

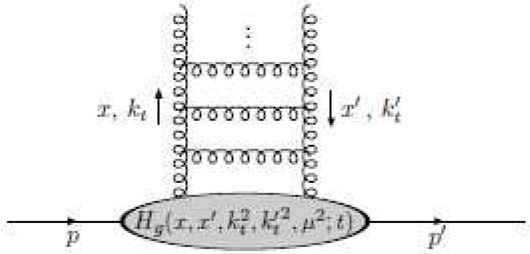
- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons.
- The use of pQCD is justified by the presence of a hard scale $\sim M_X/2$. This ensures an infrared stable result via the Sudakov factor: the probability of no additional perturbative emission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



Calculating CEP : ingredients

- Soft Survival probability:
  - Non-perturbative object, must take a physical model of hadronic interactions, fitted to soft hadronic data. 'State of the art' models roughly consistent.
  - Recent TOTEM data on total, elastic and diffractive cross sections has been imporant guide for LHC predictions.



- 'Skewed' PDFs:
  - Correspond to gg coupling to proton for relevant kinematics
  - In the CEP regime can be calculated via usual global PDFs.
- Sudakov factor:
  - Resums higher order logs in $Q_\perp/M_X$, ensuring IR stable result and validity of perturbative treatment.

PRD 88, 034029 (2013) for latest results.

Important to include all  ors correctly!

One step forward, two steps back (V.I. Lenin)

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...

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-15

- 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

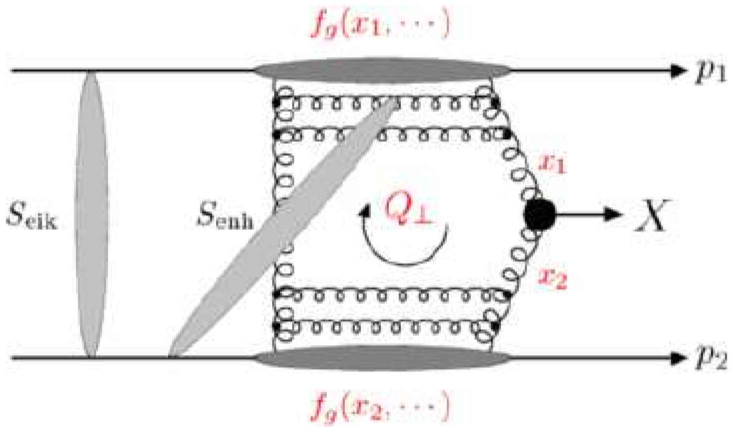
The only MC generator which consistently incorporates the calculation of survival factors and Sudakov effects

- MC + user manual available on Hepforge:

SuperChic 2 - A Monte Carlo for Central Exclusive Production

- Home
- Code
- References
- Contact

SuperChic is a Fortran based Monte Carlo event generator for central exclusive production. A range of Standard Model final states are implemented, in most cases with spin correlations where relevant, and a fully differential treatment of the soft survival factor is given. Arbitrary user-defined histograms and cuts may be made, as well as unweighted events in the HEPEVT and LHE formats. For further information see the user manual.



A list of references can be round here and the code is available here.

Comments to Lucian Harland-Lang < l.harland-lang (at) ucl.ac.uk >.

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.


THANK YOU


QUESTIONS?


Year of the Monkey
Happy Chinese New Year 2016

BACKUP

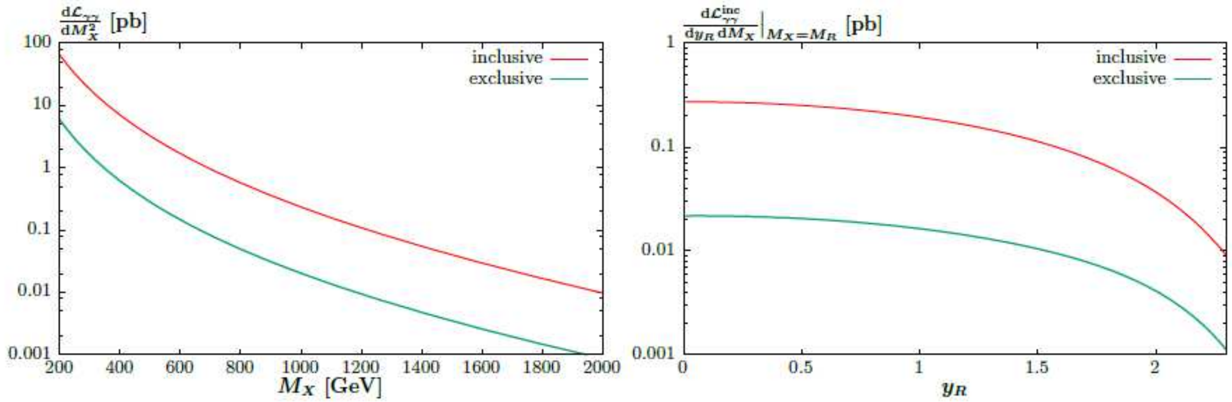


Figure 3: Inclusive and exclusive $\gamma\gamma$ luminosities for a scalar resonance at $\sqrt{s} = 13$ TeV, shown (left) differential in the invariant mass, M_X, of the produced system, integrated over rapidity y_X, (right) for the production of a resonance of mass $M_R = 750$ GeV, differential in the particle rapidity.

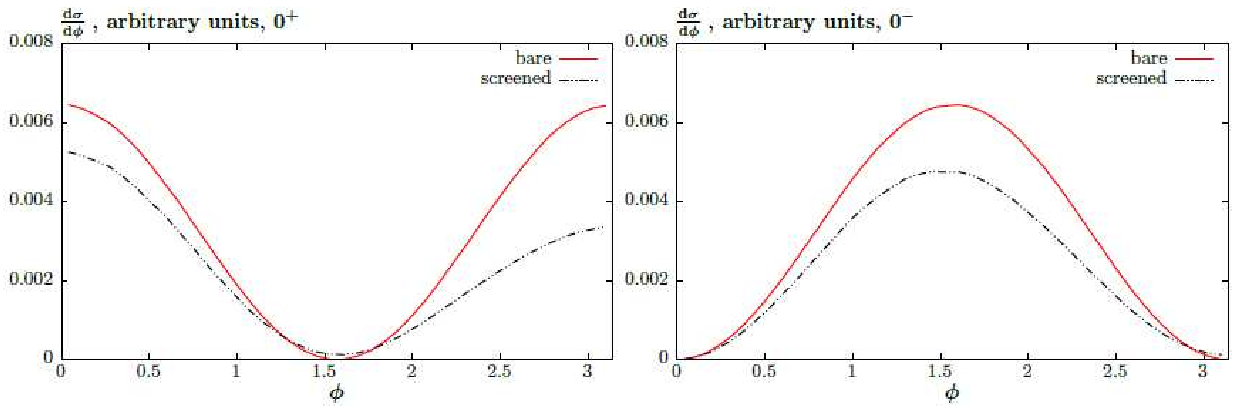


Figure 4: Distribution, in arbitrary units, with respect to the azimuthal angle ϕ between the transverse momenta of the outgoing protons for the exclusive production of a scalar (left) and pseudoscalar (right) resonance of mass $M_R = 750$ GeV at $\sqrt{s} = 13$ TeV.

MUCH NEEDED RUN II MEASUREMENTS

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

- ❑ Accurate determination of σ_{LM}^{SD}, σ_{SD}, σ_{DD} in different mass intervals TOTEM-CMS , ALFA+ ATLAS.
Prospects with the FSC counters (CMS, LHCb, ALICE).

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

- ❑ Comparison of particle distributions in the **PP**, **P**p events with those in the pp collisions (TOTEM-CMS, ALFA+ ATLAS).

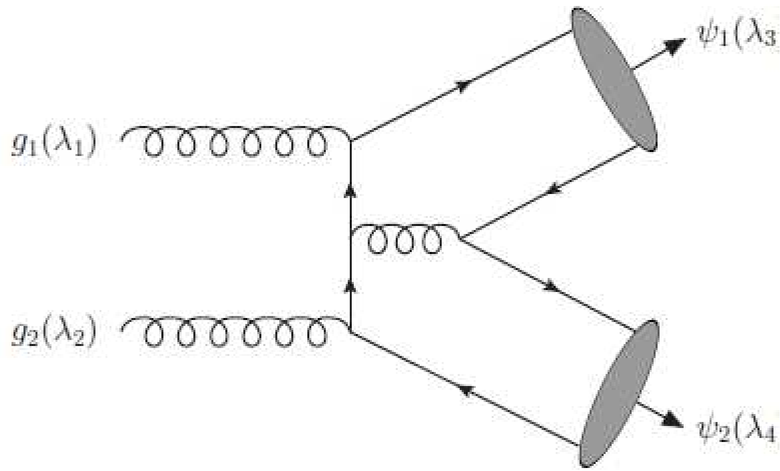
- ❑ Special LHC runs with low lumi/ large β^* are much needed.

LHL, V.A. Khoze, M.G. Ryskin, J. Phys. G42 (2015) 5, 055001

Example: exclusive $J/\psi J/\psi$ production

• Heavy quark mass ensures this is perturbative. Highly topical as a probe of (inclusive) double parton scattering, as well as tetraquark decays...

• Generically we write the CEP process in terms of the $gg \to X$ helicity amplitudes, in this case $gg \to J/\psi J/\psi$.



• In high subprocess energy ($\hat{s} \gg M_\psi^2$) limit find that amplitudes with initial-state gluons in $J_z = 0$ config. vanish, while numerically suppressed away from this limit.

$\longrightarrow$ Expect $J/\psi J/\psi$ CEP cross section to be suppressed below naive estimates. Specific result of exclusive channel, relies upon selection rule.

Recently LHCb have released the first exclusive measurement:

Observation of charmonium pairs produced exclusively in pp collisions

J. Phys. G41 (2014) 11, 115002

The LHCb collaboration†

Abstract

A search is performed for the central exclusive production of pairs of charmonia produced in proton-proton collisions. Using data corresponding to an integrated luminosity of 3 fb^{-1} collected at centre-of-mass energies of 7 and 8 TeV, $J/\psi J/\psi$ and $J/\psi\psi(2S)$ pairs are observed, which have been produced in the absence of any other activity inside the LHCb acceptance that is sensitive to charged particles in the pseudorapidity ranges $(-3.5, -1.5)$ and $(1.5, 5.0)$. Searches are also performed for pairs of P-wave charmonia and limits are set on their production. The cross-sections for these processes, where the dimeson system has a rapidity between 2.0 and 4.5, are measured to be

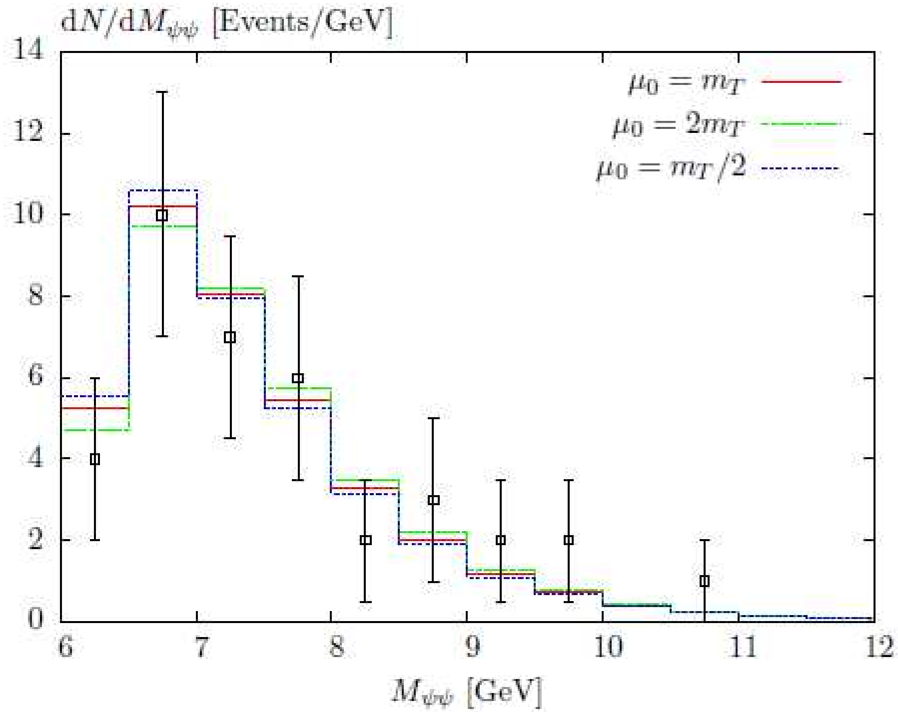
$$\begin{aligned}
\sigma^{J/\psi\, J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst})\,\text{pb},\\
\sigma^{J/\psi\, \psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\,\text{pb},\\
\sigma^{\psi(2S)\psi(2S)} &< 237\,\text{pb},\\
\sigma^{\chi_{c0}\chi_{c0}} &< 69\,\text{nb},\\
\sigma^{\chi_{c1}\chi_{c1}} &< 45\,\text{pb},\\
\sigma^{\chi_{c2}\chi_{c2}} &< 141\,\text{pb},
\end{aligned}$$

where the upper limits are set at the 90% confidence level. The measured $J/\psi\, J/\psi$ and $J/\psi\, \psi(2S)$ cross-sections are consistent with theoretical expectations.

→ Larger (MSTW/GJR) cross sections in fair agreement, within (reasonably large) theoretical and experimental uncertainties, but interesting possibility that predicted cross section are a little low.

• Can compare $J/\psi J/\psi$ invariant mass distribution to LHCb measurement

Normalized to data



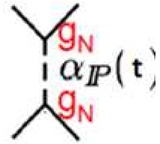
$\longrightarrow$ Encouraging agreement, within experimental uncertainties

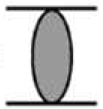
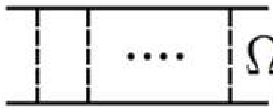
• Clearly further higher statistic data will greatly help, allowing a more precise theory/data comparison

THEORETICAL BACKGROUND

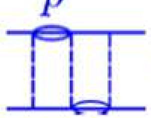
Pomeron (Gribov-1961)

Elastic amp. $T_{el}(s,b)$

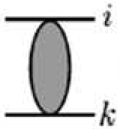
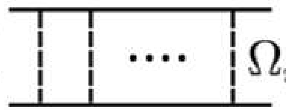
One Pomeron bare amp. $\Omega/2$ = 

$\text{Im } T_{el}$ =  $= 1 - e^{-\Omega/2} = \sum_{n=1}^{\infty}$  $\Omega/2$

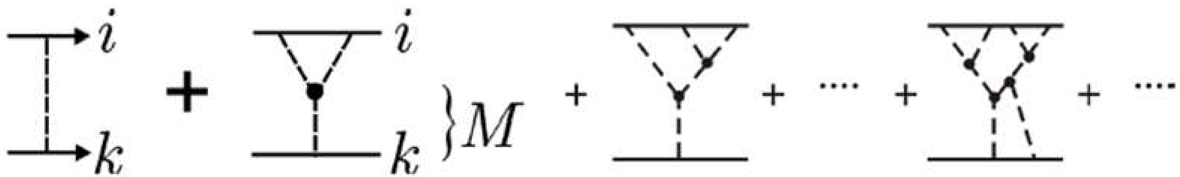
(s-ch unitarity)

Low-mass diffractive dissociation  →multichannel eikonal

introduce diff^ve^ estates ϕ_i, ϕ_k (comb^ns^ of p,p*,..) which only undergo "elastic" scattering (Good-Walker)

$\text{Im } T_{ik}$ =  $= 1 - e^{-\Omega_{ik}/2} = \sum$  $\Omega_{ik}/2$

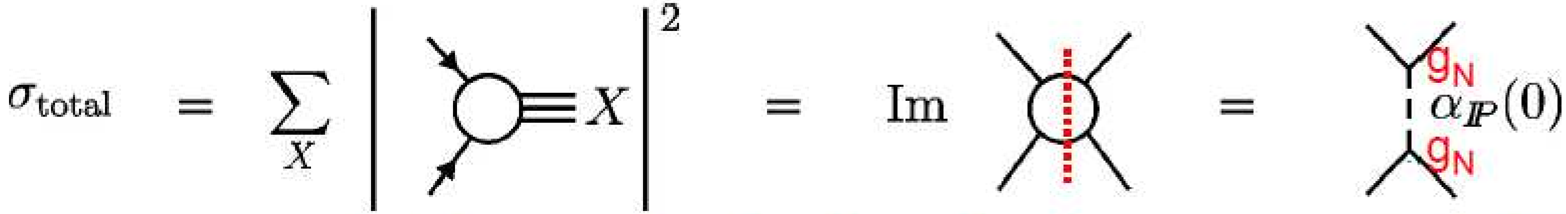
include high-mass diffractive dissociation

Ω_{ik} = 

(non-linear **PP** interactions)

Optical theorems

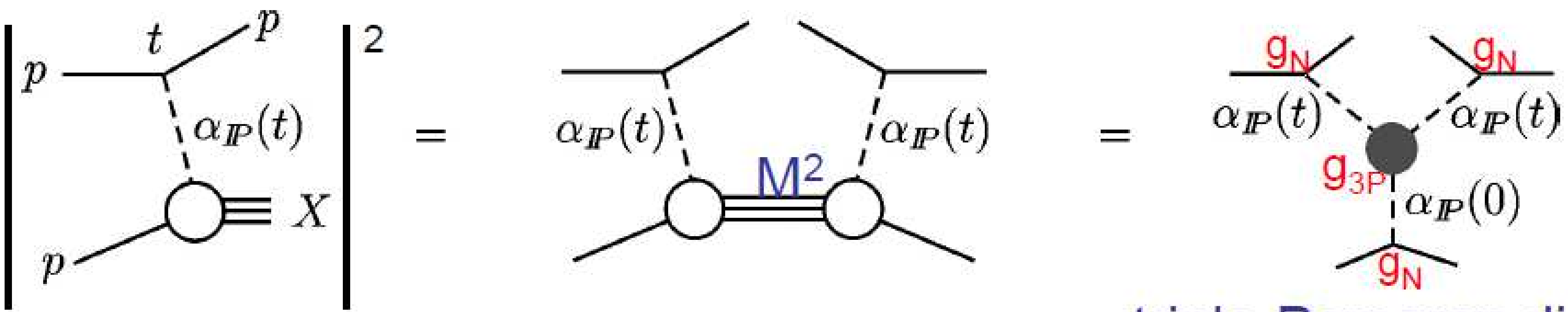
at high energy
use Regge



but screening/s-ch unitarity important so $\sigma_{\rm total}$ suppressed

$$g_N^2 \left(\frac{s}{s_0}\right)^{\alpha_{I\!P}(0)-1}$$

High-mass diffractive dissociation



triple-Pomeron diag

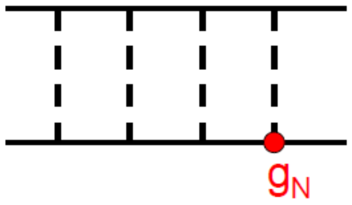
$$g_N^3 g_{3P} \left(\frac{M^2}{s_0}\right)^{\alpha_{I\!P}(0)-1} \left(\frac{s}{M^2}\right)^{2\alpha_{I\!P}(t)-2}$$

but screening even more important

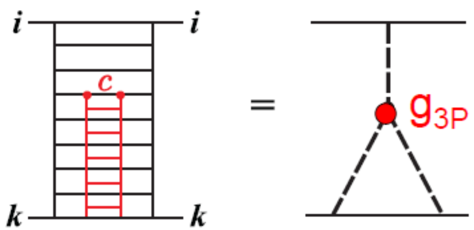
Multi-Pomeron contributions

Absorptive Effects.

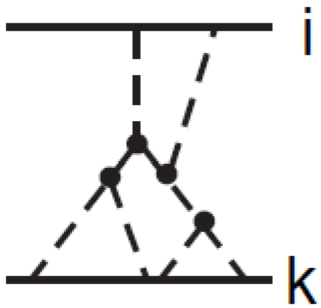
eikonal: Pomerons well separated in b-plane



enhanced: interactions with partons in an individual cascade



Rescattering of the intermediate partons in the 'parton ladder'



Running scenarios in 2015-2016

- **Roman Pot Insertion Commissioning 2015**
  - RP insertion tests are carried out in end-of-fill studies
  - Start with beams separated by 5- 6 sigma in IP5 ($L=10^{30-31}$)
  - Find an optimal set of positions of RPs and collimators.
- **Timing Detector Commissioning 2015-16**
  - Commissioning of the timing detector as a function of luminosity
  - End-of-fill studies with separated beams
- **Data Production Phase >2016**
  - RP insertion movements will executed by the LHC operator immediately after declaration of stable beams.
  - Aim at accumulating up to 100 fb^{-1} of data before LS2

Summary and Outlook

- Central exclusive production: 'hard diffractive' process, requiring non-trivial combination of soft and hard QCD. Can produce in principle any object that couples to gluons $\longrightarrow$ wide menu of processes to study

- LHC Run II has the potential to greatly increase our understanding of these processes. Please see the Forward Physics and Diffraction yellow report for status and prospects!

- new 'SuperChic 2' MC. Builds on previous MC, but with significant changes/extensions **recently released.**

- 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 and distributions are given.