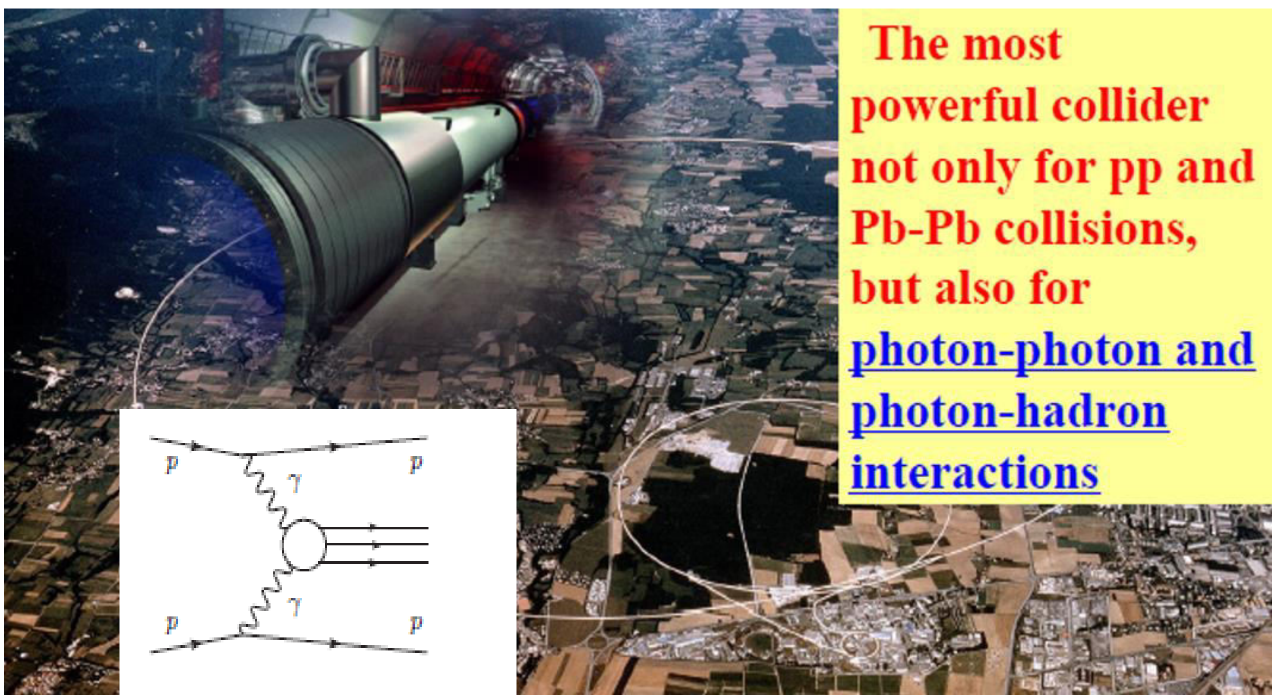
PHOTON-INDUCED PROCESSES AT HIGH ENERGY HADRON COLLIDERS (selected topics)

Valery Khoze (IPPP, Durham, UK & PNPI, St.Petersburg)



Outline

- Introduction and Motivation.
- Photon-Photon collisions .

- SuperChic MC and Survival Guide
- $\gamma\gamma$ collisions at the LHC- Applications (with an emphasis on BSM physics).
- Other Topical Examples.
- Summary and Outlook.

Emphasis reflects my own personal interests/bias as much as anything.

What is it?

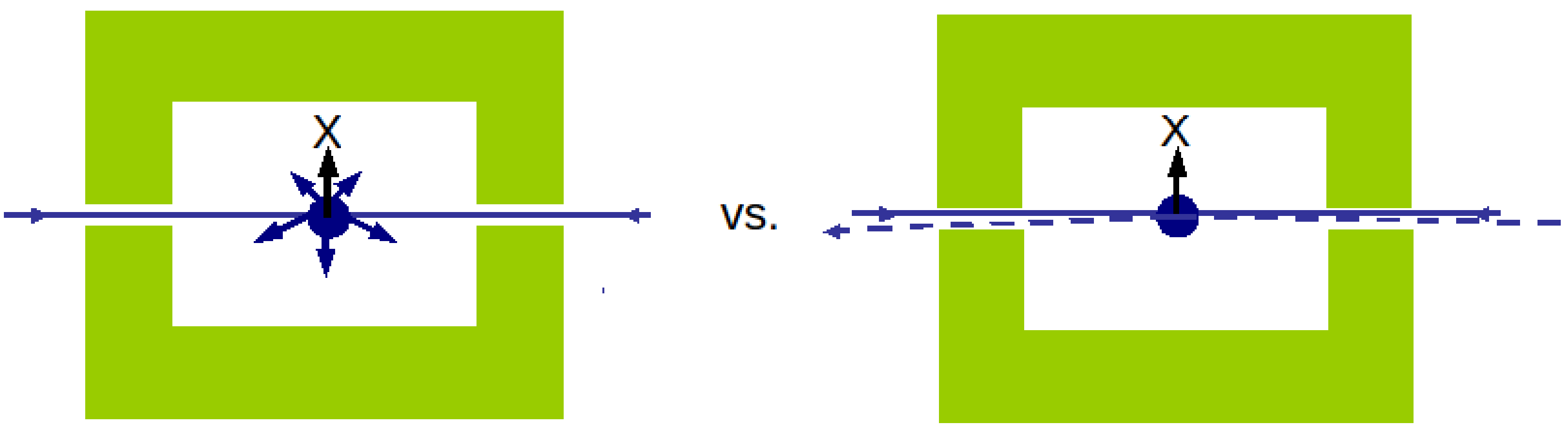
Central Exclusive Production (CEP) is the interaction:

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

- **CEP** colour singlet exchange between colliding protons, with large rapidity gaps ('+') in the final state.

Photons, Pomerons..

- 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.

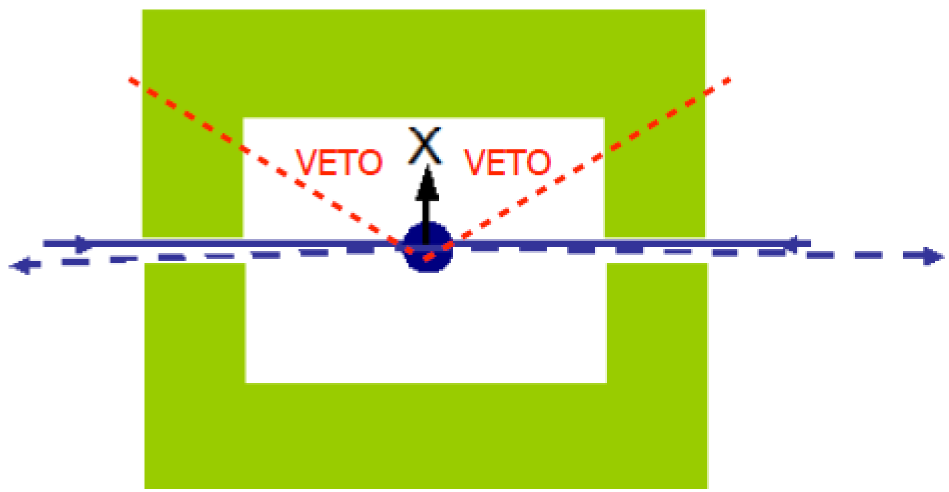


SELECTING EXCLUSIVE PHOTON-PHOTON EVENTS AT THE LHC

1) Gap-based selection: no extra activity in large enough rapidity region.

- No guarantee of pure exclusivity - BG with proton breakup outside veto region. Large enough gap $\Rightarrow$ BG small and can be subtracted.

- Pile-up contaminating gap? Either: low pile-up running (dedicated runs/ LHCb defocussed beams) or can veto on additional charged tracks only (already used to select charged - l^+l^-, W^+W^--by ATLAS/CMS/LHCb).



2) Proton tagging: $pp \to p + X + p$

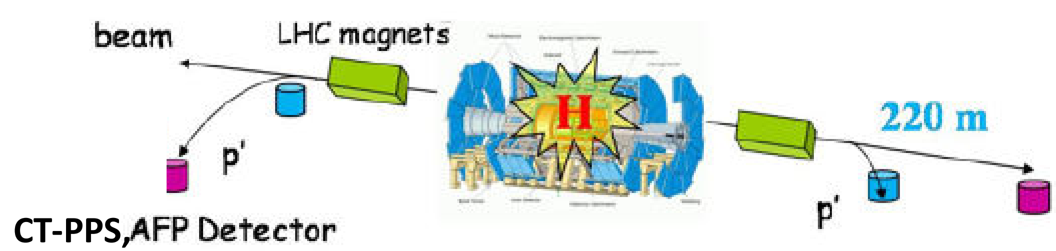
- Defining feature of exclusive events: protons intact after collision,

  $\longrightarrow$ If we can measure the outgoing protons, possi... purely exclusive event sa...

- Basic principle: us... After interaction pr... bend out of beam li...

- Ins... (mm) from beam line and $O(100\,\mathrm{m})$ from IP. Reconstruct momenta and measure arrival time of protons.

The LHC is best mass spectrometer

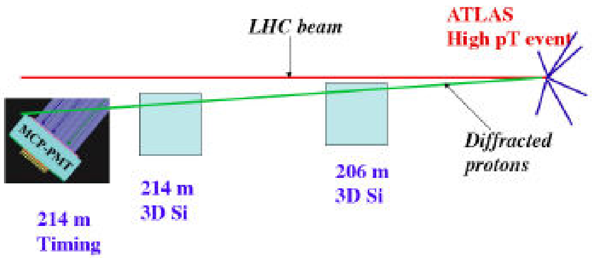


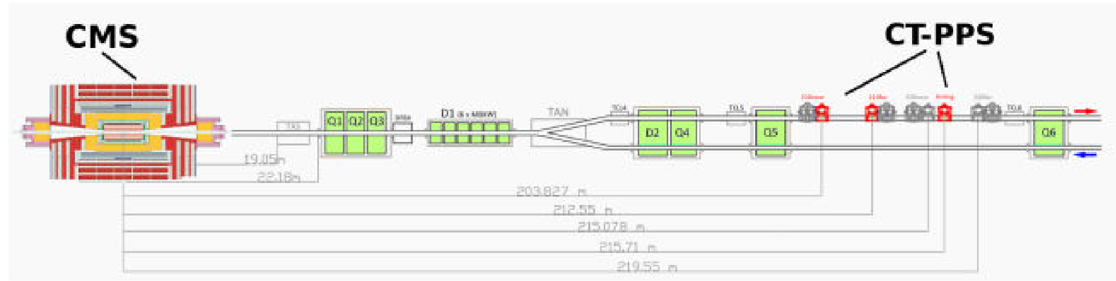
420m under discussion

(PPS, AFP first measurements with the one arm proton)

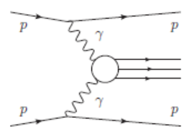
(Two arms-to come very soon PPS-CMS)

Proton detectors in CMS-TOTEM/ATLAS: today's configuration

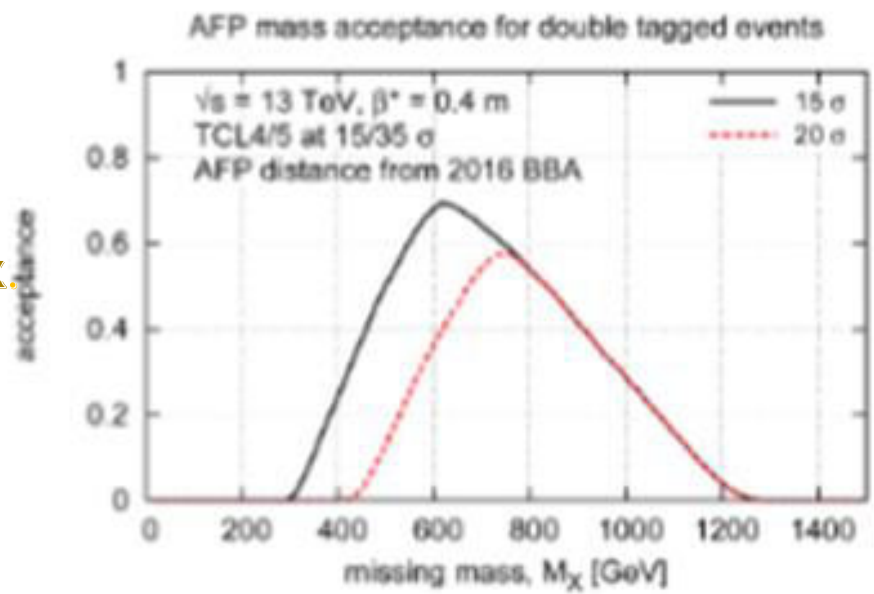




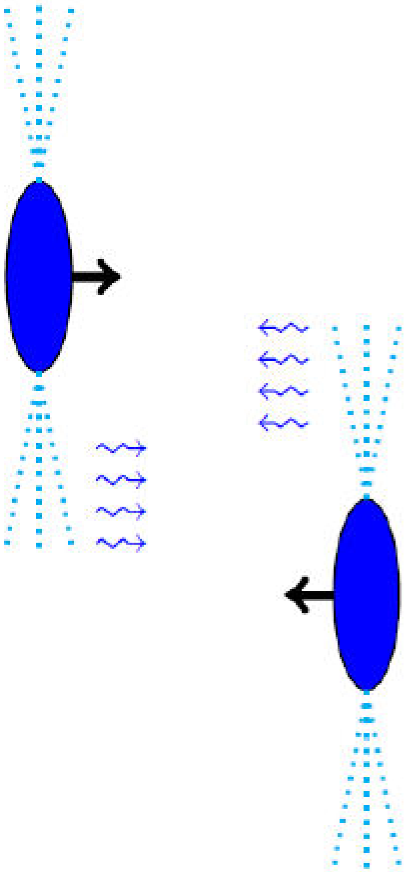
- Tag and measure protons at ± 210 m both in ATLAS (AFP) and CMS-TOTEM (PPS)
- Detectors: measure proton position (3D pixel or strip Silicon detectors) and time-of-flight (Ultrafast Si, diamond, quartz timing detectors)
- About 100 fb^{-1} of data have been accumulated by each experiment ($\sim$ 110 for PPS, 80 for AFP)
- Many analyses in progress



- THOU SHALT NOT ANNOY MACHINE PEOPLE.



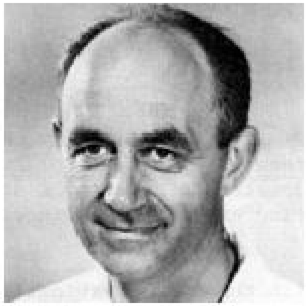
3) Ultra Peripheral HI Collisions



Nuovo Cim.,2:143-158,1925

http://arxiv.org/abs/hep-th/0205086

Therefore, we consider that when a charged particle passes near a point, it produces, at that point, a variable electric field. If we decompose this field, via a Fourier transform, into its harmonic components we find that it is equivalent to the electric field at the same point if it were struck by light with an appropriate continuous distribution of frequencies.



Enrico FERMI

The electromagnetic field surrounding these protons/ions can be treated as a beam of quasi real photons

Two ions (or protons) pass by each other with impact parameters b > 2R. **Hadronic interactions are strongly suppressed**

pp collisions

Pros

- harder EPA γ spectrum ($\omega_{\mathrm{max}} \sim$ TeV)
- more data available (~100 fb^{-1})

Cons

- large pile-up (multiple interactions per bunch crossing)
- problems with triggering on low p_{T} objects

Pb+Pb collisions

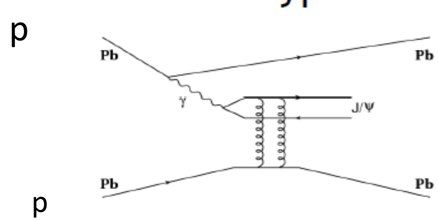
Pros

- AA ($\gamma\gamma$) x-sec $\propto Z^4$
- gluonic x-sec $\propto A^2$ → $A^{1/3}$
  $\Rightarrow$ lower QCD bkg.
- low pile-up ($< 1\%$)

Cons

- softer EPA γ spectrum ($\omega_{\mathrm{max}} \sim 0.1\mathrm{TeV}$)
- relatively small data

- Various types of interactions possible:



Photon-pomeron
(e.g. exclusive J/Psi)

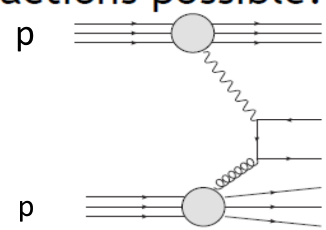
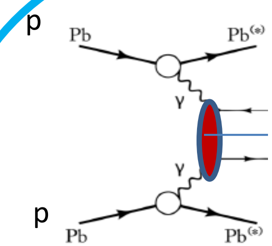


Photo-nuclear
(e.g. photoproduction of jets)

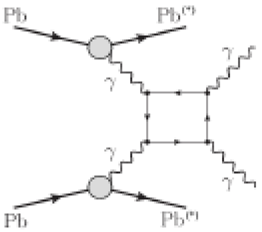


Photon-photon
(e.g. dilepton production)

CEP

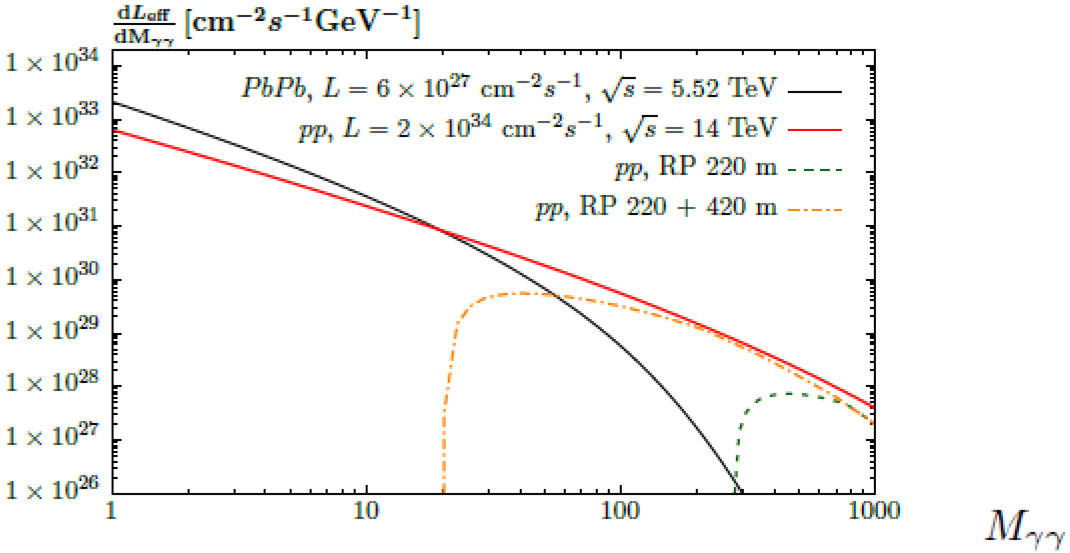
Emphasis

ATLAS@CMS(Run2)



Heavy Ion Collisions

- Photon-initiated CEP equally possible in heavy ion collisions. Indeed in some cases has significant **advantages**:
  - Significant $\sim Z^4$ enhancement in rate. After accounting for differing luminosities, still ~ 2 relative to pp , but with no pile-up.
  - QCD-initiated production essentially absent - clear interpretation.
  - Low pile-up - can go to low $M_{\gamma\gamma}$.
  - Conversely, steep fall off at high mass - pp essential here $\Rightarrow$ **complementary**.

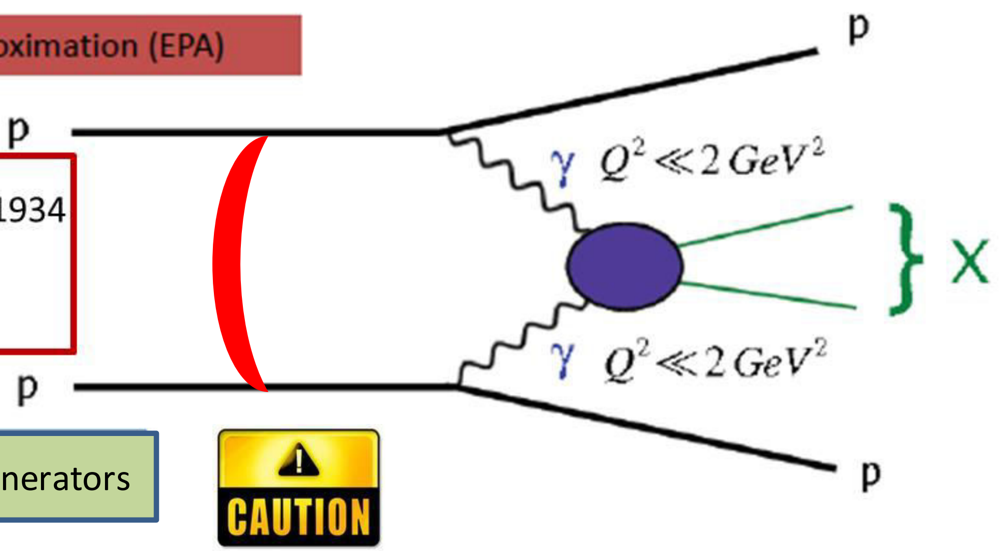


Modelling Exclusive Photon-Photon collisions

- In exclusive photon-mediated interactions, the colliding protons must both coherently emit a photon, and remain intact after the interaction. How do we model this?
- Answer is well known- the 'equivalent photon approximation' (EPA): cross section described in terms of a flux of quasi-real photons radiated from the proton, and the $\gamma\gamma \to X$ subprocess cross section.

Equivalent photon approximation (EPA)

C.F. von Weizsacker, 1934
E.J. Williams , 1934
E. Fermi, 1925



introduced to major event generators

Equivalent photon approximation

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

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

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

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

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

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

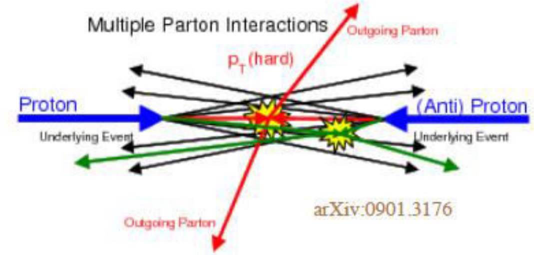
Received 25 April 1974
Revised version received 5 July 1974

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

$$\langle S_{\mathrm{eik}}^2\rangle = 0.72 \quad : \quad J_P = 0^+$$
$$\langle S_{\mathrm{eik}}^2\rangle = 0.77 \quad : \quad J_P = 0^-$$

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

SURVIVAL GUIDE

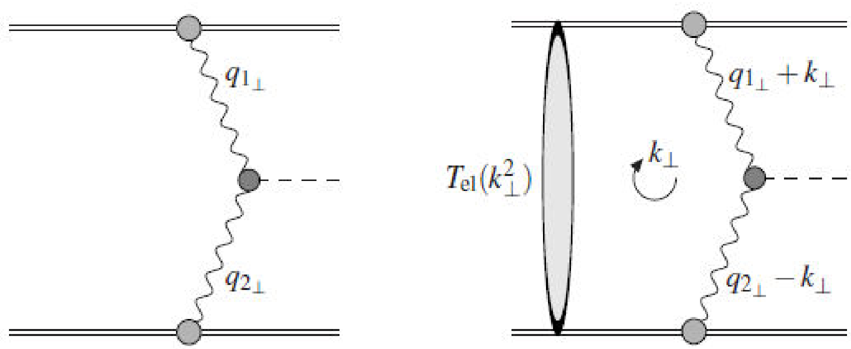


Soft survival factor

- 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).

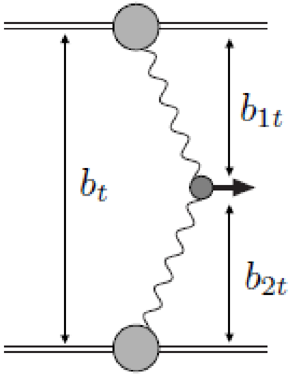
  $\rightarrow$ Must multiply our cross section by probability of no underlying event activity, known as the soft 'survival factor'.



Soft survival factor

- How do we calculate the survival factor? Work in impact parameter space and apply 'eikonal' approach:

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



$\exp(-\Omega(s, b_t))$: Poissonian probability of no inelastic scattering at impact parameter b_t .

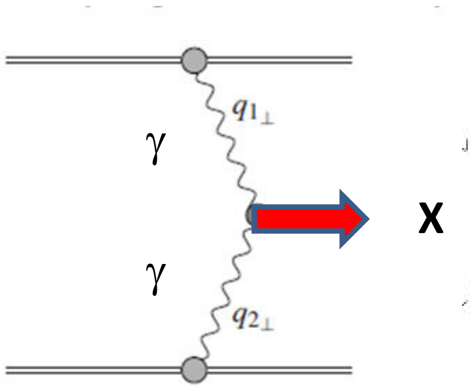
↑ proton opacity

- Underlying event generated by soft QCD. Cannot use pQCD ⇒ take phenomenological approach to this non-pert. observable.

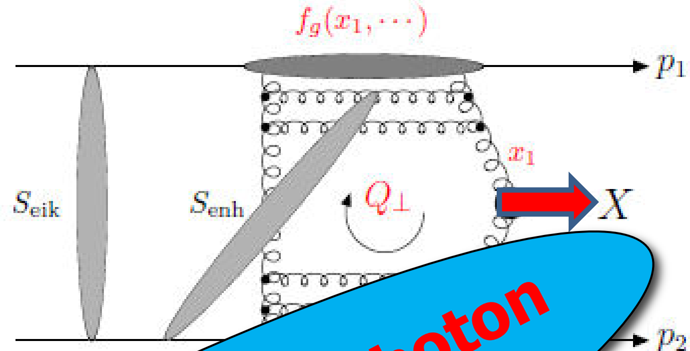
- Have: $$\frac{d\sigma^{pp\to pXp}}{dM_X^2 dy_X} = \langle S^2 \rangle \frac{d\mathcal{L}_{\gamma\gamma}^{\rm EPA}}{dM_X^2 dy_X} \hat{\sigma}(\gamma\gamma \to X)$$

KMR, GLM, Ostapchenko, Lund MCs

Well established in the QCD-mediated processes, e.g. CDF-diffractive dijets (2000), CMS/ATLAS- dijets in events with LRG (2015),H1 –diffractive dijet photoproduction (2011).



VS.



The LHC is the high energy photon collider

- Naively expect strong interacti … α.
- However QCD enhance … akness: exclusive event requires no ext … to final state. Requires introduction of S … ng factor:

$$T_g(Q_\perp^2,\mu^2) = \exp\left(-\int_{Q_\perp^2}^{\mu^2} \frac{\mathrm{d}k_\perp^2}{k_\perp^2}\frac{\alpha_s(k_\perp^2)}{2\pi}\int_0^{1-\Delta}\left[zP_{gg}(z)+\sum_q P_{qg}(z)\right]dz\right)$$

'Large' Pomeron size in the production of the small size objects.

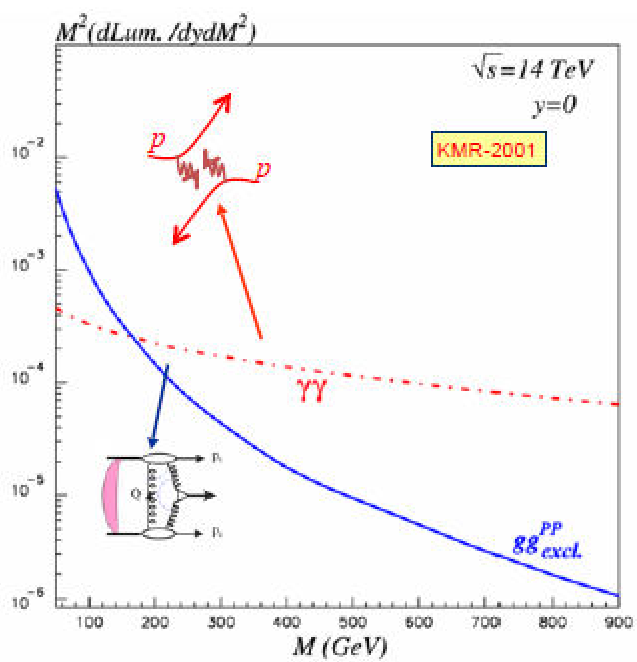
- Increasing M_X $\Rightarrow$ larger phase space for extra gluon emission stronger suppression in exclusive QCD cross section. Gluons like to radiate!

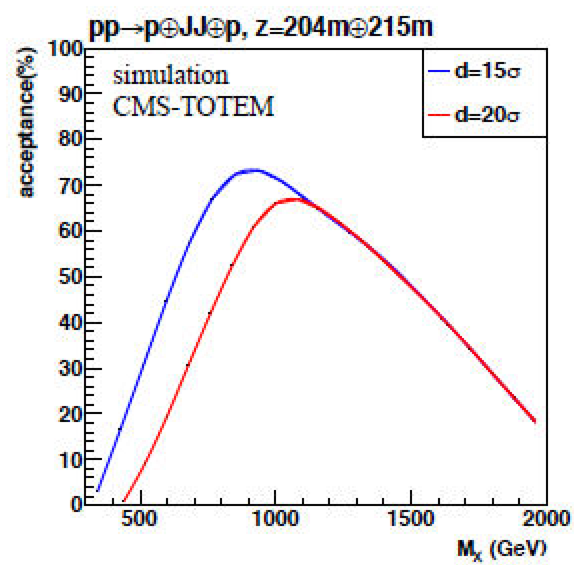
+ absorptive/rescattering effects- survival factor $S^2_{\rm soft}$

gg vs. $\gamma\gamma$

- Situation summarised in 'effective' exclusive gg and $\gamma\gamma$. luminosities. This Sudakov suppression in QCD cross section leads to enhancement in $\gamma\gamma$ already* for $M_X \gtrsim 200$ GeV - well before CT-PPS/AFP mass acceptance region.

$\longrightarrow$ Can study $\gamma\gamma$ collisions at the LHC with unprecedented $s_{\gamma\gamma}$.



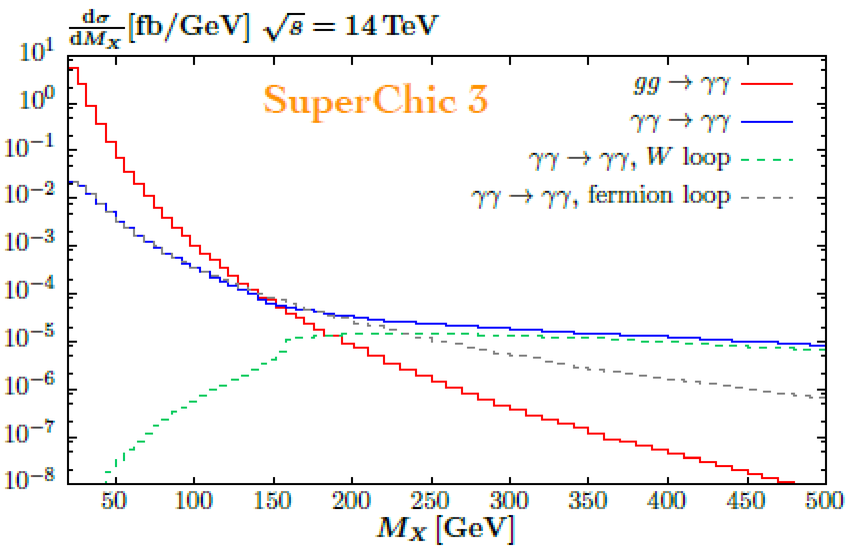


*Caveat - this is enhancement in initial state only.

16 Of course depends on coupling to produced state.

★ As mass of central system M_X increases, QCD-initiated production cross section suppressed by no radiation probability $\Rightarrow$ BG often low*.

- Example of $\gamma\gamma$ production:

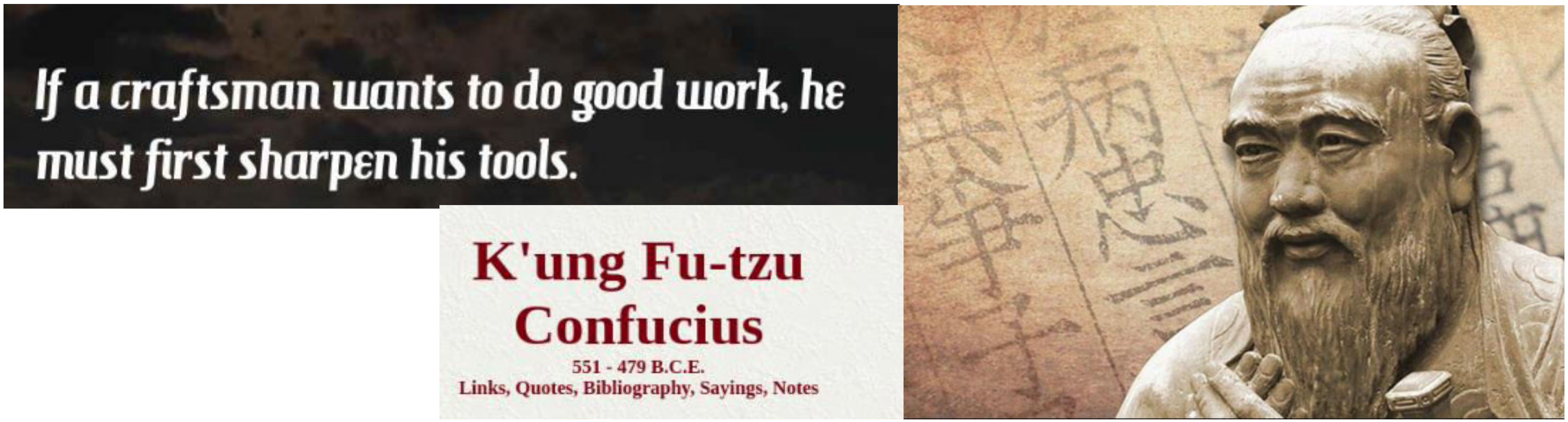


- CEP: unique possibility to observe photon-initiated production of states with EM coupling in clean/well understood environment.
- However typically considering high mass region (RPs) and relatively low cross sections (EM couplings). **Statistics limited**.

$\longrightarrow$ Increased statistics from HL-LHC running offer **clear advantage** here, in particular in terms of pushing to higher mass.

*Precise level depends on particular process.

CEP(photon)- TOOLS



FPMC; Starlight; LPAIR, SuperChic-2,3 (photon-induced processes)

ExHuME; SuperChic-2,3;FPMC; CEP@PYTHIA; CepGen; Dime; ExDiff;GenEx (CEP-QCD), Lund-Leif&Radek

SuperChic-3 incorporates pp,  ollisions and a complete treatment of soft survival effects.

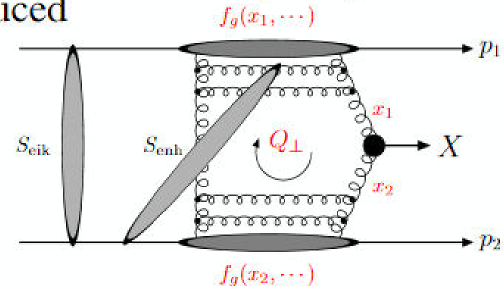
Photon-photon collisions in Superchic

Production mechanisms

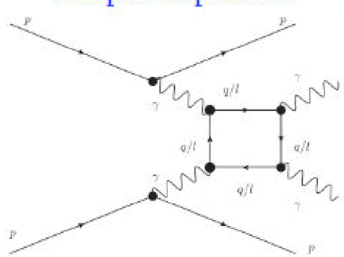
Exclusive final state can be produced via three different mechanisms, depending on kinematics and quantum numbers of state:

Gluon-induced

C-even, couples to gluons

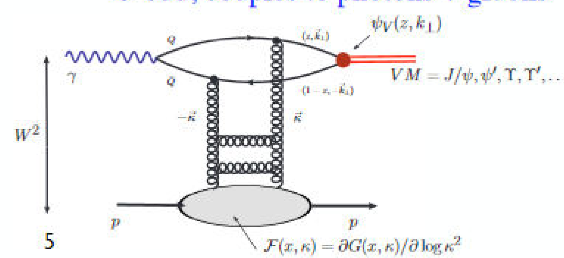


Couples to photons



Photon-induced

C-odd, couples to photons + gluons



Photoproduction

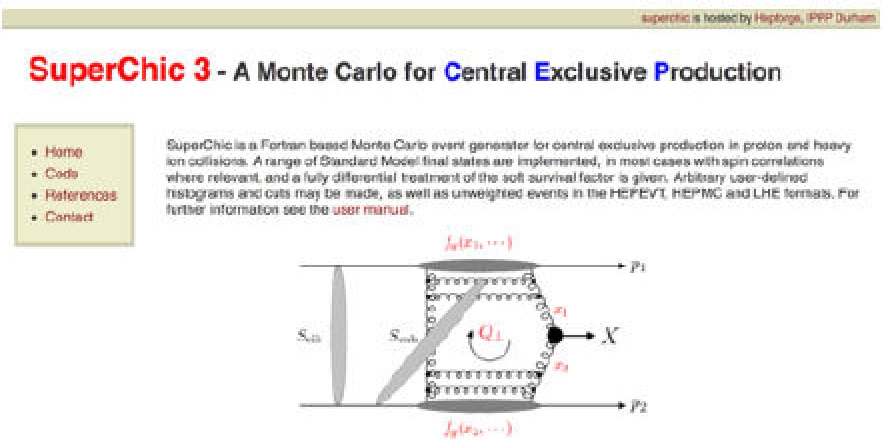
5

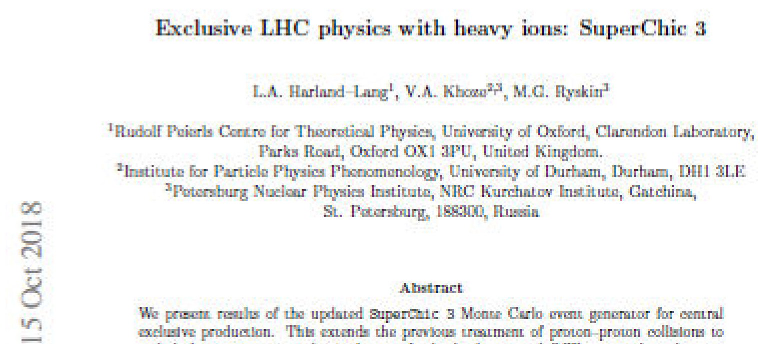
Tools for future studies - SuperChic MC

- A MC event generator for CEP processes. **Common platform** for:
  - QCD-initiated CEP.
  - Photoproduction.
  - Photon-initiated CEP.

- Previously generated pp collisions only, but recently updated to include pA and AA collisions.

arXiv:1810.06567




15 Oct 2018

Exclusive LHC physics with heavy ions: SuperChic 3

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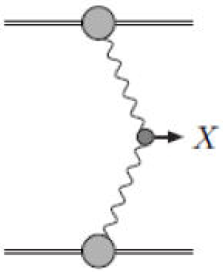
Abstract

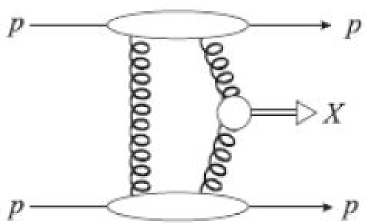
We present results of the updated SuperChic 3 Monte Carlo event generator for central exclusive production. This extends the previous treatment of proton–proton collisions to

https://superchic.hepforge.org

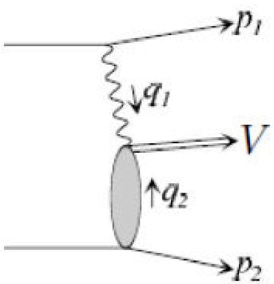
SuperChic MC - processes generated



★ W^+W^-, l^+l^-, LbyL, SM Higgs, ALPs, monopoles, monopolium.



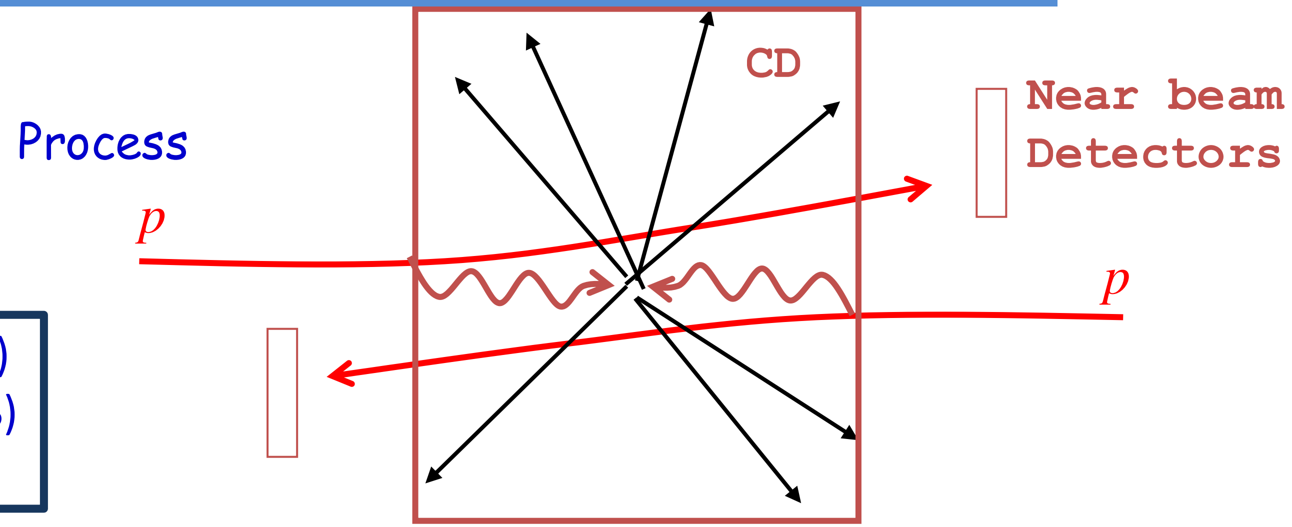
★ SM Higgs, dijets, trijets, light meson pairs, heavy quarkonia (single and double), $\gamma\gamma$.



★ Light to heavy vector meson production.

- In all cases in pp , pA and AA collisions.

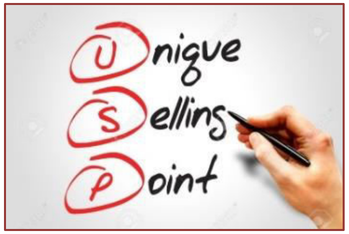
γγ collisions- applications



Installed (AFP)
Installed (PPS)
data taken

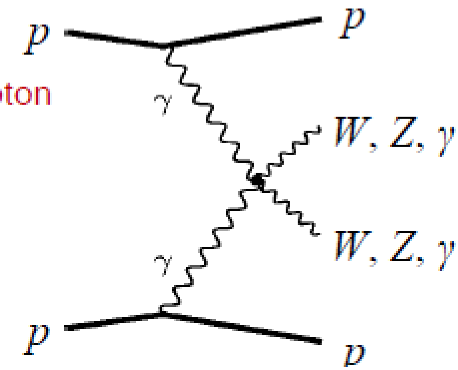
Extensive Program

- $\gamma\ \gamma \rightarrow \mu\mu$, ee QED processes
- $\gamma\ \gamma \rightarrow$ QCD (jets..)
- $\gamma\ \gamma \rightarrow$ WW anomalous couplings
- $\gamma\ \gamma \rightarrow$ squark, top… pairs
- $\gamma\ \gamma \rightarrow$ Charginos (natural SUSY)
- New BSM objects



Anomalous Gauge Quartic Couplings

- Low Cross sections: ~few fb
  - AFP has a Missing-Mass resolution (from the proton measurements) of 2-4 %
- Match with invariant central object mass is efficient: ($Z \rightarrow ee$, $\gamma\gamma$)
  - powerful rejection of non-exclusive backgrounds
- Much interest in this from theory side
  - e.g. "LHC Forward Physics" CERN-PH-LPCC-2015-001)

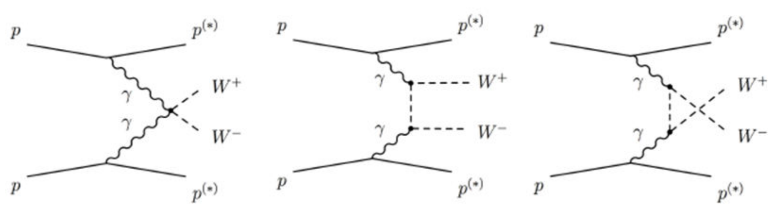


"Probing anomalous quartic gauge couplings using proton tagging at the Large Hadron Collider", M. Saimpert, E. Chapon, S. Fichet, G. von Gersdorff, O. Kepka, B. Lenzi, C. Royon; 23/05/2014

hep-ph/09082020, Louvain Group

- Exclusive W^+W^- production: no contribution from $q\bar{q} \rightarrow W^+W^- \Rightarrow$ sensitive to $\gamma\gamma \rightarrow W^+W^-$ process alone.

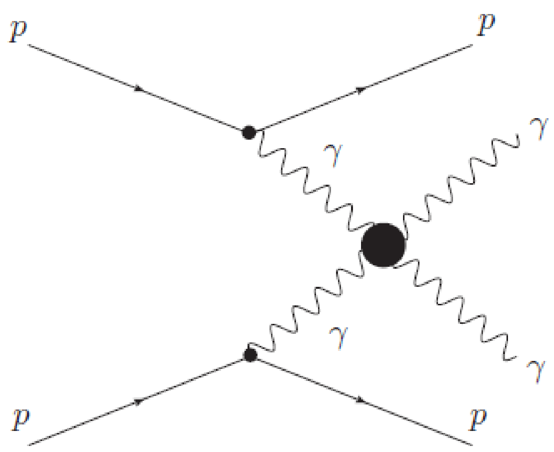
$\rightarrow$ Directly sensitive to any deviations from the SM gauge couplings. Predicted in various BSM scenarios. Composite Higgs, warped extra dimensions....



- Limits have been set at LEP, and in inclusive final-states at the Tevatron and LHC. How does the exclusive case compare?

Currently very encouraging ATLAS & CMS data

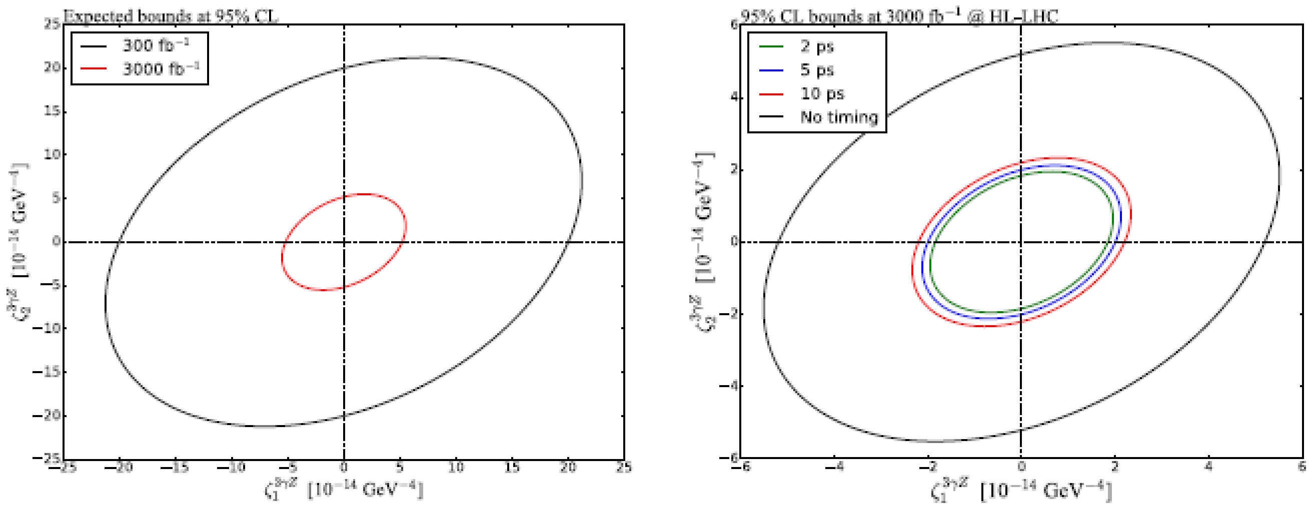
Search for extra dimensions in the universe using γ induced processes



- Additional channels: WW, ZZ, γZ, dilepton production ($\gamma\gamma$ described in more detail as an example)

- Search for production of two photons and two intact protons in the final state: $pp \rightarrow p\gamma\gamma p$
- Number of events predicted to be increased by extra-dimensions, composite Higgs models, dark matter particles
- Anomalous couplings can appear via loops of new particles coupling to photons or via resonances decaying into two photons
- In addition, SM production of WW or dileptons will be still statistically limited after run III

Anomalous couplings@ HL-LHC



Left: Comparison between 300 fb^{-1} and 3000 fb^{-1}. **Right:** (Zoomed-in; change of scale in X-Y axis) comparison between the use of timing $\delta t = 2, 5, 10$ ps. $Z\gamma \to \text{hadrons} + \gamma$ benefits the most from the use of timing.

- Expected improvements from HL-LHC impressive ~ an order of magnitude (~ 5 orders of magnitude better than current best inclusive limits).

Recent Developments

prospects for compressed SUSY searches in photon-initiated CEP.

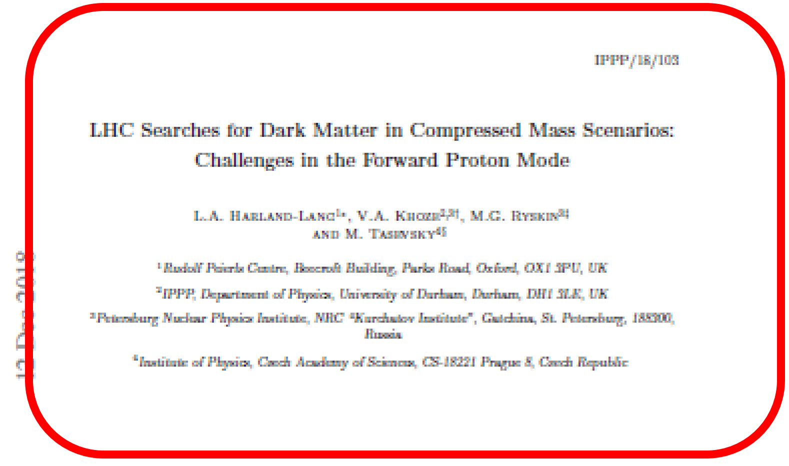
- Signal for this study:

$$\gamma\gamma \to \tilde{l}^+\tilde{l}^- \to l^+l^-\tilde{\chi}_0\tilde{\chi}_0$$

implemented in SuperChic, as well as more challenging case:

$$\gamma\gamma \to \tilde{\chi}^+\tilde{\chi}^- \qquad \text{(hadron/leptonic decays)}$$

- In addition, contribution from proton dissociation included in effective way, interfaced to SuperChic.
- Future work: include (more) complete treatment of dissociation. Stay tuned!


IPPP/18/103

LHC Searches for Dark Matter in Compressed Mass Scenarios: Challenges in the Forward Proton Mode

L.A. Harland-Lang[1*], V.A. Khoze[2,3†], M.G. Ryskin[3‡] and M. Tasevsky[4§]

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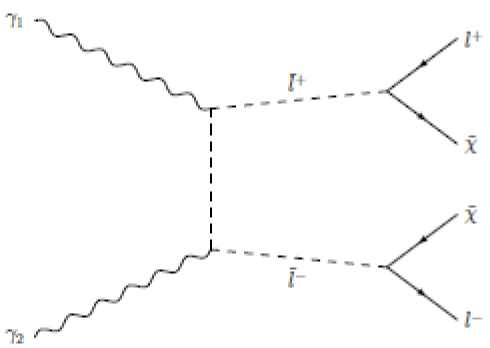
12 Dec 2018

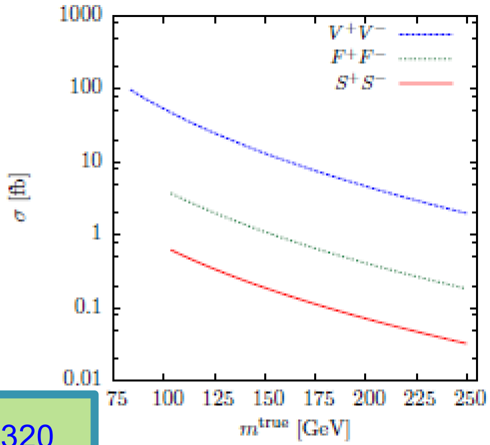
$$pp \to p + \gamma\gamma + p \, ,$$
$$\gamma\gamma \to X^+X^- \, ,$$

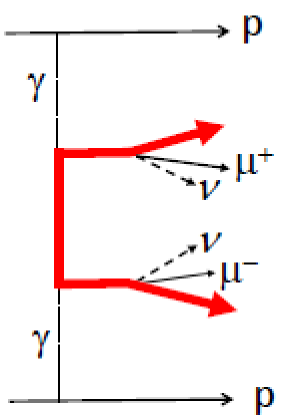
Diphoton X-Pair Production

where X = W–boson, lepton, slepton, chargino...

- If particle decays semi–invisibly, then additional information from tagged proton momenta can be used to measure masses and discriminate BG.







HKSS, arXiv:1110.4320

- Consider exclusive production of chargino pair $\tilde{\chi}_1^+\tilde{\chi}_1^-$, decaying via

$$\tilde{\chi}_1^+(\tilde{\chi}_1^-) \to l^+(l^-) + \nu(\overline{\nu}) + \tilde{\chi}_1^0 \, ,$$

electroweakinos

where the $\tilde{\chi}_1^0$ is an LSP neutralino.

- For cases that $\Delta M = M(\tilde{\chi}_1^0) - M(\tilde{\chi}_1^\pm)$ is relatively small, can be difficult to observe inclusively. (compressed mass BSM scenarios)

- to report current status of our ongoing long-term studies on prospects of searches at the LHC for ELECTROWEAKINO pair production via photon fusion with forward proton detectors (AFP, CT-PPS)

- exemplified within the framework of the compressed mass **MSSM**

First discussed: KMR, J.Phys. G44 (2017) no.5, 055002 **HKRT JHEP 1904 (2019) 010**

Some recent studies: L.Beresford, Jesse Liu, ArXiv:1811.0645

S.I. Godunov et al, ArXiv: 1906.08568

SUSY – solution to various shortcomings of SM (as an example only)

If (it looks like) squarks and gluinos are too heavy,
sleptons, charginos, neutralinos- the main target. **(null search result so far)**

MSSM : charginos $\tilde{\chi}^{\pm}_{1,2}$ four neutralinos $\tilde{\chi}^{0}_{1,2,3,4}$

$\tilde{\chi}^{0}_{1}$, natural candidate for cold Dark Matter –**LSP** [arXiv:1710.02406](https://arxiv.org/abs/1710.02406)

(and quite a few other papers)

natural SUSY:
existence of light nearly
mass-degenerate Higgsinos/chargin…
Mass~ 100-200Ge…
mass splitting…

Most chall…
scenario…
between…

Motivated by naturalness, cosmological observations and (g-2) phenomenology.

Naturalness and light Higgsinos: why ILC is the right machine for SUSY discovery

Howard Baer
University of Oklahoma, Norman, OK 73019, USA
E-mail: baer@ou.edu

Mikael Berggren, Suvi-Leena Lehtin…
DESY, Hamburg, Ger…
E-mail: …

…, *University of Tokyo, Tokyo, Japan E-mail:*

…upersymmetry, a theoretically and experimentally well-motivated …ers around the predicted existence of four light, nearly mass-degenerate Hig…inos with mass ∼ 100 – 200 GeV (not too far above m_Z). The small mass splittings amongst the higgsinos, typically 4-20 GeV, results in very little visible energy arising from decays of the heavier higgsinos. Given that other SUSY particles are considerably heavy, this makes detection challenging at hadron colliders. On the other hand, the clean environment of an electron-positron collider with $\sqrt{s} > 2m_{higgsino}$ would enable a decisive search of these required higgsinos, and thus either the discovery or exclusion of natural SUSY. We present a detailed simulation study of precision measurements of higgsino masses and production cross sections at $\sqrt{s} = 500$ GeV of the proposed International Linear Collider currently under consideration for construction in Japan.

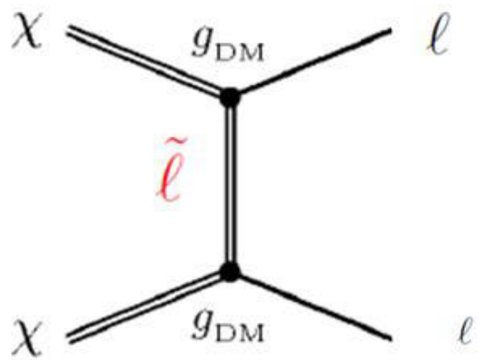
$$e^+e^- \rightarrow \widetilde{\chi}_1^+\widetilde{\chi}_1^- \rightarrow \widetilde{\chi}_1^0\widetilde{\chi}_1^0 q\bar{q}' e\nu_e(\mu\nu_\mu).$$

What about the LHC during MY lifetime ?

Co-annihilation

(1702.00750, model-1a)

Dark matter annihilation

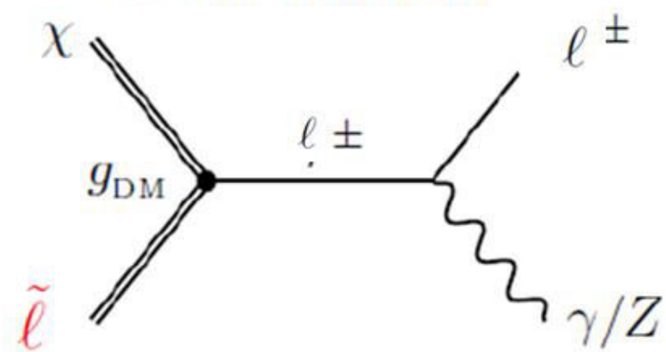


to bring DM abundance down to the observed value

Initially DM in thermal equilibrium with SM, later it freezes out

- Overproduces dark matter (Unless large couplings)
- We need a mechanism to reduce the DM relic density

Co-annihilation:



Freeze-out temperature $T_F \sim m_{DM}/25$

Boltzmann factor $\exp\left(-\frac{\Delta M}{T}\right)$ ⟹ $\Delta M \lesssim m_{DM}/25$

We need **mass splitting of 4% of m_{DM}**

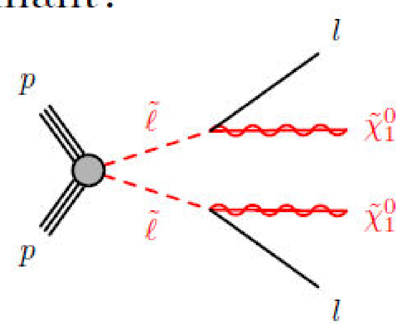
SUSY at the LHC

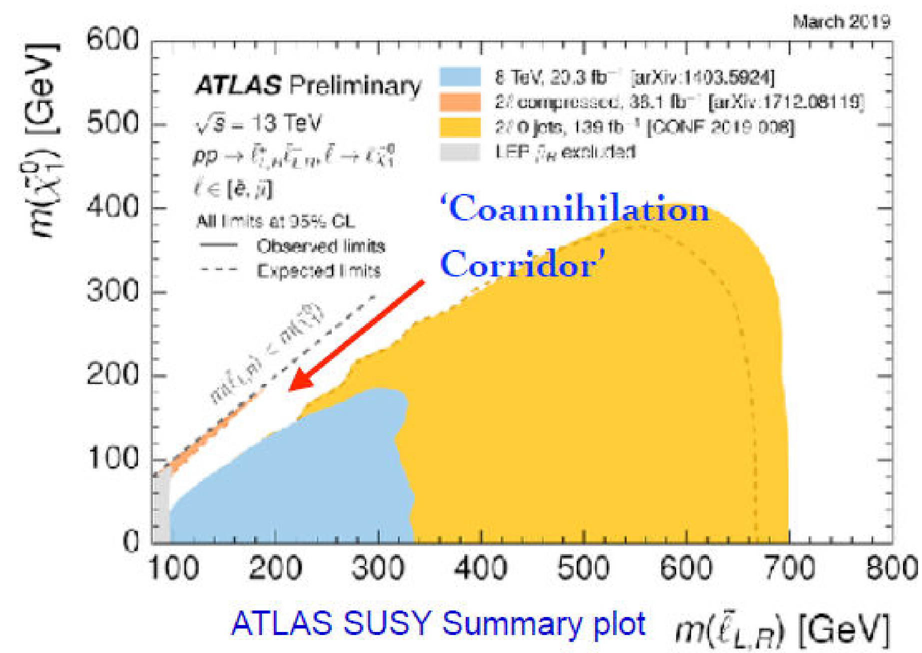
- **Pre-LHC**: EW-scale SUSY theoretically well motivated BSM scenario: hierarchy problem, coupling unification, natural DM candidate…
- **Post-LHC** folklore: no EW-scale SUSY to be seen!

Lightest SUSY particle = 'LSP'

- Only half true: most significant limits based on 'classic' large missing $E_\perp$ signal, requiring **largish** SUSY particle **mass splittings**.

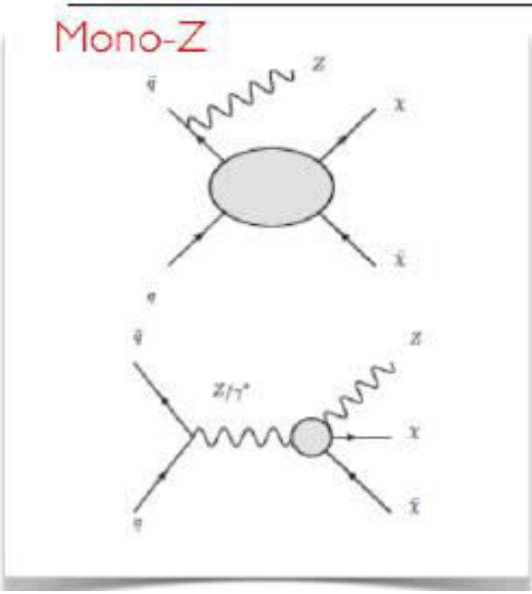
- For e.g. small slepton-neutralino mass differences, LEP constraints still dominant!

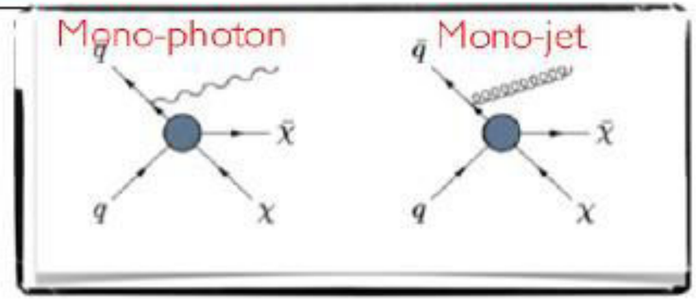


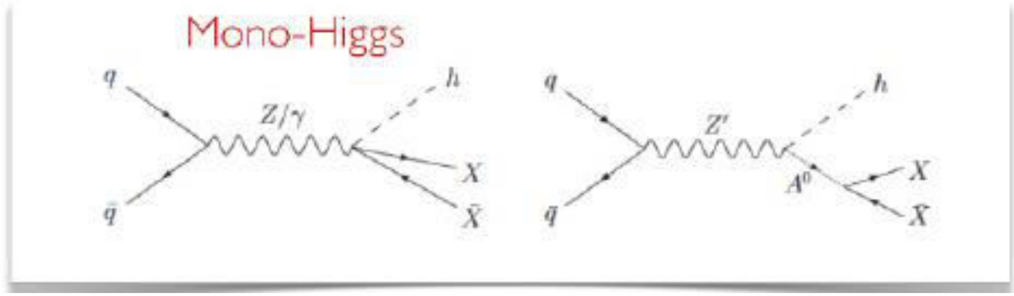


Mono-Mania (at the LHC)

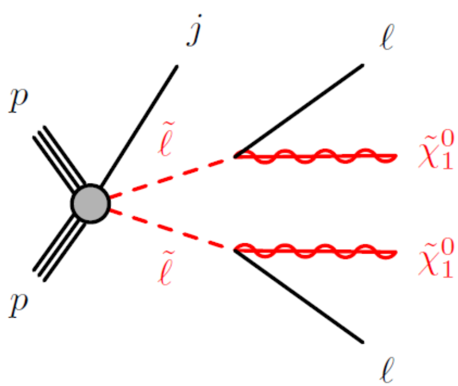
DM Searches @ LHC O. Buchmüller

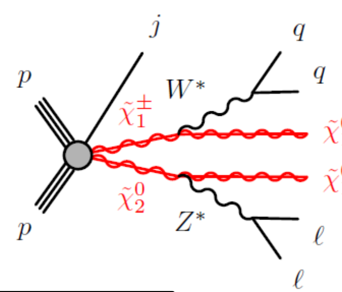






Searches for Electroweakinos at the LHC



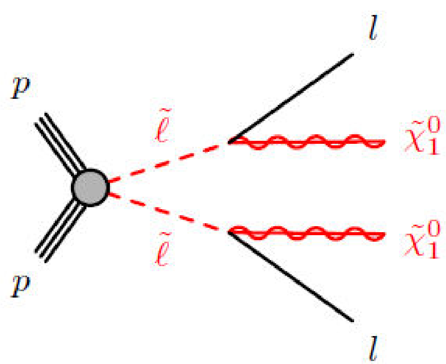


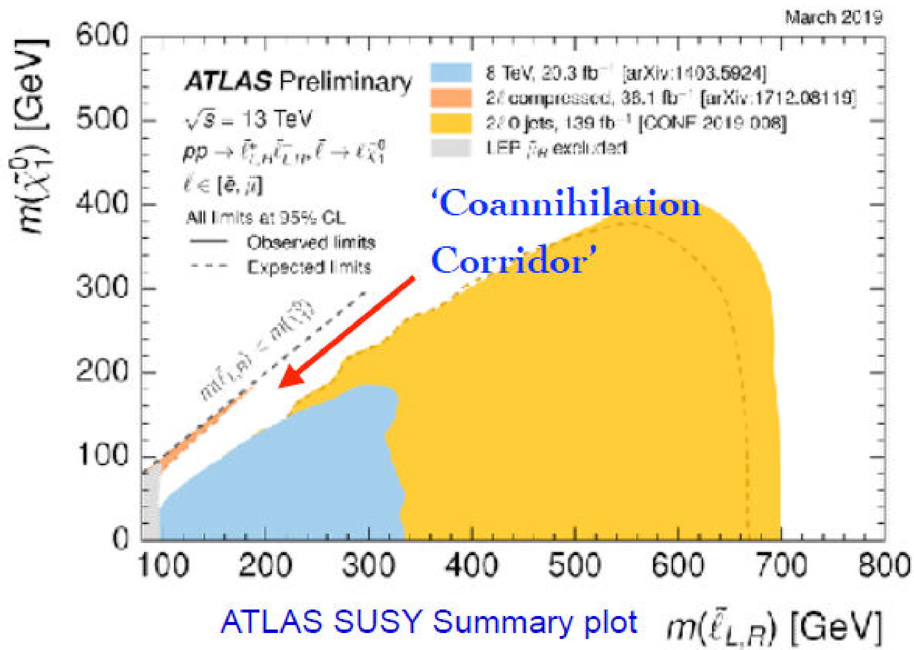
Model dependence

SUSY at the LHC

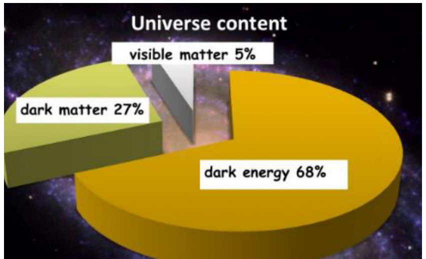
- Such '**compressed SUSY**' scenarios not just dreamt up to avoid limits.
- **Theoretically motivated** by naturalness, $(g-2)$ phenomenology, and cosmological considerations (coannihilation $\Rightarrow$ correct DM abundance).
- Inclusive cross sections not small (up to ~ 100s of fb) $\Rightarrow$ huge number of events may be produced at LHC, but **lost in BG**.

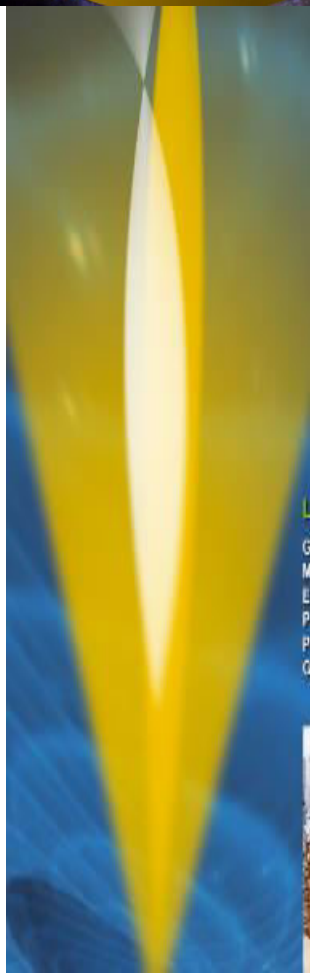
- How can **Photon-initiated** production help?



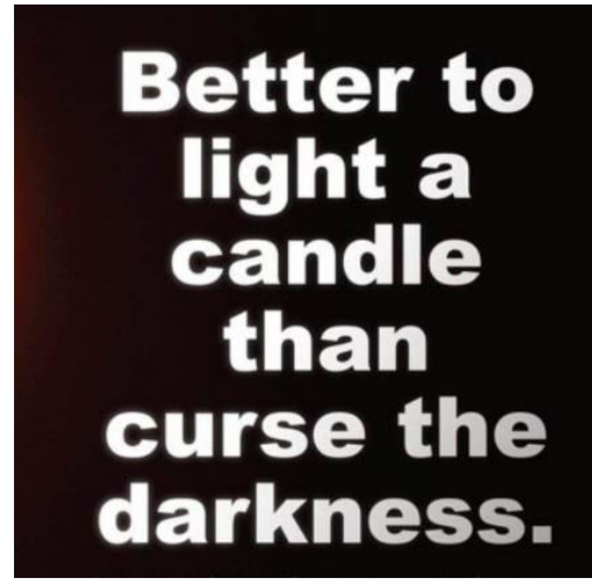


ATLAS SUSY Summary plot





(SUSY, DM -null LHC search results so far)

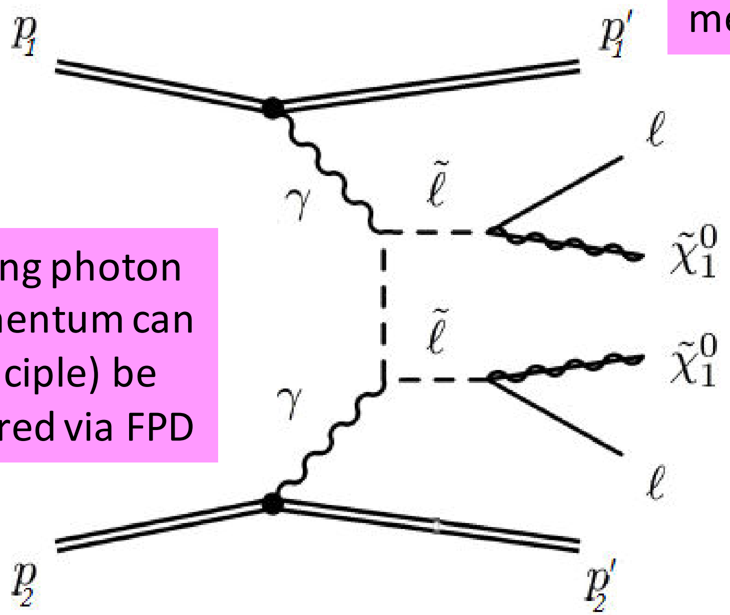


Advantage of exclusivity & compressed mass

Outgoing proton 4-momentum measured in FPD

$\xi_i = 1 - \frac{E_{p_i'}}{E_{p_i}}$, i=1,2 measured precisely in FPD

Lepton 4-momentum measured in Central detector



Incoming photon 4-momentum can (in principle) be measured via FPD

4-momentum of system of 2 DM particles could be constrained from photon & lepton 4-momenta

FPD measures precisely mass $M_{\tilde{l}} - M_{\tilde{\chi}_1^0}$ system. If mass splitting low → FPD can give quite a precise hint about $2m_{DM}$

CEP and SUSY

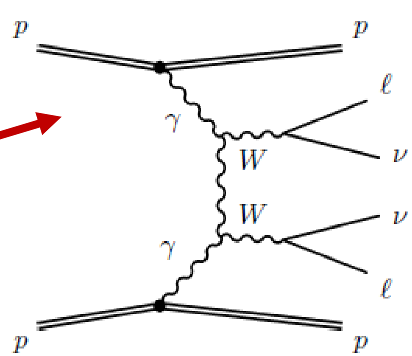
- Possibility of ~ 100 GeV mass slepton/chargino production at LHC begin swamped by huge inclusive BGs.
- **Exclusive photon-initiated** production a natural mechanism:

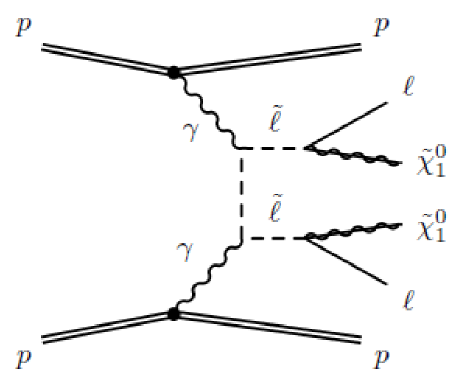
  ★ **Well understood**, model-independent signal cross section.

  ★ Irreducible WW BG can be controlled. No need for large missing $E_\perp$.

  ★ **Proton tagging**: can reconstruct mass of central system from protons alone ('missing mass'). Crucial handle for BGs.

- But, how feasible is this in **high pile-up** environment?





Classes of Background

$(M_{\tilde{l}}, M_{\tilde{\chi}_1^0}) = (120, 110)$ GeV

↓

$(M_{\tilde{l}}, M_{\tilde{\chi}_1^0}) = (300, 280)$ GeV

- Take **slepton pairs** for concreteness. Signal selection:

  ★ Low $\Delta M_{\tilde{l}\tilde{\chi}_0} \Rightarrow$ two relatively low $p_\perp$ leptons, with low m_{ll} , in central detector.

  ★ Two proton hits in AFP/PPS (~ 220m) acceptance.

$$5 < p_{T,l_1,l_2} < 40 \text{ GeV}$$
$$2 < m_{l_l l_2} < 40 \text{ GeV}$$
$$|\eta_{l_1,l_2}| < 2.5\ (4.0)$$
$$0.02 < \xi_{1,2} < 0.15$$

- What are **backgrounds**?

  ★ Irreducible CEP of **W pairs**.

  ★ Reducible **semi-exclusive** production $(l^+l^-\ldots)$ with proton from dissociation system giving hit in forward proton detector (FPD).

  ★ Reducible **pile-up** background: conicidence of non-diffractive event with hits from independent diffractive events.

- Realistic analysis must consider all three.

$M_{\tilde{l}}$ =120-300GeV, $\Delta M = M_{\tilde{l}} - M_{\tilde{\chi}_1^0} = 10 - 20$ GeV

Major backgrounds

- $\gamma\gamma \to W^+W^- \to l^+\nu + l^-\bar{\nu}$
- Low mass $\gamma\gamma \to l^+l^-$ production
  Semi-exclusive process with proton from (SD,DD) dissociation detected in the FPD.
- Semi-exclusive QCD-initiated BGs due to low-pt (mainly c-quark) jets, with SD and DD followed by proton hits in the FPD.
- Coincidence of inelastic lepton pair production with two independent SD/DD events from the PU interactions that mimics the signal.
  (danger for other New Physics searches with $\sigma \leq 1$ fb)
- $\tau\tau$, dimeson, vector resonances etc…

Results

$$(M_{\tilde{l}}, M_{\tilde{\chi}_1^0}) = (120, 110)\ \text{GeV} \longrightarrow (M_{\tilde{l}}, M_{\tilde{\chi}_1^0}) = (300, 280)\ \text{GeV}$$

$|\eta| < 2.5$

Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{PU}$		
	0	10	50
Excl. sleptons	0.6—3.9	0.5—3.3	0.3—1.9
Excl. l^+l^-	1.4	1.2	0.7
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.7	0.6	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0(\sim 0)$	0.1(0.1)	1.8(2.4)

$|\eta| < 4.0$

Event yields / $\mathcal{L} = 300$ fb^{-1}	$\langle\mu\rangle_{PU}$		
	0	10	50
Excl. sleptons	0.7—4.3	0.6—3.6	0.3—2.1
Excl. l^+l^-	1.1	0.9	0.5
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.6	0.5	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0(\sim 0)$	0.03(0.05)	0.6(0.7)

- Final signal yield- **handful** of events.
- Irreducible WW BG under control. Most significant BG from **pile-up**, with dilepton production + **dissociation** a close runner-up.

Future Improvements

- What improvements might we expect in the future?

  ★ Cut on distance between **secondary** and **primary** vertex: reduce BG from decays of heavier particles (dominant part of inclusive BG).

  ★ Improved **ToF resolution** in **FPDs** (ToF rejection increases linearly with decreasing resolution).

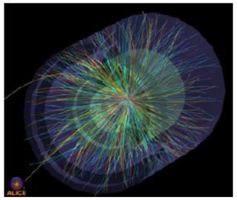
  ★ Radiation hard **ZDCs** with timing to suppress proton dissociation BG.

  ★ Add **timing info** to **central detector** - considered for HL-LHC upgrades at forward rapidity, and envisaged by CMS centrally.

CONCLUSIONS

- Have discussed possibility to search for compressed SUSY scenarios via exclusive photon-initiated production at LHC.
- Highly attractive proposal, as very hard to probe via inclusive channels.
- However, important to consider all sources of backgrounds in pile-up heavy nominal LHC environment.
- Possible to bring the backgrounds under control, at the price of a limited significance S ~ 2, B ~ 2 events for 300 fb^{-1}.
- But not the end of the story- only a first study, and many potential avenues for improvement to explore.
- Ongoing work: more complete treatment of proton dissociation in SuperChic. Stay tuned!

Processes of interest



Heavy Ion Collisions

★ Light-by-light SM signal, but also e.g. Born-Infeld extensions.

★ Axion-like particle production.

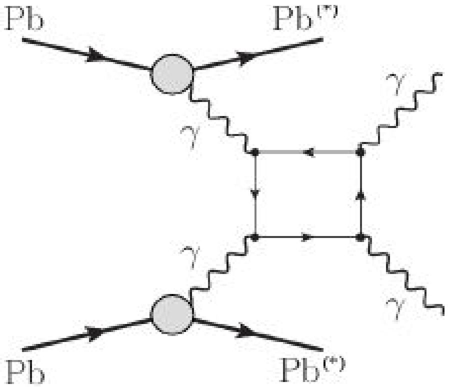
★ Magnetic monopoles.

★ Other possibilities? Gravitons, radions, unparticles, SUSY?

- A principle drawback of heavy ions for these studies is the low luminosity $\Rightarrow$ benefit from increased datasets can be significant.

SM

- [D. d'Enterria et al. PRL 111 (2013) 0804
- [A. Szczurek et al. PRC 93 (2016) 4, 044



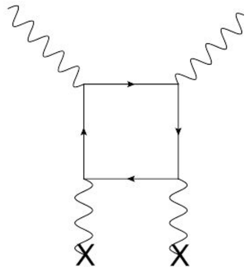
Production mode	BSM particle/interaction	Remarks
Ultraperipheral	Axion-like particles	$\gamma\gamma \to a$, $m_a \approx 0.5$–$100\,\text{GeV}$
	Radion	$\gamma\gamma \to \phi$, $m_\phi \approx 0.5$–$100\,\text{GeV}$
	Born-Infeld QED	via $\gamma\gamma \to \gamma\gamma$ anomalies
	Non-commutative interactions	via $\gamma\gamma \to \gamma\gamma$ anomalies
Schwinger process	Magnetic monopole	Only viable in HI collisions
Hard scattering	Dark photon	$m_{A'} \lesssim 1\,\text{GeV}$, advanced particle ID
	Long-lived particles (heavy ν)	$m_{LLP} \lesssim 10\,\text{GeV}$, improved vertexing
Thermal QCD	Sexaquarks	DM candidate

Table 1: Examples of new-physics particles and interactions accessible in searches with HI collisions at the LHC, listed by production mechanism. Indicative competitive mass ranges and/or the associated measurement advantages compared to the pp running mode are given.

16

Long and chequered history

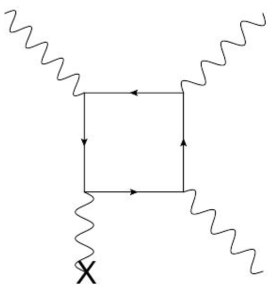
(nonlinear effects of QED)



Delbrück **1933**

Scattering of gamma-rays by a Coulomb field of heavy nuclei.
First observed-1953 for 1.33 MeV on lead nuclei.
Most accurate high-energy results- Novosibirsk,VEPP-4M 1998.

Delbrück scattering



First claims of observation- DESY, PRD 8(1973) 3813.
Criticised by V.A.Khoze et al, ZhETF Pis.Red.19 (1974) 47.
First observation- Novosibirsk, VEPP-4M 2002.

Photon splitting in atomic Coulomb field

first direct observation of $\gamma\gamma \to \gamma\gamma$ scattering

(ArXiv:1702.01625)

(CMS-Arxiv:1902.0139)

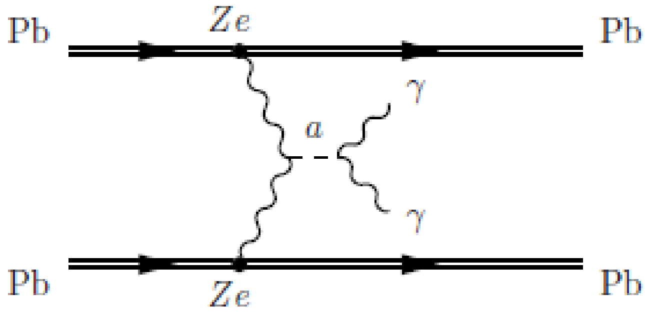
New processes

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

- SuperChic has the capability to simulate any arbitrary process given the $\gamma\gamma \to X$ amplitudes.

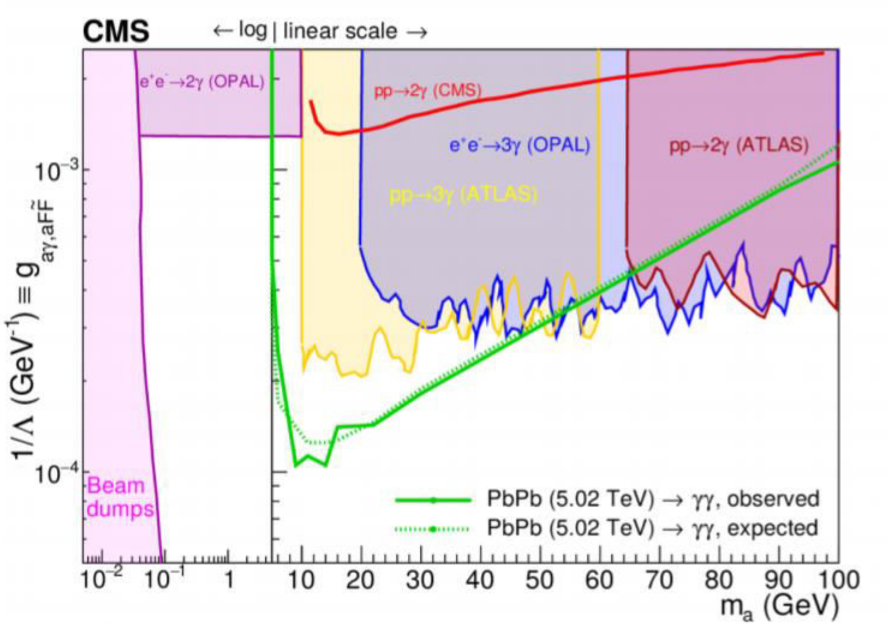
$\longrightarrow$ Simple to implement new processes within framework. Suggestions/collaboration welcome!

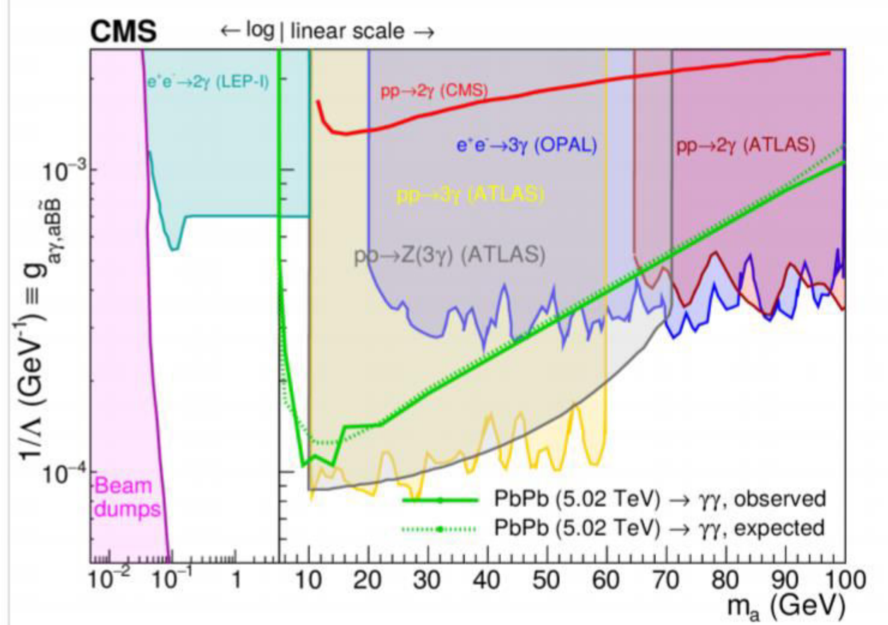
axion-like particles **ALPs**



- Limits in cross-section → limits in $g_{a\gamma}$ vs. m_a plane
- ALPS coupling only to photons (left plot)
  - Best exclusion limits so far over the m_a = 5–50 GeV
- ALPS coupling to photons or hypercharge (right plot)
  - New constraints in the m_a = 5-10 GeV.

arXiv: 1810.04602





Journal of Physics G: Nuclear and Particle Physics

PAPER

Can invisible objects be 'seen' via forward proton detectors at the LHC?

V A Khoze[1,2], A D Martin[1,3] and M G Ryskin[1,2]

Published 7 April 2017 • © 2017 IOP Publishing Ltd

Journal of Physics G: Nuclear and Particle Physics, Volume 44, Number 5

$$pp \to p + \text{invisible} + p,$$

An attractive idea, but huge backgrounds caused by soft proton dissociation, photon bremsstrahlung and PU (at high lumi)

$p \to p + \gamma$, $N^* \to p + \gamma$ and $N^* \to p + \pi^o$. $p \to p\pi^+\pi^-$

Measurements at low lumi ($\mu \sim 1$)with 'veto' detectors (like ZDC and FSC/ADA/ADC)

LHCb, ALICE

New Result - The Odderon

- Recent result from CMS-TOTEM: evidence for QCD Odderon.

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Experiments at the Large Hadron Collider uncover possible evidence of elusive 'odderon' that physicists have sought after for decades

- Physicists have been looking for subatomic quasiparticle, 'odderon' since 1970s
- It involves collisions in which an odd number of gluons are exchanged
- While it hasn't been seen in earlier experiments, technology is now more precise

By CHEYENNE MACDONALD FOR DAILYMAIL.COM
PUBLISHED: 00:46, 2 February 2018 | UPDATED: 00:46, 2 February 2018

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

TOTEM-2017-002
16 December 2017

CERN-EP-2017-335
19 December 2017

First determination of the ρ parameter at $\sqrt{s} = 13$ TeV – probing the existence of a colourless three-gluon bound state

The TOTEM Collaboration

New Scientist

THIS WEEK 7 February 2018

LHC finds hints of strange quasiparticle called the odderon

WE MAY have glimpsed an odd member of the particle family tree.

International Business Times

Science

What is Odderon? LHC uncovers possible subatomic quasiparticle which existed only in theory

- Scientists have been searching for the elusive odderon since the 1970's.

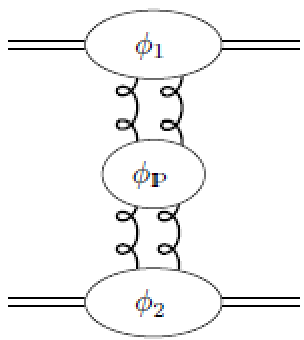
By India Ashok
February 2, 2018 11:54 GMT

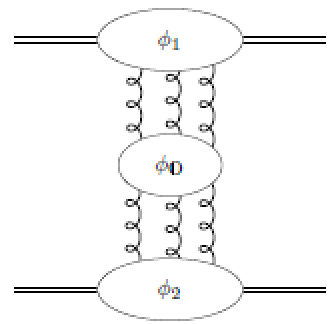
What is the Odderon?

- Most easily pictured perturbatively. For high energy scattering ($s/|t| \gg 1$) with $\alpha_s \ll 1$, dominant elastic amplitude given by resummation of $\sim \alpha_S \ln s$.
- What colour-singlet gluon configurations can we exchange?

gg : C-even, dominant. QCD Pomeron.

ggg : can be C-odd. QCD Odderon.





- Odderon: prediction of QCD*. Detailed calculation $\rightarrow$ does not die away with energy. Although moving to non-perturbative regime will complicate matters, expect on general grounds for Odderon to contribute.
- General QCD expectation - C-odd (i.e. $\sigma_{pp} \neq \sigma_{p\bar{p}}$) exchange at high energies. Yet for a long time no clear experimental evidence. Where is it?

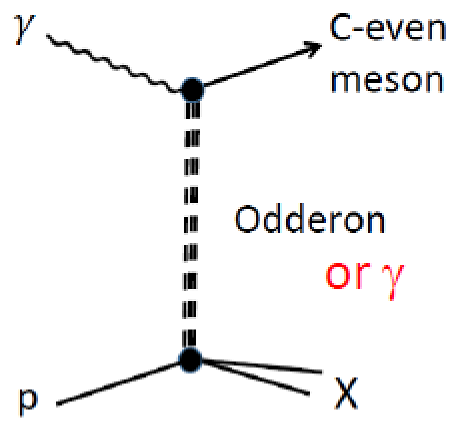
HKMR-2018

(Victor)

SEARCHES for ODDERON

Odderon signals

- pp scatt Odderon exch. is a small correction to even-signature term $(g_{pO})^2$
- photoproduction of C even mesons π^0, f_2, η ...



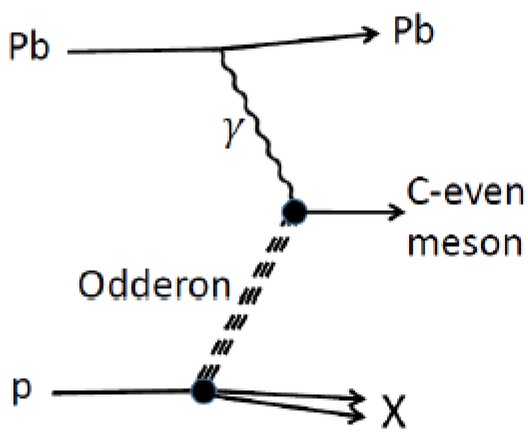
g_{pO}

No evidence in HERA data

upper limits $\sigma(\pi^0)$=39nb, $\sigma(f_2)$=16nb

Need to suppress back[gd] due to γ exchange

- ultraperipheral production in p-Pb collisions



Z^2 in photon flux

Odderon signal in p-Pb collisions?

$d\sigma/dy_M\|_{y_M=0}$	Expected upper limits [μb]
π^0	7.4
η	3.4
$f_2(1270)$	3.0

Summary & Outlook

- No immediate plans for a future $\gamma\gamma$ collider, but the LHC is already a photon-photon collider!
- The $\gamma\gamma$ initial state naturally leads to exclusive events, with intact outgoing protons.
- Theory well understood, and use as highly competitive and clean probe of EW sector and BSM physics already demonstrated at LHC. Much further data with tagged protons to come.
- Such studies equally possible (with higher $s_{\gamma\gamma}$) at FCC.
-
  - **SuperChic** - a MC event generator for CEP processes.
  - Unified platform for QCD-induced, photoproduction and photon-photon collisions.
  - Fully differential treatment of survival factor.
- Photon-mediated processes provide a very efficient tool to probe various aspects of the SM and BSM physics.


THANK YOU


QUESTIONS?

BACKUP

Motivation: photon-induced CEP

- **Photon-initiated** CEP of particular interest:

  ★ Very well understood initial state, via **equivalent photon approximation**:

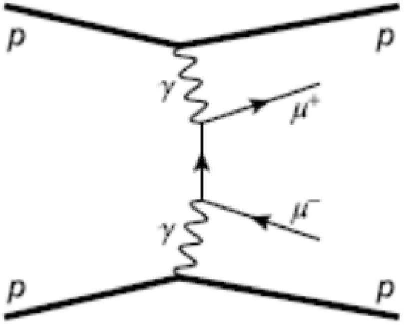
(Well known) EM Form Factors

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

Photon flux

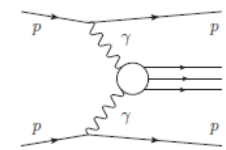
  ★ Low photon $Q^2 \Rightarrow$ large proton-proton impact parameter impact of QCD ('survival factor') small and under control.

$\longrightarrow$ LHC as a $\gamma\gamma$ collider! **Clean probe of BSM** with EW couplings.



FP420 AND RESURRECTION OF 'DIFFRACTIVE HIGGS' (15 YEARS ON)

- searching for lower mass new objects in CEP requires far away (~400m) FDs



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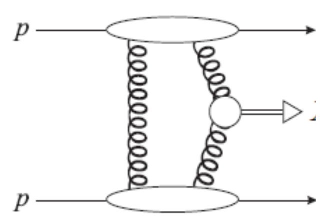
The FP420 R&D project (2004-2009)

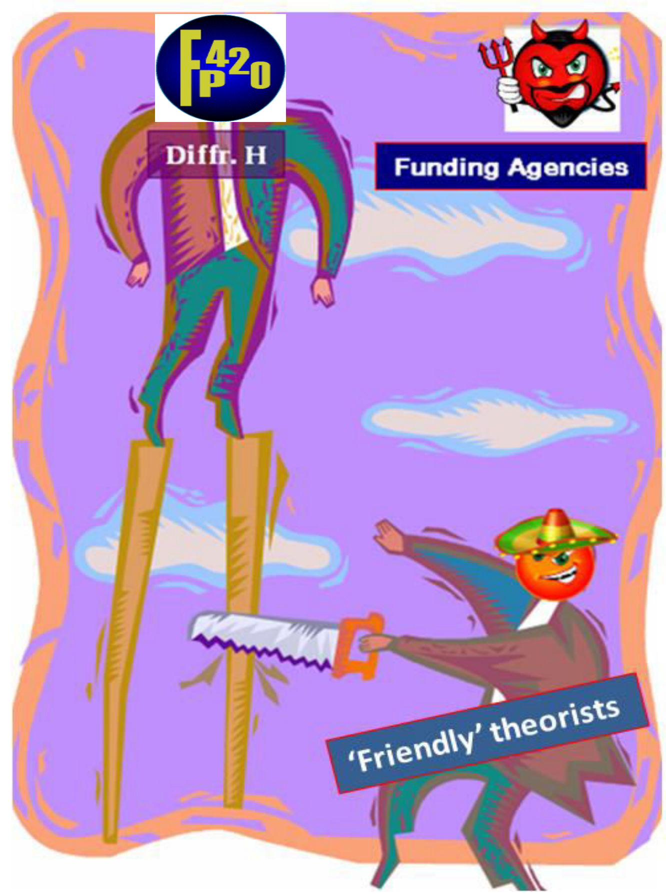
- FP420 was a joint R&D collaboration between CMS and ATLAS to develop a forward proton detector system to tag outgoing protons.
- Key questions:
  - Can suitable forward detectors be placed close to the LHC beam
  - What is the physics potential of these detectors?
  - Will they cover an interesting region of Higgs mass?
- Final report is available at JINST 4:T10001,2009 [arXiv:0806.0302]

❖ QCD-initiated production: potential for e.g. exclusive jet and H studies analysed (though there are more).

★ **Jets**: gg colour-singlet initial state range of unique QCD studies.

★ **Higgs**: completely unseen mode, Higgs properties (CP, couplings) via independent method.





96 GeV-'light Higgs'

Prospects for Proton Tagged Physics at the High Lumi LHC

P. Newman - C. Royon, for the LPCC Forward Physics WG
Birmingham, UK - Lawrence, KS, USA

February 27 2019

LHCC open session, with inputs from ALICE, ATLAS, CMS, LHCb, TOTEM

- 210-250 m: medium to high mass sensitivities, similar to present AFP/PPS (region before Q4 and not good since acceptance cut by TCL4 and region before Q5 important to reach high mass)
- 400-450 m: sensitivity to low masses down to 40-50 GeV