NANYANG TECHNOLOGICAL UNIVERSITY
Institute of Advanced Studies

CONFERENCE ON
PARTICLES AND COSMOLOGY
5 to 9 March 2018
Nanyang Executive Centre, NTU, Singapore

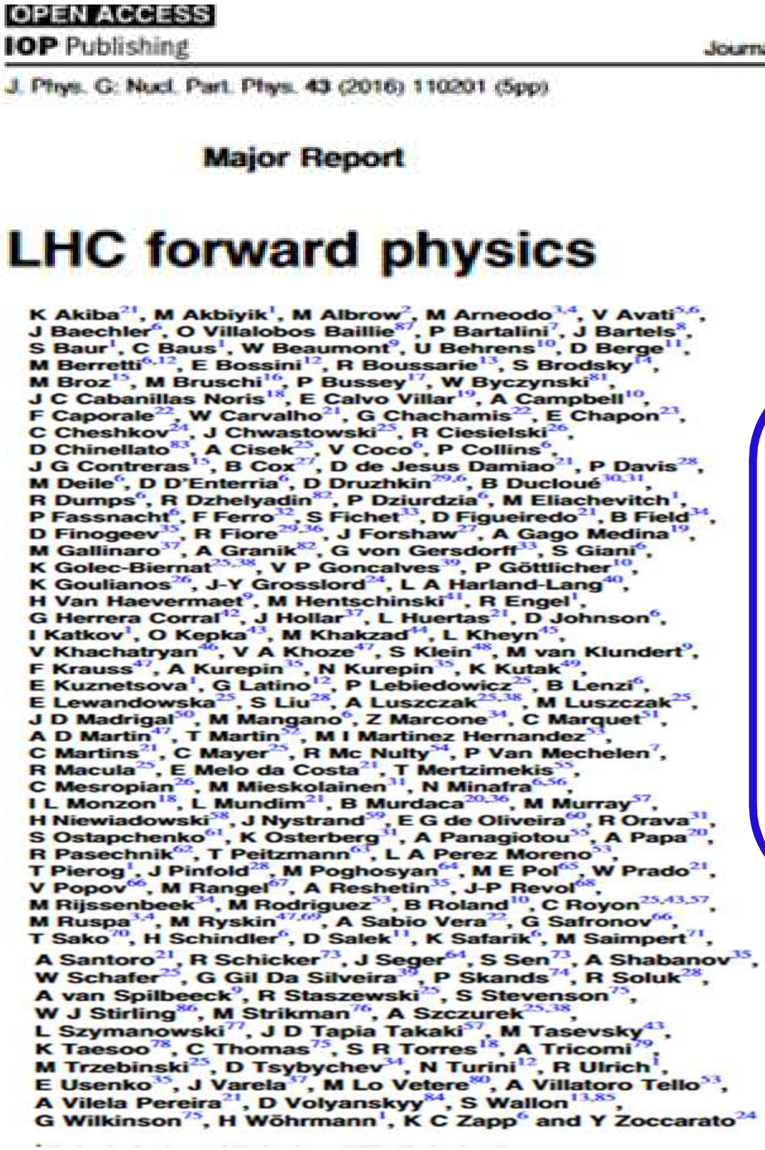
李氏基金
LEE FOUNDATION

FORWARD PHYSICS at the LHC: PRESENT&FUTURE (selected topics)

Ip³

RSE
The Royal Society of Edinburgh
KNOWLEDGE MADE USEFUL

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



OPEN ACCESS
IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 43 (2016) 110201 (5pp)
doi:10.1088/0954-3899/43/11/110201

Major Report

LHC forward physics

K Akiba[21], M Akbiyik[1], M Albrow[2], M Arneodo[3,4], V Avati[5,6],
J Baechler[6], O Villalobos Baillie[87], P Bartalini[7], J Bartels[8],
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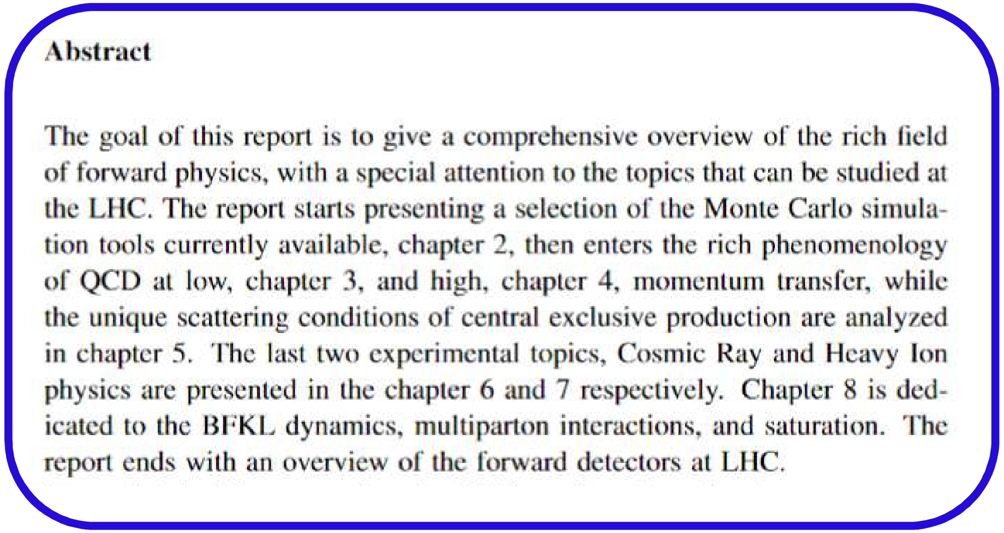
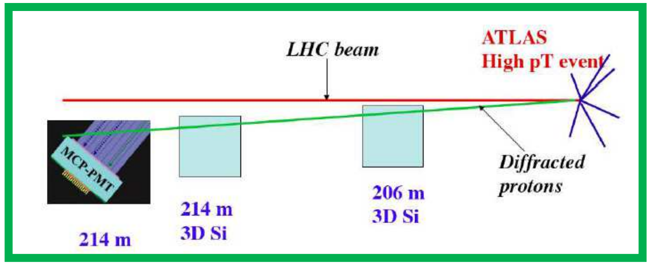
90 Institutes, 350 pp

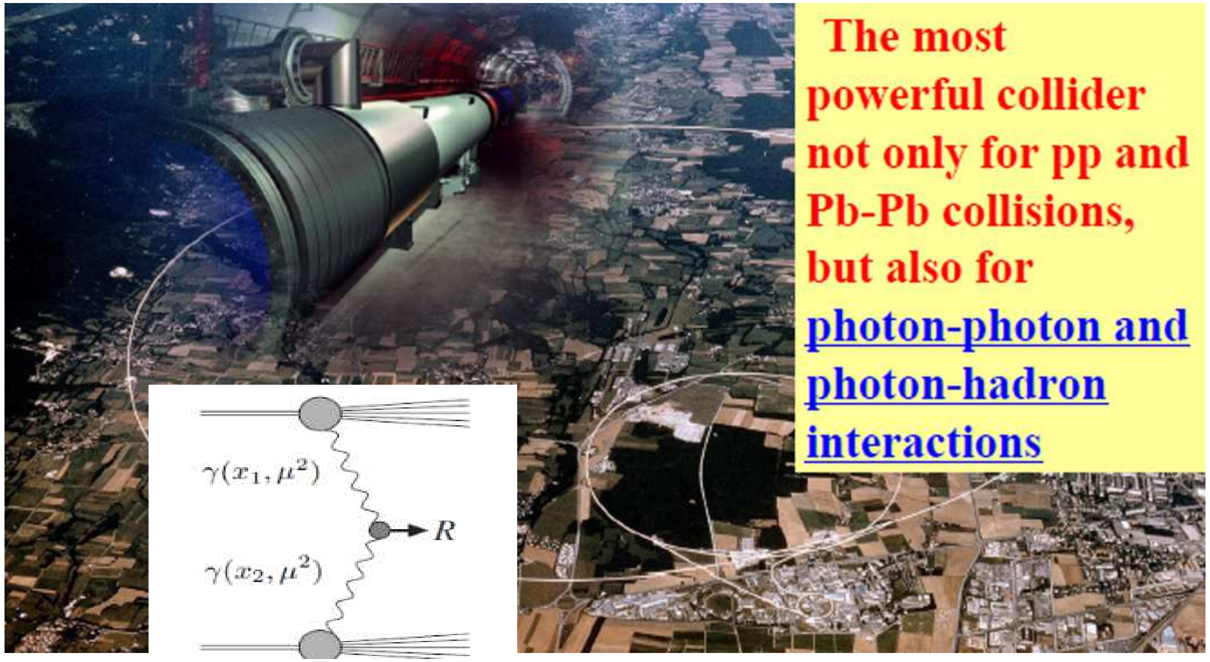


Abstract

The goal of this report is to give a comprehensive overview of the rich field of forward physics, with a special attention to the topics that can be studied at the LHC. The report starts presenting a selection of the Monte Carlo simulation tools currently available, chapter 2, then enters the rich phenomenology of QCD at low, chapter 3, and high, chapter 4, momentum transfer, while the unique scattering conditions of central exclusive production are analyzed in chapter 5. The last two experimental topics, Cosmic Ray and Heavy Ion physics are presented in the chapter 6 and 7 respectively. Chapter 8 is dedicated to the BFKL dynamics, multiparton interactions, and saturation. The report ends with an overview of the forward detectors at LHC.



+ machine people + theorists



The most powerful collider not only for pp and Pb-Pb collisions, but also for photon-photon and photon-hadron interactions

Unique and diverse LHC forward physics program :

- Variety of collisions : pp, Ap, AA, high energy photon-photon, ‘pion-proton’.
- Wealth of physics tasks –from fundamental problems of ‘old’ strong interactions and UHE cosmic rays to the novel searches for New Physics signals and Luminometry.
  CEP-high purity gluon factory.

Achilles heel of the LHC precision measurements

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

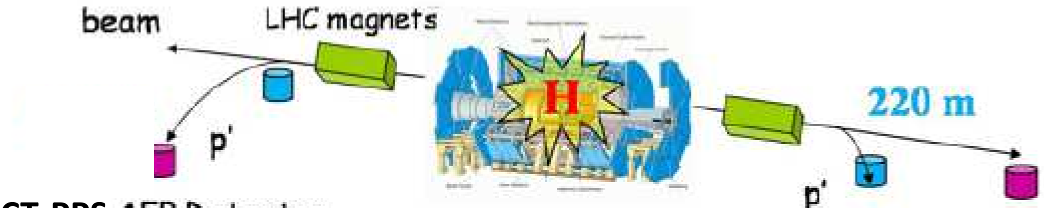
- Defining feature of exclusive events: protons intact after collision,

  $\longrightarrow$ If we can measure the outgoing protons

  purely exclusive event sa

- Basic principle: us After
interaction pr y bend out of
beam li
- Ins O(mm) from beam line and O(100 m)
from IP. Reconstruct momenta and measure arrival time of protons.

The LHC is best mass spectrometer



CT-PPS,AFP Detector

TOTEM/ALFA –special runs

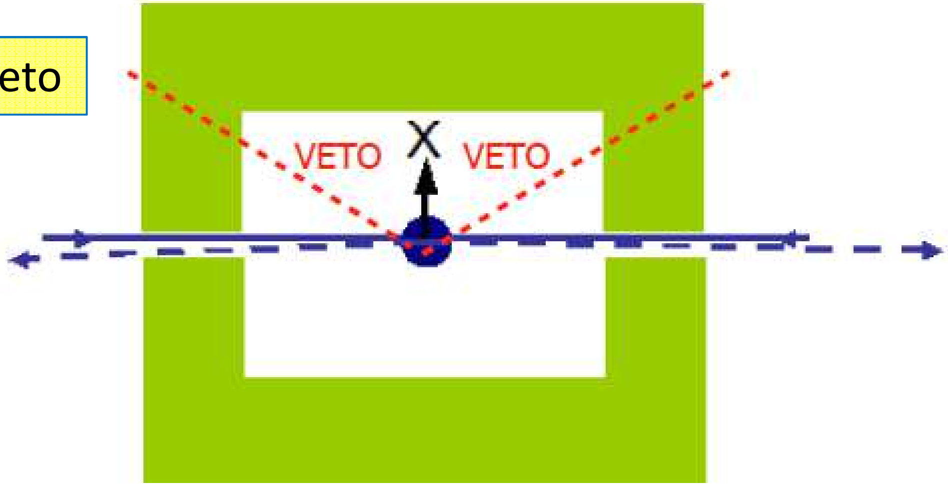
MIND THE GAP

2) 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 ⇒ 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).

ALICE/LHCb-Rap Gap Veto



PAY THE PRICE!

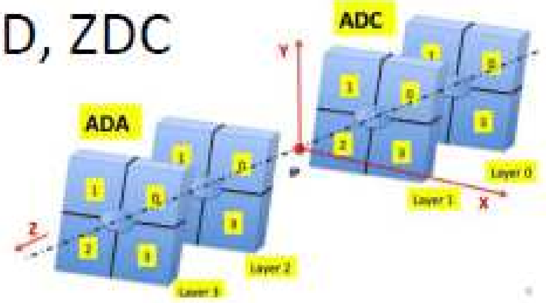
Forward detectors – present situation

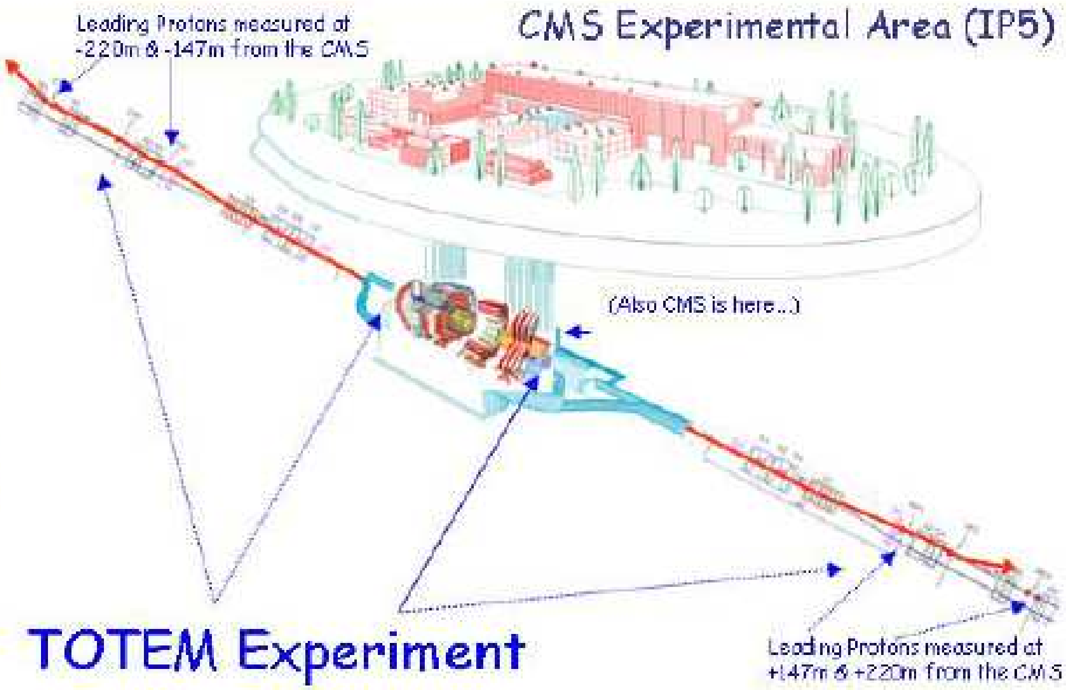
CMS: ZDC, TOTEM , FSC

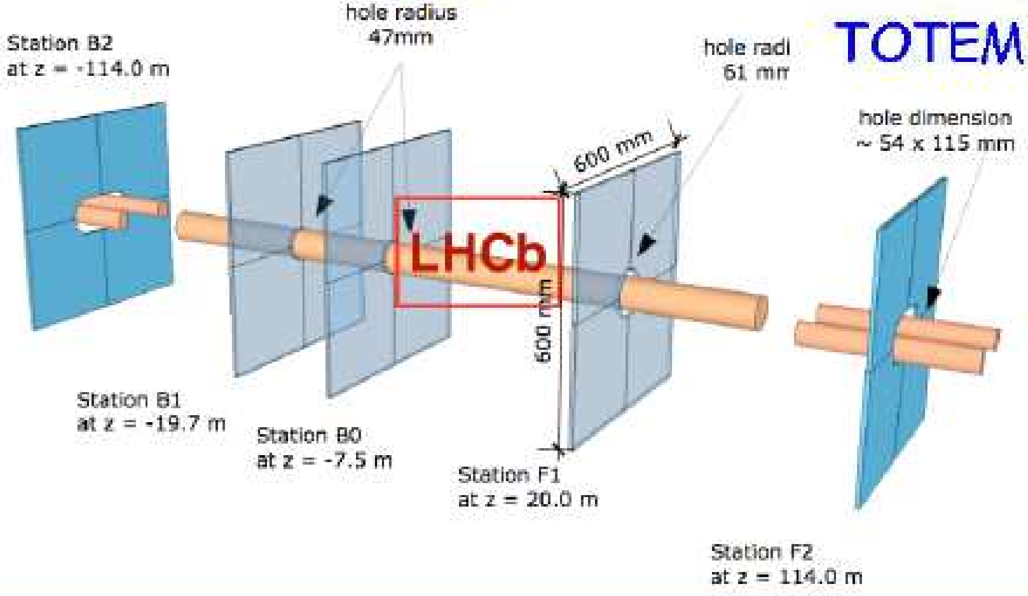
ATLAS: AFP, ALPHA, ZDC

LHCb: HERSCHEL

ALICE: AD, ZDC

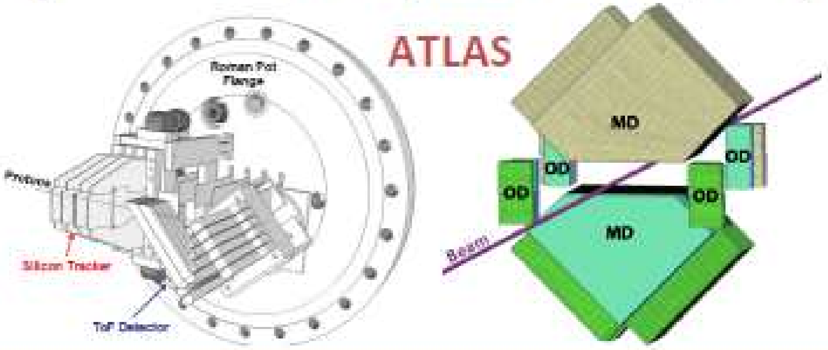






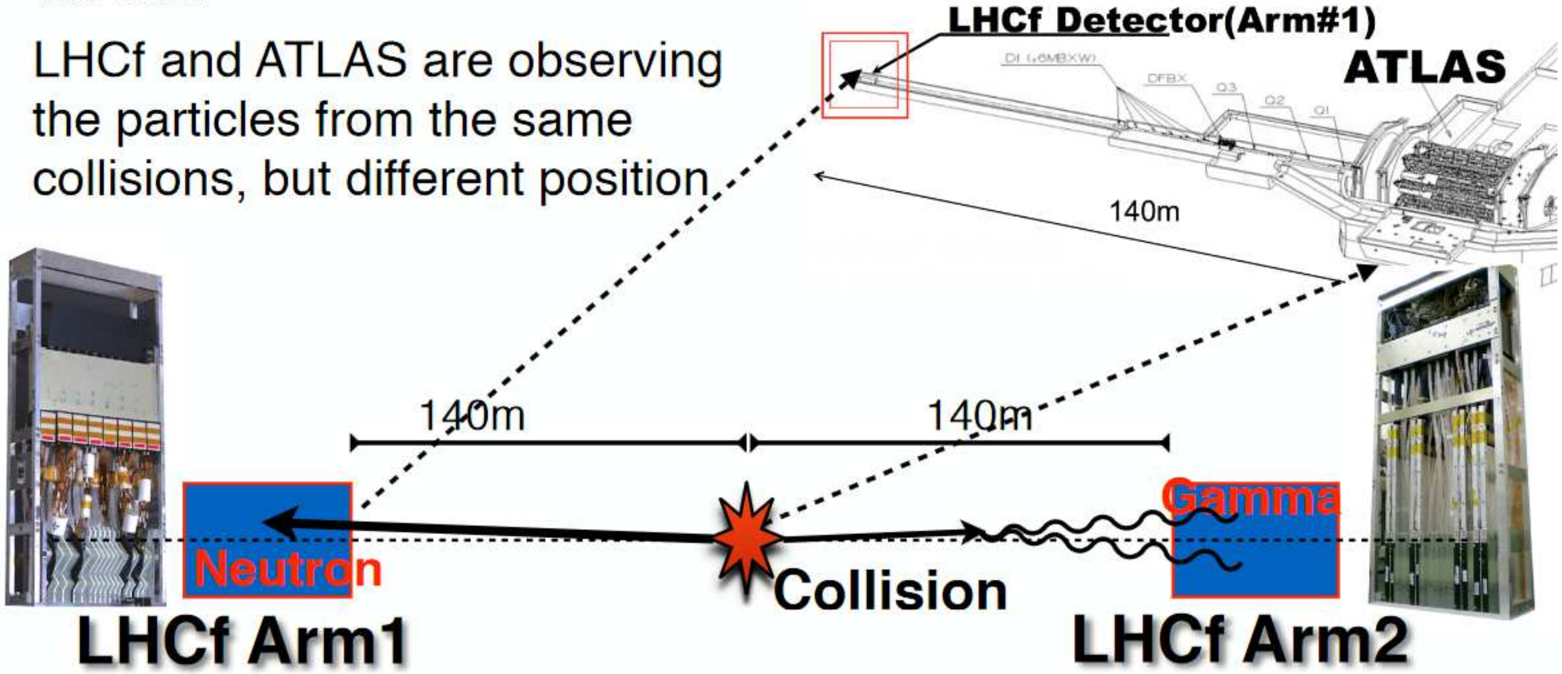
Left: ALFA detectors (vertical RPs, high-β*)

Right: AFP detectors (horizontal RPs, low-β*



The LHCf experiment

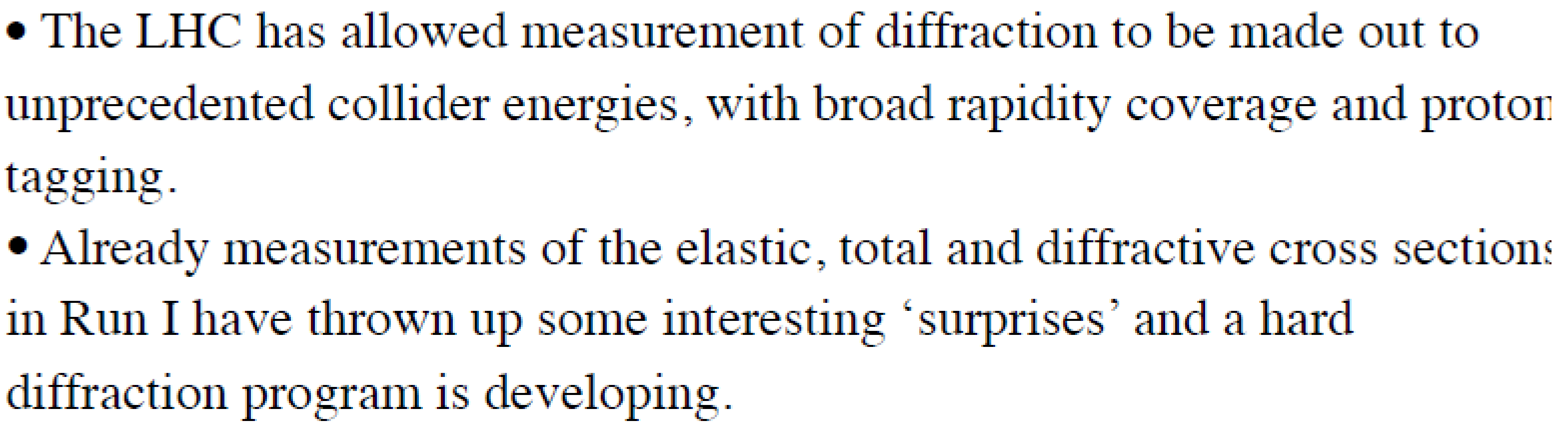
- Measure hadronic production cross section of neutral particles emitted in the very forward region of LHC.
- To afford the data for verifying and improving the hadronic interaction models.



LHCf and ATLAS are observing the particles from the same collisions, but different position.

The η coverage of the calorimeter: $|\eta|>8.4$

Diffractive Physics 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 already a lot to offer : TOTEM &ALFA …

Fundamental questions:

- Asymptotics of the total cross section,
  how far we are now with the LHC.

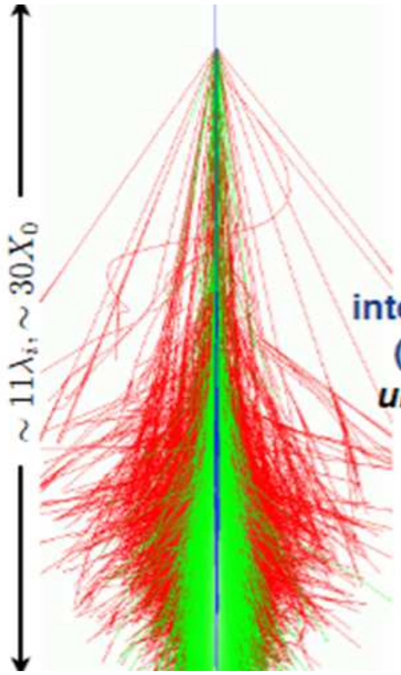
- Elusive Odderon- expected in QCD
  a C-odd partner of the Pomeron- trajectory with J=1
  guaranteed by the number of colours N_C>2.

Test of hadronic interaction models

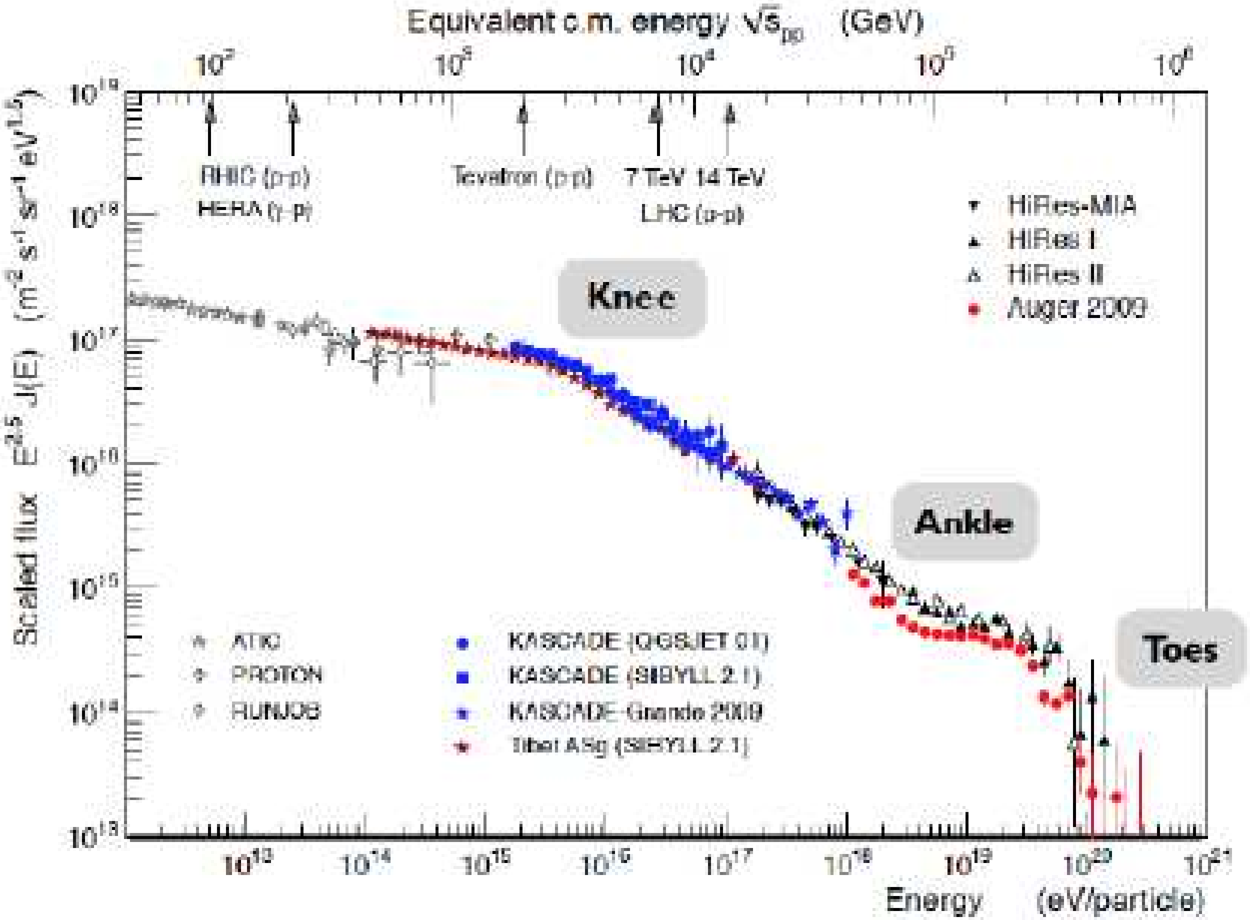
primary cosmic-ray particle (type *unknown*)

Total Inelastic Cross Section

- Crucial quantity for understanding cosmic ray air showers



interactions (partly) *unknown*



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

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

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

- Forward Proton mode - Important testable constraints on the cross sections.

$$\sigma_T(s) \leq \frac{\pi}{m_\pi^2} \log^2\left(\frac{s}{s_0}\right)$$ Froissart–Martin theorem

$\ln^2 s$ **Not a MUST !**

$$\Delta\sigma = \sigma_T^{\bar{p}p} - \sigma_T^{pp} \xrightarrow[s\to\infty]{} 0.$$ Y. Ya. Pomeranchuk, JETP **7** (1958) 499.

$$\frac{\sigma_T^{\bar{p}p}}{\sigma_T^{pp}} \xrightarrow[s\to\infty]{} 1$$ general Pomeranchuk theorem

$$|\Delta\sigma| \leq \text{const} \cdot \log s\,.$$

Odderon in asymptotic theories NL (1973)

$$\sigma_T(s) \leq \frac{\pi}{m_\pi^2}\log^2\left(\frac{s}{s_0}\right)$$ Froissart–Martin theorem

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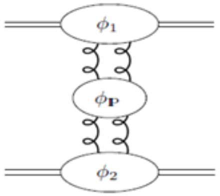
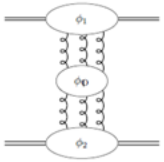
Odderon in asymptotic theories NL (1973)

QCD



Pomeron- the total cross section section asymptotics- pQCD
a compound state of two reggeized gluons BFKL (1975—1978)
Regge theory-Gribov (1962).



Odderon-difference of particle and antiparticle cross sections-pQCD
a compound state of three reggeized gluons
The Bartels-Kwieciński-Praszałowicz Equation (1980)

Until very recently no firm experimental observation

TOTEM-2017-002
16 December 2017

News

Comparison with COMPETE model predictions:

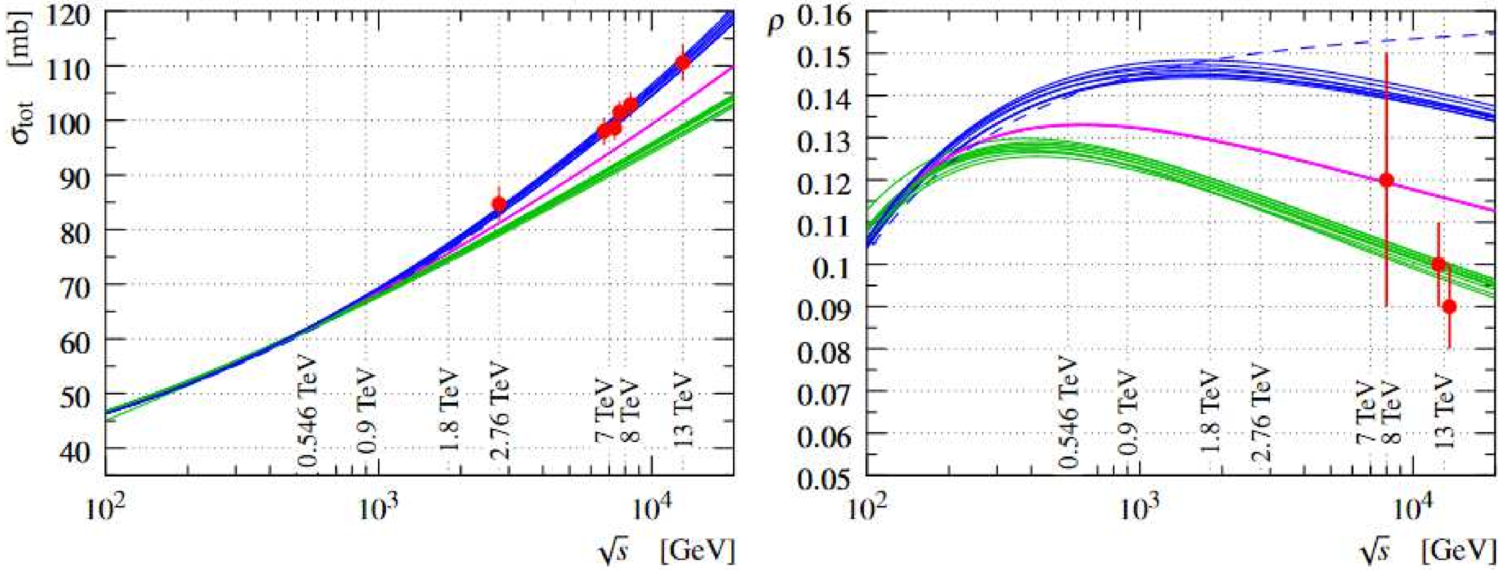


Fig. 18: Predictions of COMPETE models [32] for pp interactions. Each model is represented by one line (see legend). The red points represent the reference TOTEM measurements. The σ_{tot} point at 13 TeV corresponds to (110.6 ± 3.4) mb as determined in [6]. The two ρ points at 13 TeV correspond to the two cases discussed in Section 6.2: the left point to the fit with $N_b = 3$ and $|t|_{\max} = 0.15\,\mathrm{GeV}^2$, the right point to $N_b = 1$ and $|t|_{\max} = 0.07\,\mathrm{GeV}^2$.

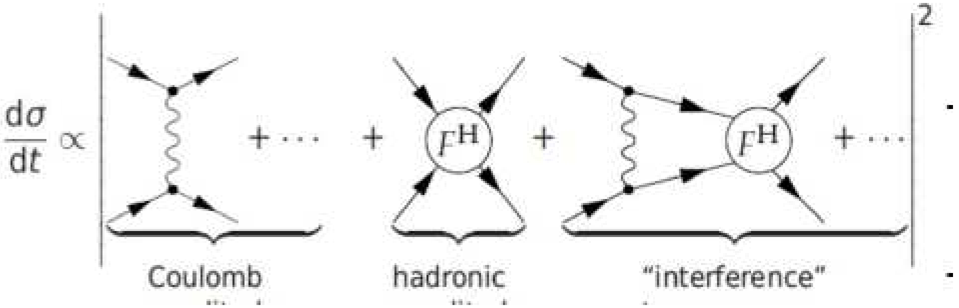
Coulomb-Nuclear Interference

TOTEM-2017-002
16 December 2017

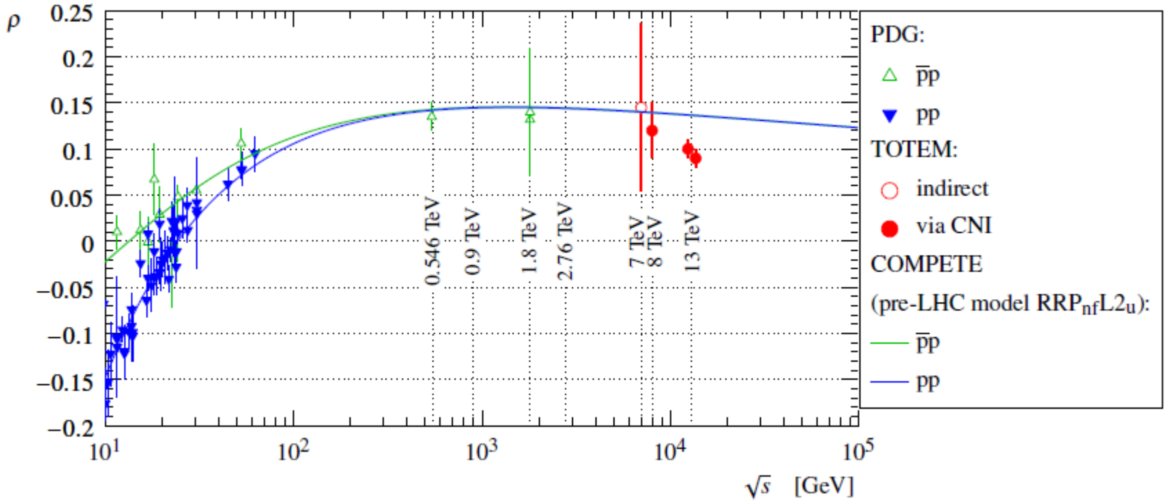
$\sqrt{s} = 13\,\text{TeV}$ using a special $\beta^* = 2.5\,\text{km}$ optics. t, down to $|t| = 8 \times 10^{-4}\,\text{GeV}^2$

$$\rho(s) = \frac{\operatorname{Re} A(s, t = 0)}{\operatorname{Im} A(s, t = 0)} .$$

$\rho = 0.09 \pm 0.01$ and $\rho = 0.10 \pm 0.01$, depending on different physics assumptions



$$\frac{d\sigma^C}{dt} = \frac{4\pi\alpha^2}{t^2}\mathcal{F}^4 ,$$



The very high value of β∗ implies very low beam divergence which is essential for accurate measurement at very low ItI.

KMR- arXiv:1712.00325

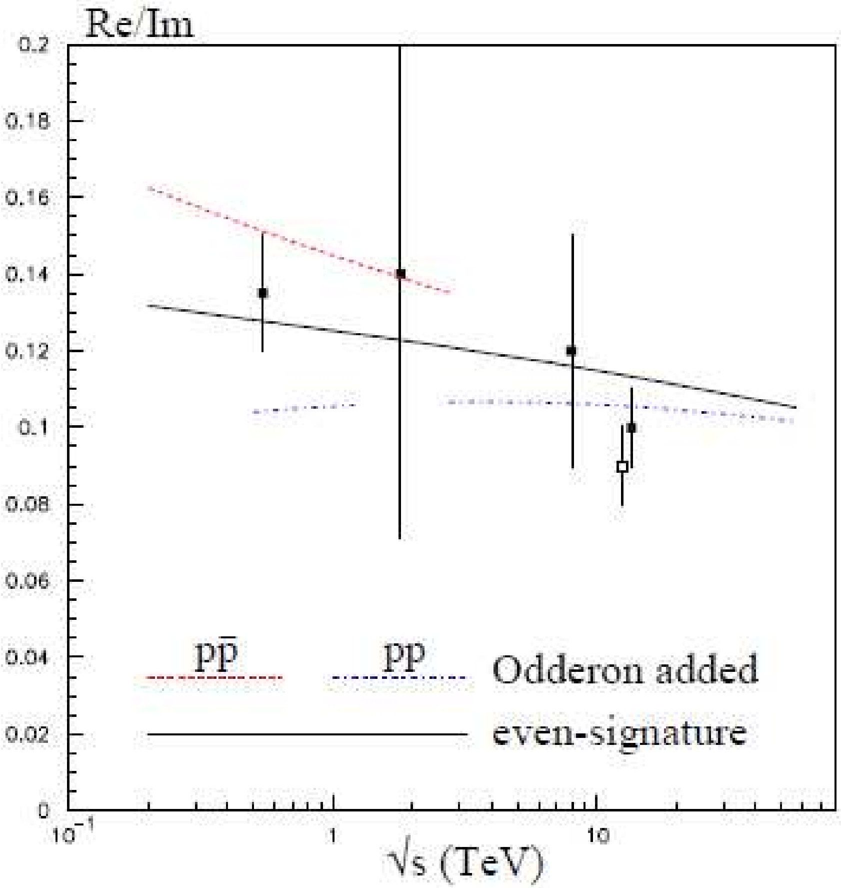


Figure 2: The energy dependence of the ρ =ReA/ImA ratio. The data are taken from [3, 20, 21, 2]; the first two data points correspond to $p\bar{p}$ scattering and the last points to pp scattering. At 13 TeV we also show by the open square the value of ρ obtained under the same conditions as that used by the UA4/2 group (see footnote 1). The values of ρ given by the model [4] are shown by the solid curve. The dashed curves include a *possible* QCD Odderon contribution calculated as described in the text.

The inclusion of the Odderon does improve the calculated value of ρ at 13 TeV.

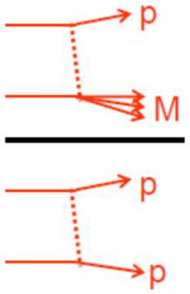
Durham 2013 model

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)



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

Unexpectedly small

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

Impact on the EAS characteristics : consistency of the current data with almost pure proton composition in the energy range

S. Ostapchenko (arXiv:1402.5084)

$$E_0 = 10^{18} - 10^{20}\ \text{eV}$$

➔ 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.

SEARCHES FOR THE NEW PHYSICS IN THE FORWARD PROTON MODE

CENTRAL EXCLUSIVE PRODUCTION PROCESSES

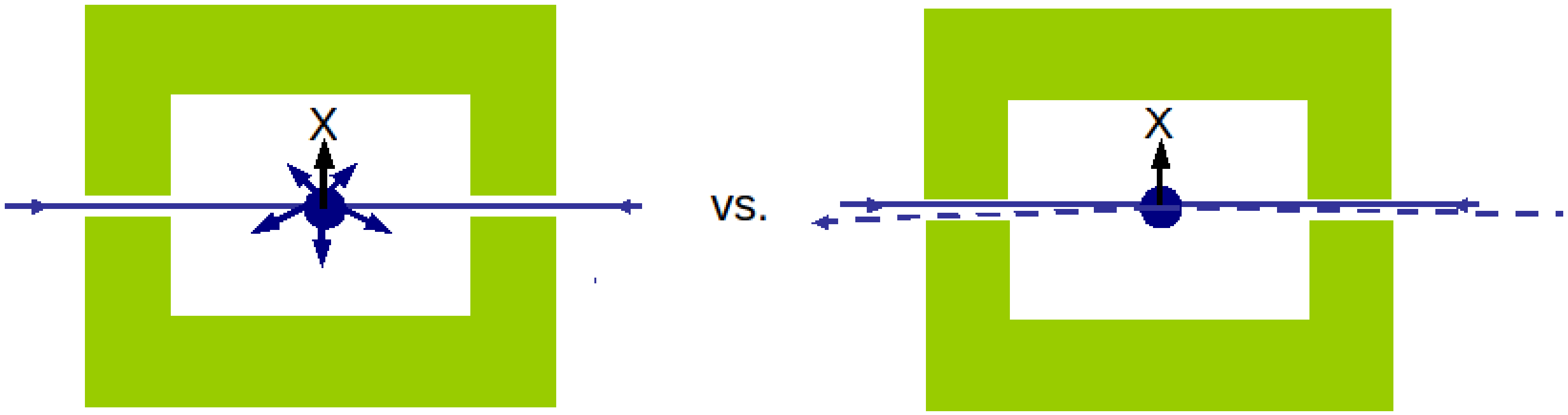
Central Exclusive Production (CEP) is the interaction:

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

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

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.



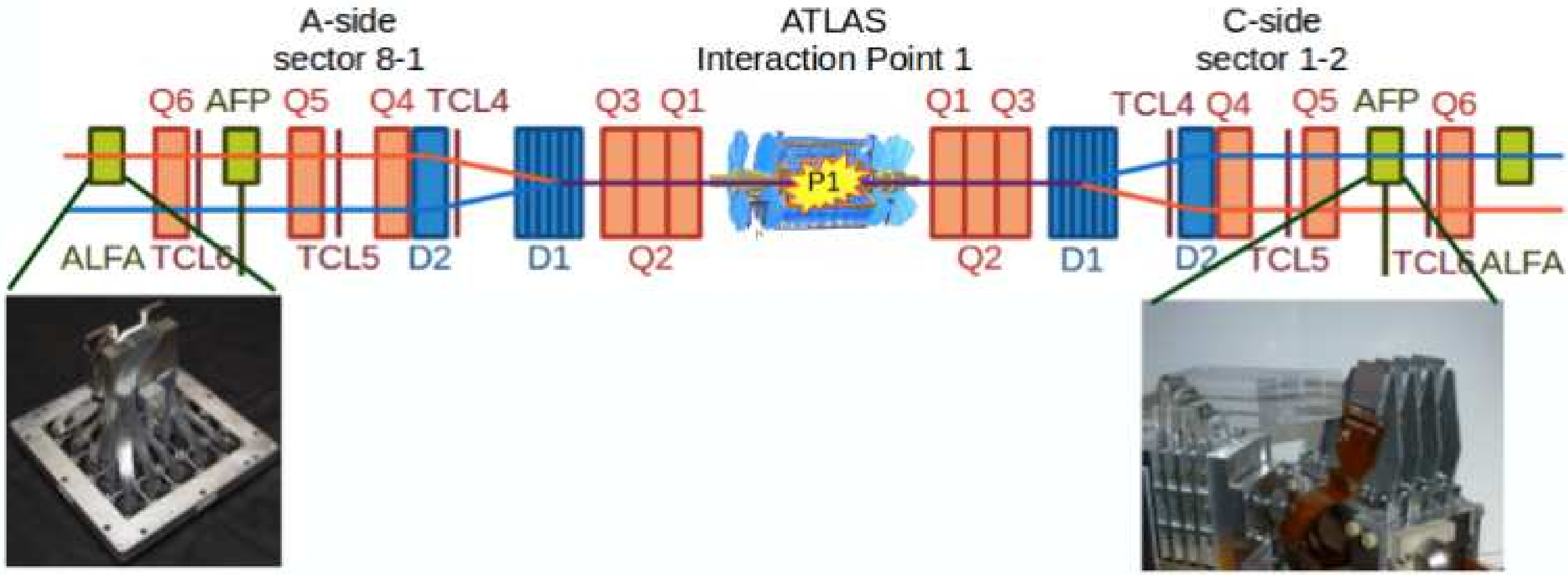
ATLAS Forward Detectors for Diffraction

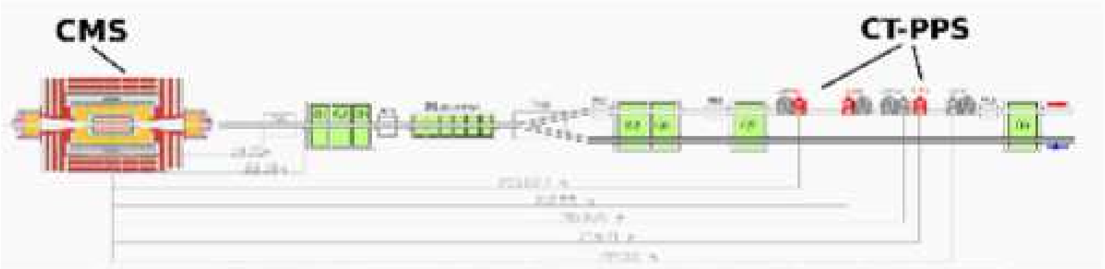
In ATLAS it is possible to **identify diffractive events** by, e.g. large rapidity gaps

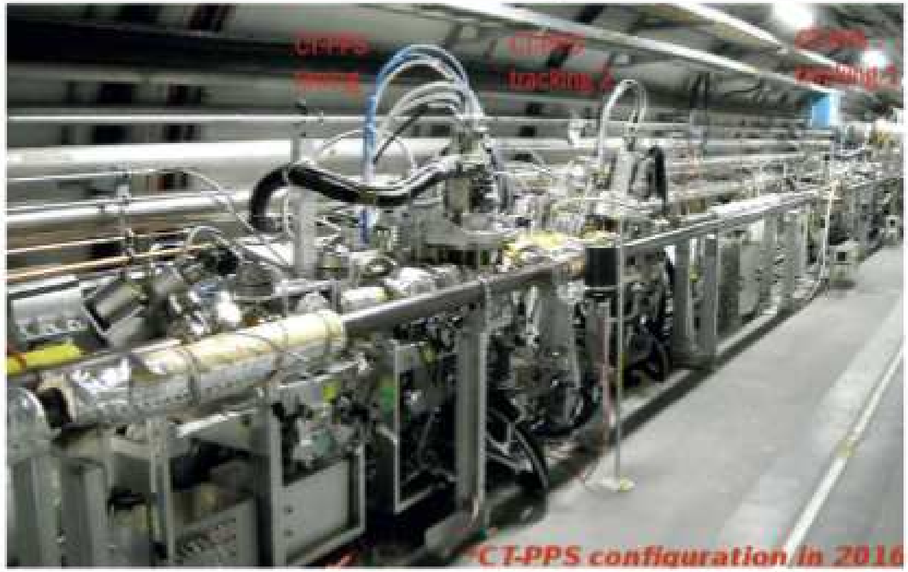
However, ATLAS is equipped with two forward detectors for **proton tagging**

- ALFA (Absolute Luminosity For ATLAS) vertical Roman Pots
  at $z = \pm 237$ and $z = \pm 245$ m for *elastic* and *diffractive* scattering measurements
- AFP (ATLAS Forward Proton) horizontal Roman Pots
  at $z = \pm 205$ and $z = \pm 217$ m for *diffractive* scattering measurements "NEW"

➡ Tag protons leaving intact the interaction point to **identify diffractive processes**

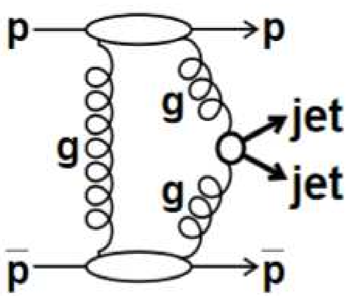


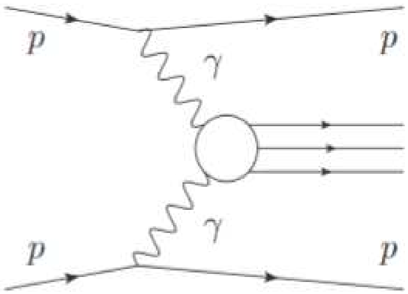


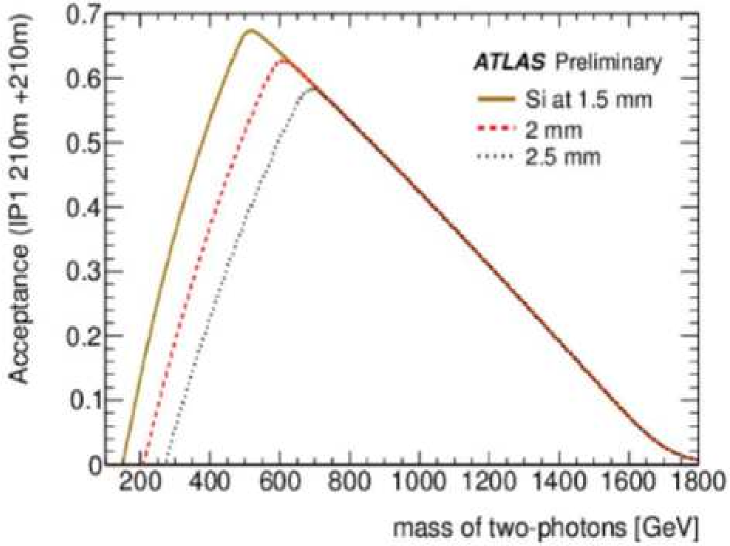


- Joint CMS and TOTEM project: https://cds.cern.ch/record/1753795, see Fabio's talk
- d scattered protons out of the beam envelope
- Detect scattered protons a few mm from the beam (both sides of CMS
- First data taking in 2016:$\sim$ 15 fb^{-1}

What is AFP/CT-PPS?







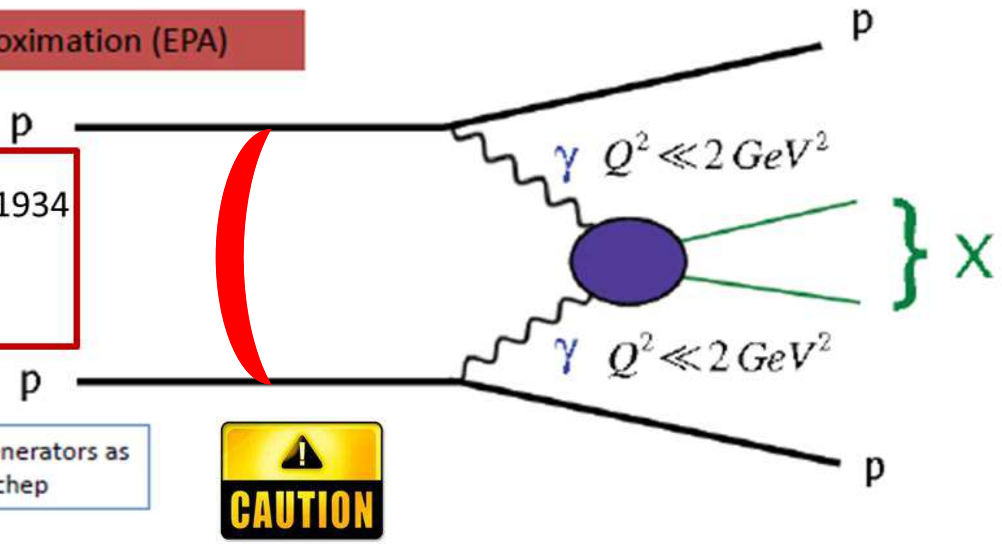
- Tag and measure protons at ±210 m: AFP (ATLAS Forward Proton), CT-PPS (CMS TOTEM - Precision Proton Spectrometer)

- Sensitivity to high mass central system, X, as determined using AFP/CT-PPS: Very powerful for exclusive states: kinematical constraints coming from AFP and CT-PPS proton measurements

Exclusive Photon-Photon collisions

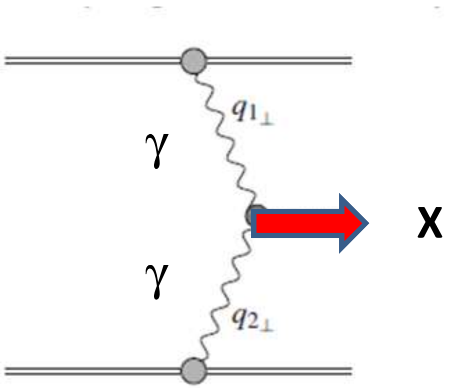
- In exclusive photon-mediated interactions, the colliding protons must both coherently emit a photon, and remain intact after the interaction. How do we model this?
- Answer is well known- the ‘equivalent photon approximation’ (EPA): cross section described in terms of a flux of quasi-real photons radiated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

Equivalent photon approximation (EPA)

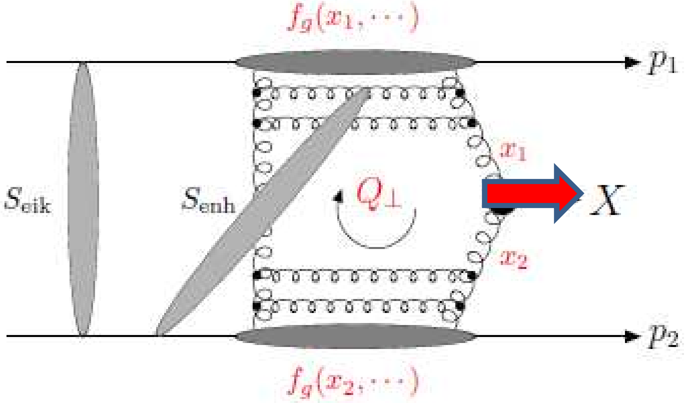


C.F. von Weizsacker, 1934
E.J. Williams , 1934
E. Fermi, 1925

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



VS.



- Naively expect strong interaction to dominate- $\alpha_S \gg \alpha$.
- However QCD enhancement can also be a weakness: exclusive event requires no extra gluon radiation into final state. Requires introduction of Sudakov suppressing factor:

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

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

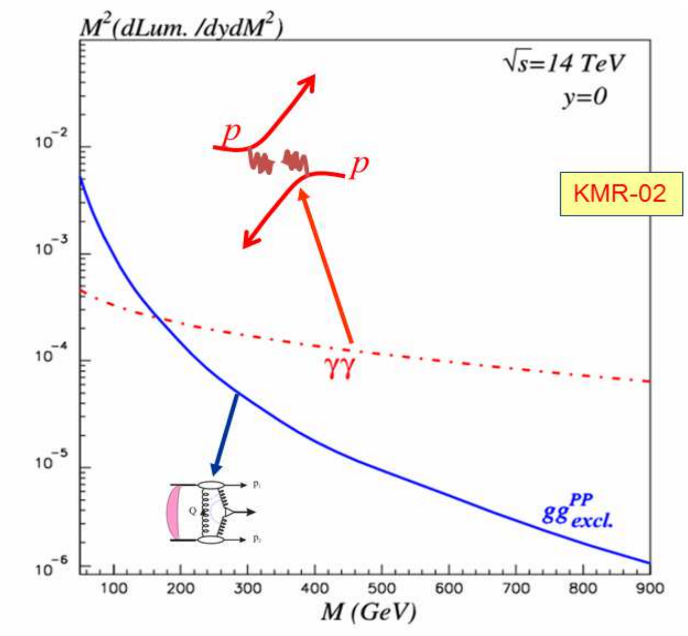
- Increasing M_X ⇒ larger phase space for extra gluon emission stronger suppression in exclusive QCD cross section. Gluons like to radiate!

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

KMR-2001

$\alpha_s^2/8 \rightarrow \alpha^2$

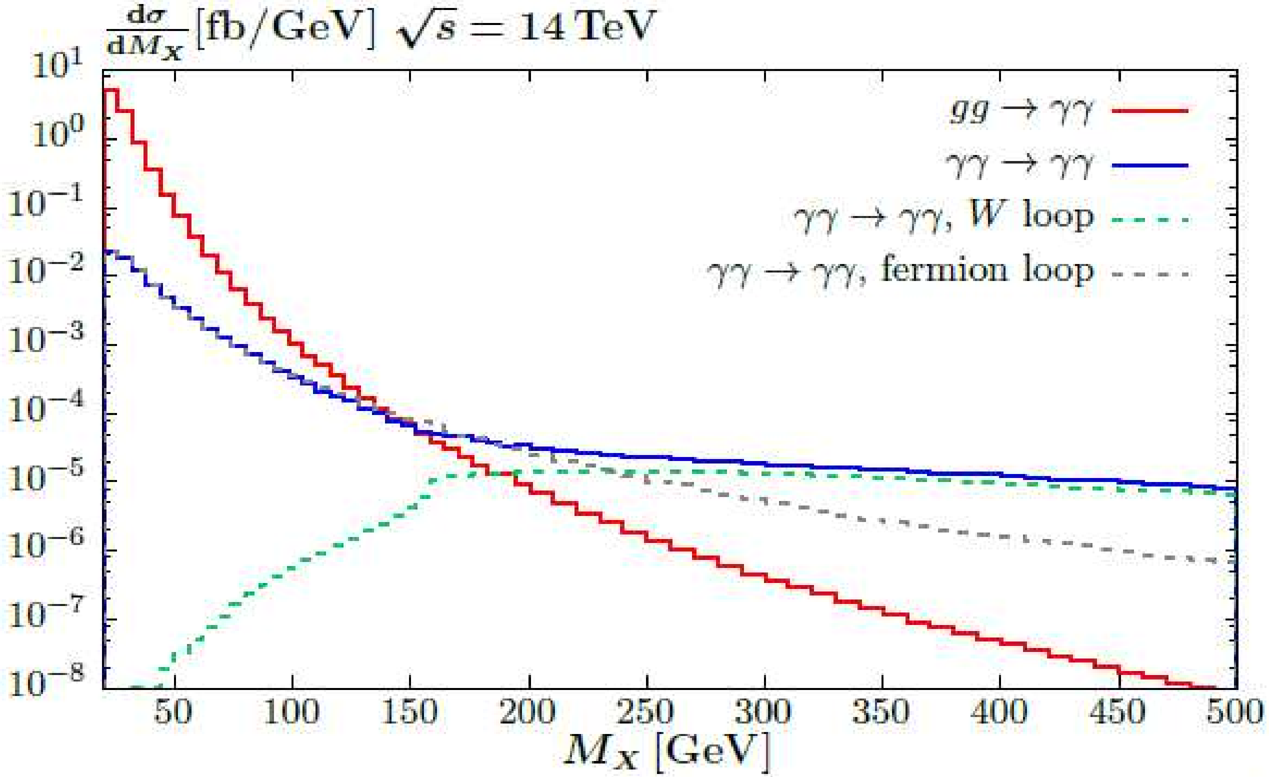
QCD 'radiation damage' in action



- 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 $M_X \gtrsim 200\,\mathrm{GeV}$ - well before CT-PPS/AFP mass acceptance region.

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

Light-by-light scattering



SuperChic

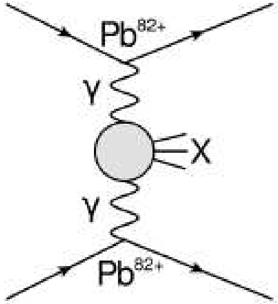
$p_\perp^\gamma > 10\,\text{GeV}$

$|\eta^\gamma| < 2.4$

- Impact of W loops at high mass clear. For $s_{\gamma\gamma} \gg M_W^2$ completely dominates!
- Also shown is QCD-mediated contribution (‘gg’). In the mass region the $\gamma\gamma$ mediated contribution dominates ($\longrightarrow$ Sudakov suppression of gg).

Ultra-Peripheral Collisions

- Ions do not necessarily collide 'head-on' - for 'ultra-peripheral' collisions, with $b > R_1 + R_2$ the ions can interact purely via EM and remain intact $\Rightarrow$ exclusive $\gamma\gamma$-initiated production.



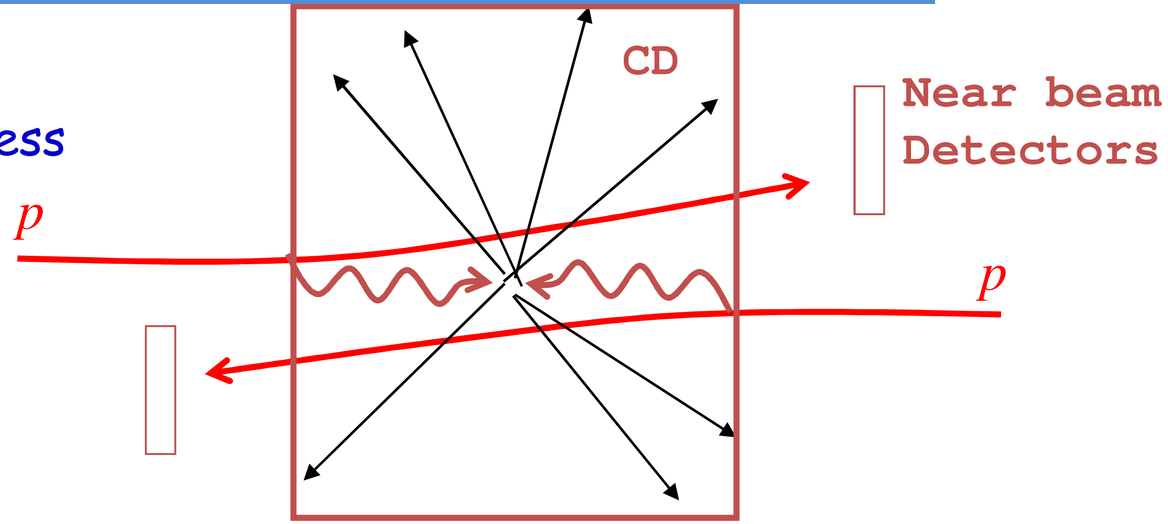
[Fermi, Nuovo Cim. 2 (1925) 143]
[Weizsacker, Z. Phys. 88 (1934) 612]
[Williams, Phys. Rev. 45 (10 1934) 729]

$$\boxed{Q^2 < \frac{1}{R^2} \quad \text{and} \quad \omega_{\max} \approx \frac{\gamma}{R}}$$

- Ions interact via coherent photon exchange- feels whole charge of ion $\Rightarrow$ cross section $\propto Z^4$. For e.g. Pb-Pb have $Z^4 \sim 5 \times 10^7$ enhancement!
- Photon flux in ion tends to be cutoff at high M_X, but potentially very sensitive to lower mass objects with EW quantum numbers.

γγ collisions- applications

Process



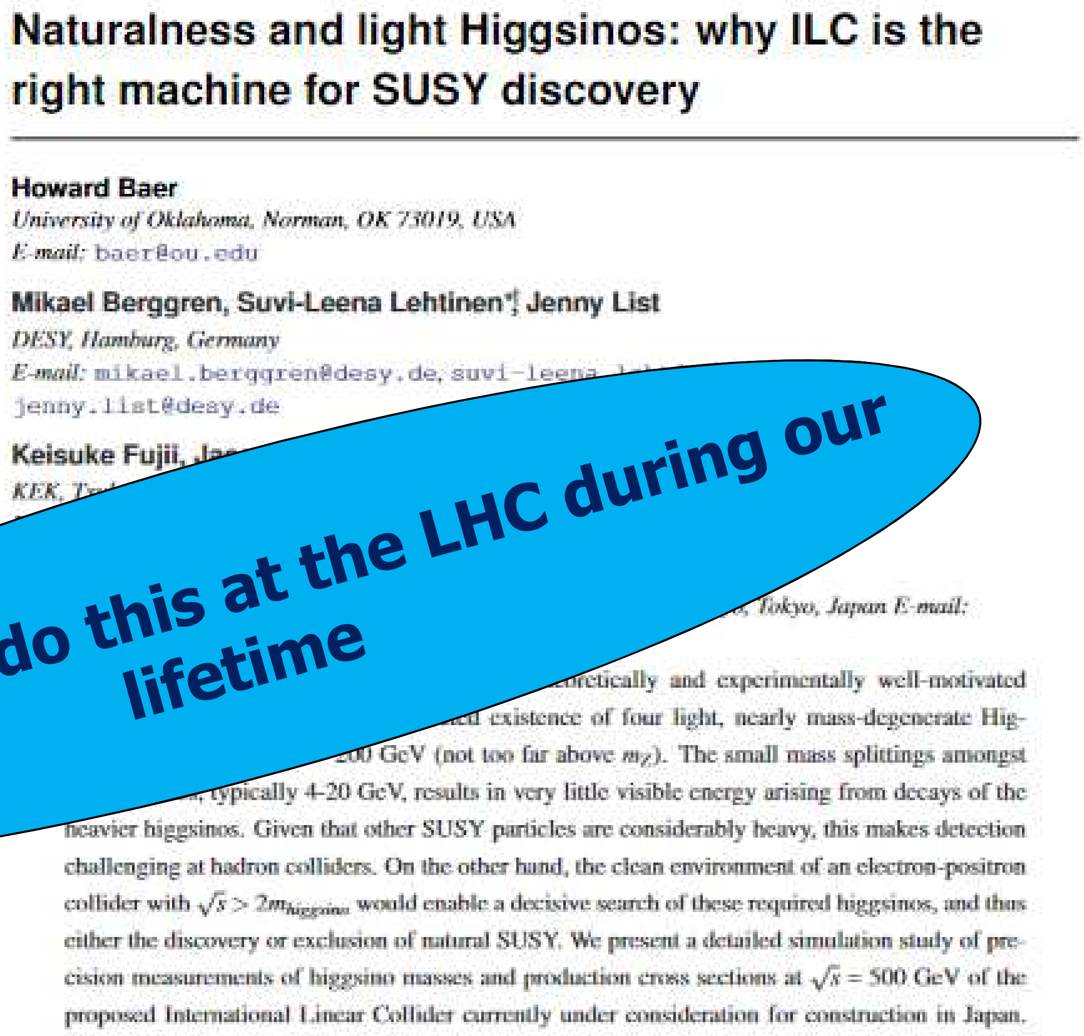
Installed (AFP)
Installed (CT-PPS)
projects

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

arXiv:1710.02406

Radiatively –driven natural SUSY
existence of light nearly
mass-degenerate Higgsinos
Mass~ 100-200GeV,
mass splitting ~ 4-20 GeV



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 Lehtinen*[†] Jenny List
DESY, Hamburg, Germany
E-mail: `mikael.berggren@desy.de`, `suvi-leena`
`jenny.list@desy.de`

Keisuke Fujii, Ja
KEK, Ts

Tokyo, Japan E-mail:

oretically and experimentally well-motivated
ed existence of four light, nearly mass-degenerate Hig-
00 GeV (not too far above m_Z). The small mass splittings amongst
, 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.

We can try to do this at the LHC during our lifetime

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

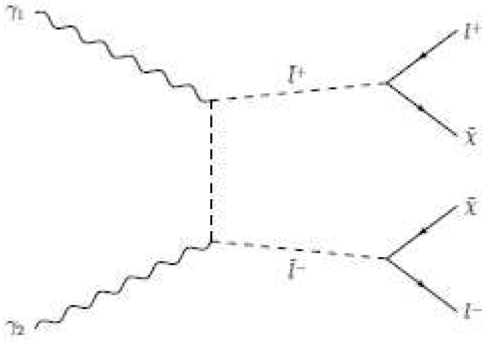
Diphoton X-Pair Production

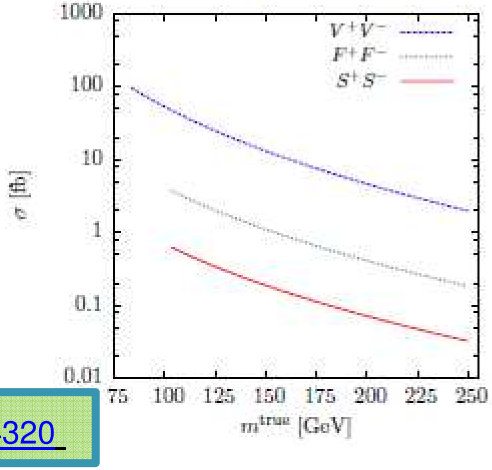
$$pp \to p + \gamma\gamma + p \,,$$
$$\gamma\gamma \to X^+X^- \,,$$

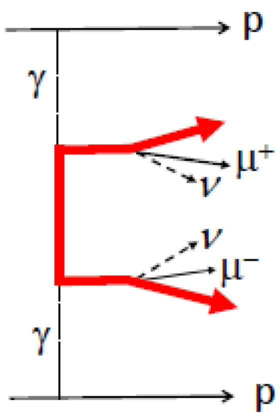
where X = W–boson, lepton, slepton, chargino...

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

(Sven)







HKSS, arXiv:1110.4320

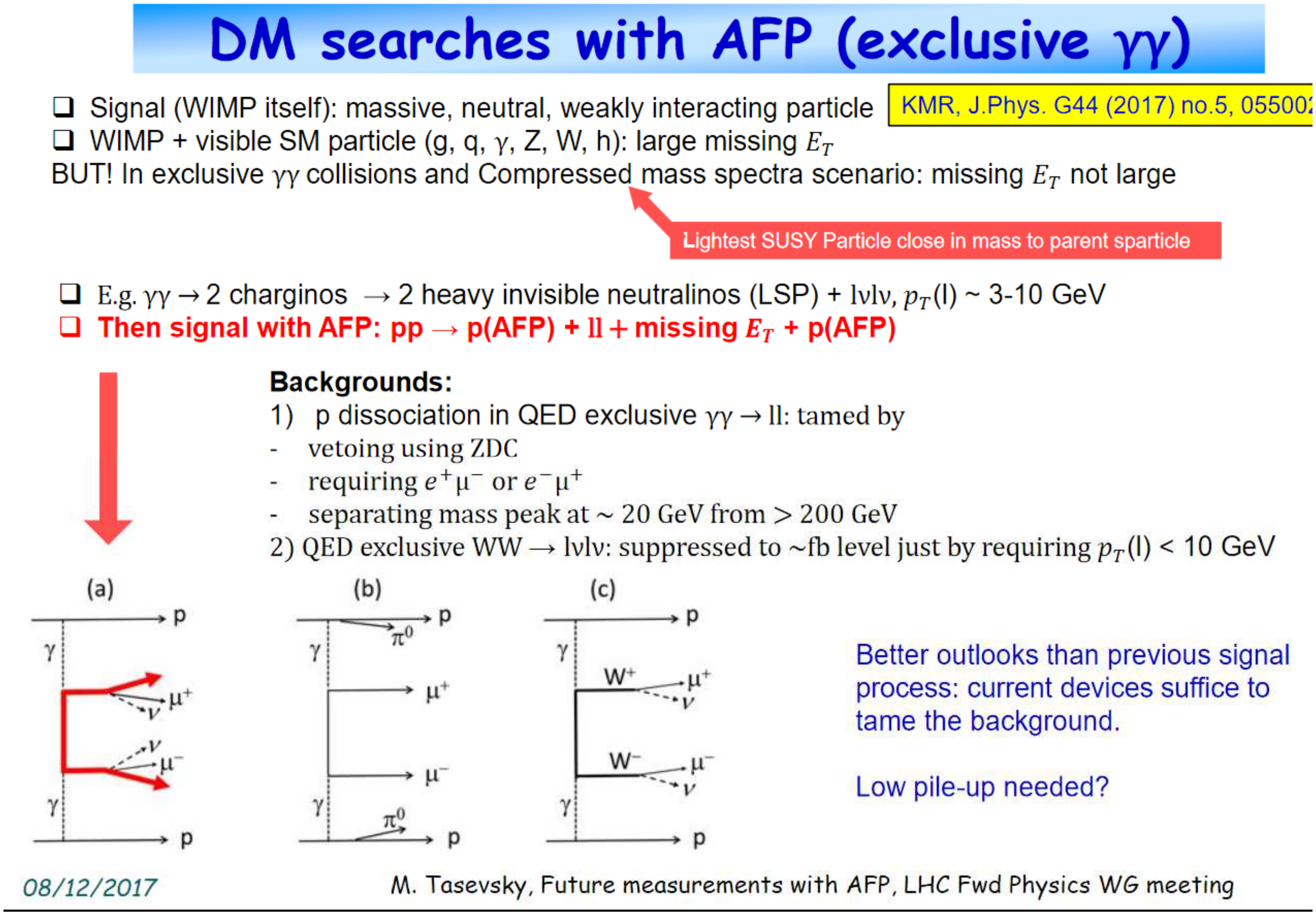
- Consider exclusive production of chargino pair $\tilde{\chi}_1^+\tilde{\chi}_1^-$, decaying via

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

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

electroweakinos

- 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**)



DM searches with AFP (exclusive $\gamma\gamma$)

KMR, J.Phys. G44 (2017) no.5, 05500

☐ Signal (WIMP itself): massive, neutral, weakly interacting particle
☐ WIMP + visible SM particle (g, q, γ, Z, W, h): large missing E_T
BUT! In exclusive $\gamma\gamma$ collisions and Compressed mass spectra scenario: missing E_T not large

Lightest SUSY Particle close in mass to parent sparticle

☐ E.g. $\gamma\gamma \to$ 2 charginos $\to$ 2 heavy invisible neutralinos (LSP) + $l\nu l\nu$, p_T(l) ~ 3-10 GeV
☐ **Then signal with AFP: pp $\to$ p(AFP) + ll + missing E_T + p(AFP)**

Backgrounds:
1) p dissociation in QED exclusive $\gamma\gamma \to$ ll: tamed by
- vetoing using ZDC
- requiring $e^+\mu^-$ or $e^-\mu^+$
- separating mass peak at ~ 20 GeV from > 200 GeV

2) QED exclusive WW $\to l\nu l\nu$: suppressed to ~fb level just by requiring p_T(l) < 10 GeV

Better outlooks than previous signal process: current devices suffice to tame the background.

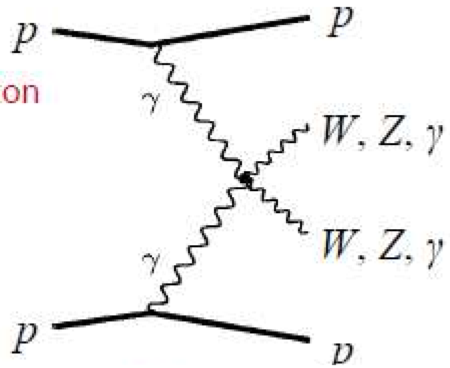
Low pile-up needed?

08/12/2017 M. Tasevsky, Future measurements with AFP, LHC Fwd Physics WG meeting

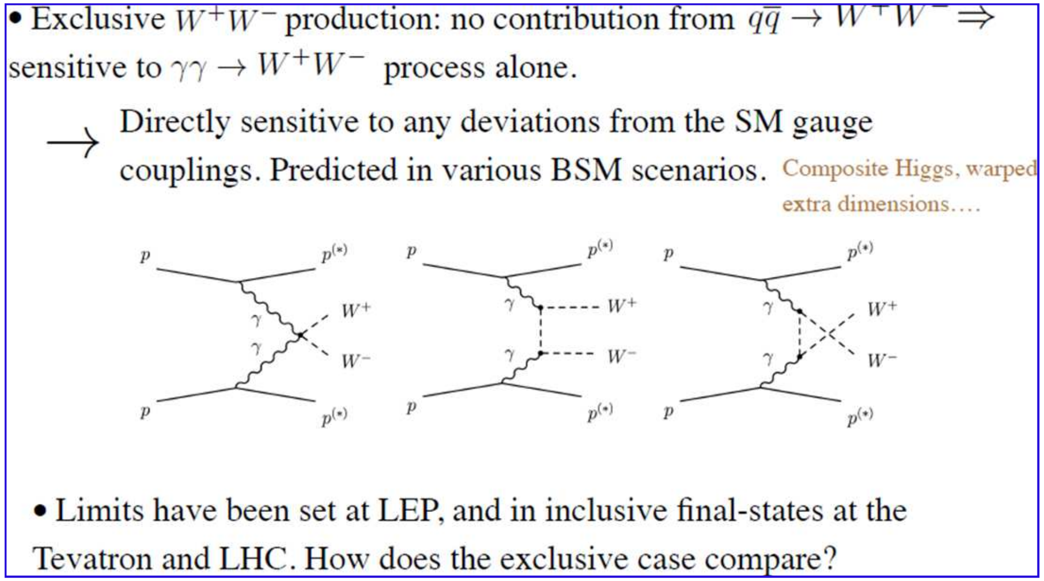
Low energy release, but clear operating environment .

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: ($Z \to ee$, $\gamma\gamma$)
  - 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



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

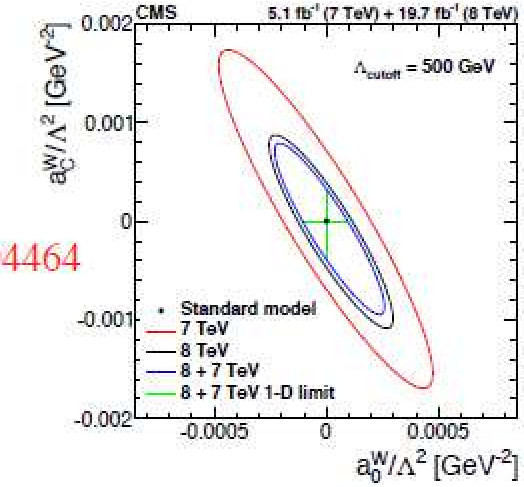
$\longrightarrow$ Directly sensitive to any deviations from the SM gauge couplings. Predicted in various BSM scenarios. Composite Higgs, warped extra dimensions....

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

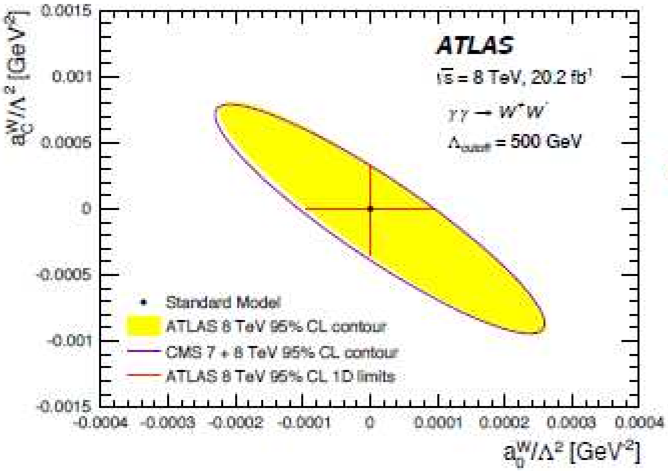
Currently
very encouraging
ATLAS & CMS data

Anomalous couplings - data

- ATLAS + CMS data: $W \to l\nu$ pair production with no associated charged tracks $\Rightarrow$ use this veto to extract quasi-exclusive signal. Use data-driven method to subtract non-exclusive BG ($p \to p^*$).



arXiv:1604.04464



arXiv:1607.03745

- These data place the most stringent constraints to date on AGCs: two orders of mag. better than LEP, and ~ order of mag. tighter than equivalent inclusive LHC.
- Direct consequence of exclusive selection $\Rightarrow$ precisely understood $\gamma\gamma$ collisions, but at a hadron collider.

Search for light-by-light scattering

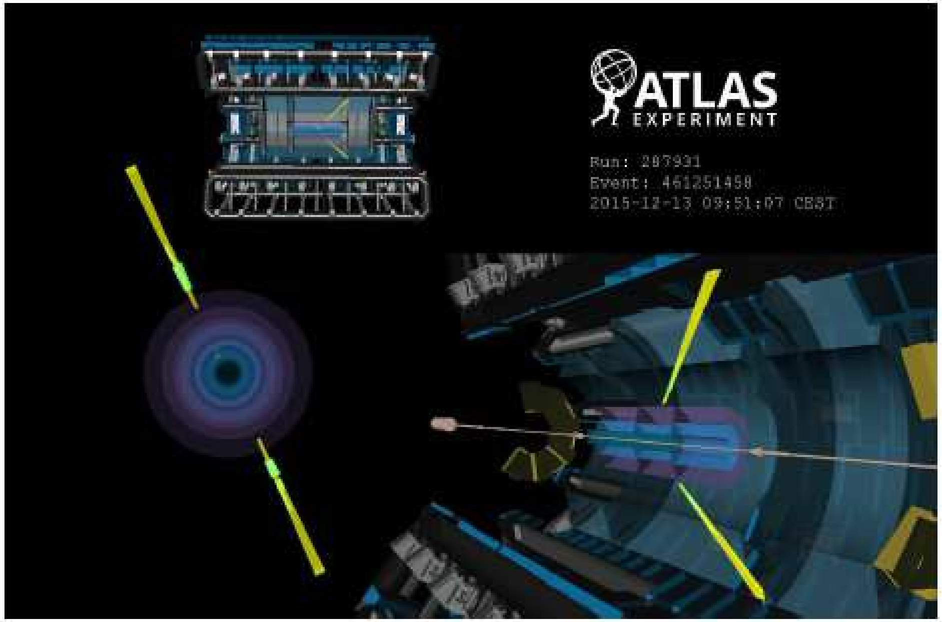
ATLAS @ $\sqrt{s_{NN}}$ = 5.02 TeV:

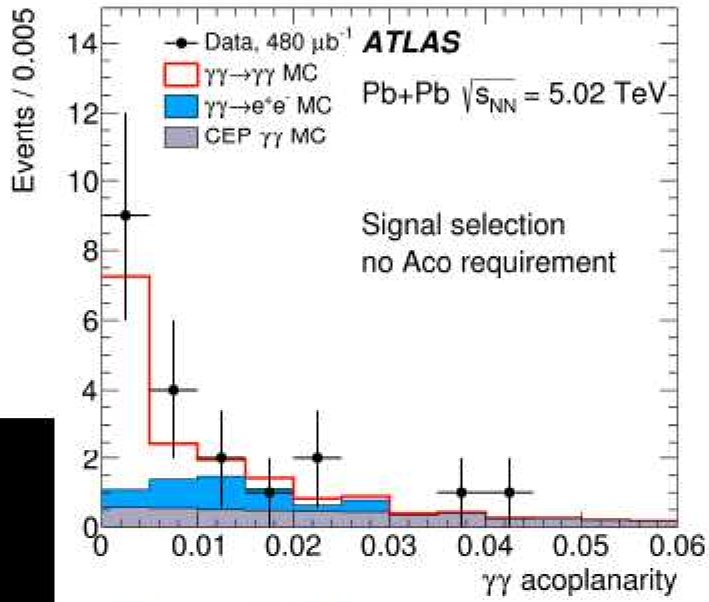
13 events (bkgd 2.6) $\Rightarrow$ 4.4σ evidence

σ = 70 ± 20 (stat) ± 17 (syst) nb

($p_{T,\gamma} > 3$ GeV, $|\eta_\gamma| < 2.4$, $M_{\mu+\mu-} > 6$ GeV, $p_T(\gamma\gamma) < 2$ GeV, Aco < 0.01)

ATLAS coll., ArXiv:1702.01625(2017)





SM predictions:

- 45 ± 9 nb

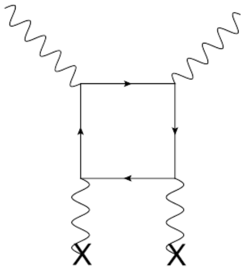
D. d'Enterria et al., PRL 111 (2013) 080405

- 49 ± 10 nb

A. Szczurek et al., PRC 93 (2016) 044907

Long and chequered history

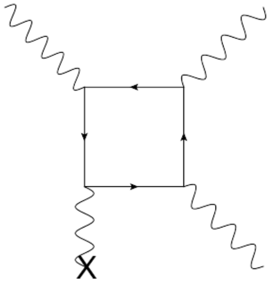
(nonlinear effects of QED)



Delbrück **1933**

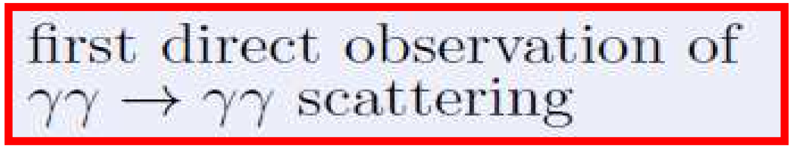
Scattering of gamma-rays by a Coulomb field of heavy nuclei.
First observed-1953 for 1.33 MeV on lead nuclei.
Most accurate high-energy results- Novosibirsk,VEPP-4M 1998.

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)

LHC limits on axion-like particles from heavy-ion collisions

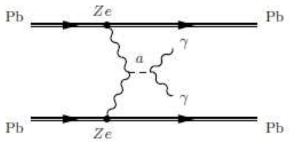
(Matthias)

ArXiv:1709.07110

$$\mathcal{L}_a = \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}\frac{a}{\Lambda}F\widetilde{F}$$

J. Jaeckel and M. Spannowsky, "Probing MeV to 90 GeV axion-like particles with LEP and LHC," *Phys. Lett.* **B753** (2016) 482–487, `arXiv:1509.00476 [hep-ph]`.

J. Jaeckel, M. Jankowiak, and M. Spannowsky, "LHC probes the hidden sector," *Phys. Dark Univ.* **2** (2013) 111–117, `arXiv:1212.3620 [hep-ph]`.



: Exclusive ALP production in ultra-peripheral Pb-Pb co

$7\,\text{GeV} < m_a < 100\,\text{GeV},$

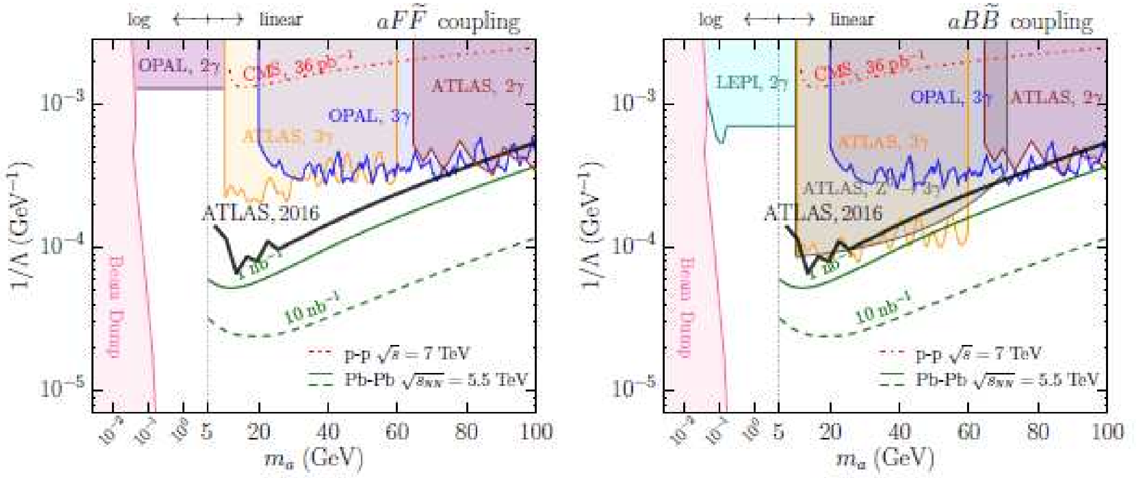


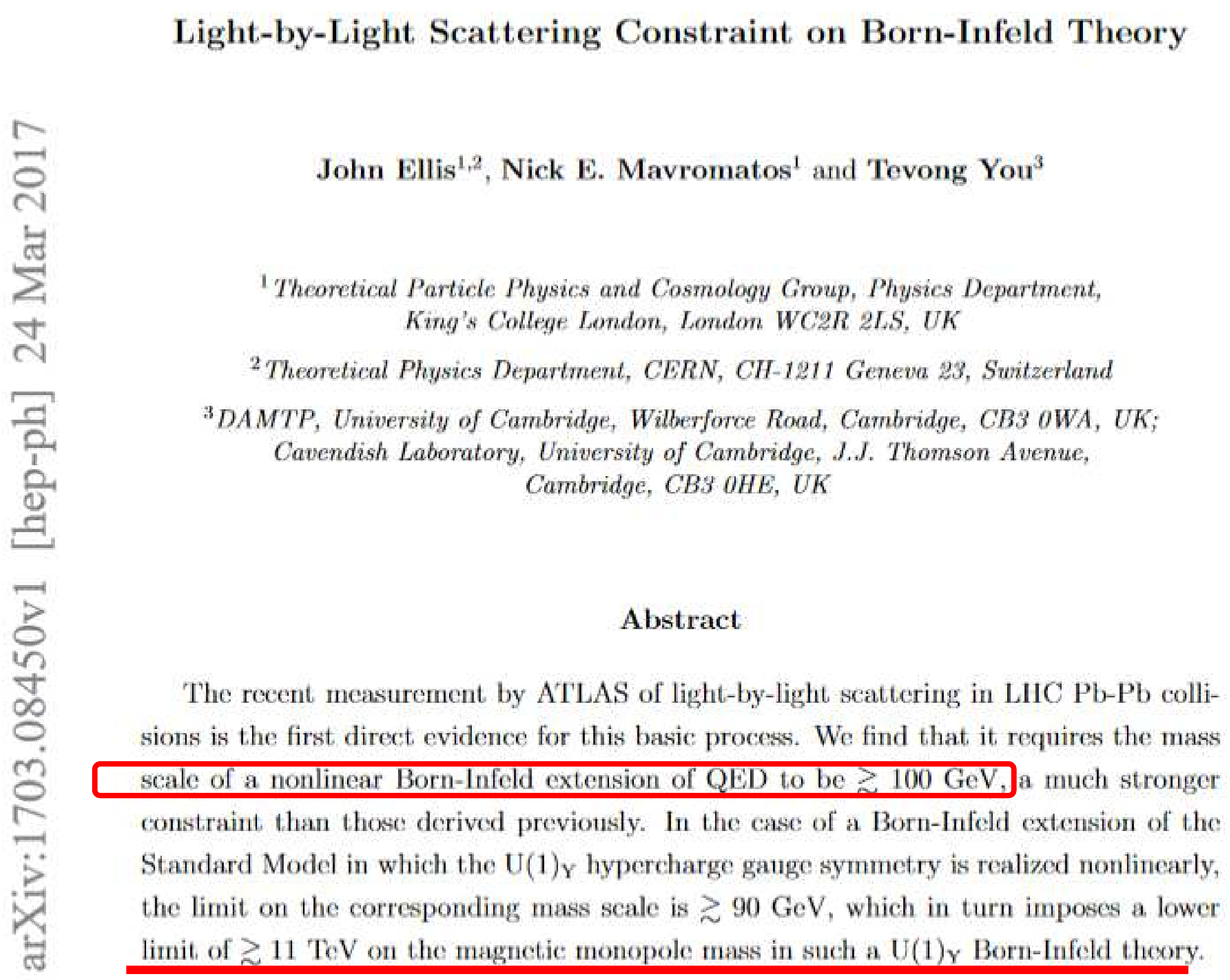
Fig. 2: *Left:* We show 95% exclusion limits on the operator $\frac{1}{4}\frac{1}{\Lambda}aF\tilde{F}$ using recent ATLAS results on heavy-ion UPCs [2] (solid black line). The expected sensitivity assuming a luminosity of 1 nb^{-1} (10 nb^{-1}) is shown in solid (dashed) green. For comparison, we also give the analogous limit from 36 pb^{-1} of exclusive p-p collisions [17] (red dot-dash). Remaining exclusion limits are recast from LEP II (OPAL 2γ, 3γ) [22] and from the LHC (ATLAS 2γ, 3γ) [23, 24] (see [1] for details). *Right*: The corresponding results for the operator $\frac{1}{4\cos^2\theta_W}\frac{1}{\Lambda}aB\widetilde{B}$. The LEP I, 2γ (teal shaded) limit was obtained from [14].

LbyL Scattering Constraint on Born-Infeld Theory

[arXiv:1703.08450]

$$\mathrm{L}_{\mathrm{QED}} = -\frac{1}{4}\mathrm{F}_{\mu\nu}\mathrm{F}^{\mu\nu} \rightarrow \mathrm{L}_{\mathrm{BI}} = \beta^2\left(1 - \sqrt{1 + \frac{1}{2\beta^2}\mathrm{F}_{\mu\nu}\mathrm{F}^{\mu\nu} - \frac{1}{6\beta^4}\mathrm{F}_{\mu\nu}\tilde{\mathrm{F}}^{\mu\nu}}\right)$$

Interest from the string-theoretic point of view
ArXiv: 1701.07375



Light-by-Light Scattering Constraint on Born-Infeld Theory

John Ellis[1,2], **Nick E. Mavromatos**[1] and **Tevong You**[3]

[1] *Theoretical Particle Physics and Cosmology Group, Physics Department,*
King's College London, London WC2R 2LS, UK

[2] *Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*

[3] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, UK;*
Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue,
Cambridge, CB3 0HE, UK

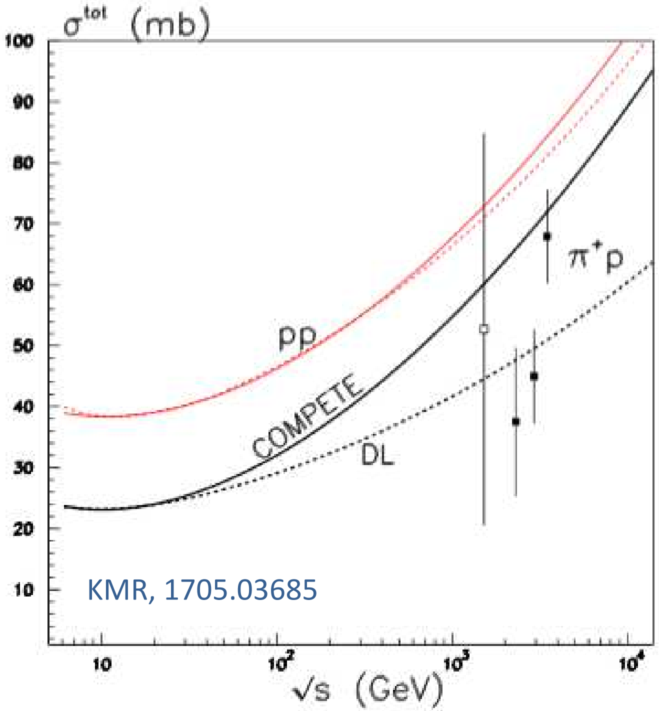
Abstract

The recent measurement by ATLAS of light-by-light scattering in LHC Pb-Pb collisions is the first direct evidence for this basic process. We find that it requires the mass scale of a nonlinear Born-Infeld extension of QED to be $\gtrsim$ 100 GeV, a much stronger constraint than those derived previously. In the case of a Born-Infeld extension of the Standard Model in which the $U(1)_Y$ hypercharge gauge symmetry is realized nonlinearly, the limit on the corresponding mass scale is $\gtrsim$ 90 GeV, which in turn imposes a lower limit of $\gtrsim$ 11 TeV on the magnetic monopole mass in such a $U(1)_Y$ Born-Infeld theory.

PION-PROTON INTERACTIONS

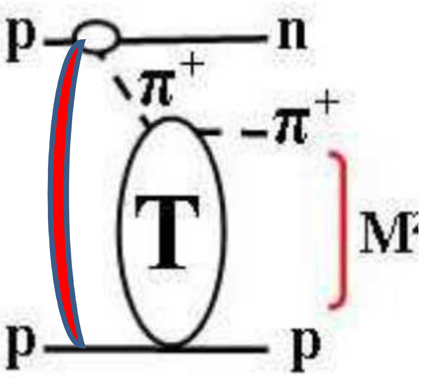
Direct measurements only up to 25 GeV, but we can use the LHCf HE forward neutron data.

R. Ryutin , 1612.03418.
KMR, 1705.03685

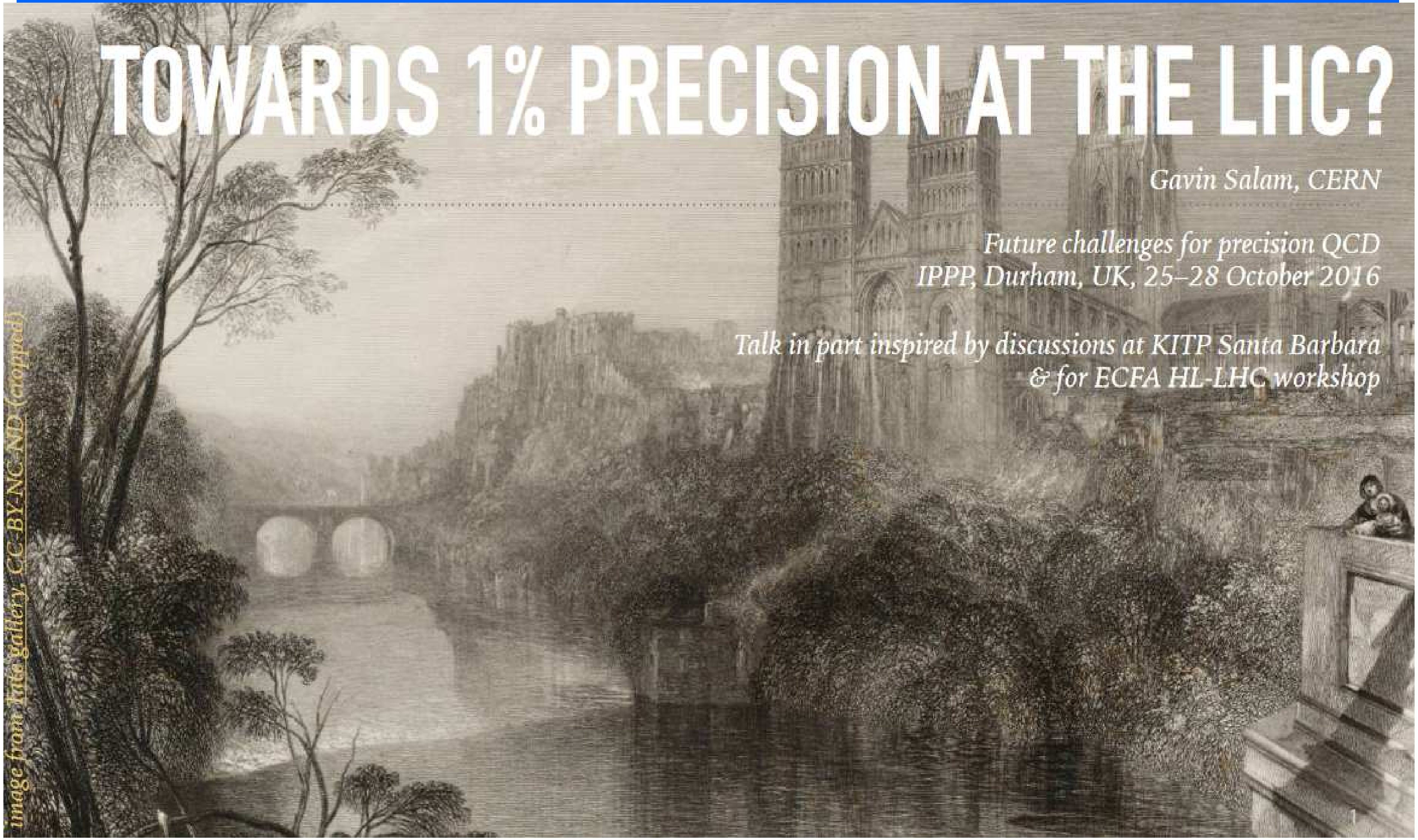


KMR, 1705.03685

Figure 5: The four values of π^+p total cross section that we extract from the LHCf data on leading neutrons [1], compared with expectations based on fits to lower-energy hadron-hadron total cross section data parametrized by two Regge poles, DL [35], or using the COMPETE parametrization [40]. Note that the results of both parametrizations coincide in the region of the existing πp cross section data, that is for $\sqrt{s} < 25$ GeV.



Luminometry
(can we break the 2% wall ?)



TOWARDS 1% PRECISION AT THE LHC?

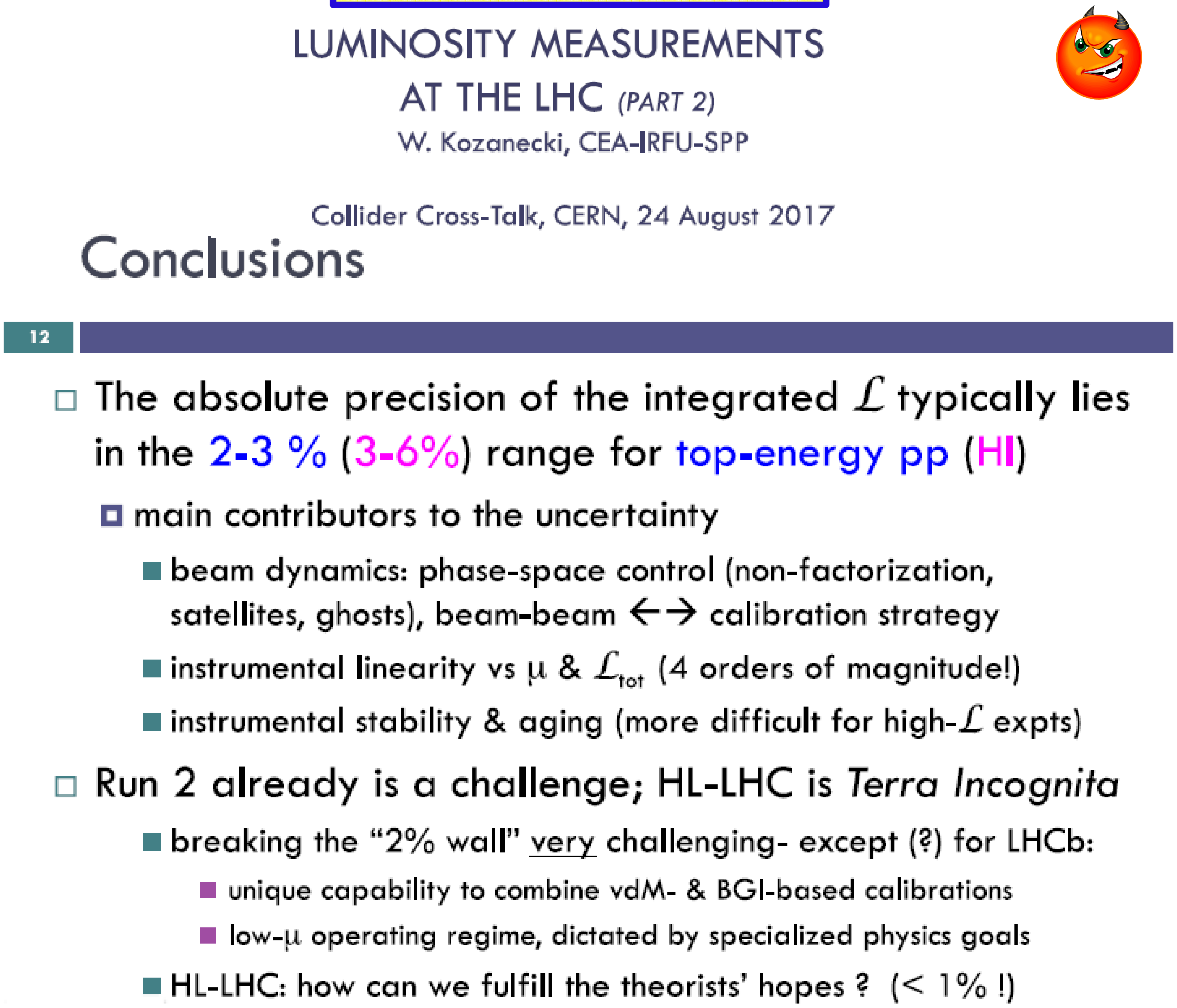
Gavin Salam, CERN

Future challenges for precision QCD
IPPP, Durham, UK, 25–28 October 2016

Talk in part inspired by discussions at KITP Santa Barbara
& for ECFA HL-LHC workshop

image from Tate gallery, CC-BY-NC-ND (cropped)

What do the expert say?



LUMINOSITY MEASUREMENTS AT THE LHC *(PART 2)*

W. Kozanecki, CEA-IRFU-SPP

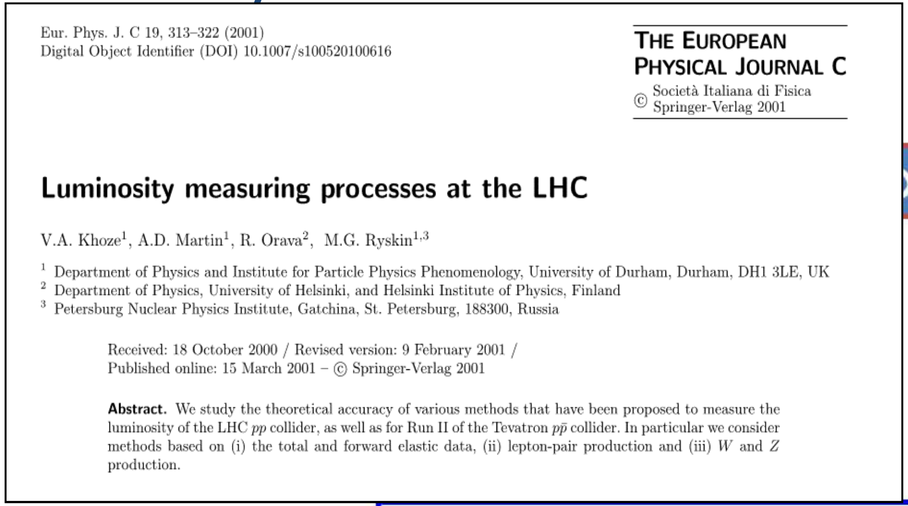
Collider Cross-Talk, CERN, 24 August 2017

Conclusions

12

- The absolute precision of the integrated $\mathcal{L}$ typically lies in the 2-3 % (3-6%) range for top-energy pp (HI)
  - main contributors to the uncertainty
    - beam dynamics: phase-space control (non-factorization, satellites, ghosts), beam-beam ←→ calibration strategy
    - instrumental linearity vs μ & $\mathcal{L}_{tot}$ (4 orders of magnitude!)
    - instrumental stability & aging (more difficult for high-$\mathcal{L}$ expts)
- Run 2 already is a challenge; HL-LHC is *Terra Incognita*
  - breaking the “2% wall” very challenging- except (?) for LHCb:
    - unique capability to combine vdM- & BGI-based calibrations
    - low-μ operating regime, dictated by specialized physics goals
  - HL-LHC: how can we fulfill the theorists’ hopes ? (< 1% !)

Maybe it is time to resurrect the dilepton CEP monitor ?



Eur. Phys. J. C 19, 313–322 (2001)
Digital Object Identifier (DOI) 10.1007/s100520100616

THE EUROPEAN
PHYSICAL JOURNAL C
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Springer-Verlag 2001

Luminosity measuring processes at the LHC

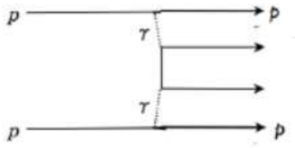
V.A. Khoze[1], A.D. Martin[1], R. Orava[2], M.G. Ryskin[1,3]

[1] Department of Physics and Institute for Particle Physics Phenomenology, University of Durham, Durham, DH1 3LE, UK
[2] Department of Physics, University of Helsinki, and Helsinki Institute of Physics, Finland
[3] Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg, 188300, Russia

Received: 18 October 2000 / Revised version: 9 February 2001 /
Published online: 15 March 2001 – © Springer-Verlag 2001

Abstract. We study the theoretical accuracy of various methods that have been proposed to measure the luminosity of the LHC pp collider, as well as for Run II of the Tevatron $p\bar{p}$ collider. In particular we consider methods based on (i) the total and forward elastic data, (ii) lepton-pair production and (iii) W and Z production.

Lepton Pair Production



- ■ First proposed for luminometry by. V. Budnev et al, Nucl. Phys. **B63** (1973) 519.
- ■ First studies of feasibility for the dimuons at the LHC: A.Shamov and V.Telnov-1998 (ATLAS TDR-99)
- ■ Strong-interaction effects- KMOR, Eur.Phys.J.C19:313-322,2001
- ■ First observation of exclusive l^+l^- by CDF: 2007
- ■ New results for exclusive dileptonss: CMS,ATLAS, LHCb

Myth:

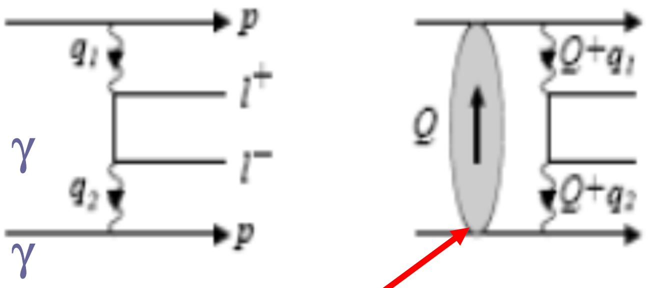
- **Pure QED process** –thus, theoretically well understood (higher-order QED effects- reliably calculable).

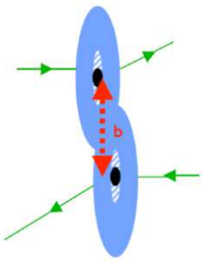
Reality

- Strong interaction effects (we collide protons after all).
- **Backgrounds**:

mis-ID, various contributions due to the incomplete exclusivity (lack of full detector coverage), pileup...

Strong interaction between colliding protons (rescattering corrections).





(large impact parameters)

Notorious survival factor.

Usually, for photon-photon central production $S^2_{\gamma\gamma}(LHC) \simeq 0.9$

However, in the case of $pp \rightarrow p + \ell^+\ell^- + p$ absorption effects could be very small.

In particular, for low $p_t(\mu\mu) \sim$ 10–50 MeV absorpt. correction $2\delta < 0.3\%$.
Could be additionally suppressed by the lepton acoplanarity cuts.

Polarization Structure of the diphoton amplitude!

unfortunately, so far
No practical proposal has been put forward by any LHC experiments

Looking Forward to a Bright Future of Forward Physics at the LHC


THANK YOU


QUESTIONS?


狗年大吉
2018
Happy Chinese New Year
of the Dog

BACKUP

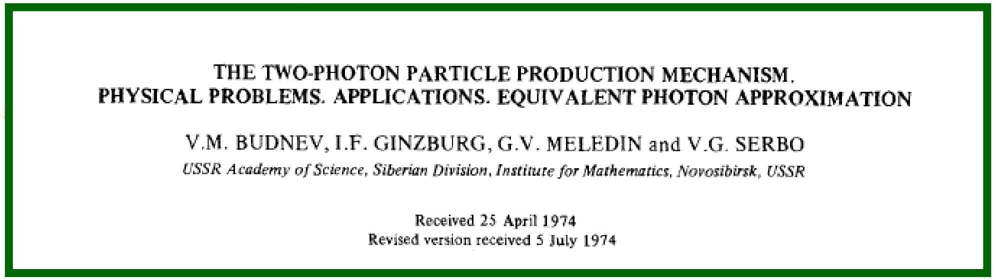
Equivalent photon approximation

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

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

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

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



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

V.M. BUDNEV, I.F. GINZBURG, G.V. MELEDIN and V.G. SERBO
USSR Academy of Science, Siberian Division, Institute for Mathematics, Novosibirsk, USSR

Received 25 April 1974
Revised version received 5 July 1974

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

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

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

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

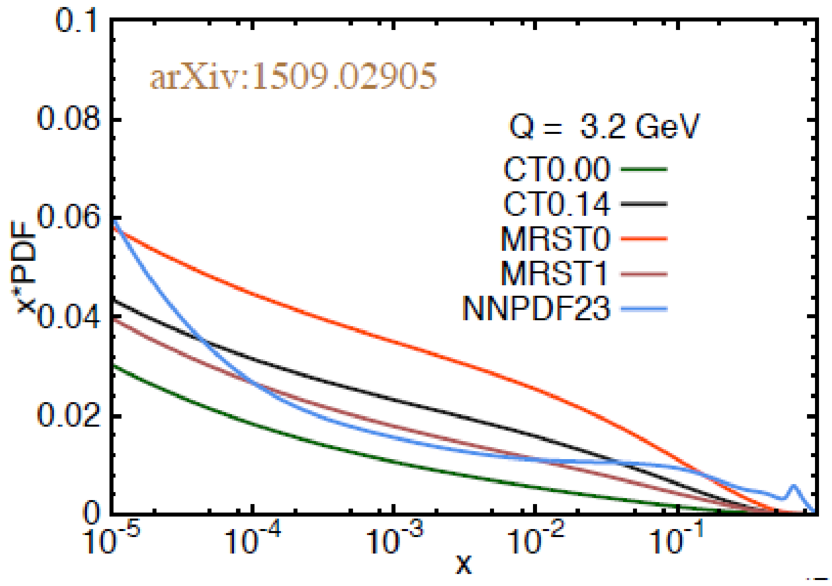
- Earlier photon PDF sets either:

Not so long ago

  - ‘Agnostic’ approach. NNPDF2.3QED: treat photon as we would quark and gluons. Freely parametrise $\gamma(x, Q_0)$ and fit to DIS and some LHC W, Z data.

worrisome range

  - ‘Model’ approach. MRST2004QED/CT14QED: take simple ansatz for photon emission from quarks. Compare/fit to ZEUS isolated photon DIS.



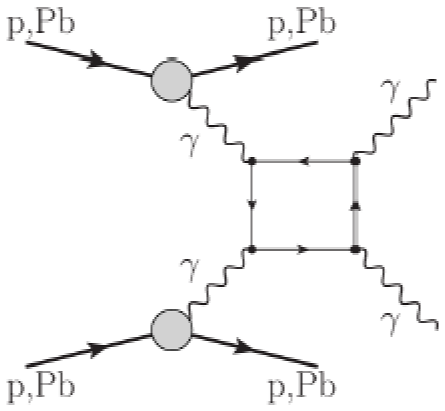
- Comparing these different sets reveals apparently large uncertainties.

➤ Model-independent uncertainty (NNPDF) was 50–100%

Light-by-light scattering in Pb+Pb

- **Motivation**

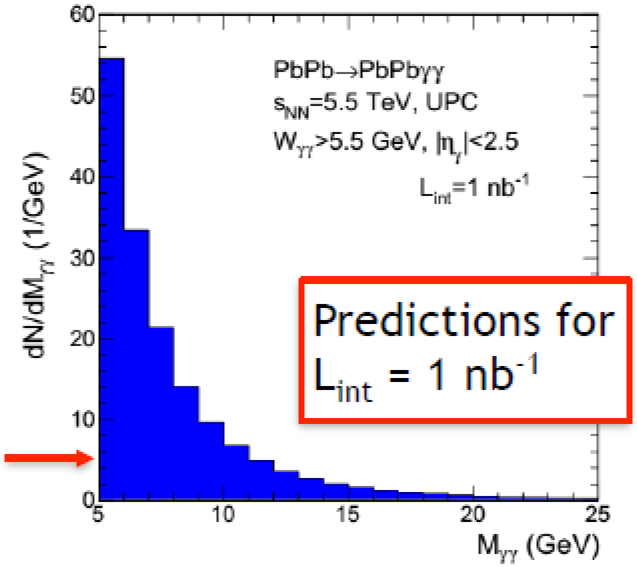
[Nature Physics (2017)]



- Light-by-light ($\gamma\gamma \rightarrow \gamma\gamma$) scattering
  - Tested indirectly in measurements of the anomalous magnetic moment of the electron and muon
  - Previous LbyL measurements involve Delbruck scattering and photon splitting process at low-energies

- Proposed as a possible channel to study
  - Anomalous gauge couplings
  - Contributions from BSM particles

- Recent studies/predictions for SM rates
  - [**D. d'Enterria et al.** PRL 111 (2013) 080405]
  - [**A. Szczurek et al.** PRC 93 (2016) 4, 044907]

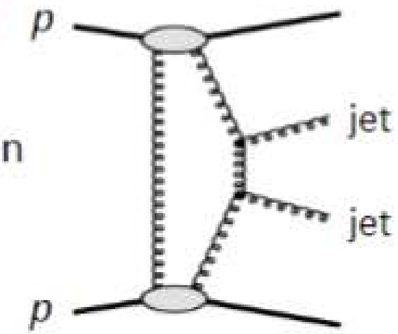


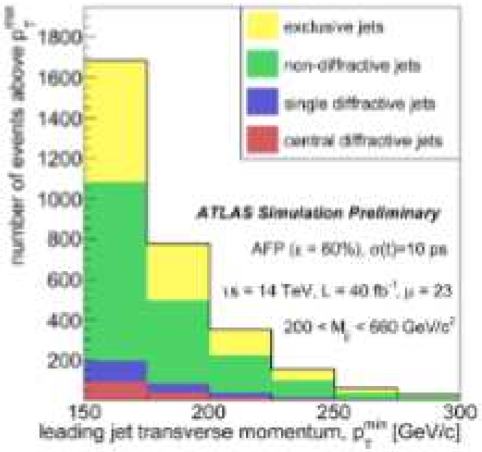
Predictions for L_{int} = 1 nb^{-1}

Physics with AFP 2+2 (high μ)

Central Exclusive Jet Production

First observed by CFD@Tevatron
Low σ → high pile-up run
→ double tag
→ ToF to control bkg



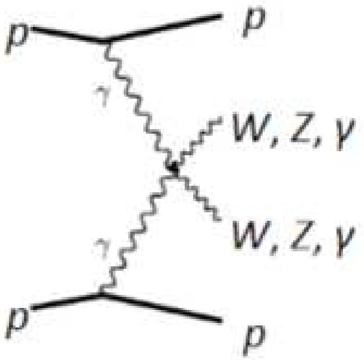


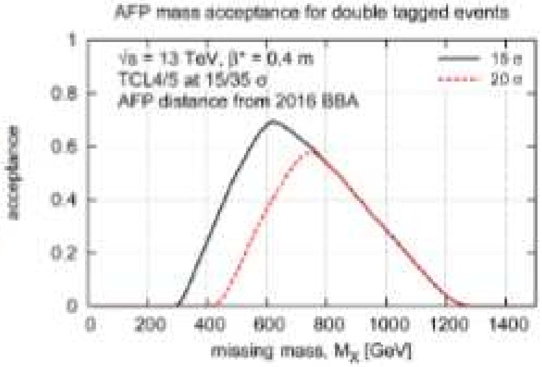
Compare mass and rapidity of central and pp systems

Photon-induced WW/ZZ/γγ Production

Best sensitivity to aQGC (few % missing mass resolution): factor 100 better than "standard" LHC analyses (sensitivity to higgless models, extra dimensions)

New Particles?





Dileptons good for calibration

The (foreseeable) future

- **Run III** (2020-2022)
  - Run with possibly improved detector (luminosity in standard runs increased mostly by leveling)
- **HL-LHC** (2025 and beyond)
  - Available space/optics?
  - Detector at 420 m for exclusive Higgs (defined spin-parity state) and H→bb (couplings)?
  - γγ→WW/ZZ/γγ and new high-mass resonances
  - ...

Research Program will depend on LHC strategy
and Previous Results