Recent CMS+TOTEM Results on Exclusive Production, Diffraction and Light-by-Light Scattering

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On behalf of CMS & TOTEM

Forward Physics at LHC, EIC, Cosmic rays etc., Guanajuato , Mexico
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Contents

Introduction

Central (semi-)exclusive $\pi^+ \pi^-$ production at $\sqrt{s}$ = 5, 7, & 13 TeV
- protons not detected, forward rapidity gaps
(Double Pomeron Exchange – hadron spectroscopy, including elusive glueballs)

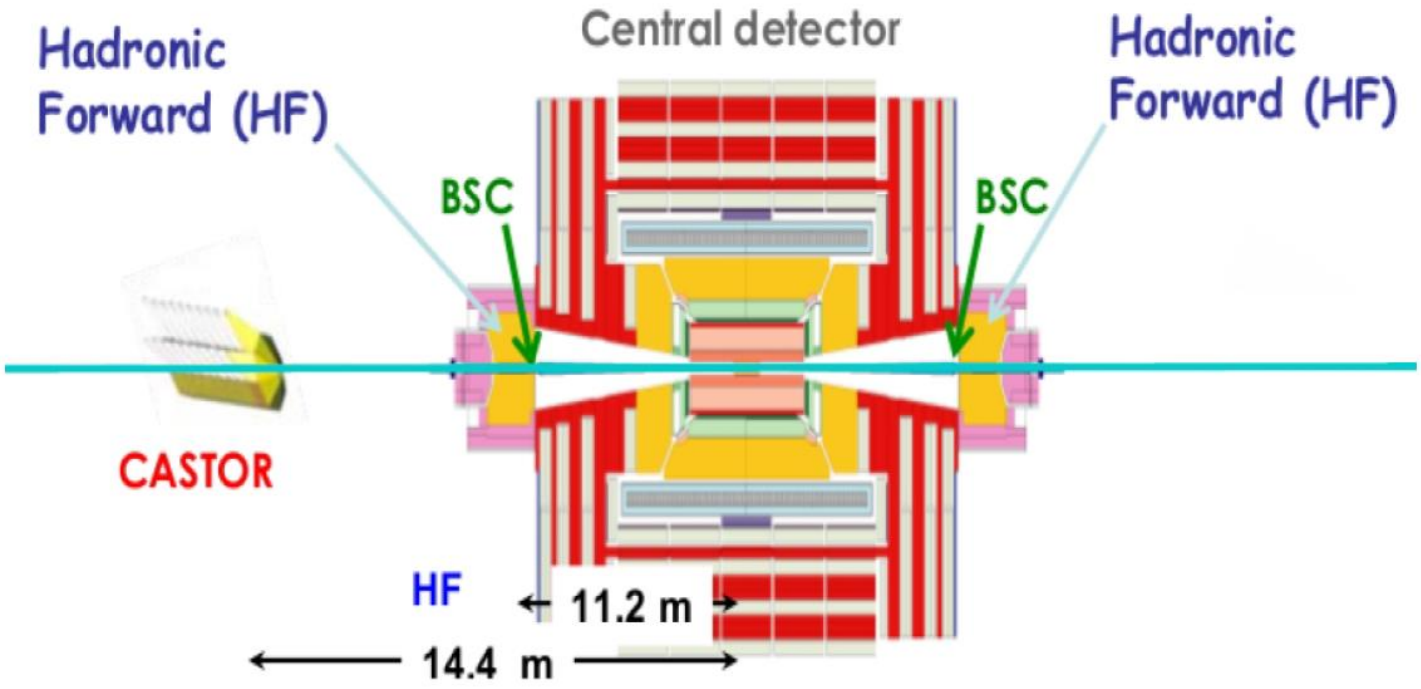
To come: p + p → p + X + p where X = exactly 2 or 4 hadrons

Diffractive dijets: p + p → p + JJ + anything. Proton in TOTEM Roman pots, jets in CMS

Light-by-light scattering in heavy-ion collisions $\gamma + \gamma \longrightarrow \gamma + \gamma$

Summary

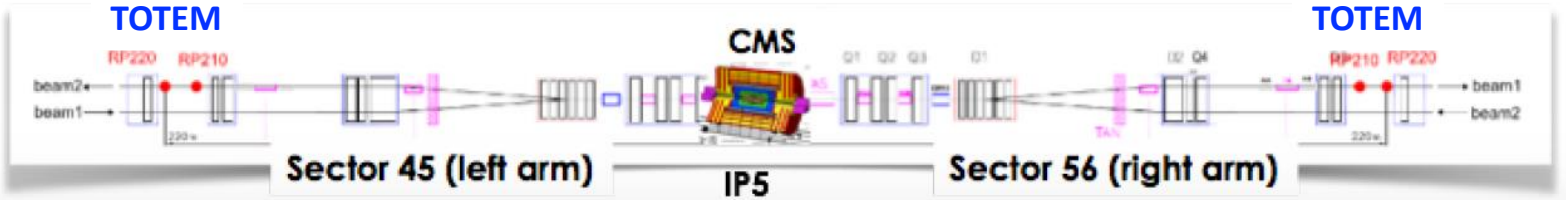
Note: Physics with **Precision Proton Spectrometers (PPS)** not covered
See talk by Christophe Royon.



Hadron Forward Calorimeter (HF) : $2.9 < |\eta| < 5.2$

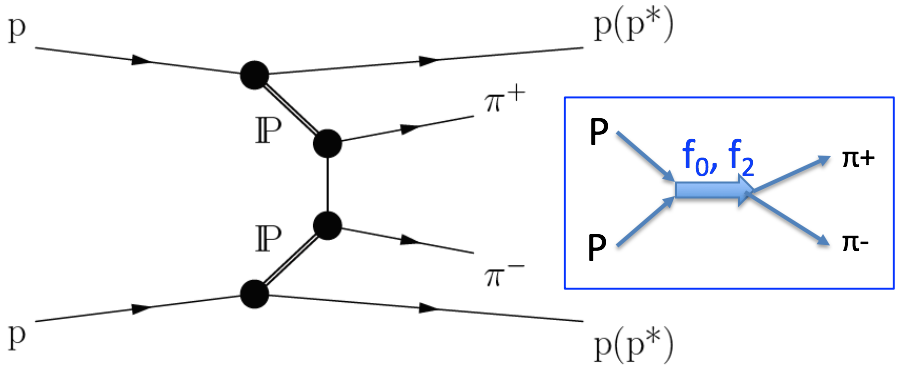
CASTOR calorimeter: $-6.6 < \eta < -5.2$

TOTEM Roman Pots for proton tagging at ± 220 m from IP:

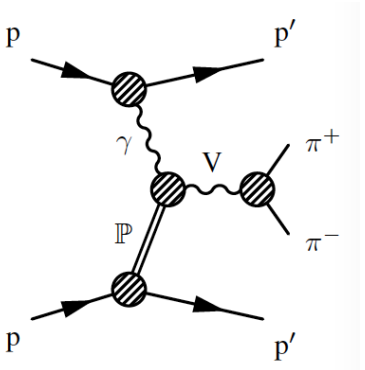


Exclusive and semi-exclusive π+ π- production in pp collisions at √s = 7 TeV (paper submitted) and at √s = 5.02 and 13 TeV (in preparation)

Exclusive final state: **p + π^+ π^- +p**. Semi-exclusive allows dissociation p* e.g. p → p π^+ π^-
These studies do not detect protons, so dissociation is included, and all |t|, Δϕ of protons



Double pomeron exchange
Alsp K^+K^-, $K^0_s K^0_s$, K*K*, ϕϕ, p-$\overline{p}$, etc.



Photoproduction
Smaller cross section (EM)
One proton p' at very small |t|

Why interesting?
4-momentum transfer in **elastic scattering** carried by pomeron –
Strongly interacting color singlet – challenge to QCD as low Q^2 = large distance, non-perturbative
Meson spectroscopy not well understood, especially **non-{q-qbar} states like glueballs {gg}, {ggg}**

pp Collisions at √s = 7 TeV taken in 2010 at low luminosity
Mean number of inelastic collisions/bunch crossing μ ~ 1

Trigger: only bunch-crossing from BPTX = bunch pick-ups : **zero-bias**
(Highly prescaled - 33.2 million triggers) Integrated luminosity L = 450 μb^{-1}

Off-line selection:

Exactly 2 charged tracks with common vertex on beam-line
Impact parameter track – beam line **< 3.2 mm, $|z_{vtx}| < 15$ cm**

Only one vertex

Fiducial cut on tracks: **$p_T > 0.2$ GeV/c and $|\eta| < 2.$**

Number of events selected = 57.6 K

But most of these have **activity in calorimeters** which extend to $|\eta| = 4.9$
due to additional neutral particles and forward or low-p_T charged particles

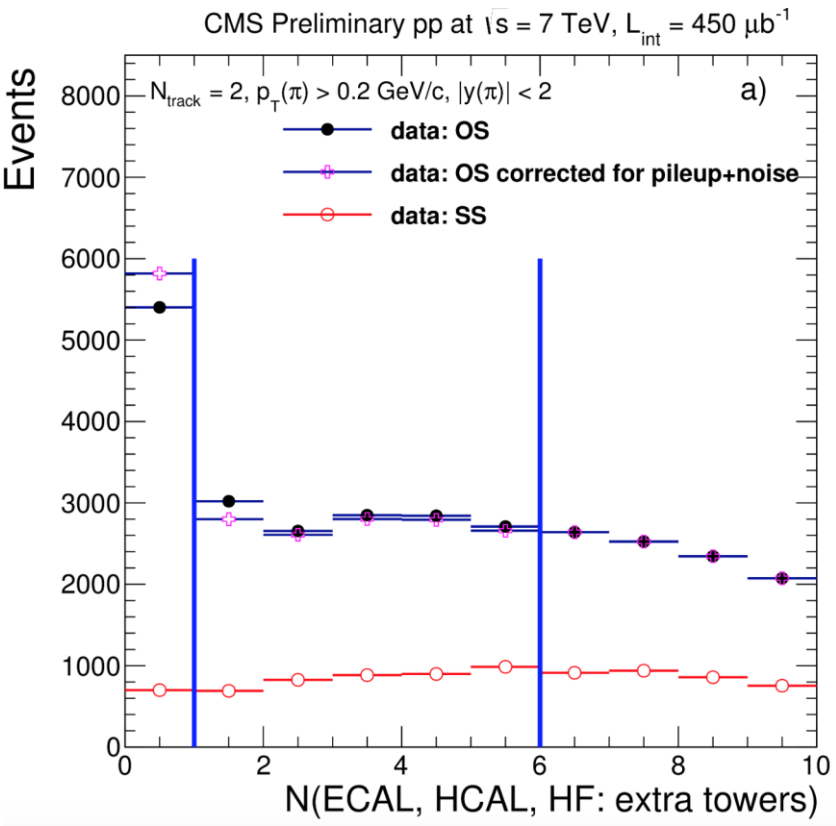
Then require: **No activity in calorimeters** above noise levels in $|\eta| < 4.9$
Levels vary from 0.52 GeV (EM Barrel) to 4 GeV (HF = Hadron Forward)

Excluding calorimeter towers
hit by tracks, plot shows distribution
of **number of extra towers in calorimeters.**

Clear **excess in Q = 0** (+-) (OS) pairs at $N_{extra} = 0$
5,402 events
Not in Q = 2 (++, - -) (SS) pairs, 700 events

$N_{extra} > 2$ distributions fit Negative Binomial Distribution (NBD) – extrapolate to estimate background under 'signal'.

'Signal' defined as [p or p*] + [$\pi^+ \pi^-$] + [p or p*]
where p* = all hadrons in blind region $|\eta| > 4.9$
→
Diffractive dissociation with M(p*) up to ~ 27 GeV included as not detected ('semi-exclusive')



Q: Are they all pions?

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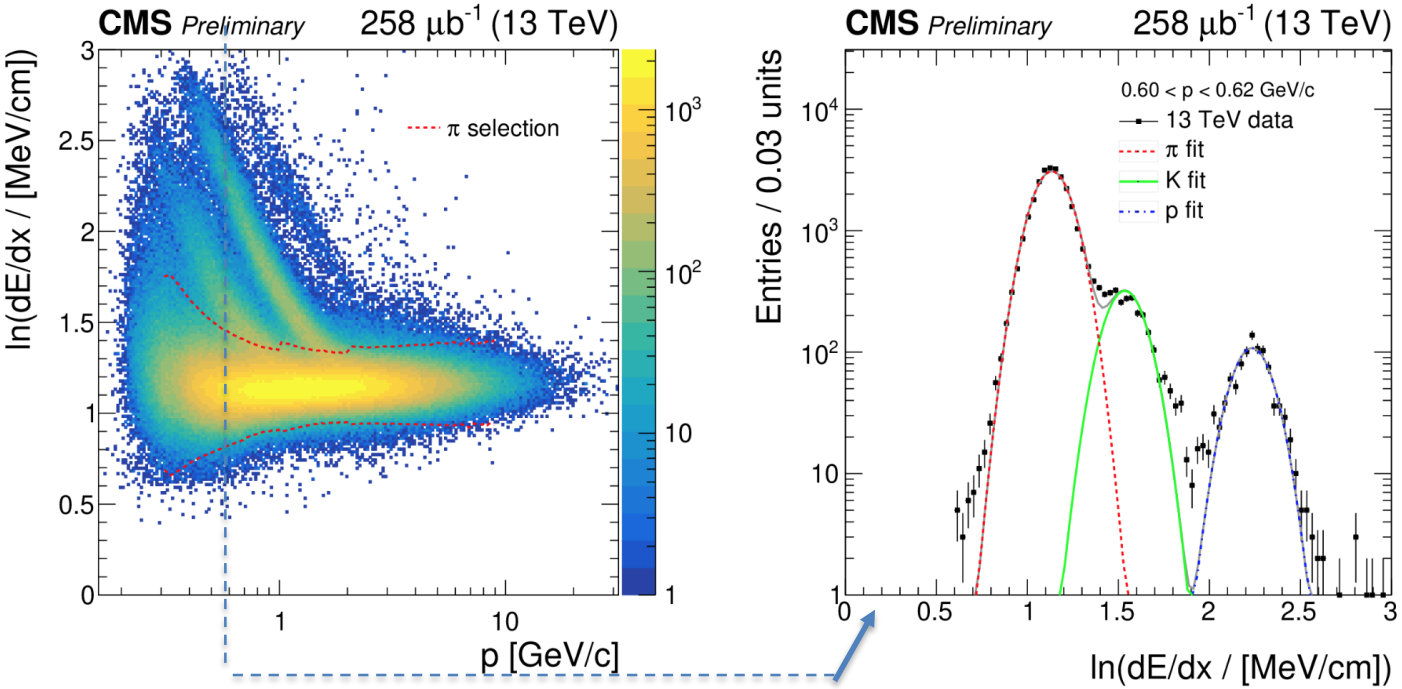
Hadron identification only by ionization loss dE/dx in silicon strip trackers

Example *for illustration* from higher statistics 13 TeV data, N_{track} <= 4 - not fully exclusive



At low momenta some separation, but even at p = 0.6 GeV/c π & K merge.

Note that K/π ratio ~ 10%.

In 7 TeV 2-track sample for p_T < 0.7 GeV **89.4% π+π-**, 2.5% K+K-, 0.1% $\overline{pp}$, 8% other

Since π efficiency/background changing, all tracks are given pion mass, plots include ~ 10% B/G

7 TeV final 2-track sample

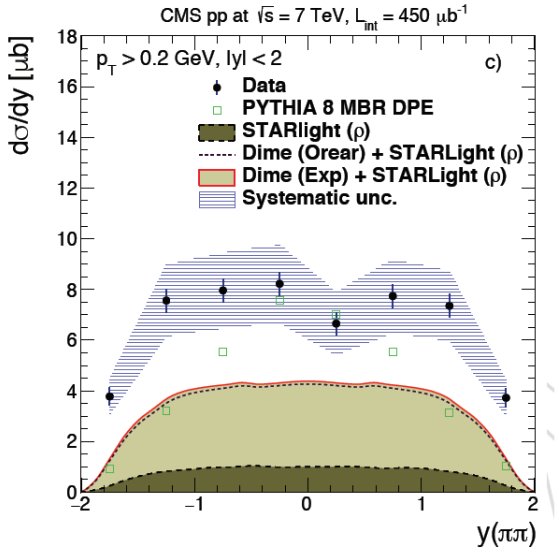
Left plots: linear, Right :log

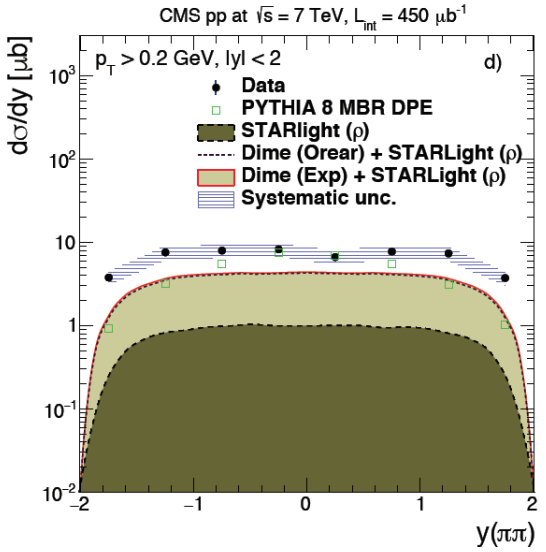
Comparison to event generators
+ GEANT4 detector simulation
PYTHIA 8 MBR DPE
STARLIGHT (ρ – photoproduction)
- Minor contribution
DIME + STARLIGHT (2 F.F.)

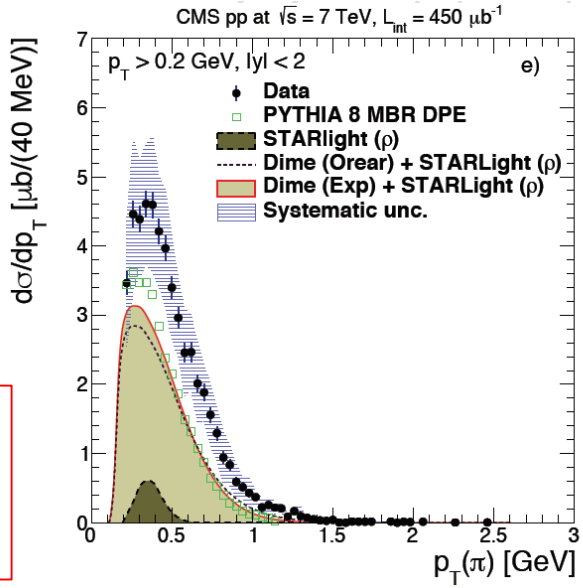
True rapidity (assuming pions) of pair.
Drop at |y| = 2 is acceptance (tracks have |y| < 2)

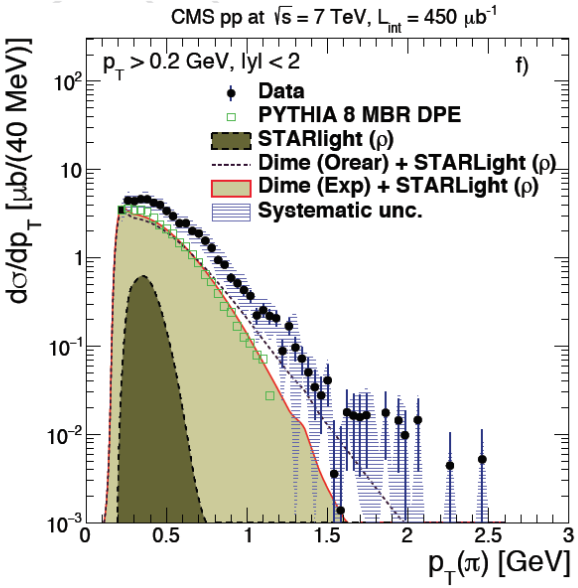
Transverse momentum p_T of single pions

Data are higher than predictions but include p* dissociation, generators do not.

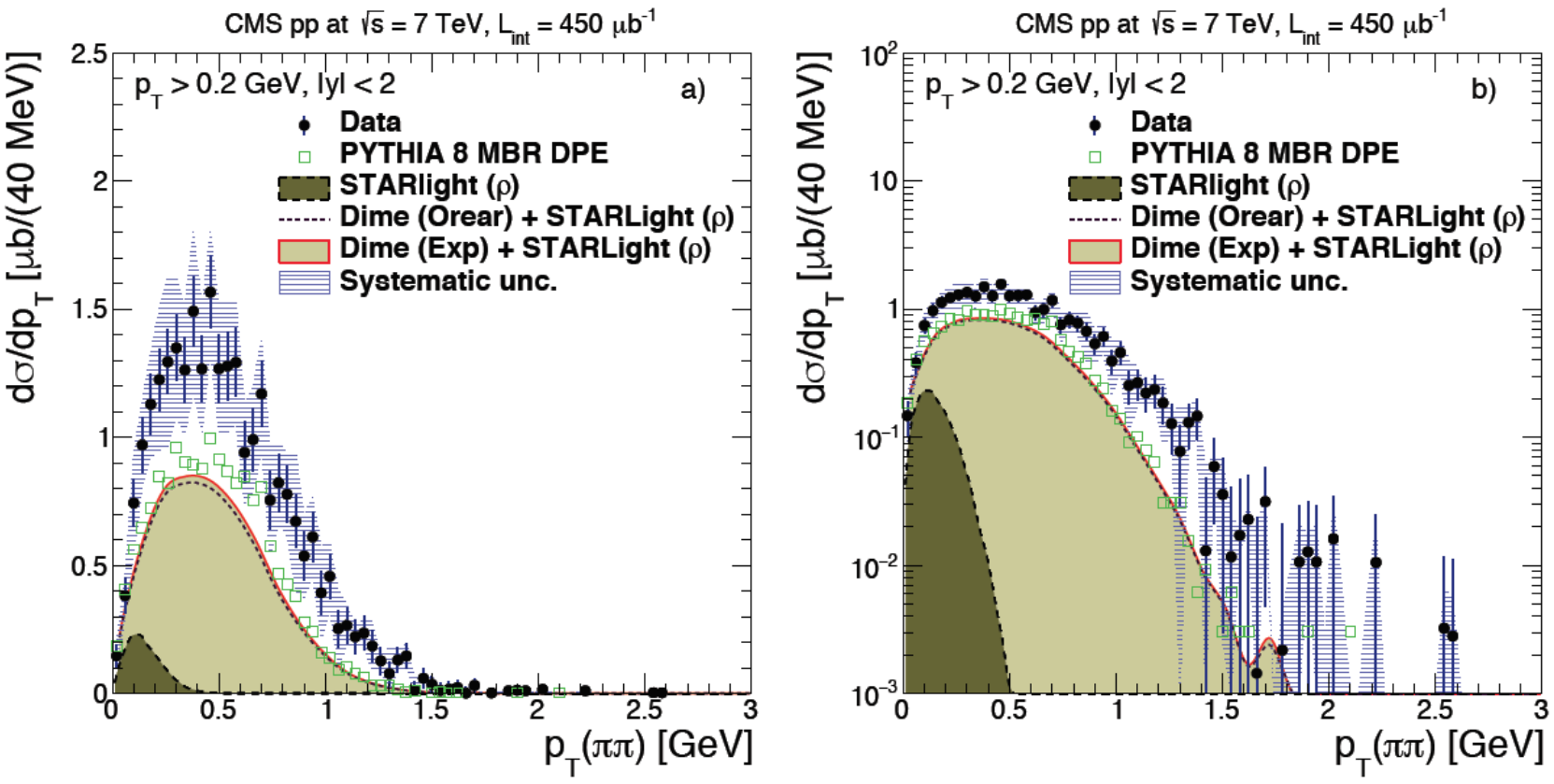




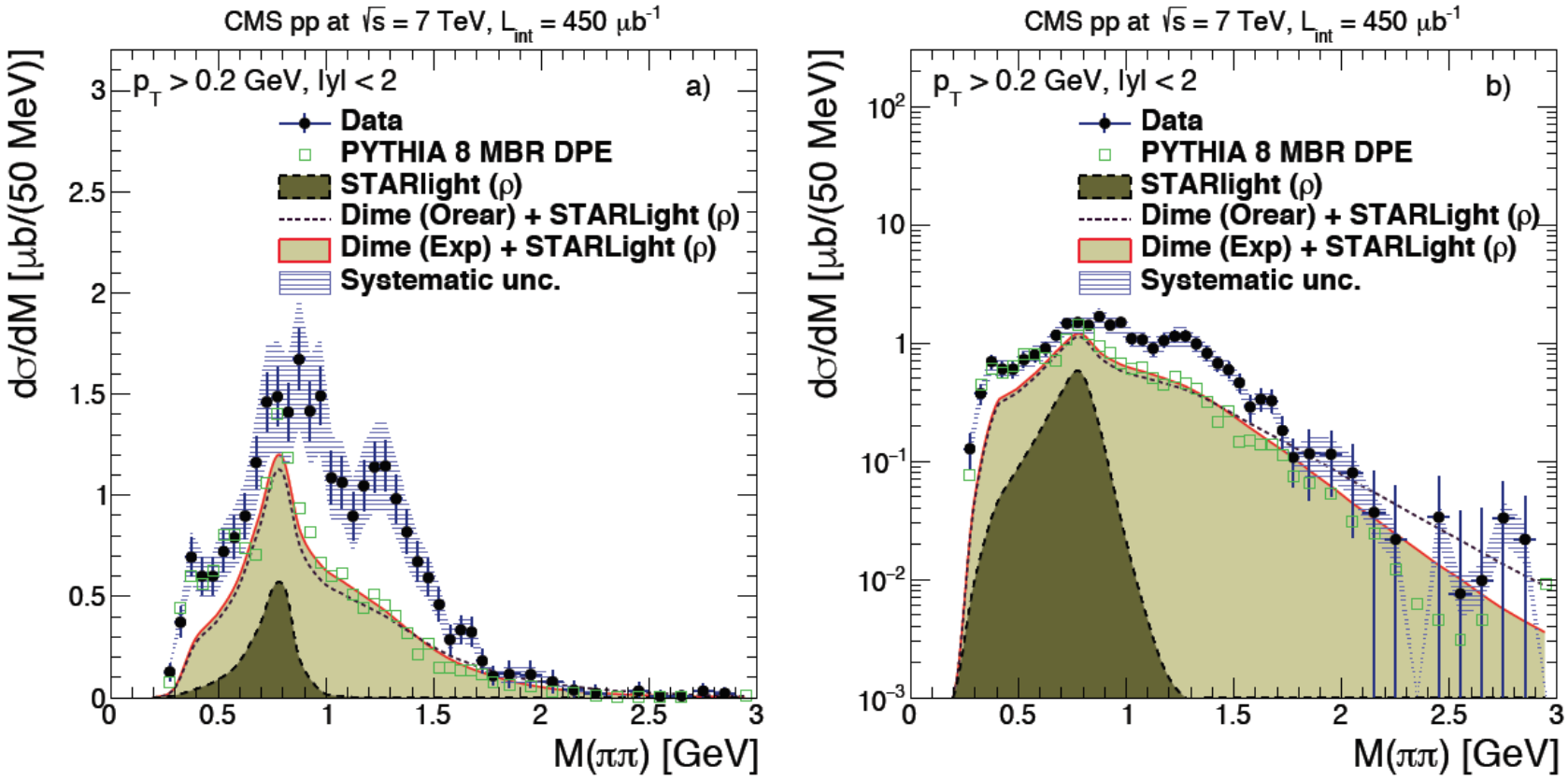




p_T distribution of central π+ π- pair : linear scale (Left) and log (Right)



Phase-space rise from $p_T = 0$ (including that of forward p/p*)
Shapes in reasonable agreement with expectation.
Photoproduction (STARLIGHT) only at small p_T



Differential cross sections as functions of M(π+π-) [include ~10% non-ππ]
Integral is **26.5 ± 0.3(stat) ± 5.0(syst) ± 1.1 (lumi) μb.** ~ 50% larger than models w/o p*

Compatible with some $\rho(770)$, drop at 1 GeV - $f_0(980)$ region & KK threshold), $f_2(1270)$
Small 'blip' at 350 MeV is compatible with ϕ -> K^+K^- with K given m(π)

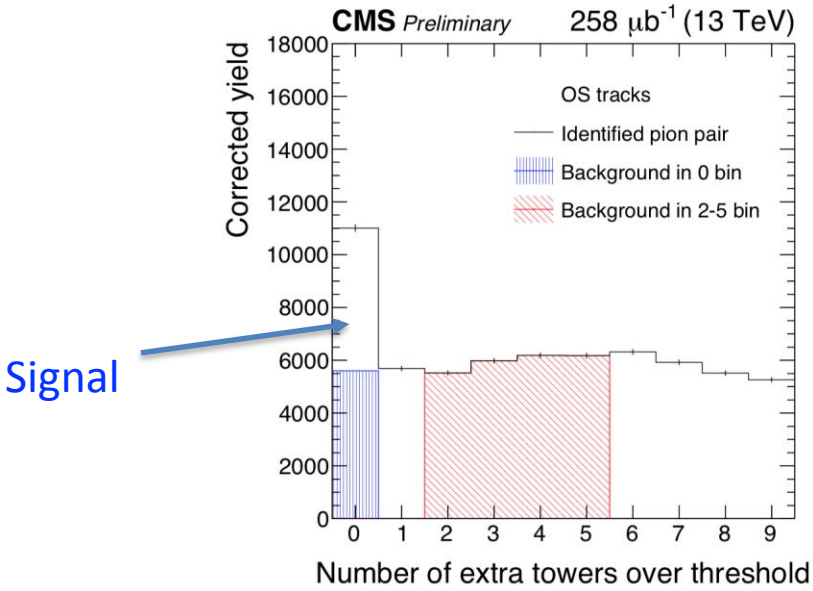
Repeat GAP - $\pi^+ \pi^-$ - GAP study at √s = 5.02 and 13 TeV

As for 7 TeV analysis:
Exclusive final state: $p + \pi^+ \pi^- + p$. Semi-exclusive allows dissociation p* e.g. $p \rightarrow p \pi^+ \pi^-$
These studies do not detect protons, so dissociation is included, and all |t| of protons
Expect very little √s - dependence

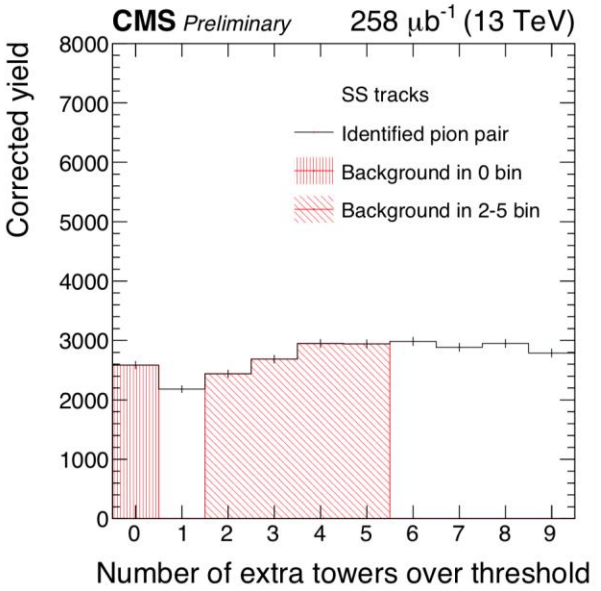
√s = 5.02 TeV run was made for comparison with Pb-Pb run

Conditions and selections similar but not identical.
Calorimeter thresholds changed
|η(π)| extended from 2.0 to 2.4 .

Opposite sign pairs



Same sign pairs

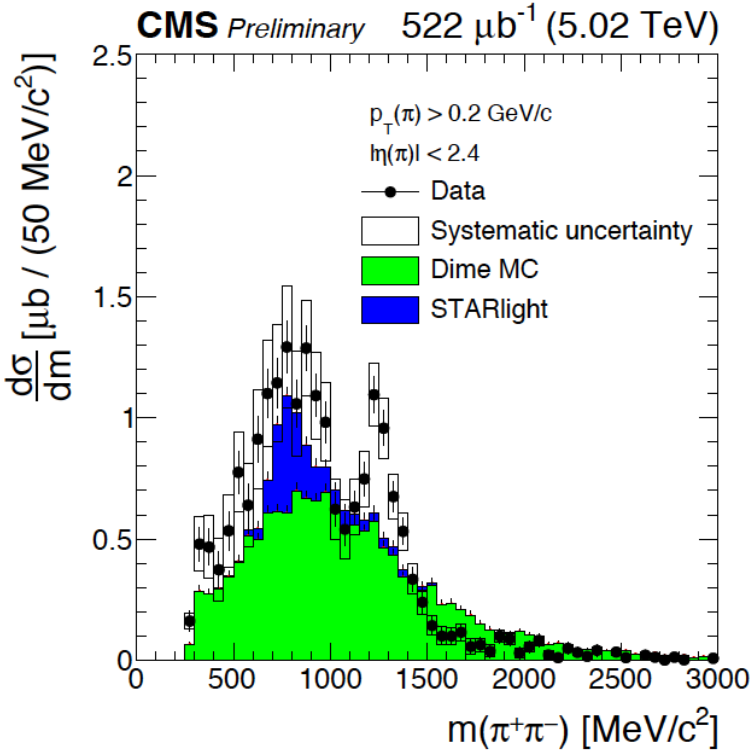


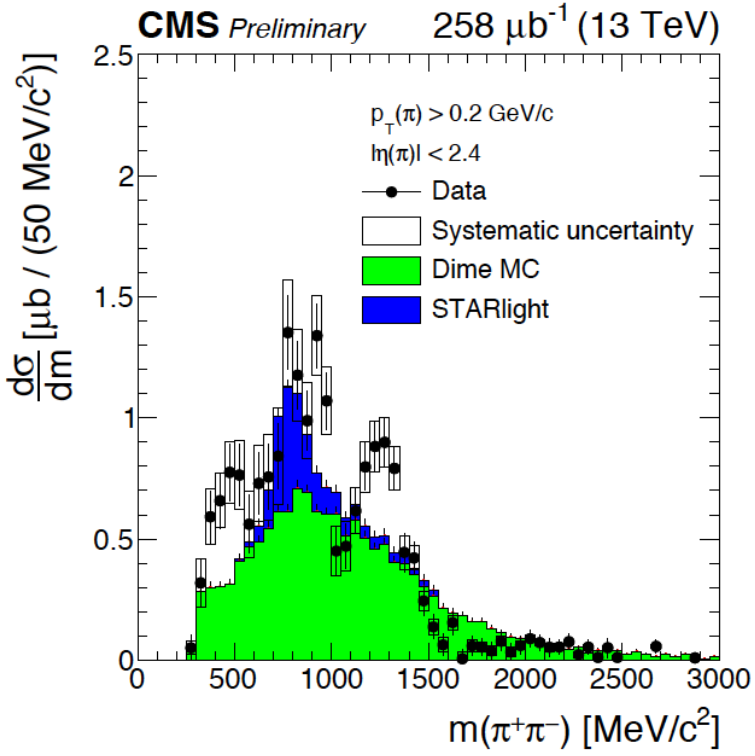
$$\sigma_{pp\to p'p'\pi^+\pi^-}(\sqrt{s} = 5.02\,\text{TeV}) = 19.6 \pm 0.4(\text{stat.}) \pm 3.3(\text{syst.}) \pm 0.01(\text{lumi.})\ \mu\text{b},$$
$$\sigma_{pp\to p'p'\pi^+\pi^-}(\sqrt{s} = 13\,\text{TeV}) = 19.0 \pm 0.6(\text{stat.}) \pm 3.2(\text{syst.}) \pm 0.01(\text{lumi.})\ \mu\text{b}.$$

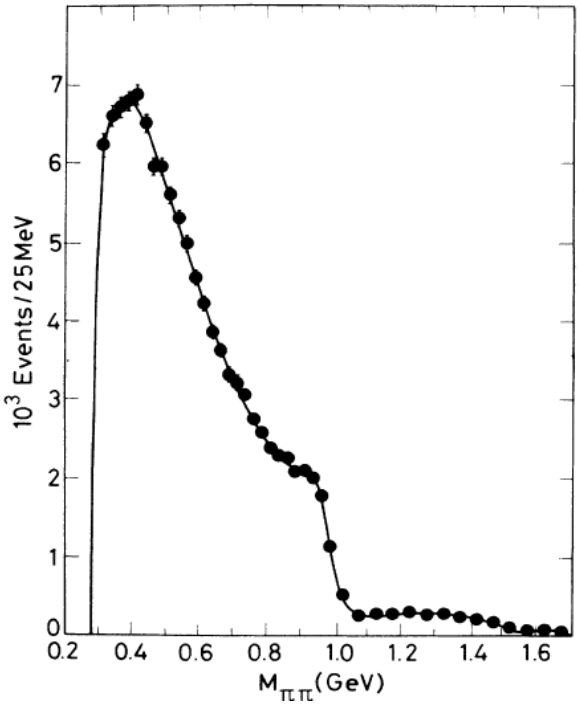
Spectra all show: Low mass bump*, including possible small ρ photoproduction signal, drop at 1 GeV/c^2 associated with **$f_0(980)$**, clear **$f_2(1270)$** and tail to ~ 3 GeV/c^2

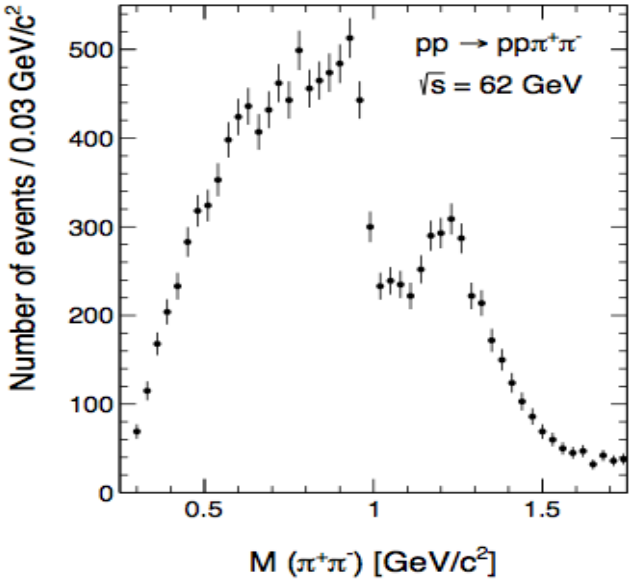
* Broad **$f_0(500) = \sigma$** should contribute

Need: **much higher statistics, and protons detected to select exclusive and t_1, t_2, $\Delta\phi$**









Other Experiments
DPE → π+π-

Several expts. at lower √s
E.g. two for comparison
Intersecting Storage Rings (ISR) √s = 63 GeV

Axial Field Spectrometer (R807)

PL 133 B (1983) 268 & NP B 264 (1986) 154

Exactly two central π+ π-
2C constraint with 2 forward p's $x_F > 0.95$
p's non-colinear (UP*UP or DN*DN = = TT or BB for TOTEM)
$-t = 0.01 - 0.06$ GeV^2 $|y(\pi\pi)| < 1$

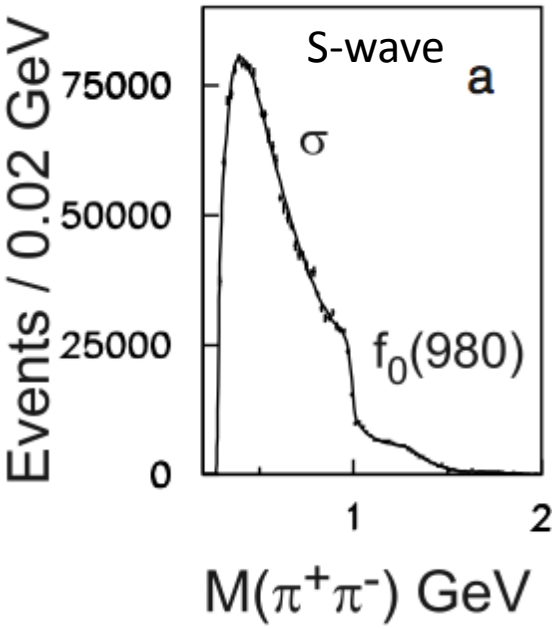
Shown to be dominated by S-wave (J=0) - $f_0(500) = \sigma$
$f_0(980)$ as « cliff » and broad state ~ 1300 MeV

Split Field Magnet : Breakstone et al.
Z.Phys.C **31** (1986) p.185 & ibid. **40** (1988) p.41
$-t > 0.1$ GeV^2 with e^{6t} distribution
Also sharp $f_0(980)$ then $f_2(1270)$ dominant.
Similar to GAP - (π+ π-) – GAP data (all |t|)

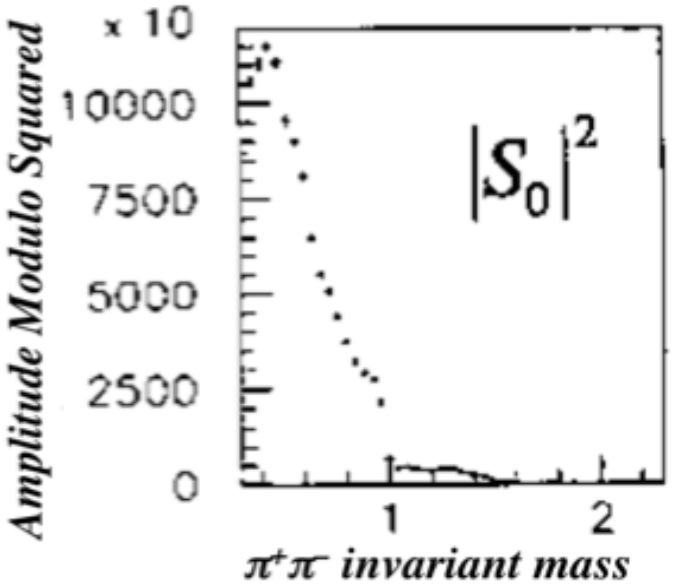
Why different? Low mass acceptance, but
Small |t| and larger |t| ?
$J_z = 0$ rule at t → 0 suppresses J = 2 states

Other Experiments
DPE → π+π-

WA102 (SPS FT 450 GeV/c)



E710 (Fermilab FT)



These were at lower (fixed target) energies √s, measured the protons and selected S-wave (J = 0) with phase-shift analysis.

$f_2(1270)$ dominates in GAP-ππ-GAP data (all |t| - mostly |t| > 0.1

Where are the glueballs?

Especially : Where is the lightest scalar glueball (vacuum-like)?

$f_0(600)$? Very broad ππ resonance.

Not on pomeron trajectory (only J > 1) … on a "daughter trajectory"?

Lattice QCD : around 1650 MeV +/- about 100 MeV

One widely studied scenario:

Two scalar-isoscalar quarkonia : nn == (uu + dd)/√2 and ss

And one bare glueball : gg

} Mix & give 3 states: f0(1370), f0(1500), f0(1710)

T.Gutsche (PPNP 67 (2012) 380:

$$\begin{pmatrix} 1370 \\ 1500 \\ 1710 \end{pmatrix} = \begin{pmatrix} 0.75 & 0.60 & 0.26 \\ -0.59 & 0.80 & -0.14 \\ -0.29 & -0.15 & 0.95 \end{pmatrix} \begin{pmatrix} nn \\ G \\ ss \end{pmatrix}$$

On the other hand:
W.Ochs (2015)

$$\begin{pmatrix} 1370 \\ 1500 \\ 1710 \end{pmatrix} = \begin{pmatrix} 0.86 & 0.13 & -0.50 \\ 0.43 & -0.61 & 0.61 \\ 0.22 & 0.76 & 0.60 \end{pmatrix} \begin{pmatrix} nn \\ ss \\ G \end{pmatrix}$$

The situation is confusing! $f_0(1710)$ -> K+K- >> π+ π- unlike glueball domination.

And at least one of these states may be an excited q- $\bar{q}$

Good high statistics DPE data with PWA (p's detected) & different channels should resolve.

Other (non-)production mechanisms e.g. γ + γ → X and γ + IP → Y should help, Radiative Y decay

Looking Forward: TOTEM + CMS Common Data taking

Special High-β* (90m) runs for TOTEM at √s = 13 TeV
TOTEM: Elastic scattering $d\sigma/dt$ and total cross section σ_T
Low pile-up: μ ~ 0.2 collisions per bunch crossing.

Latest and best set in July 2018, 4 days, total integrated luminosity ~ 6 pb^{-1}
CMS detectors operated, selecting coincident events with minimal track activity.
Analysis on-going of exclusive p + p → p + X + p events, X = 2 or 4 charged tracks

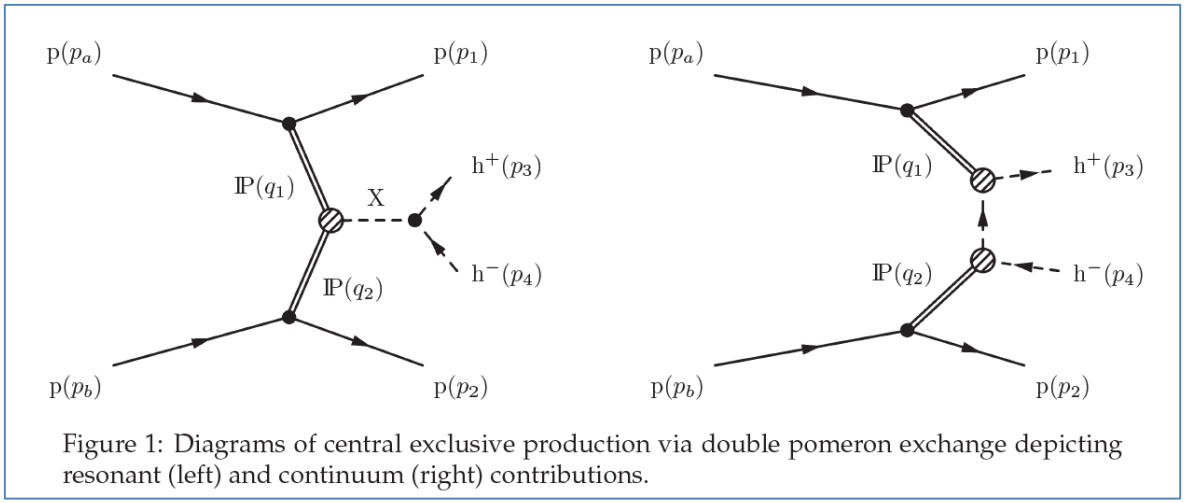
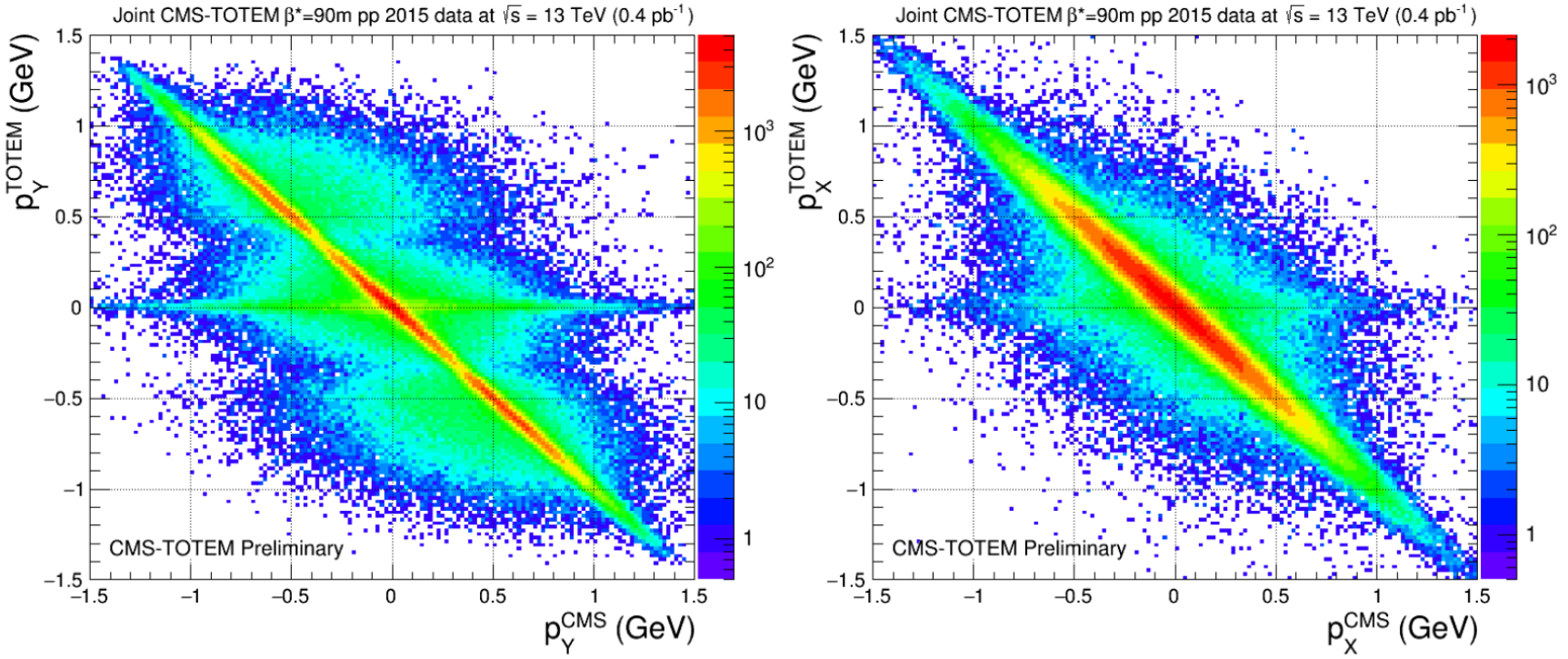


Figure 1: Diagrams of central exclusive production via double pomeron exchange depicting resonant (left) and continuum (right) contributions.

$|t|_{min}$ ~ 0.05 GeV^2
Suppresses γ exchange

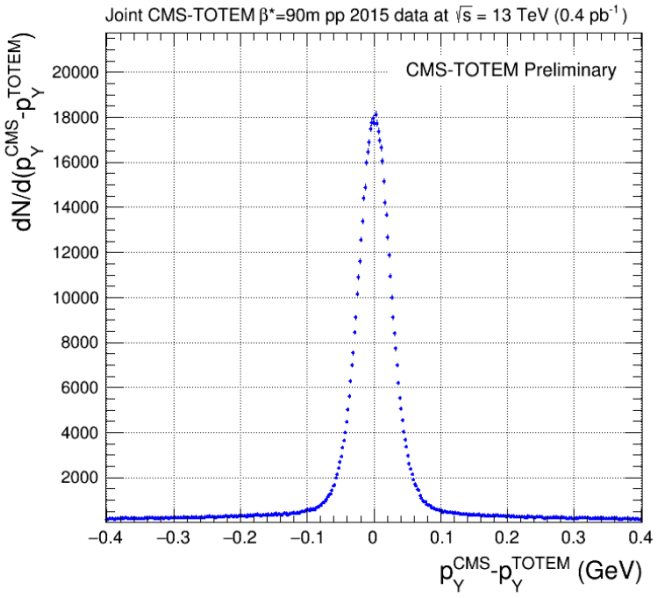
Data dominated by double pomeron exchange: continuum + resonances
Quantum number filter: $I^G J^{PC} = 0^+ 0^{++}$ and $0^+ 2^{++}$ (Isospin = 0, J even)
Long-standing puzzles in scalar mesons and glueball spectrum

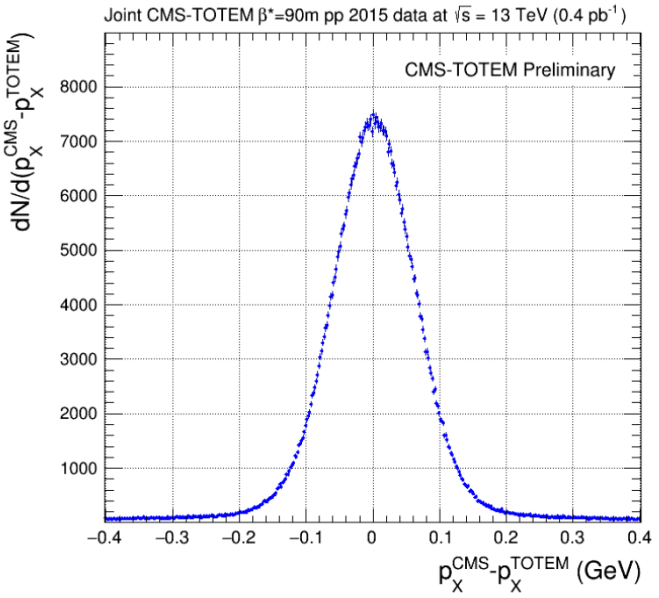
Selection of exclusive 2-track h^+h^- events by p_x, p_y balance
Total transverse momentum of 4 tracks Σp_T < ~ 100 MeV/c
Unlike Gap-X-Gap events can study dependence on protons' t_1, t_2, $\Delta\phi$
-> Phase shift analysis to separate spectra of J = 0, 2, … states



Transverse momenta p_Y and p_X of the scattered protons detected in Roman Pots (TOTEM) vs transverse momenta of two pion tracks measured in the central tracking system (CMS) for the $pp \rightarrow pp\pi^+\pi^-$ production. Events on the diagonal correspond to the exclusive $\pi^+\pi^-$ production.

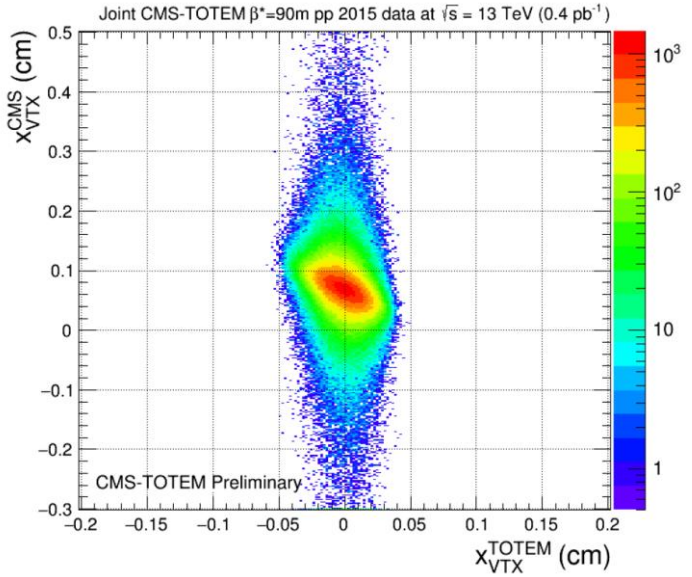
Good balance in px and py required between protons and CMS central tracks
Ensures exclusivity





The **x-position of the vertex** (interaction point) can be reconstructed independently from the two protons in TOTEM and the two tracks in CMS.

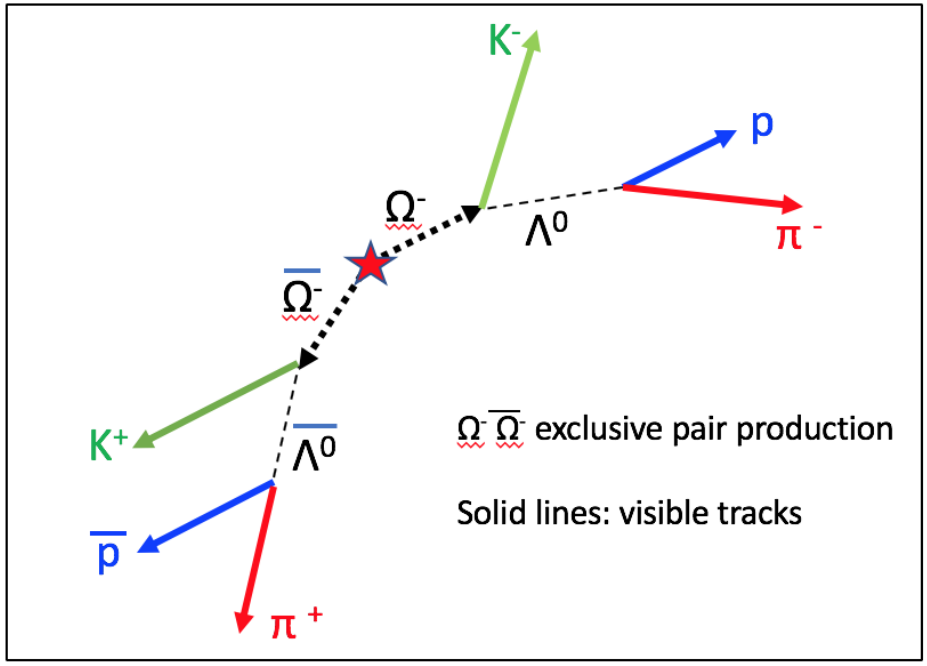
(Opposite sign convention – tilt)



Future: DPE should be 'flavor-blind' for same mass baryons. Interesting potential study:

Exclusive central production of baryon pairs with 0, 1, 2, 3 strange quarks

pp , $\Lambda^0 \Lambda^0$, $\Xi^- \Xi^-$, $\Omega^- \Omega^-$ are accessible



Charmed meson pairs D^0-D^0bar
→ $D^0_s + D^0_s$ even more so!

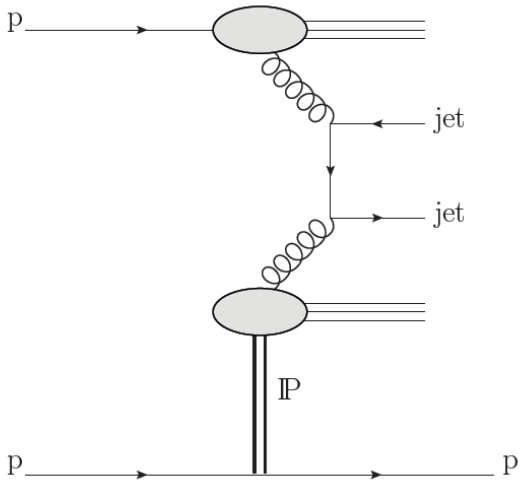
Imagine the value:
Dedicated 2-day run
Could give ~ 100 million
fully measured DPE events!

Ω^- : M = 1672.45 MeV, $c\tau$ = 2.46 cm, 68% BR - > Λ K
Λ^0 : M = 1115.68 MeV, $c\tau$ = 7.89 cm, 64% BR - > p π

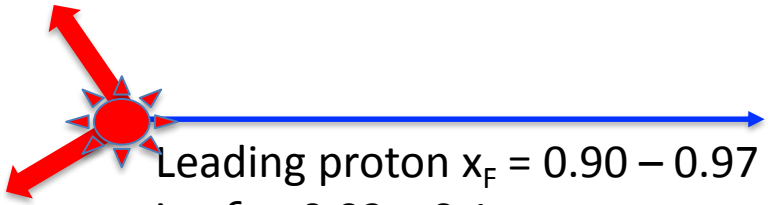
For
Ξ^- → Λ π - same topology, replace K with π
M = 1321.71 MeV, $c\tau$ = 4.91 cm, 99.9% BR - > Λ π

Measurement of dijet production with a leading proton in proton-proton collisions at $\sqrt{s} = 8$ TeV

CMS-PAS-FSQ-12-033
TOTEM-NOTE-2018-001



Two jets measured in CMS
$E_T > 40$ GeV $|\eta| < 4.4$



Leading proton $x_F = 0.90 – 0.97$
i.e. $\xi = 0.03 – 0.1$
$0.03 < |t| < 1$ GeV^2
Measured in TOTEM Roman pots

Including L ⟷ R

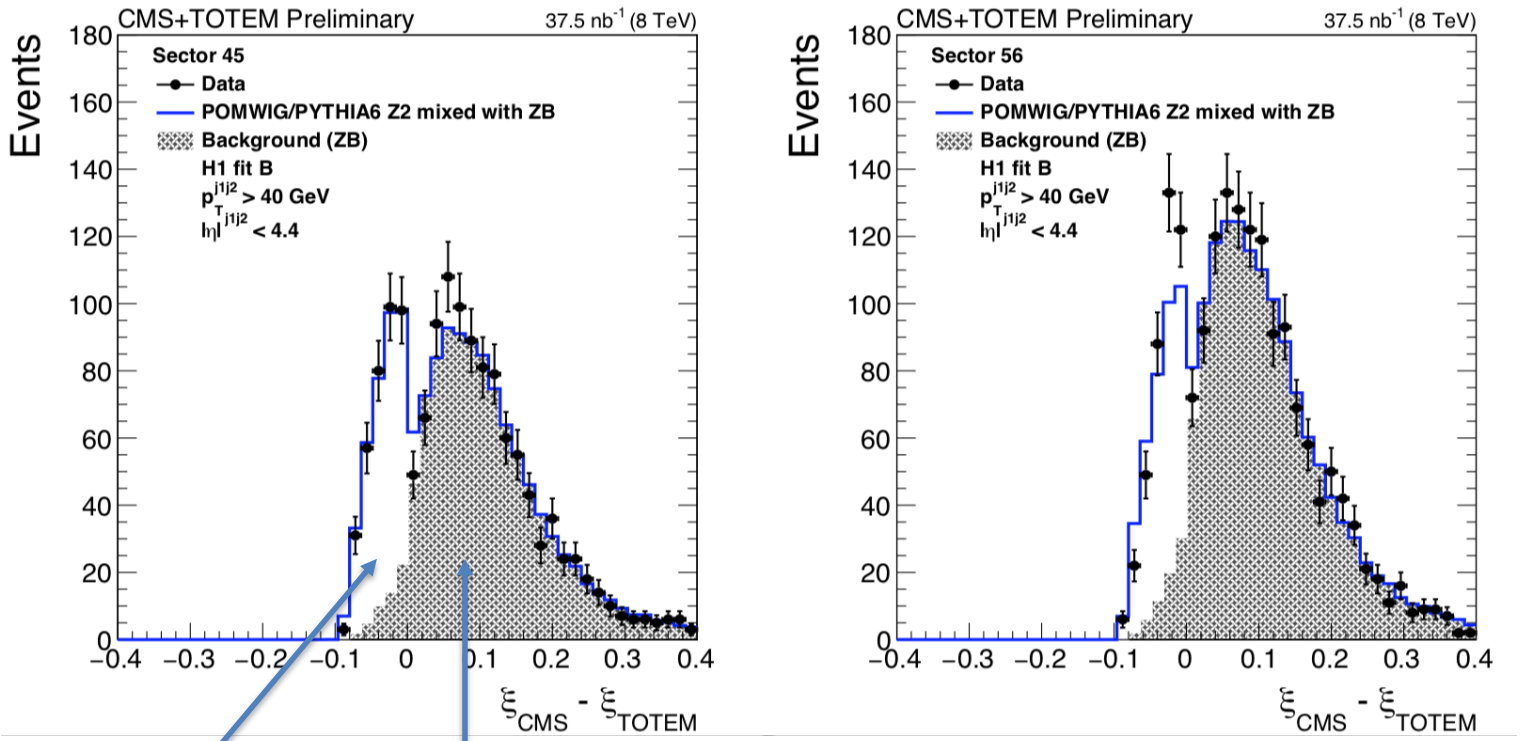
Observed first at CERN p-pbar collider (UA8), √s = 630 GeV, jets $E_T > 5$GeV
Measured at Tevatron p-pbar collider by CDF and D0 at √s = 1800, 1960 GeV
Structure probe of pomeron, understanding 'survival probabilities'
and factorisation breaking between e-p (HERA) and hadron-hadron

Background from random coincidence between proton and jets from different collisions
Fractional momentum loss ξ_{TOTEM} of proton measured through machine lattice -> 215 – 220m
It can also be estimated, ξ_{CMS} from all particles in CMS detector $|\eta| < 4.9$

TWO DIRECTIONS

$$\xi^{\pm}_{CMS} = \frac{\sum \left(E^i \pm p^i_z\right)}{\sqrt{s}}$$

Missed particles (especially forward) make $\xi_{CMS} < \xi_{TOTEM}$
Additional particles from another collision make $\xi_{CMS} > \xi_{TOTEM}$



Good single events

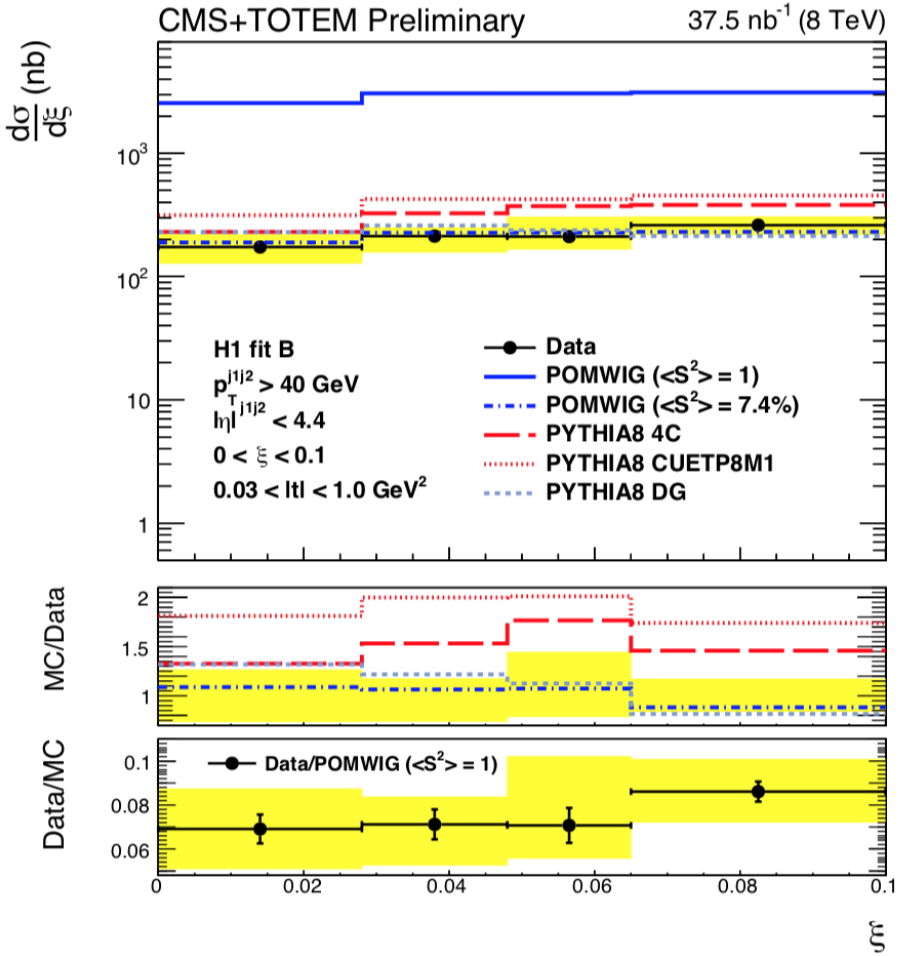
Pile-up background
(Decreases as luminosity decreases)

Distribution in $\xi = 1 - x_F$

$d\sigma/d\xi$ ~ flat in agreement with MC's.

> Low mass diffraction peaks at low-ξ and by $\xi \sim 0.05$ Regge (non-IP) exchange becomes more important.

Here **two high-E_T jets enhance high-ξ**
Q: Is it still pomeron exchange?



Measured **integrated cross-section** for:
$\xi < 0.1$, $0.03 < |t| < 1.0$ GeV^2
>= 2 jets $p_T > 40$ GeV, $|\eta| < 4.4$
Average of L-going and R-going proton configurations

$$\sigma_{jj}^{pX} = 21.7 \pm 0.9\,(\text{stat})\,{}^{+3.0}_{-3.3}\,(\text{syst}) \pm 0.9\,(\text{lumi})\,\text{nb}$$

Cross section as a function of t:

Exponential fit:In the region $0.03 < |t| < 0.45\,\mathrm{GeV}^2$

$$d\sigma/dt \propto \exp^{-b|t|}$$

$$b = 6.6 \pm 0.6\,(\mathrm{stat})\,^{+1.0}_{-0.8}\,(\mathrm{syst})\,\mathrm{GeV}^{-2}$$

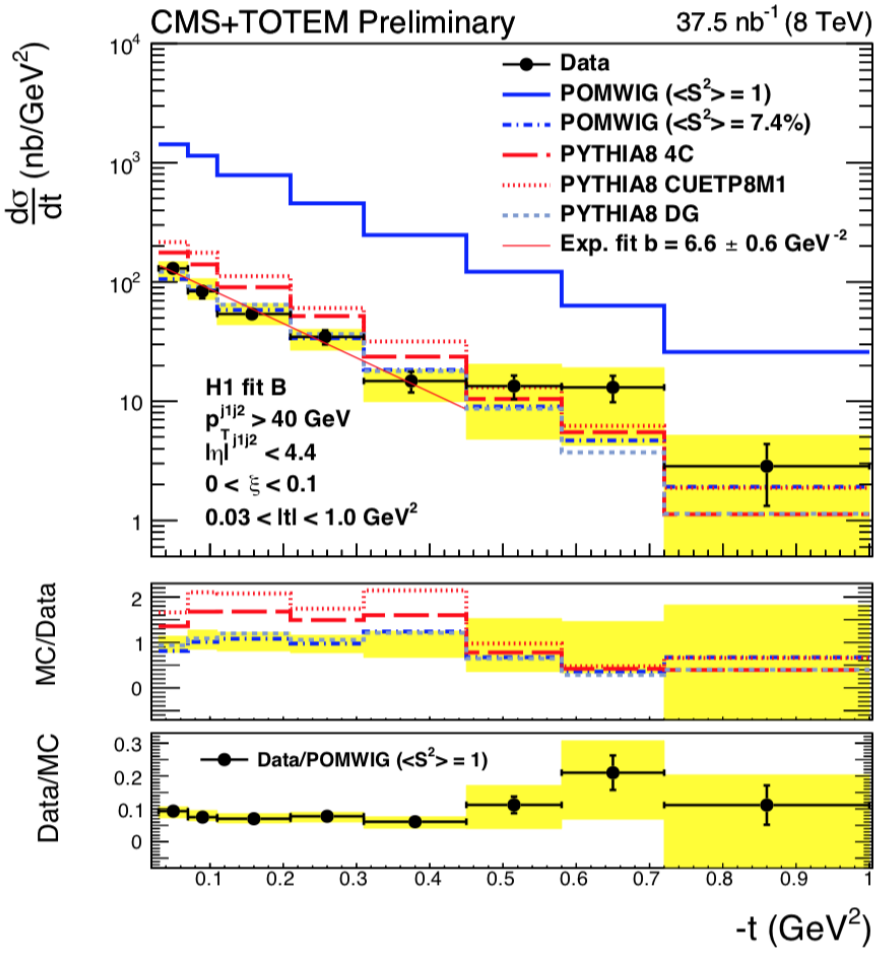
CDF: 5-6 GeV^{-2}

t-distribution, slope as in soft diffraction
~ ½ that of elastic scattering.
But flattens above |t| > ~ 0.5 GeV^{-2}
Event generators in fair agreement on shape

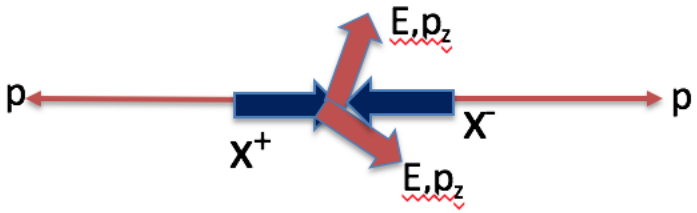
Top line is with no gap survival probability factor for illustration only. <S^2> = 1

Good fit has <S^2> = 0.074

Other quark and gluon interactions destroy the gap

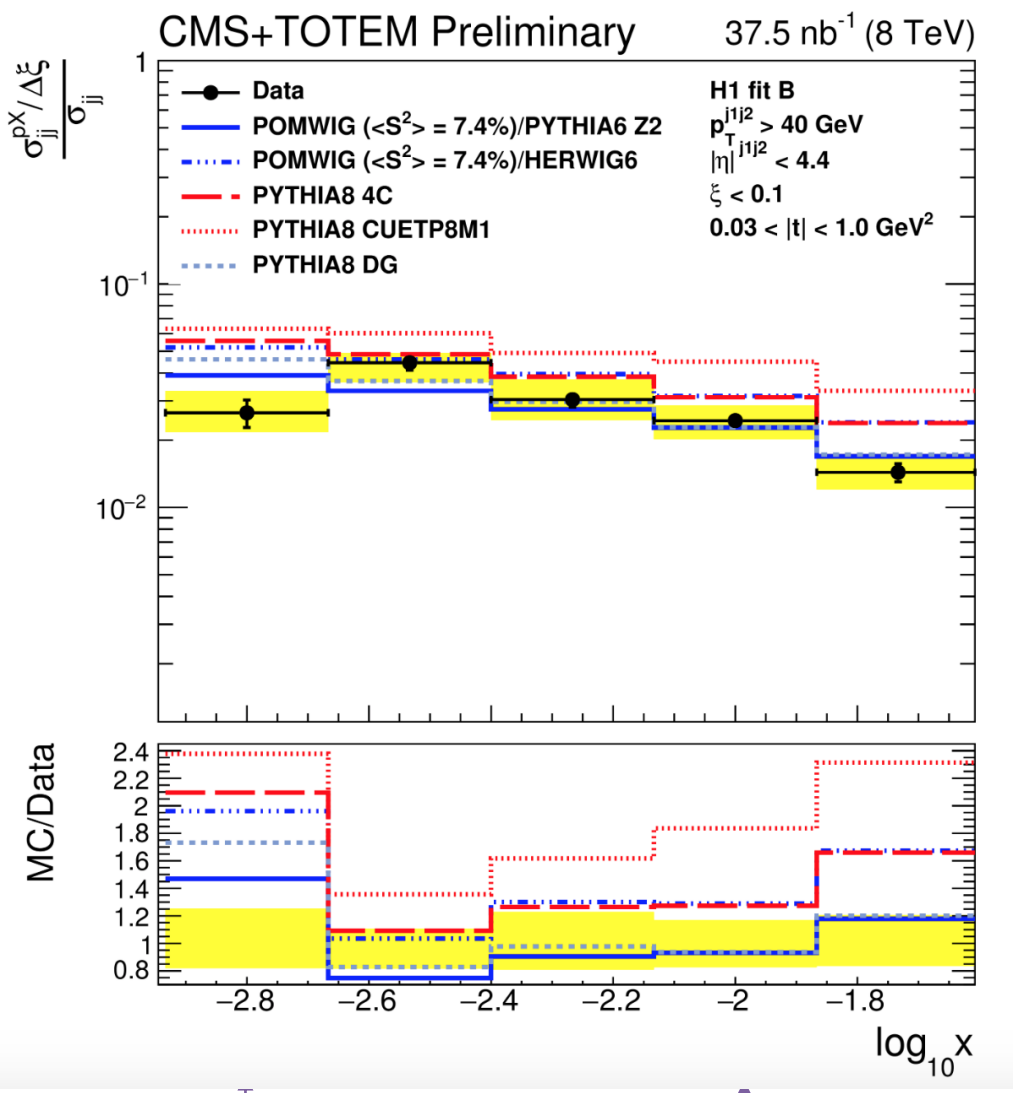


Ratio of diffractive dijets to all dijets vs x = momentum fraction in proton of partons initiating the hard scattering



Bjorken-x's of scattering partons given by jets 4-vectors (2 → 2, 3)

$$x^{\pm} = \frac{\sum_{\text{jets}} \left(E^{\text{jet}} \pm p_z^{\text{jet}}\right)}{\sqrt{s}}$$

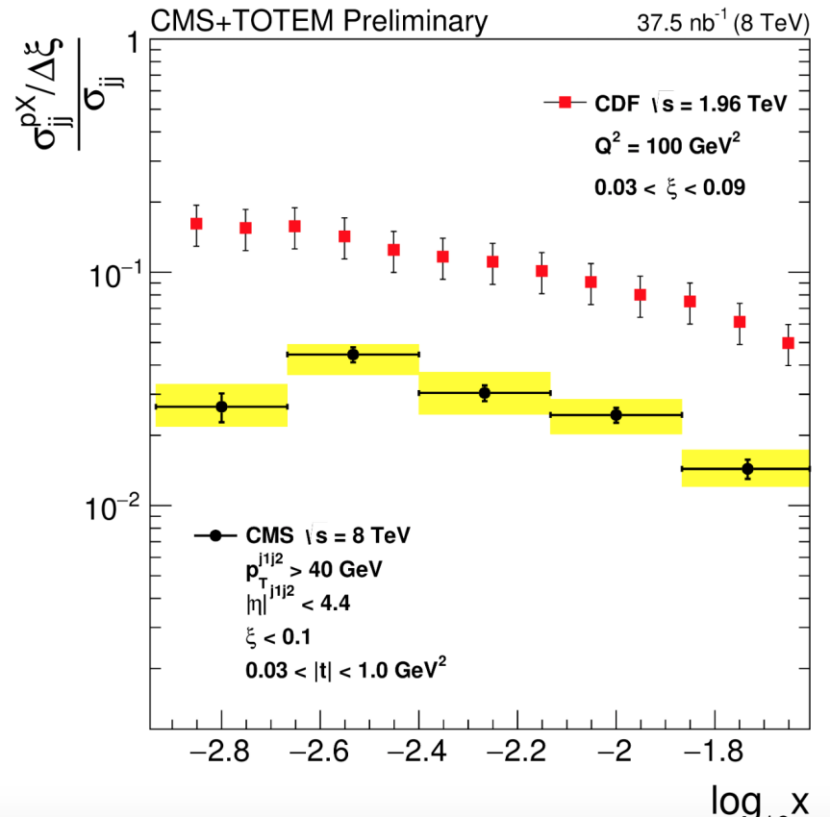


X = 0.0016

X = 0.01

‘Diffractive dijet fraction of all dijets ’
> decrease from Tevatron, but higher E_T

$$x^{\pm} = \frac{\sum_{\text{jets}} \left(E^{\text{jet}} \pm p_z^{\text{jet}} \right)}{\sqrt{s}}$$



If pomeron exchange, fraction of pomeron momentum carried by scattering parton = β, with:

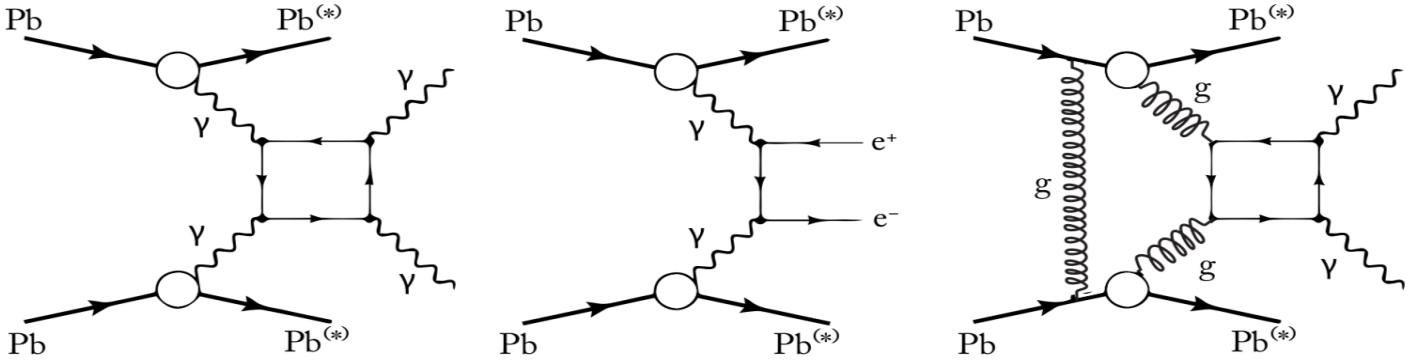
$$\beta = x^{\pm} / \xi_{\text{TOTEM}}$$

Figure 6: Ratio per unit of ξ of the single-diffractive and inclusive dijet cross sections in the kinematic region given by $\xi < 0.1$ and $0.03 < |t| < 1\,\text{GeV}^2$. The vertical bars indicate the statistical uncertainties and the yellow band indicates the total systematic uncertainty. The red points represent the results obtained by CDF at $\sqrt{s} = 1.96\,\text{TeV}$ for jets with $Q^2 \approx 100\,\text{GeV}^2$ and $|\eta| < 2.5$, with $0.03 < \xi < 0.09$.

Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

arXiv:1810.04602 [hep-ex]
Phys. Lett. B (subm.)

Photons with $E_T > 2$ GeV $|\eta_\gamma| < 2.4$

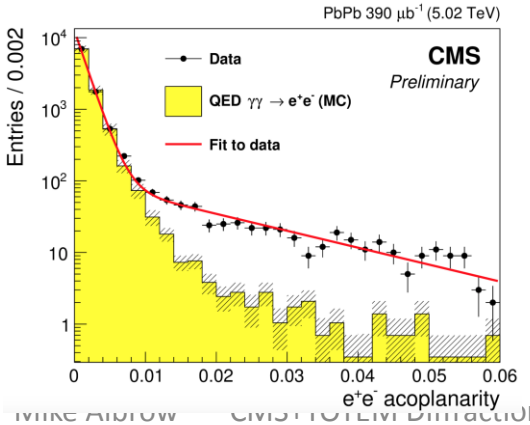


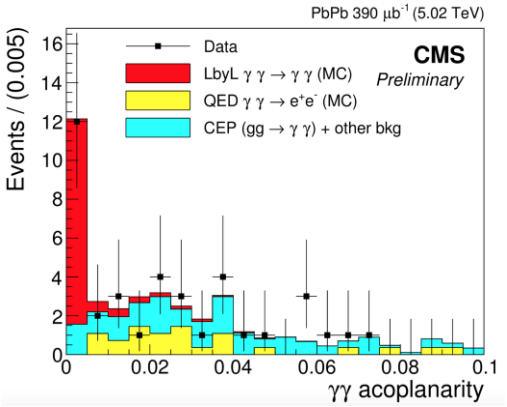
Process of interest
Cross section small - $\alpha^4 \sim 3 \times 10^{-9}$
But enhanced by $Z^4 = 5 \times 10^7$ cf pp

Quasi-real γ have $Q^2 < 10^{-3}$ GeV^2
and E_γ up to ~ 80 GeV

Control sample, σ much higher
Same trigger and selections
but two tracks, e+ e-
Background if tracks missed

IP + IP → $\gamma + \gamma$
Observed in pp in CDF
(Not yet claimed at LHC)
Acoplanarity A_ϕ larger
because $p_T(IP) > p_T(\gamma)$





Observed: 14 events
Expected: 11.1 ± 1.1 (th) signal
4.0 ± 1.2 (stat) background events,
Significance: 4.1 σ (expected 4.4 σ)

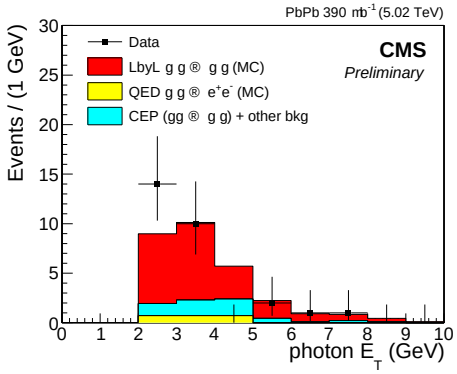
Distributions agree well with
LbL scattering Monte Carlo:

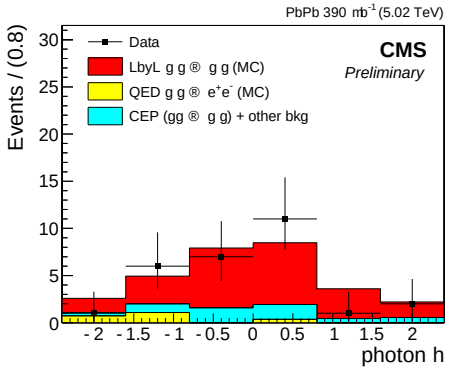
Theoretical predictions: D'Enterria and da Silveira
Phys Rev Lett 111(2013) 080405

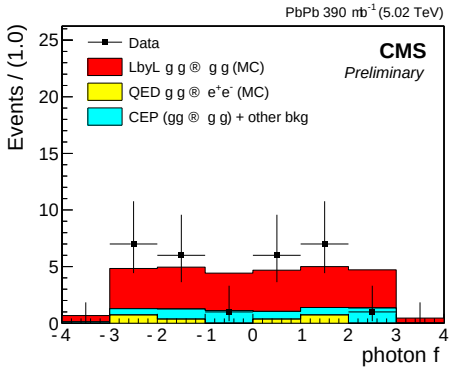
$$\sigma_{\mathrm{fid}}(\gamma\gamma \to \gamma\gamma) = 138 \pm 14\,\mathrm{nb}.$$

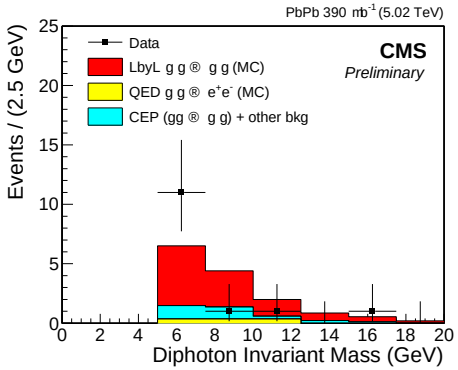
Ratio $\gamma + \gamma$: $e^+ + e^-$

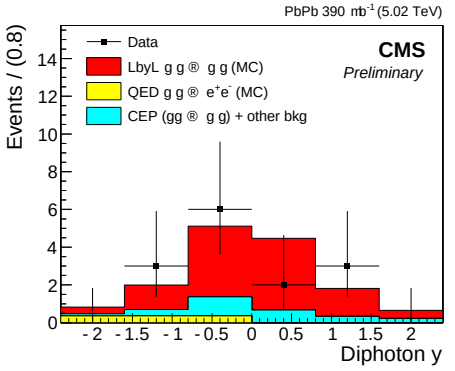
$$R = (25.0 \pm 9.6\,(\mathrm{stat}) \pm 5.8\,(\mathrm{syst})) \times 10^{-6},$$

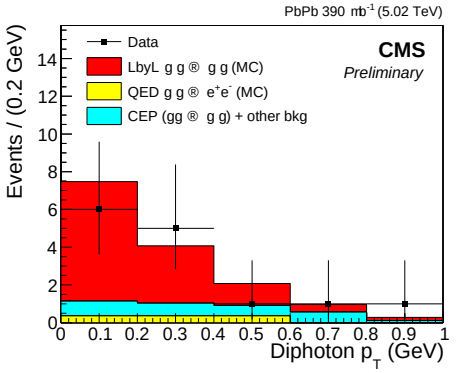






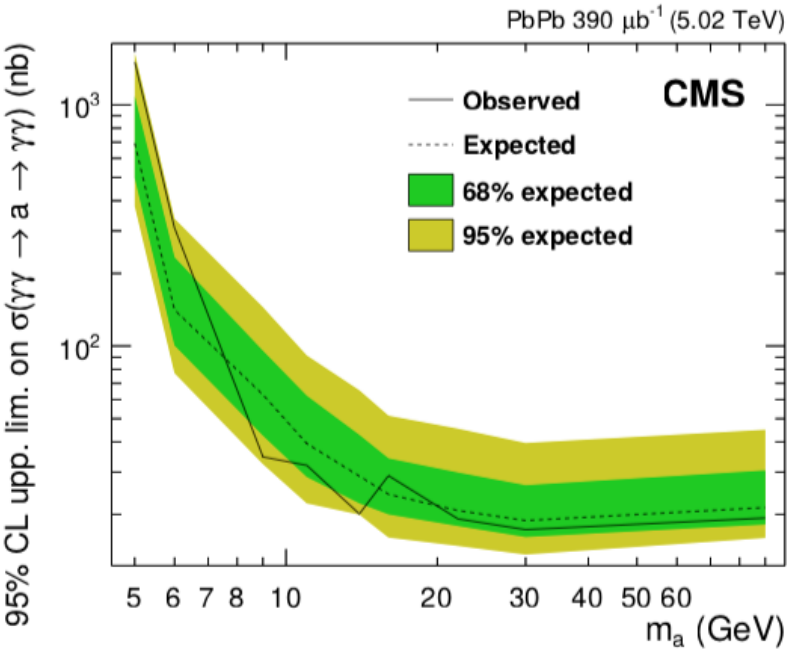


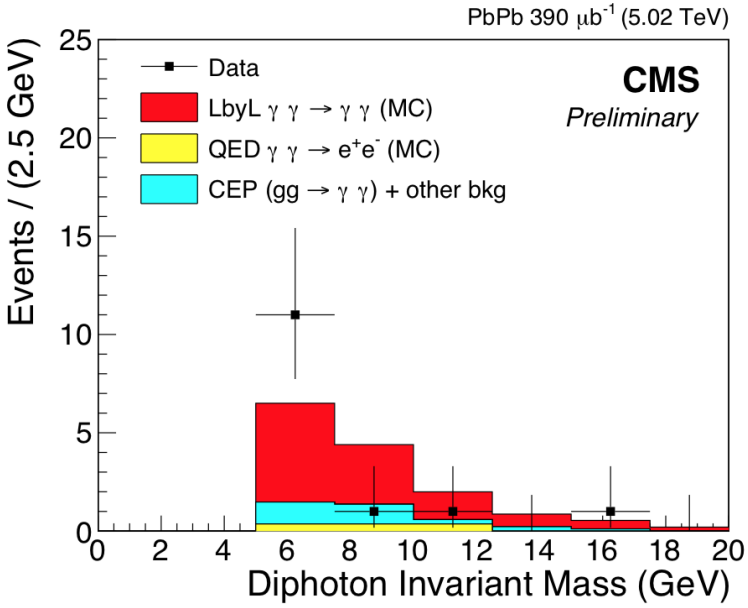


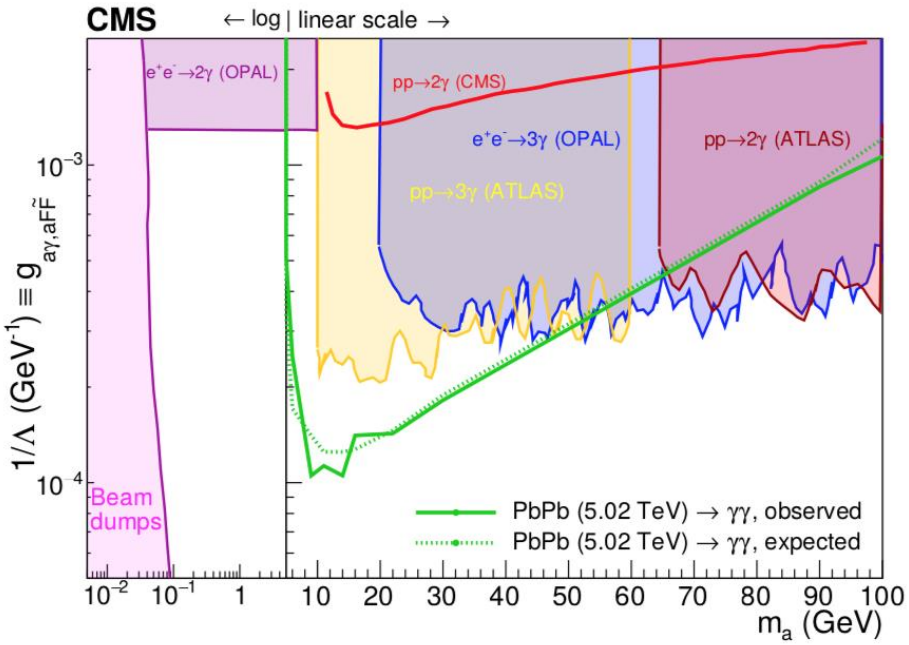


$$\sigma_{\mathrm{fid}}(\gamma\gamma \to \gamma\gamma) = 120 \pm 46\,(\mathrm{stat}) \pm 28\,(\mathrm{syst}) \pm 4\,(\mathrm{theo})\,\mathrm{nb},$$

Observed M($\gamma\gamma$) limits PseudoScalar axion-like particles (a) through $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$
Sensitive to higher masses







New limits very competitive for
M(a) = 5 – 50 GeV
~ ATLAS, and better than e^+e^- at LEP

SUMMARY

Small selection of some recent CMS & [TOTEM + CMS] results – all low pile-up

Color singlet exchanges : **pomeron and/or photon interactions**

Central exclusive production of low mass hadron systems (resonances, glueballls?)
DPE: Potentially a large field of study (tagged IP + IP collisions, jets …)

High-E_T jet production from pomeron interactions - high mass diffraction.

Pb + Pb collisions as $\gamma\gamma$ collider and $\gamma\gamma \rightarrow \gamma\gamma$ as probe of new physics e.g. axions?

Stay tuned!

Thank You