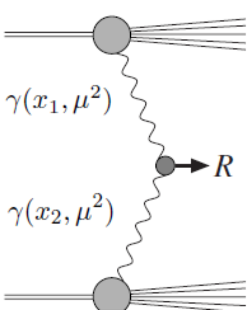
LHC Working Group on Forward Physics and Diffraction

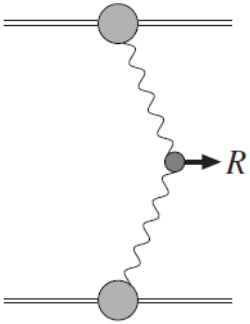
15-16 March 2016
CERN
Europe/Zurich timezone

$\gamma\gamma$ fusion and diphoton resonance production

V.A. Khoze (IPPP, Durham)

(in collaboration with Lucian Harland-Lang and Misha Ryskin)



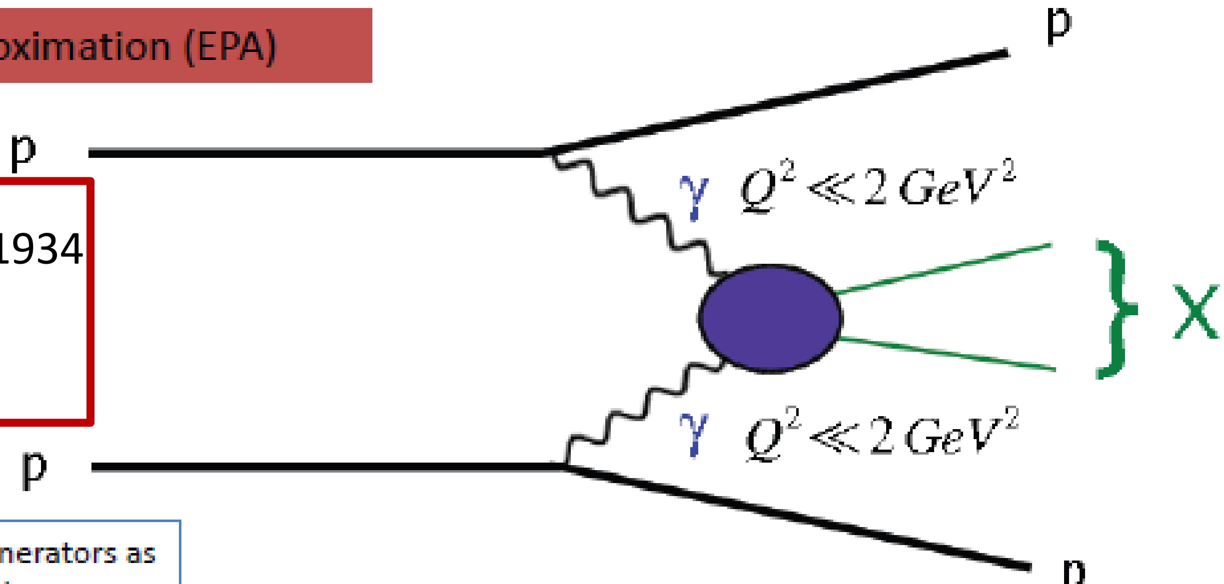


‘Central Exclusive Production’

LHC as a γγ 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

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

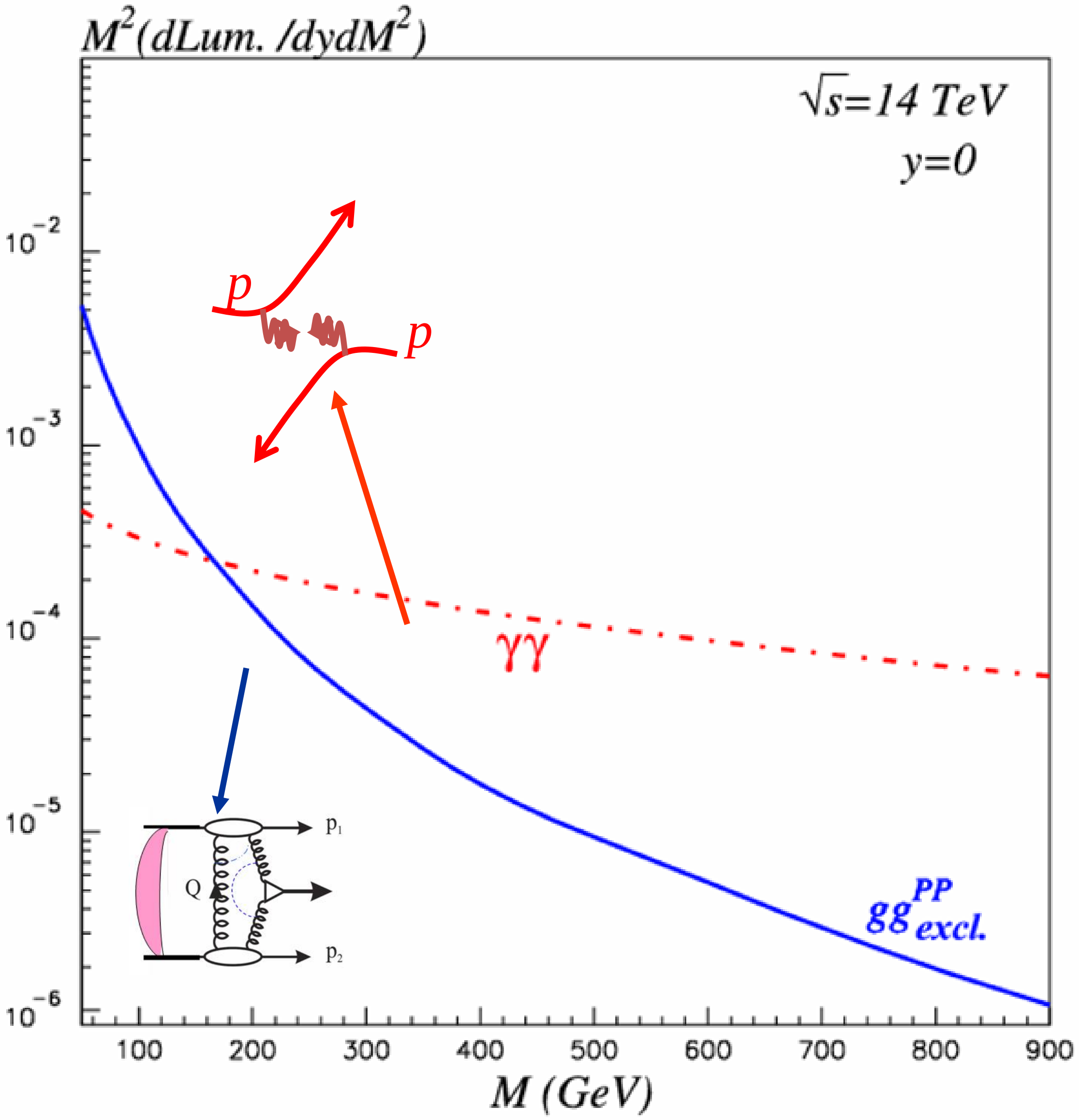
low γ virtuality WARNING (SuperChic 2 HKR-1508.02718)

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

QCD ‘radiation damage’ in action

KMR-2002

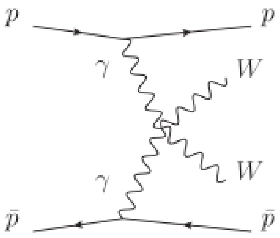
(Fichet et al, 1512.05751)



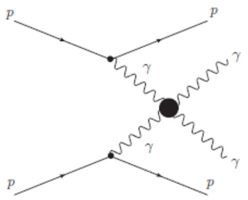
(C.Royon et al, K. Piotrzkowski et al)

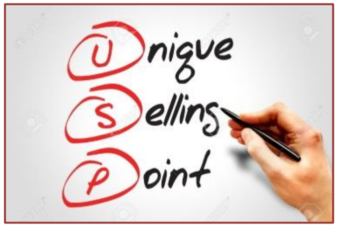
Reach at LHC

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 @ $\mathcal{L} = 30\ (200)\ \mathrm{fb}^{-1}$ 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 $\gamma\gamma$- Resonance that Stole Christmas”

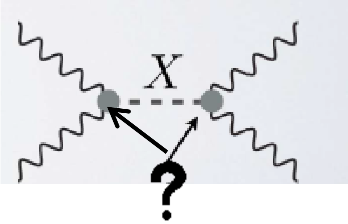
ATLAS &CMS seminar on 15 Dec. 2015

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.

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. + many more

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

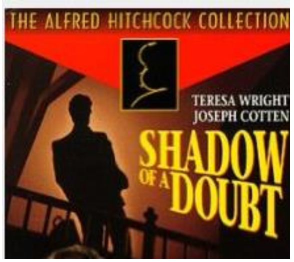
- The simplest model.
- Allows the most precise theoretical predictions.
- Provides strong motivations for the CT-PPS and AFP projects.
- ‘Easier’ to shoot down experimentally.

already some clouds in the horizon , but let us wait and see (until this summer)

(Talk by K.Terashi at KIAS, March 2nd)

Intriguing excess observed around 750 GeV in diphoton search

- Local 3.6σ, global 2.0σ with NWA
- 0.3σ increase with LWA : Best fit Γ/m ~ 6% (Γ ~ 45GeV)
- Event characteristics consistent with mass sideband



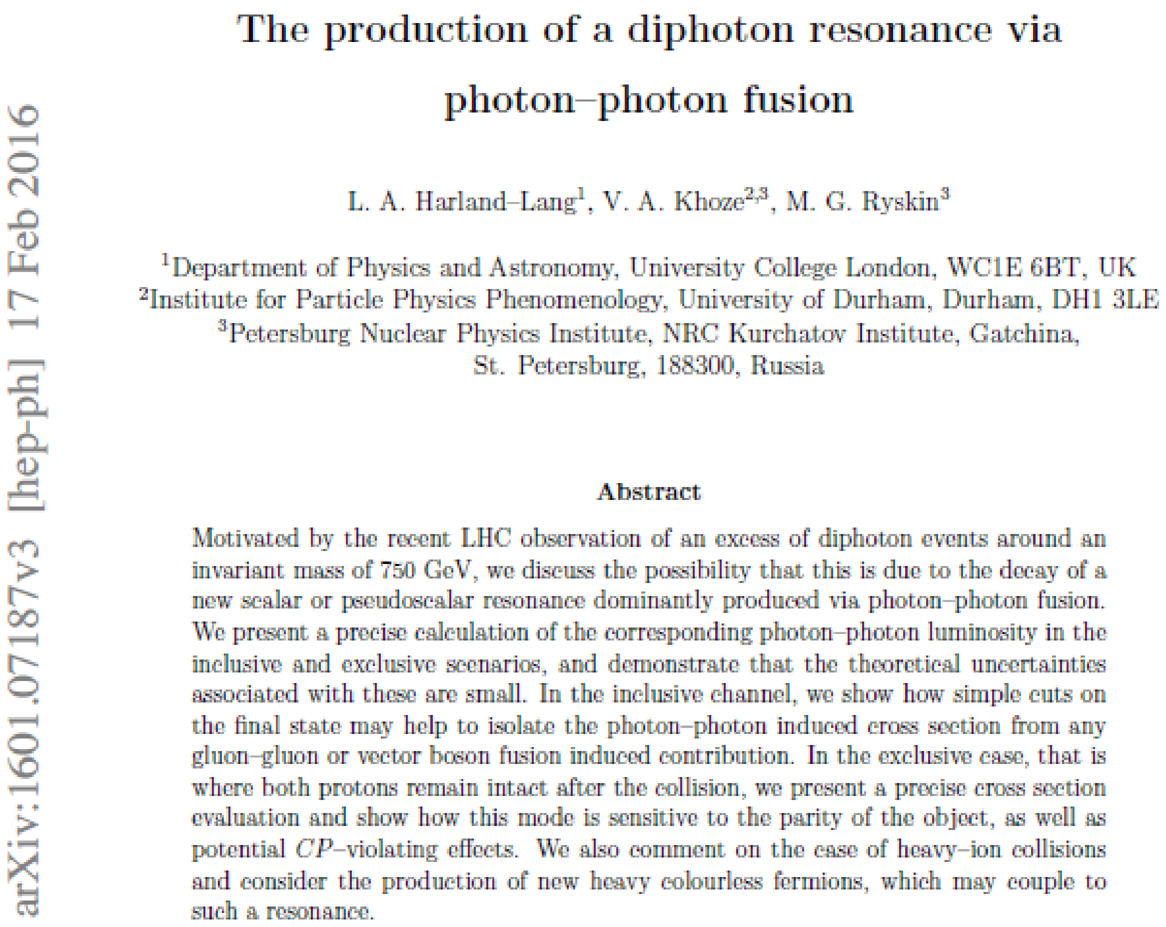
No excess seen in other channels

- Analysis likely needs to be improved to reach model predictions
- Other signatures to cover? What to do about invisible?

Expect ~25 fb^{-1} for 2016 (up to ~10 fb^{-1} by ICHEP)

Very likely to confirm or reject the diphoton excess by summer!

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.



arXiv:1601.07187v3 [hep-ph] 17 Feb 2016

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.

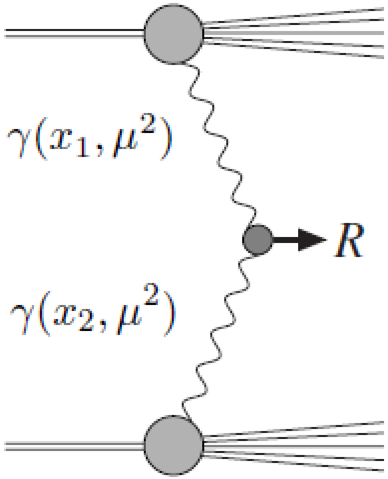
Modelling $\gamma\gamma$ fusion

- We are interested in resonance production in pp collisions via the subprocess $\gamma\gamma \to R$.

$\longrightarrow$ Can write LO cross section in usual factorized form:

$$\sigma(R) = \int \mathrm{d}x_1 \mathrm{d}x_2 \, \gamma(x_1, \mu^2)\gamma(x_2, \mu^2) \, \hat{\sigma}(\gamma\gamma \to R)$$

but in terms of *photon* parton distribution function (PDF), $\gamma(x, \mu^2)$.



$\mu \sim M_R$

The photon PDF

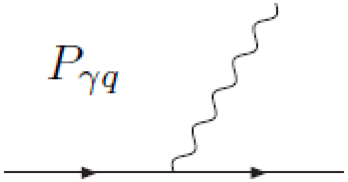
- As with other partons, the photon obeys a DGLAP evolution equation:

$$\gamma(x,\mu^2) = \gamma(x,Q_0^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1 \frac{dz}{z}\Bigg(P_{\gamma\gamma}(z)\gamma(\frac{x}{z},Q^2) + \sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2) + P_{\gamma g}(z) g(\frac{x}{z},Q^2)\Bigg)\,,$$

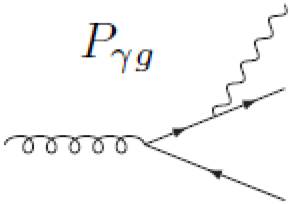
NLO in QCD

- Thus PDF at scale μ ($\sim M_R$) given in terms of:
  - PDF at starting scale $Q_0 \sim 1\,\mathrm{GeV}$.
  - Evolution term from, due to emission from quarks up to scale μ.

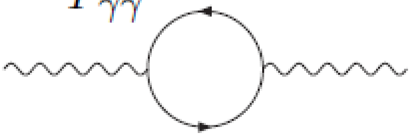
$P_{\gamma q}$



$P_{\gamma g}$



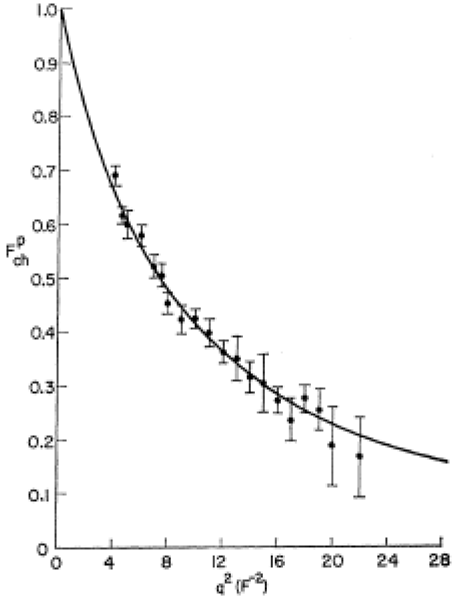
$P_{\gamma\gamma}$

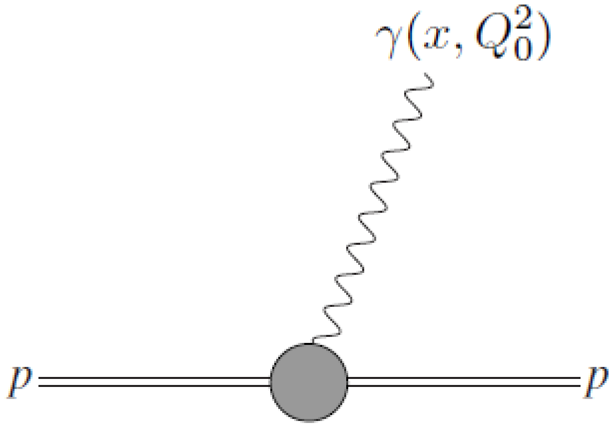


- Question: how do we model the starting distribution $\gamma(x,Q_0^2)$?

PDFs and QED

- New approach in A.D. Martin and M.G. Ryskin, arXiv:1406.2118: major part of $\gamma(x, Q_0^2)$ has been missed in previous work.
- QED is long range force: at low scales ($\sim$ low photon virtuality/large wavelength) the photon sees the entire EM charge of the proton, and 'coherent' emission is dominant process. Must include this contribution!





Coherent photon emission

- The part of $\gamma(x, Q_0^2)$ due to coherent photon emission is given by

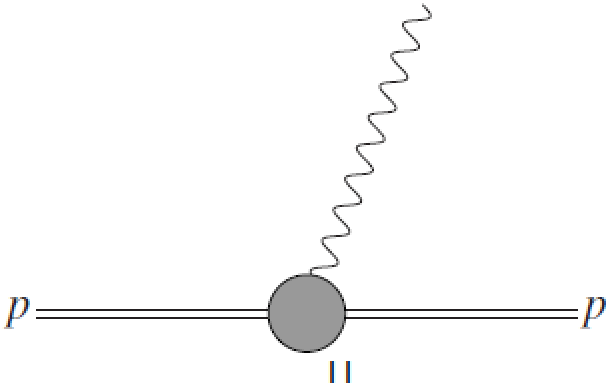
γ transverse mom.

$$\gamma_{\rm coh}(x, Q_0^2) = \frac{1}{x}\frac{\alpha}{\pi}\int_0^{Q^2<Q_0^2} \frac{{\rm d}q_t^2}{q_t^2 + x^2 m_p^2}\left(\frac{q_t^2}{q_t^2 + x^2 m_p^2}(1-x)F_E(Q^2) + \frac{x^2}{2}F_M(Q^2)\right)$$

where F_E/F_M are the proton electric/magnetic form factors. These are *very* precisely measured. Given in terms of `dipole' form factors:

$$G_E^2(Q_i^2) = \frac{G_M^2(Q_i^2)}{7.78} = \frac{1}{(1 + Q_i^2/0.71{\rm GeV}^2)^4} \longleftarrow$$

Elastic ⇒ steeply falling



Incoherent photon emission

- In addition, there will be some contribution to $\gamma(x, Q_0^2)$ due to emission from the individual valence quarks. This requires knowledge of quark PDFs in low Q^2 regime, and moreover risk of double counting with coherent piece.

  $\longrightarrow$ Inevitably requires phenomenological approach.

- We simply freeze the quark PDFs for $Q < Q_0$ and include approx. form factor for non-coherent emission:

$$\gamma_{\rm incoh}(x, Q_0^2) = \frac{\alpha}{2\pi}\int_x^1 \frac{{\rm d}z}{z}\left[\frac{4}{9}\underset{\nwarrow}{u_0}\left(\frac{x}{z}\right) + \frac{1}{9}\underset{\nearrow}{d_0}\left(\frac{x}{z}\right)\right]\frac{1+(1-z)^2}{z}\int_{Q^2_{\rm min}}^{Q_0^2}\frac{{\rm d}Q^2}{Q^2+m_q^2}\left(1-\overset{\substack{\text{form factor}\\ \downarrow}}{G_E^2(Q^2)}\right) ,$$

quarks frozen

- u_V, d_V $\downarrow$ as Q^2 $\downarrow$ for relevant x, $\Rightarrow$ freezing corresponds to upper limit.

750 GeV resonance production

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

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

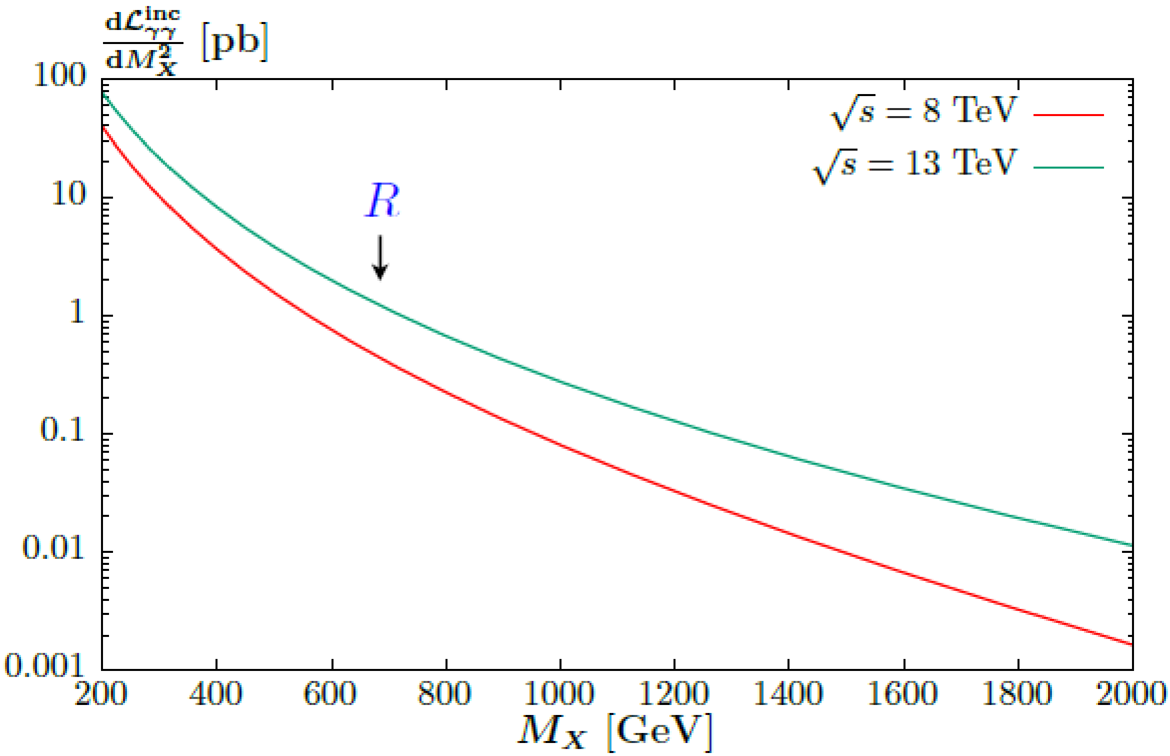
where $\gamma(x,\mu^2)$ is given by DGLAP evolution from $\gamma(x,Q_0^2)$ given before.

- 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.

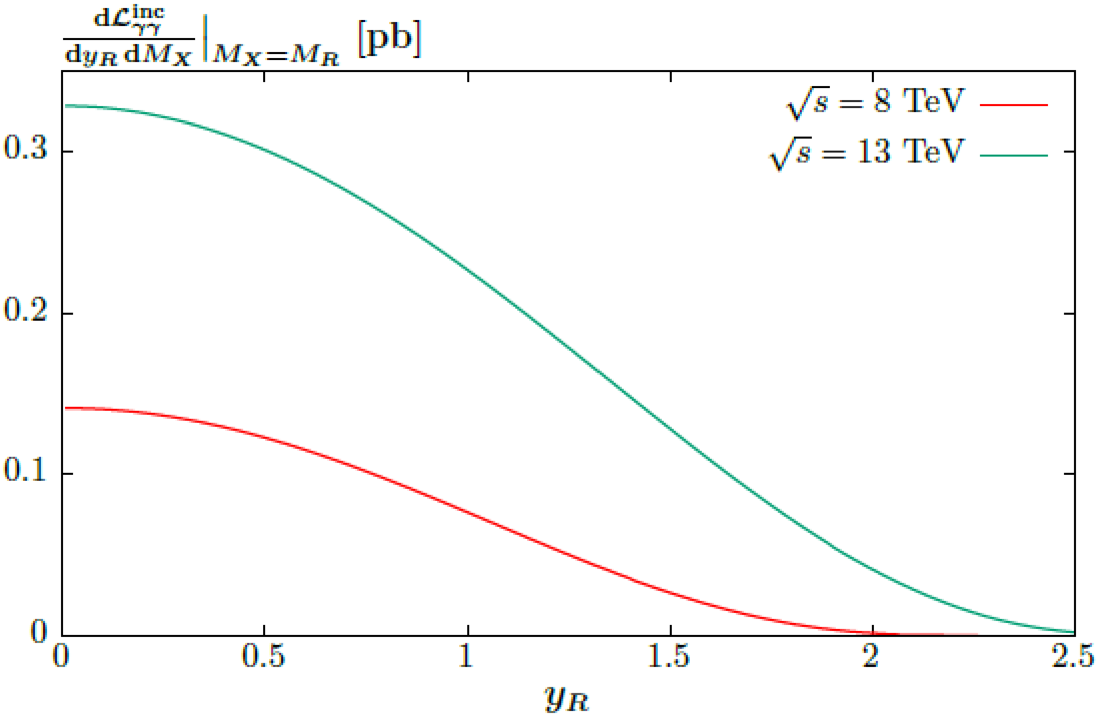
Luminosity predictions: mass dependence



$$\sigma(13\,\mathrm{TeV})/\sigma(8\,\mathrm{TeV}) \sim 2-10 \text{ for } M_X = 200-2000\,\mathrm{GeV}$$

- Ratio of luminosities steeply falling with M_X : phase space running out quicker at $\sqrt{s} = 8\,\mathrm{TeV}$.

Luminosity predictions: c.m.s. energy ratios



- For $M_R = 750\,\text{GeV}$ we find $\quad \dfrac{\mathcal{L}^{\rm inc}_{\gamma\gamma}(\sqrt{s}=13\,\text{TeV})}{\mathcal{L}^{\rm inc}_{\gamma\gamma}(\sqrt{s}=8\,\text{TeV})} = 2.9$

$\longrightarrow$ Consistent with lack of 8 TeV signal.

Luminosity predictions: 13 TeV

- Using our result for the $\gamma\gamma$ luminosity at 13 TeV we find:

$$\sigma^{\rm inc}(pp \to (R \to \gamma\gamma)) = 91\,{\rm fb}\,\left(\frac{\Gamma_{\rm tot}(R)}{1\,{\rm GeV}}\right) {\rm Br}(R \to \gamma\gamma)^2$$

or rearranging

$$\mathrm{Br}(R \to \gamma\gamma) = \frac{1}{9.5}\left(\frac{\sigma^{\rm inc}[{\rm fb}]}{\Gamma_{\rm tot}(R)/1\,{\rm GeV}}\right)^{1/2}$$

- Thus if we take $\sigma = 4 - 8\,{\rm fb}$ and $\Gamma_{\rm tot} = 45\,{\rm GeV}$ then

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

W, Z couplings must be!

$\longrightarrow$ Other couplings must be (dominantly) present.

- Conversely if we assume $\mathrm{Br}(R \to \gamma\gamma) = 100\%$ then

$$\Gamma_{\rm tot} = 44 - 88\,{\rm MeV}$$

Luminosity predictions: uncertainties

- What are the sources of uncertainty?
- The photon PDF at the starting scale, $\gamma(x, Q_0^2)$:
  - Recall we know at least 75% of this (due to coherent emission) very precisely. In addition at $\mu = M_R$ large fraction also due to DGLAP splitting of quarks, washing out uncertainty.
  - Maximally conservative estimate: setting $\gamma^{\text{incoh}}(x, Q_0^2) = 0$ gives $\sim 15\%$ smaller cross section than our upper bound. PDF fit can improve this.
- PDF uncertainty in quark/gluon PDFs in evolution: $\sim 2\%$
- Scale uncertainty: varying μ_F, μ_R independently between $(M_R/2, 2M_R)$ we find $\sim 10\%$ variation.

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

Enhancing the $\gamma\gamma$ contribution

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

  $\Rightarrow$ Production via VBF.
- 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

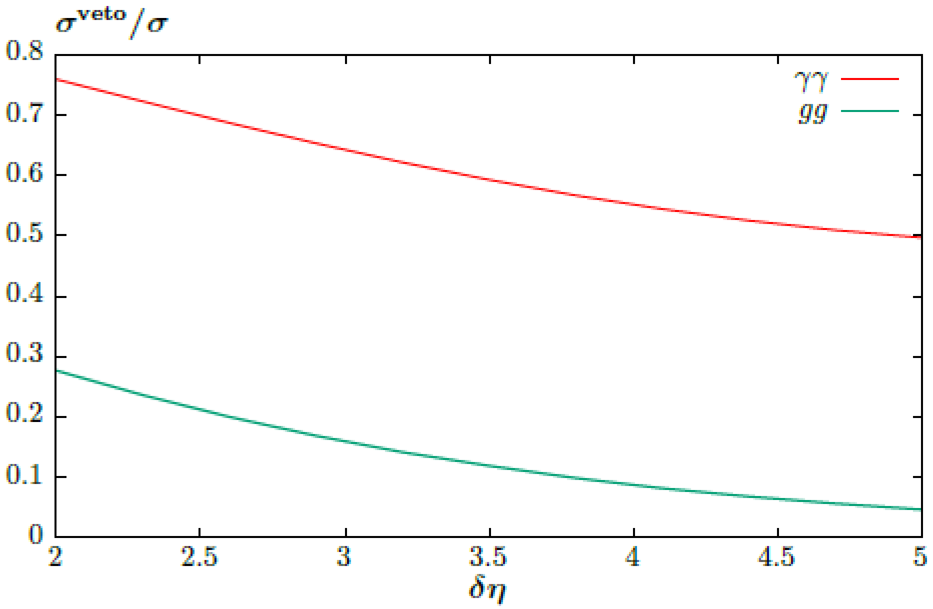
- Gluons: carry colour and like to radiate!
- Photons: colour-singlet and less likely to radiate ($\alpha \ll \alpha_S$).

$\longrightarrow$ 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. arXiv:1601.1377

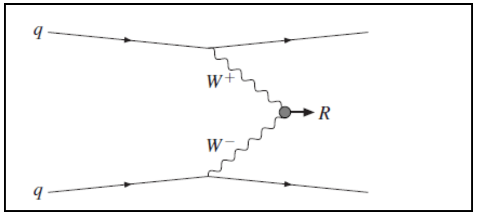
gg fusion

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

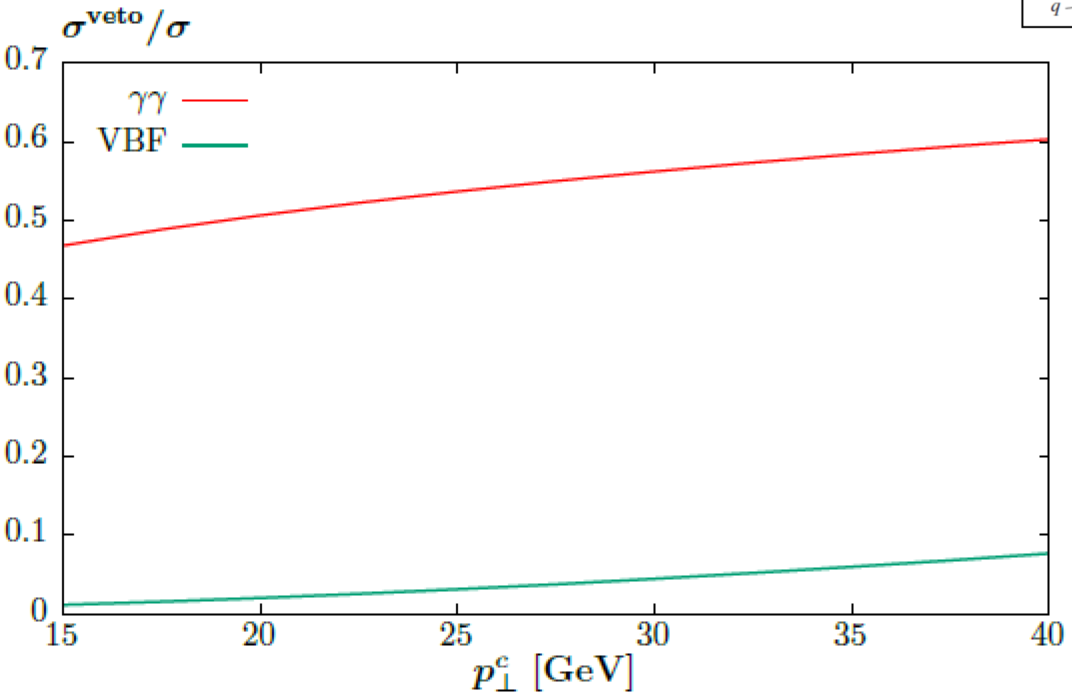


- For $\delta\eta \sim 2-3$ only $\sim 20\%$ of gg-initiated events have no additional jets, whereas for $\gamma\gamma$-initiated events $\sim 70\%$ do.
- For $k_\perp^c = 15(50)$ GeV find $\sim 50(65)$ % of $\gamma\gamma$-events with no jets, while for gg case this is below $\sim 10\%$. Expect continuum $\gamma\gamma$ BG to be similar to gg

$\longrightarrow$ Clear difference in event topology.



Vector boson fusion

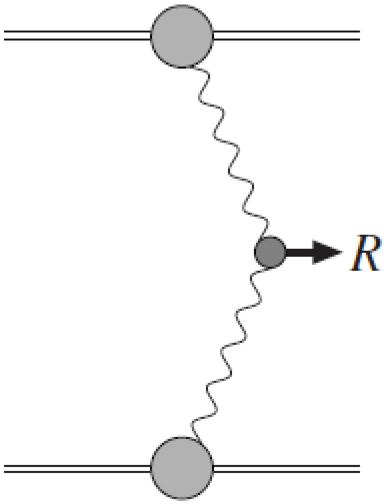


- Fraction of VBF contribution with e.g. $p_\perp^R < 20\,\mathrm{GeV}$ is $\sim$ % level, while for $\gamma\gamma$ -initiated production this is $\sim 50\%$.

⟶ Extremely different behaviour under this simple cut.

Exclusive production

- So far have only consider standard inclusive process, i.e. production of resonance $R \to \gamma\gamma$ + ‘anything else’.
- However colour-singlet $\gamma\gamma$ initial state leads naturally to exclusive final state: production of $R \to \gamma\gamma$ + nothing else, with protons remaining intact after collision.



‘Central Exclusive Production’

(talks by Christophe, Gero, Jonathan)

Resonance production with tagged protons

- Why might we be interested in exclusive resonance production? One major reason: protons remain intact and can therefore be measured.

- Detectors designed for precisely this currently installed/approved for installation:

‣ ATLAS- AFP	CERN-LHCC-2011-012
‣ CMS- CT-PPS	CERN-LHCC-2011-021

- A $M_R = 750\,\text{GeV}$ resonance is perfectly placed in terms of the mass acceptance of these detectors.

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

Exclusive production: theory

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

Two effects to consider:*

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

*in fact procedure slightly more complicated, see arXiv:1508.02718 where the photon Sudakov factor

$$S_\gamma(Q_0^2,\mu^2)=\exp\left(-\frac{1}{2}\int_{Q_0^2}^{\mu^2}\frac{\mathrm{d}Q^2}{Q^2}\frac{\alpha(Q^2)}{2\pi}\int_0^1\mathrm{d}z\sum_{a=q,l}P_{a\gamma}(z)\right)\ ,$$

corresponds to the probability for the photon PDF to evolve from scales Q_0 to μ without further branching; here $P_{q(l)\gamma}(z)$ is the γ to quark (lepton) splitting function at NLO in α_s. At LO it is given by

$$P_{a\gamma}(z)=N_a\left[z+(1-z)^2\right]\ ,$$

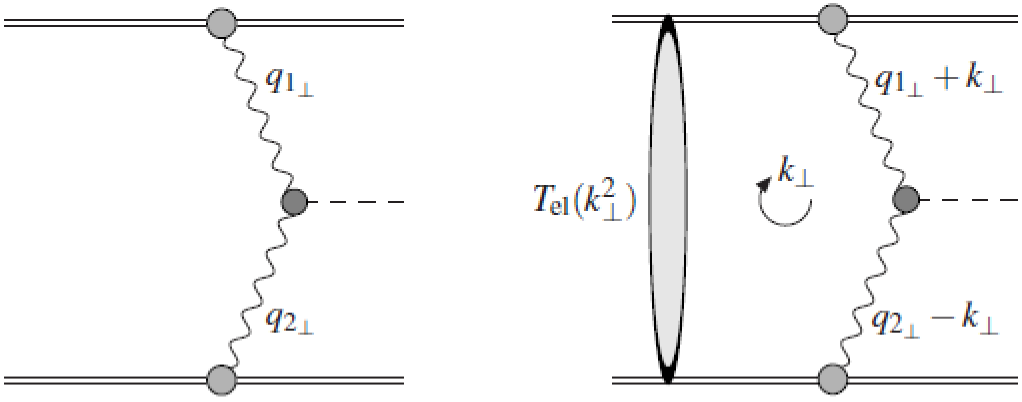
where $N_a = N_c e_q^2$ for quarks and $N_a = e_l^2$ for leptons

- As the scale $\mu\uparrow$ the phase space for emission increases and $S_\gamma\downarrow$.
- For e.g. $\mu = 750\,\mathrm{GeV}$ we have $S_\gamma^2 \sim 0.85$, i.e. $\sim 15\%$ emission probability from annihilating $\gamma\gamma$.

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 $Q^2_{1,\mathrm{min}} = \frac{\xi_1^2 m_p^2}{1-\xi_1}$

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 $S^2_{\mathrm{eik}} \to 1$.
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

SURVIVAL GUIDE

- Averaged survival factor given by (in impact parameter space)

Opacity, relates to prob. of no inelastic scatterin

$$\langle S^2_{\text{eik}} \rangle = \frac{\int d^2 b_{1t}\, d^2 b_{2t}\, |T(s, b_{1t}, b_{2t})|^2 \exp(-\Omega(s, b_t))}{\int d^2\, b_{1t} d^2 b_{2t}\, |T(s, b_{1t}, b_{2t})|^2}$$

One-channel for illustration

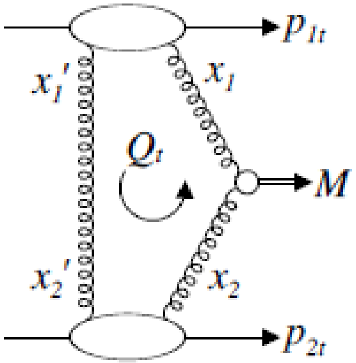
'Bare' amplitude

in $p_\perp$ space this is equivalent to

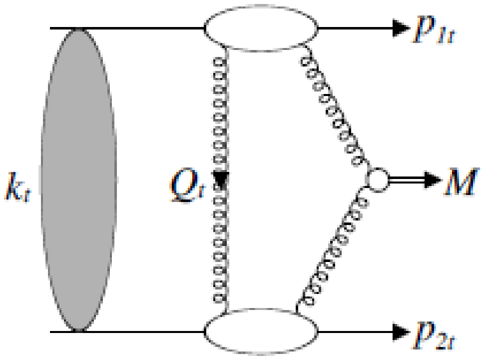
$$\langle S^2_{\text{eik}} \rangle = \frac{\int d^2 p_{1_\perp}\, d^2 p_{2_\perp}\, |T(s, p_{1_\perp}, p_{2_\perp}) + T^{\text{res}}(s, p_{1_\perp}, p_{2_\perp})|^2}{\int d^2 p_{1_\perp}\, d^2 p_{2_\perp}\, |T(s, p_{1_\perp}, p_{2_\perp})|^2}$$

where 'screened' amplitude is given by

$$T^{\text{res}}(s, p_{1_\perp}, p_{2_\perp}) = \frac{i}{s} \int \frac{d^2 k_\perp}{8\pi^2}\, T_{\text{el}}(s, k_\perp^2)\, T(s, p'_{1_\perp}, p'_{2_\perp})$$



'Bare' amplitude



'Screened amplitude'

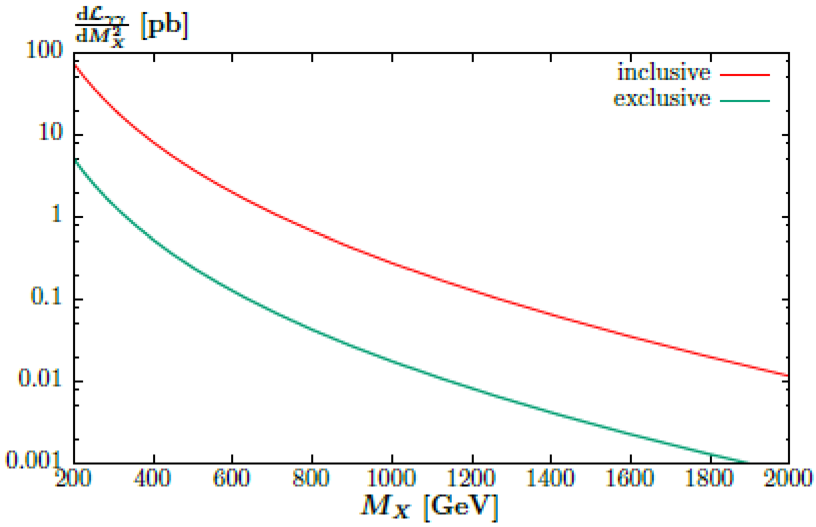
Exclusive resonance cross section

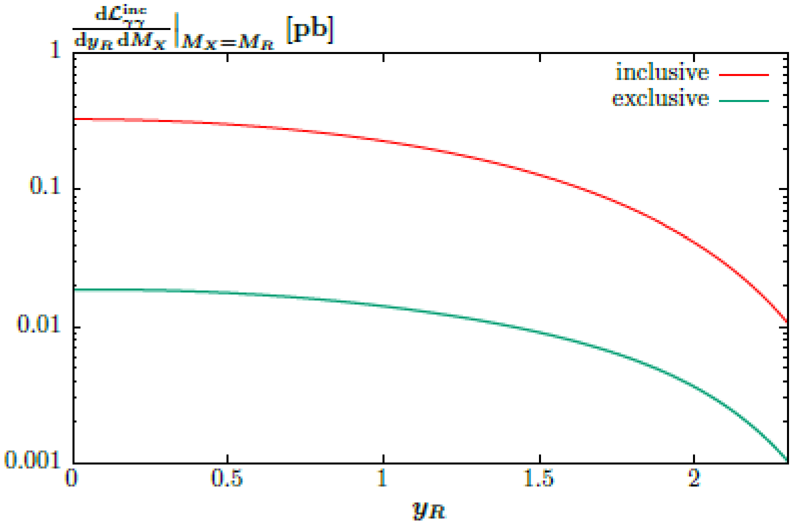
- As with inclusive case, we can consider the $\gamma\gamma$ luminosity, but for exclusive production.

- For R cross section, find:

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

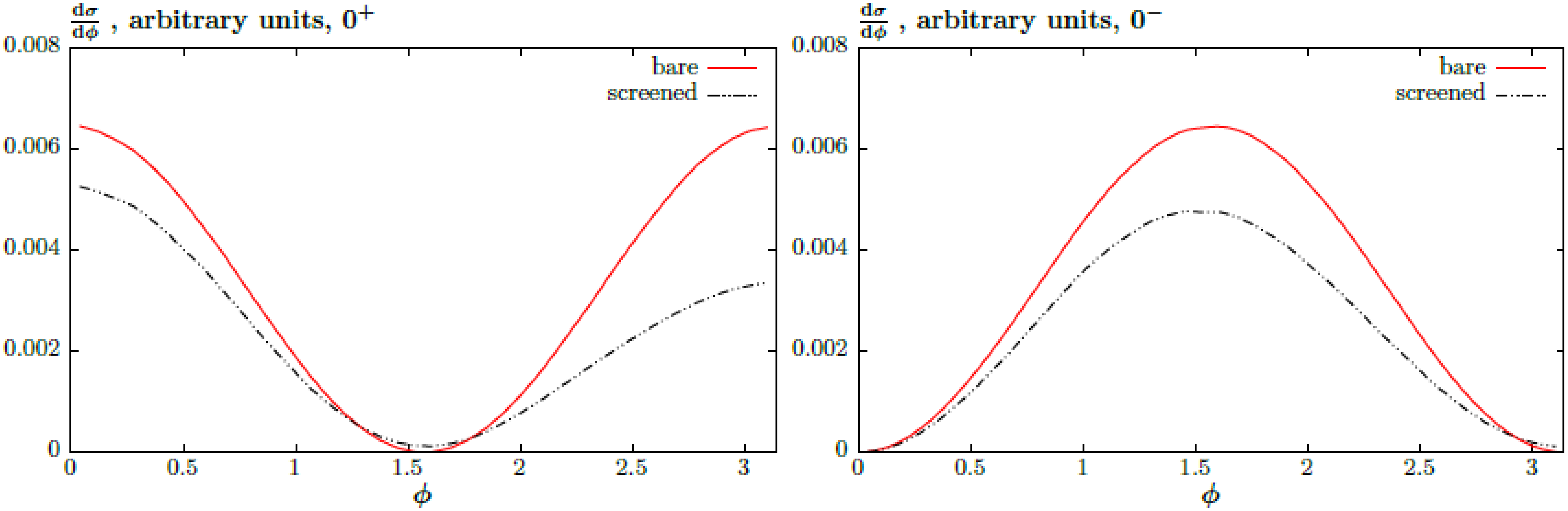
$$\sigma^{\rm exc}(pp \to (R \to \gamma\gamma)) = 0.063 \cdot \sigma^{\rm inc}(pp \to (R \to \gamma\gamma)) = \underset{\uparrow}{0.25 - 0.50}\,{\rm fb}$$





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.

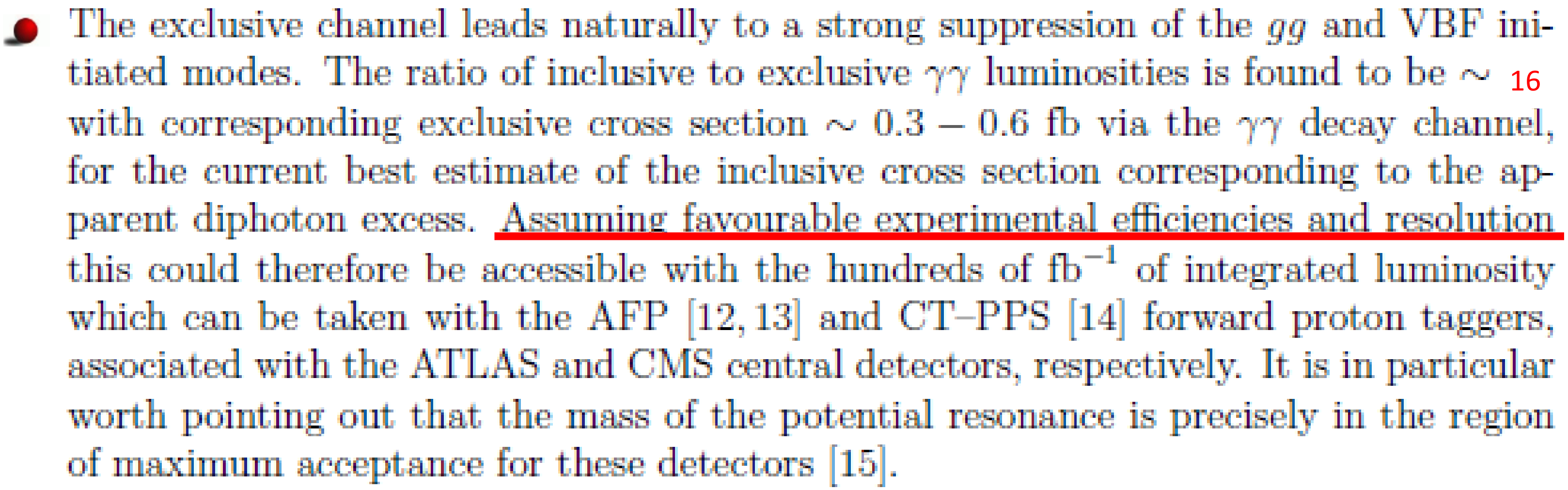
Assuming the 750 GeV- resonance survives and couples dominantly to photons :

- 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 $\text{Br}(R \to \gamma\gamma) = 3.1 - 4.4\,\%$.
- $$\boxed{\frac{\mathcal{L}^{inc}_{\gamma\gamma}(\sqrt{s} = 13\,\text{TeV})}{\mathcal{L}^{inc}_{\gamma\gamma}(\sqrt{s} = 8\,\text{TeV})} = 3.0}$$

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...



- 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.

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 $\sigma_{F\bar{F}} = 0.12$ 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

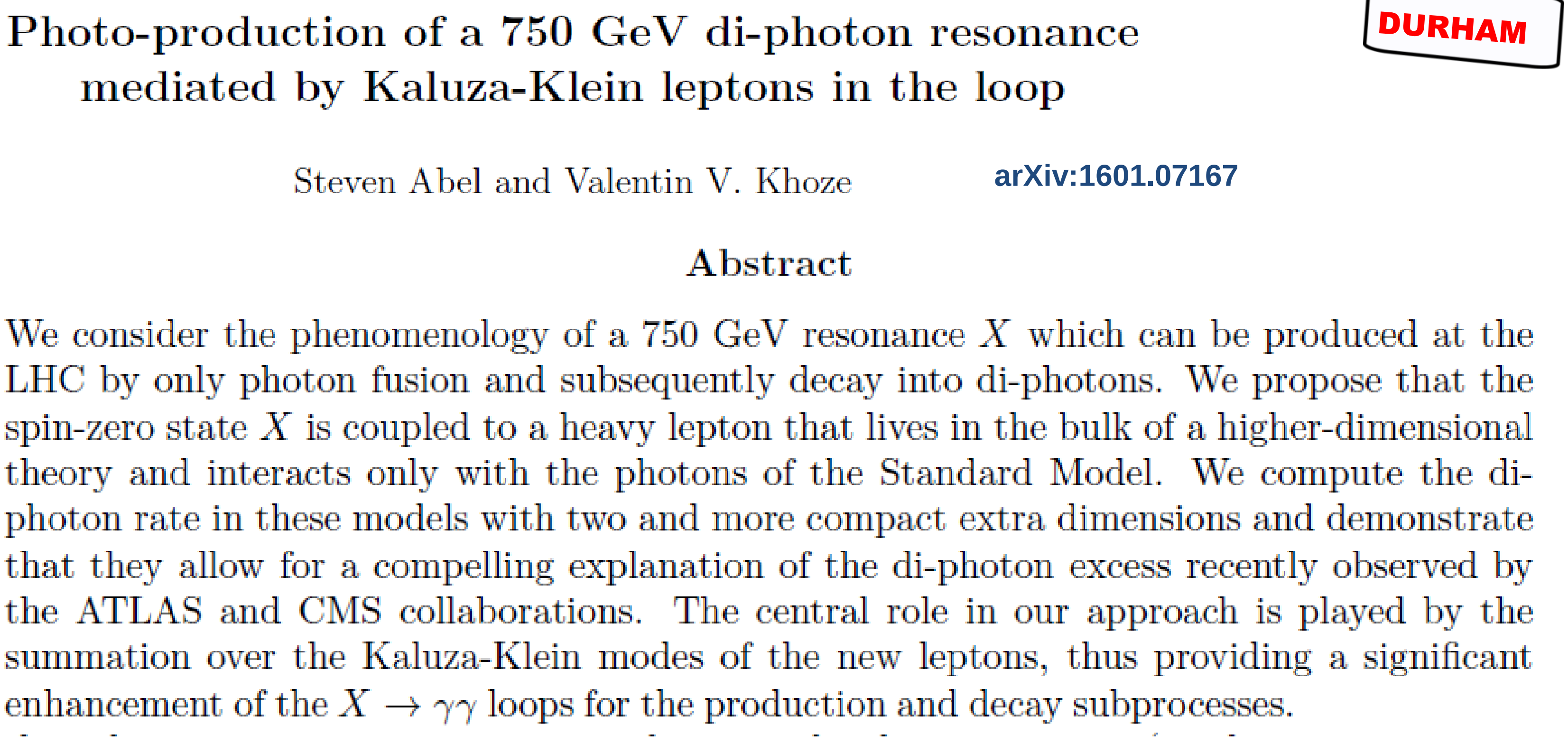


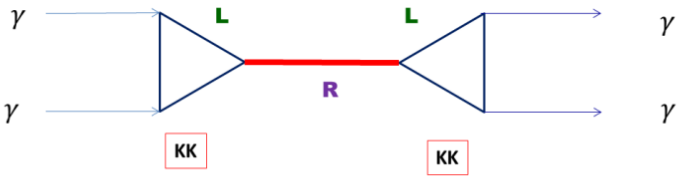
Photo-production of a 750 GeV di-photon resonance mediated by Kaluza-Klein leptons in the loop

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.



Summary

- Excess of events at 750 GeV seen so far only in $\gamma\gamma$ channel. Might be due to new resonance which couples dominantly to photons.
- Motivated by this, in arXiv:1601.03772 we present the **most** precise and up-to-date predictions for $\gamma\gamma$ initial-state.
- Photon PDF well determined: dominant contribution at Q_0 from 'coherent' emission from proton. $\sim 15-20\,\%$ uncertainty at $\mu = M_R$.
- VBF and gg production mechanisms can be separated by simple cuts on extra jet activity and $p_\perp$ of the final-state $\gamma\gamma$.
- $\gamma\gamma$-initated process naturally leads to 'exclusive' final state. Measurement of this probes only $\gamma\gamma$ initial state, and is sensitive to quantum numbers of R and CP-violating effects.

WARNING! Absorption effects in photon-induced 'CEP' processes at the LHC could be quite sizeable and should be accounted for, in particular for precise comparison


THANK YOU

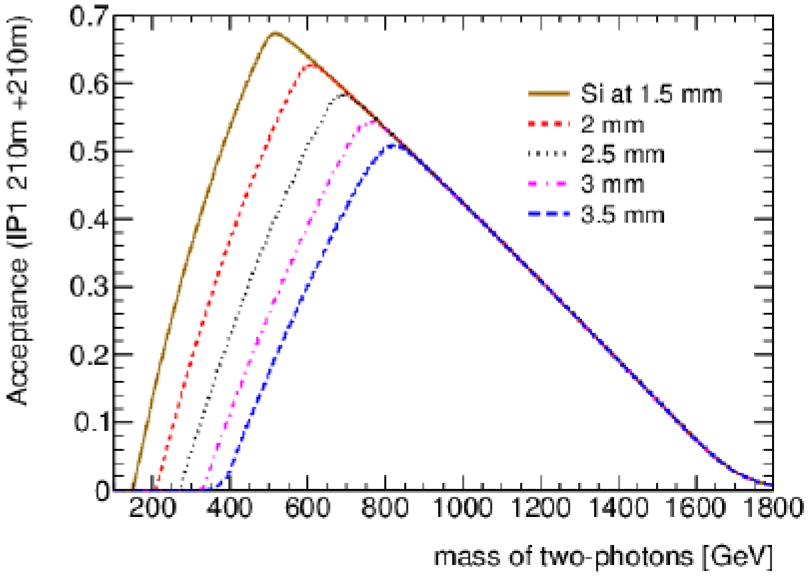

QUESTIONS?

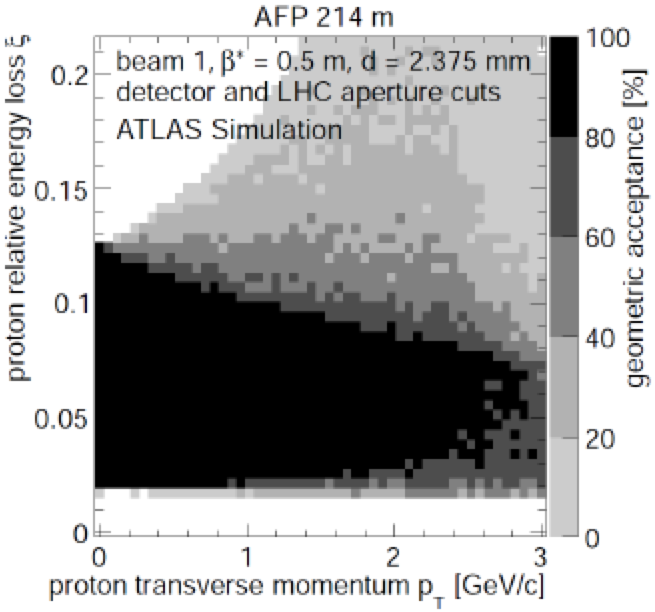
BACKUP

Kinematics

AFP

- Acceptance large for $0.015 < \xi < 0.13$
- 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)



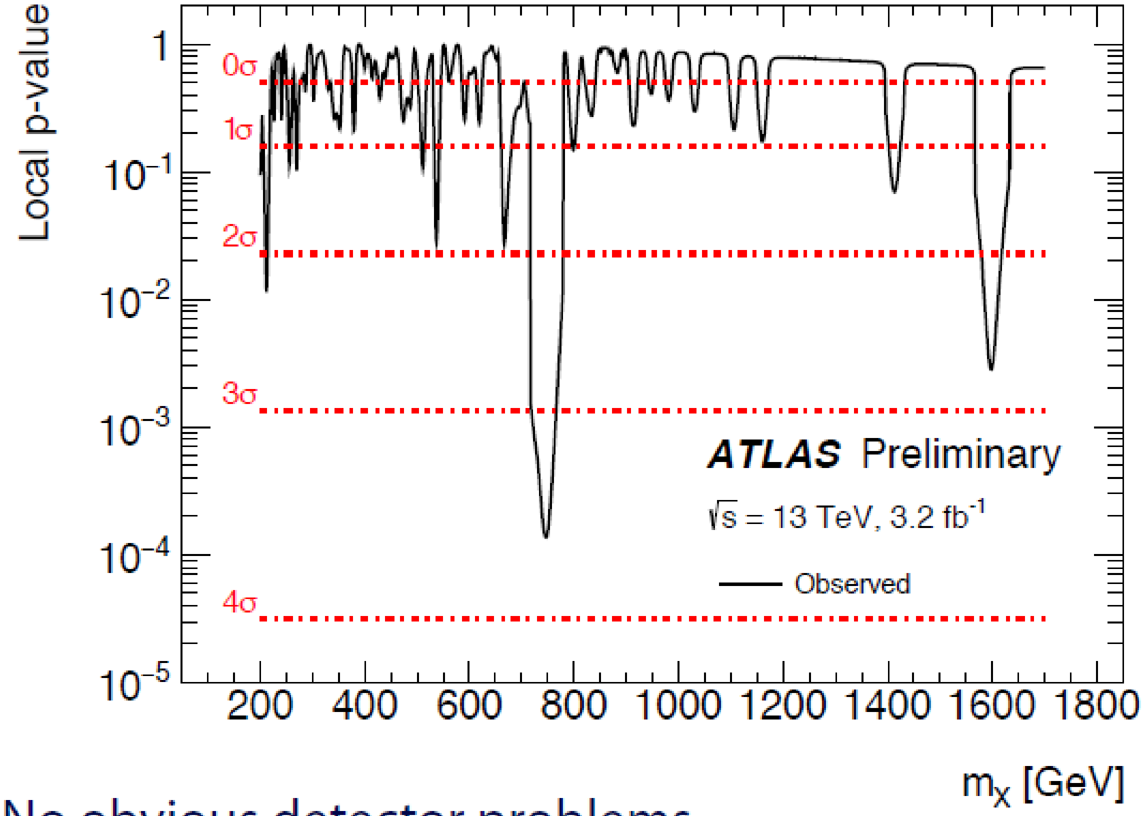


PRAGUE FZÚ

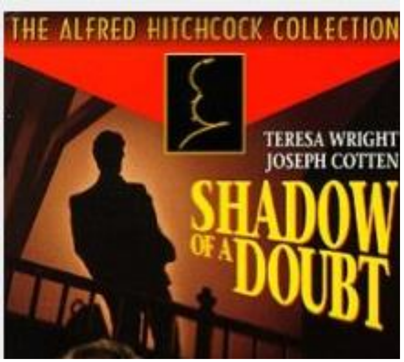
Oldrich Kepka

Diphoton

"Higgs-like" NWA scan → local(global) 3.6(2.0)σ excess around 750 GeV



- No obvious detector problems
- Event characteristics : consistent with mass sideband
- ~1.5σ pull of photon energy resolution systematics



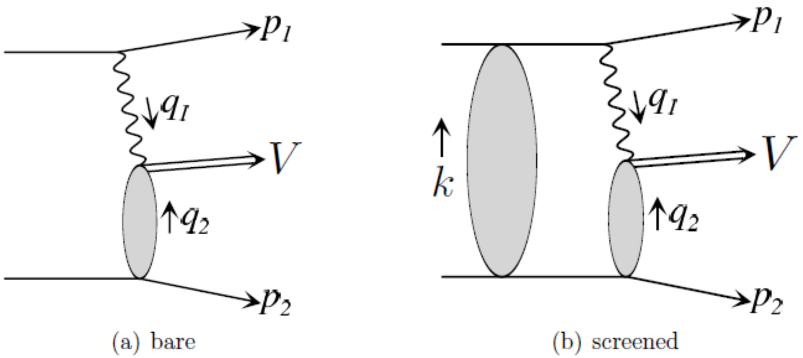
(Talk by K.Terashi at KIAS, march 2nd)

Example process: J/ψ photoproduction

- C-odd J/ψ : produced exclusively through $\gamma I\!\!P$ fusion.
- Observed by LHCb and ALICE at the LHC.

LHCb collab., J. Phys. G41 (2014) 055002 ALICE collab., Phys. Rev. Lett. 113 (2014) 23, 232504

- Survival effects less important compared to pure QCD CEP, but not negligible, in particular for precise comparisons.



(a) bare (b) screened

Figure 2: Schematic diagrams for the exclusive photoproduction process $pp \to pVp$ with (a) and without (b) screening corrections included.

J/ψ photoproduction: results

- We find:

LHCb acceptance, $\mu^+\mu^-$decay including spin corr.

		$2 < \eta^\mu < 4.5$	
		$\sqrt{s} = 7$ TeV	$\sqrt{s} = 13$ TeV
σ [pb]	$\sigma^\psi_{\text{bare}}$	$\underline{360}$	512
	$\sigma^\psi_{\text{sc.}}$	$\underline{278}$	405
	$\langle S^2_{\text{eik}} \rangle$	0.77	0.79

Interesting to test in Run II

- LHCb measure:

$$\sigma^{J/\psi\to\mu^+\mu^-}(2 < \eta^\mu < 4.5) = 291 \pm 7 \pm 19\,\text{pb}$$

$\longrightarrow$ Predictions with screening effects favoured.

What about differential tests?

Rapidity distribution

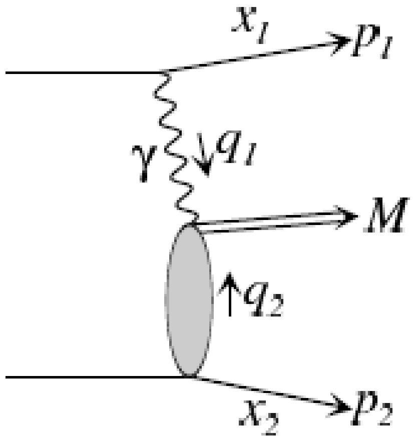
- Photon virtuality has kinematic minimum $Q^2_{1,\mathrm{min}} = \dfrac{\xi_1^2 m_p^2}{1-\xi_1}$

where $\xi_1 \approx \dfrac{M_\psi}{\sqrt{s}} e^{y_\psi}$ assuming photon emitted from proton 1

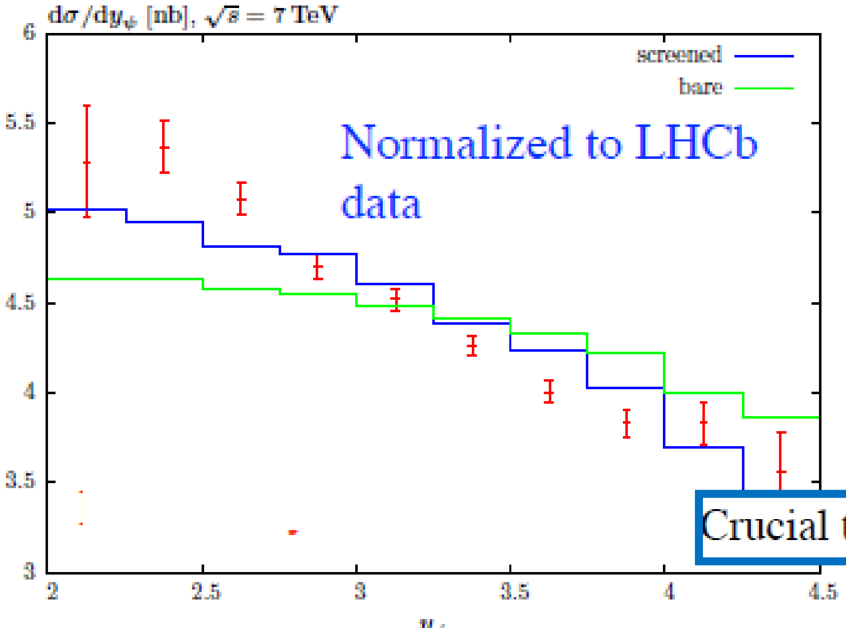
positive
z-direction

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

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



- Predicted rapidity distribution steeper due to survival effects:



Normalized to LHCb data

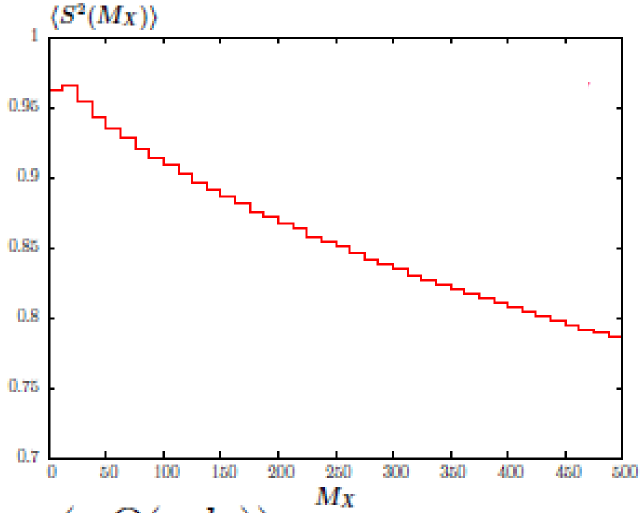
- Screened prediction gives better description

- The same is valid for $p_{\psi\perp}$ distribution.

Crucial to include in any precise phenomenological predictions.

$M_X = W_{\gamma\gamma}$

- Consider $\langle S^2(M_X)\rangle$ for W^+W^- production: clear drop with M_X seen.



- Recall expression for survival factor:

$\gamma\gamma \to X$

$$\langle S^2_{\rm eik}\rangle = \frac{\int d^2b_{1t}\, d^2b_{2t}\, |T(s, b_{1t}, b_{2t})|^2 \exp(-\Omega(s, b_t))}{\int d^2\, b_{1t} d^2b_{2t}\, |T(s, b_{1t}, b_{2t})|^2}$$

$\longrightarrow$ Important to correctly include b_t dependence of subprocess amplitude

(massless leptons)

- l^+l^- production: the $\gamma\gamma \to l^+l^-$ amplitudes vanish for $J_z = 0$ initial state photons. It turns out this leads to less absorption than naive expectations.

- In particular, this leads to dependence on event selection: by demanding small $p_\perp(l^+l^-)$, get $\langle S^2\rangle$ very close to 1.

V.A. Khoze, A.D. Martin, R.Orava, M.G. Ryskin, Eur. Phys. J. C19 (2001) 313-322

Could be potentially very useful for the accurate luminosity calibration

	$\mu^+\mu^-$	$\mu^+\mu^-$, $M_{\mu\mu} > 2M_W$	$\mu^+\mu^-$, $p_\perp^{\rm prot.} < 0.1$ GeV	W^+W^-
$\sigma_{\rm bare}$	6240	11.2	3170	87.5
$\sigma_{\rm sc.}$	5990	9.58	3150	71.9
$\langle S^2_{\rm eik}\rangle$	0.96	0.86	0.994	0.82

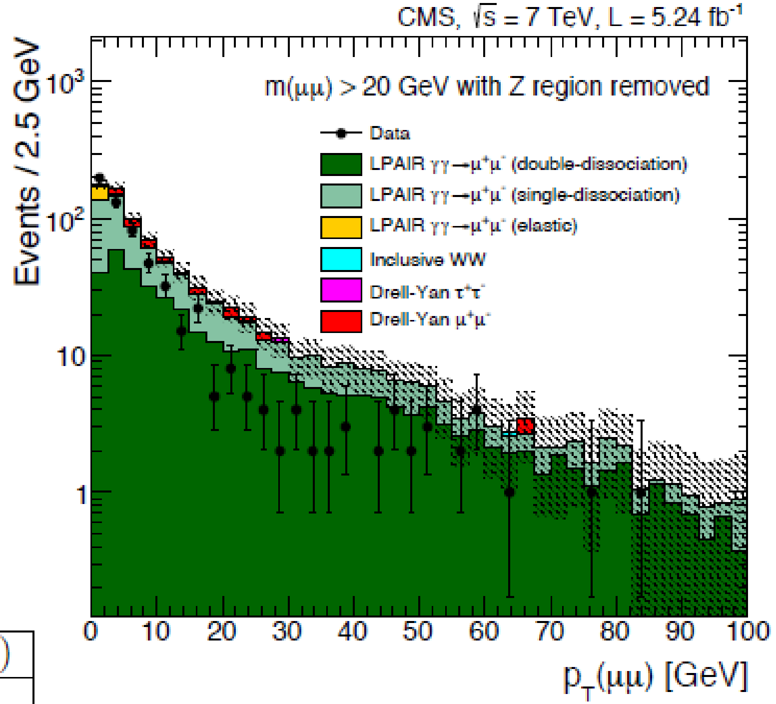
Table 5: Cross section predictions (in fb) for exclusive muon and W boson pair production at $\sqrt{s} = 13$ TeV. The muons are required to have $p_\perp > 5$ GeV and $|\eta| < 2.5$, and are shown with and without an additional cut of $M_{\mu\mu} > 2M_W$, while in the W boson case, no cuts are imposed. Results are shown for the 'bare' and 'screened' cross sections, i.e. excluding and including soft survival effects, respectively, and the resulting average suppression due to these is also given.

Rapidity gap survival - differential measurements

- Another possibility: central diffractive lepton pair production.
- In pure exclusive case $\langle S^2\rangle \sim 1$, but for proton dissociation have larger $p_\perp$ transfer and therefore smaller $\langle S^2\rangle$.

JHEP 1307 (2013) 116

- CMS $\mu^+\mu^-$ measurement: compare $p_\perp$ of $\mu^+\mu^-$ system against LPAIR. Overestimates data at higher $p_\perp$, due to survival factor.



$\longrightarrow$ Measurement sensitive to $\langle S^2(p_\perp^{\mu\mu})\rangle$.

$$pp \to Y + l^+l^- + Z$$

Not most up to date numbers, but give qualitative picture

Single	Low $M_{Y,Z}$ ($\lesssim 2.5$ GeV)	High $M_{Y,Z}$ ($\gtrsim 2.5$ GeV)	
S^2	0.86 ± 0.03	0.81 ± 0.03	
Double	(Low M_Y, Low M_Z)	(Low M_Y, High M_Z)	(High M_Y, High M_Z)
S^2	0.3 – 0.45	0.2 – 0.28	0.08 – 0.16

HKRS , Eur. Phys. J. C72 (2012) 2110