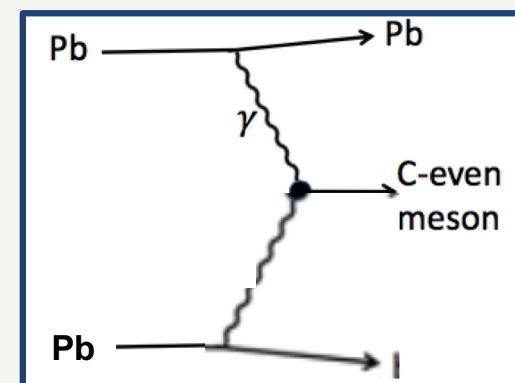
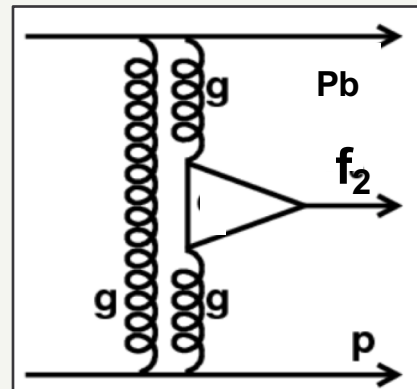
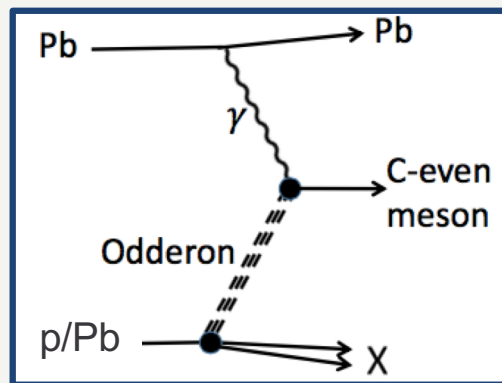


Odderon search in central production in heavy-ion collisions



R. McNulty in collaboration with
V. Khoze, A. Martin, M. Ryskin
Eur.Phys.J.C 80 (2020) 3, 288

Diffraction and low-x 2022
Corigliano, Calabro Sep 24 - 30 2022

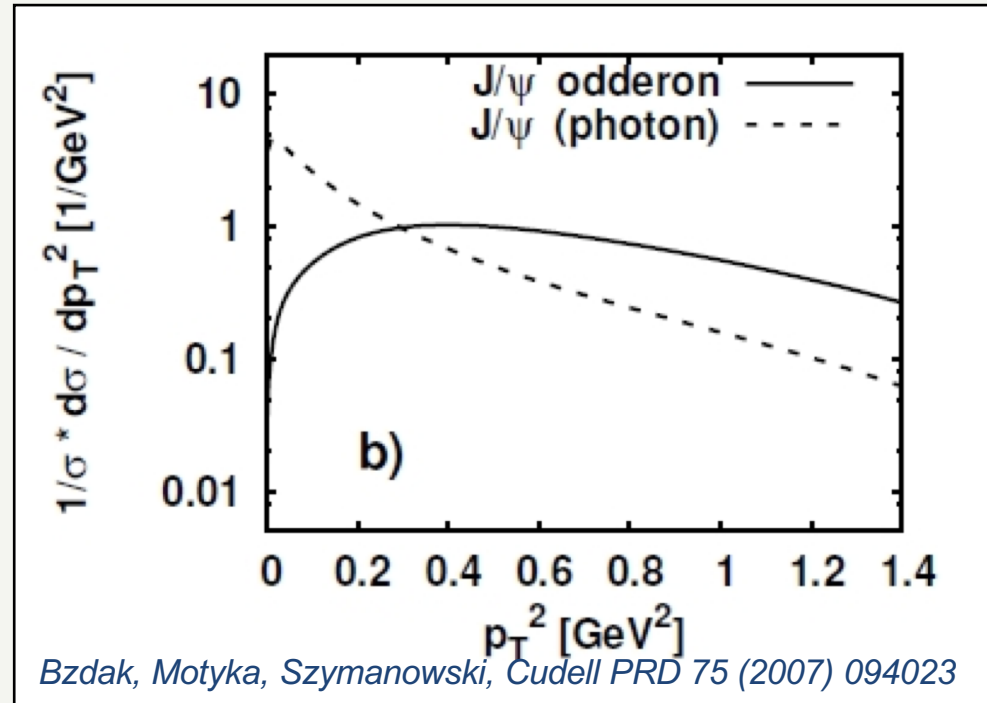
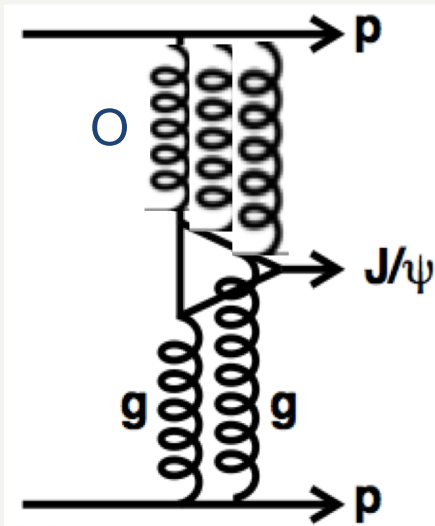


Motivation

- Odderon predicted 50 years ago: C-odd analogue of Pomeron. (L. Lukaszuk, B. Nicolescu, Lett. Nuovo Cim. 8 (1973) 405..
See C. Ewerz hep-ph/0306137 for comprehensive review)
- Fundamental to QCD
- Perturbatively 3-gluon propagator
- Indirect evidence from comparison of pp and $p\bar{p}$ elastic cross-section *at same energy*
(Phys.Rev.Lett. 127 (2021) 6, 062003)
- Much discussion about whether this is sufficient for 'discovery'
- Ideally would like a more direct observation, and independent confirmation.

Method 1: High p_T CEP of vector mesons.

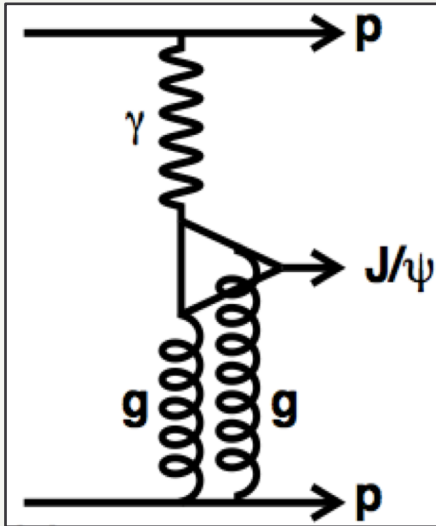
Replace $1^- g$ with $1^- O$



$d\sigma^{\text{corr}}/dy$	J/ψ		Υ	
	odderon	photon	odderon	photon
Tevatron	0.3–1.3–5 nb	0.8–5–9 nb	0.7–4–15 pb	0.8–5–9 pb
LHC	0.3–0.9–4 nb	2.4–15–27 nb	1.7–5–21 pb	5–31–55 pb

Odderon contribution might be 1-10% at LHC and would dominate at high p_T
 but experimentally **this is difficult to see**

Method 1: High p_T CEP of vector mesons.

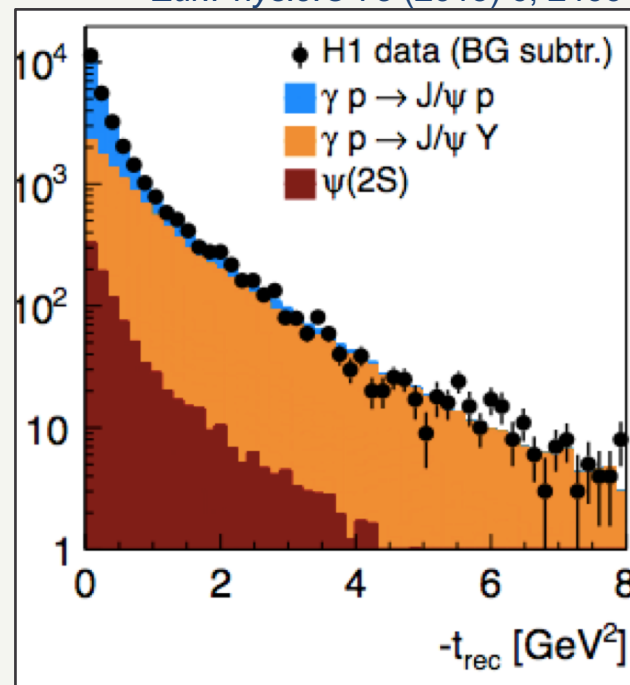


Photoproduction of J/ψ has been measured at HERA (γ from e), Tevatron and LHC (γ from p or A)

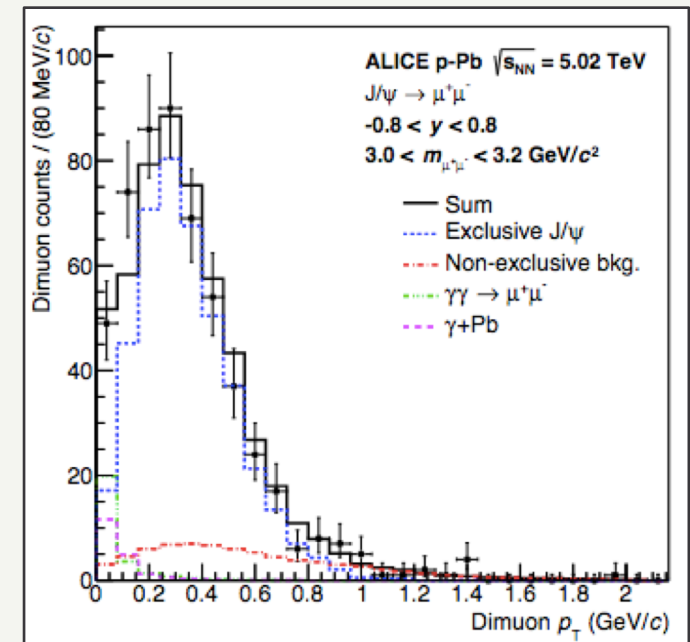
In Regge theory the momentum transfer through the Pomeron is usually modelled and the experimental data broadly supports this

$$\frac{d\sigma}{dt} \sim e^{bt}$$

Eur.Phys.J.C 73 (2013) 6, 2466



Eur.Phys.J.C 79 (2019) 5, 402

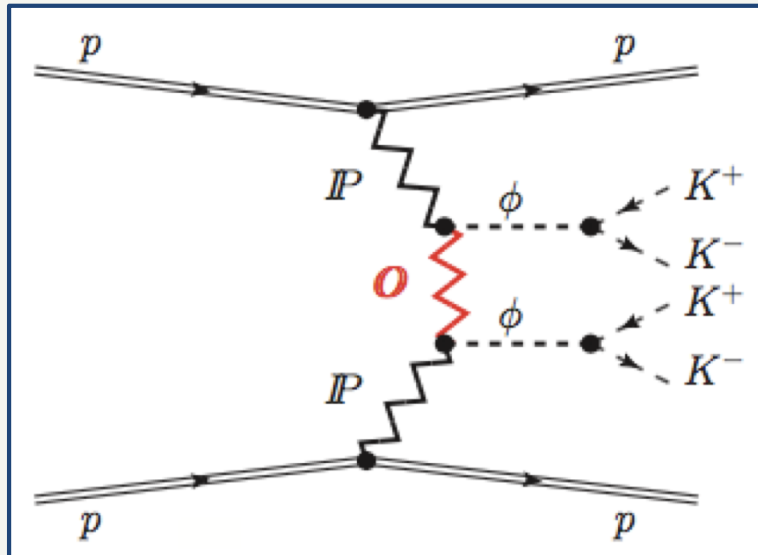


Note:

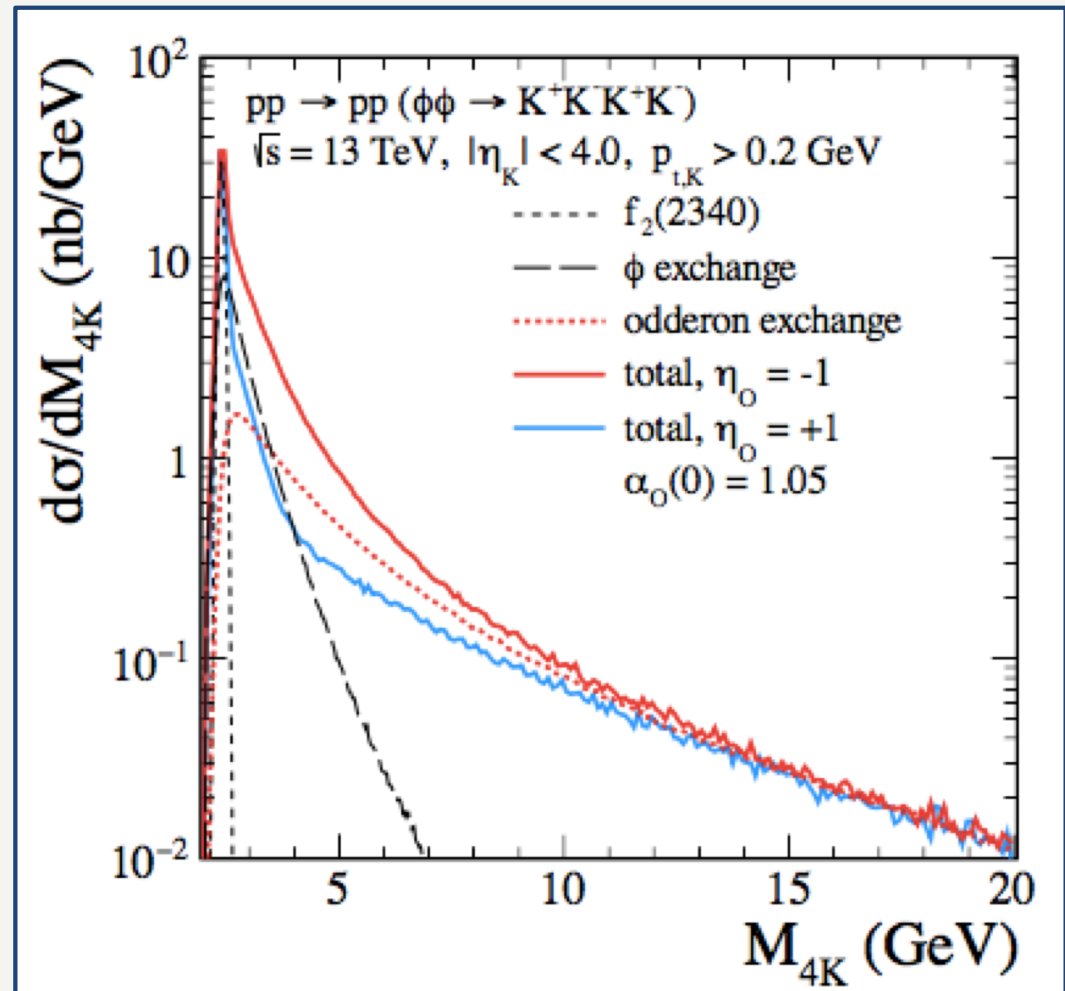
1. H1 required power-law to fit high p_T tail
2. Backgrounds dominate at high p_T

Method 2: High mass CEP of VM pairs

Visible in high mass tail of $\phi\phi$?



An intriguing aspect of $\phi\phi$ is that it may have a contribution from odderon, visible at high mass.

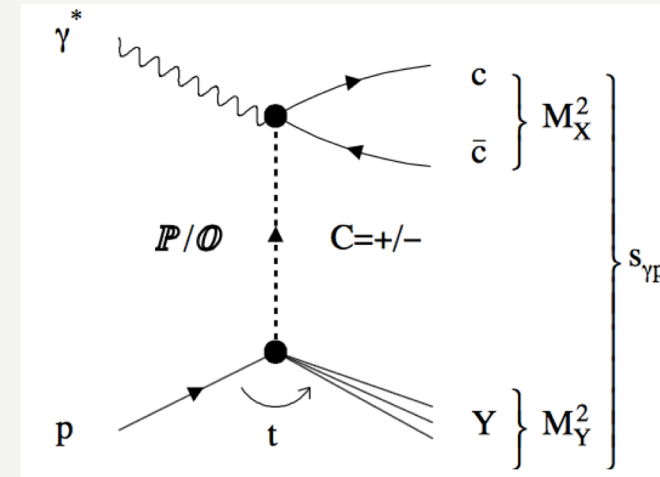


P. Lebiedowicz, O. Nachtmann, A. Szczurek
PRD 101 (2020) 9, 094012

Method 3: Interference C+/C-

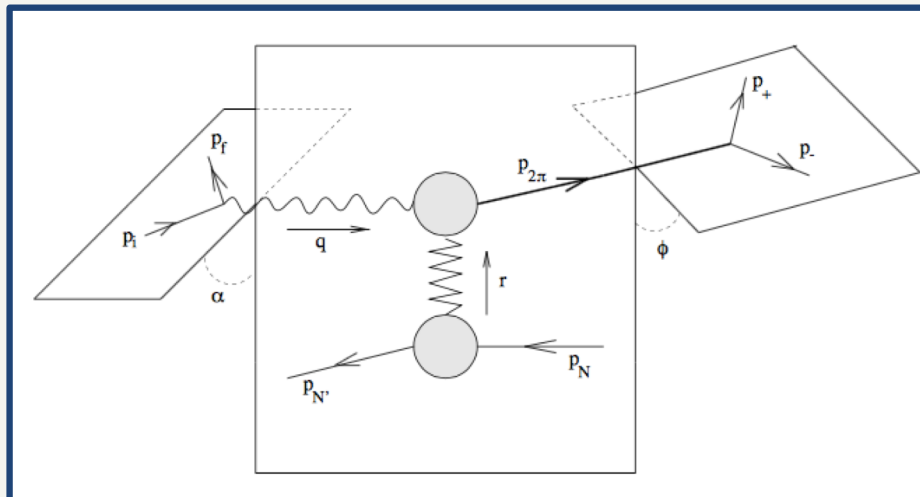
Interference of photoproduction processes

Brodsky, Rathsman, Merino, PLB461 (1998) 114.
 Hagler, Pire, Szymanowski, Teryaev, EPJ26 (2002) 261.
 Ginzburg, Ivanov, Nikolaev, EPJdirect 1 (2003) 1.
 Bolz, Ewerz, Maniatis, Nachtmann, Sauter,
 Schoening, JHEP 1501 (2015) 151.

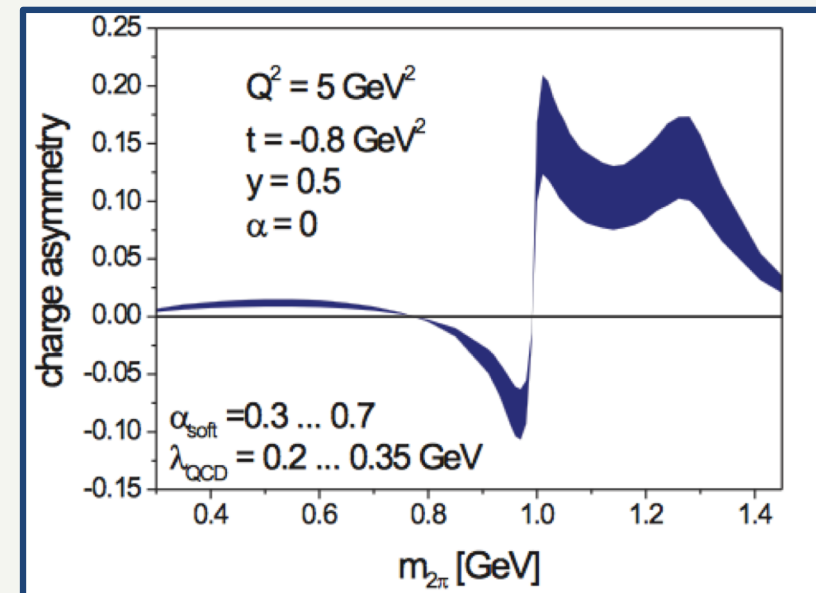


$$A(Q^2, t, m_{2\pi}^2, y, \alpha) = \frac{\sum_{\lambda=+,-} \int \cos \theta d\sigma(s, Q^2, t, m_{2\pi}^2, y, \alpha, \theta, \lambda)}{\sum_{\lambda=+,-} \int d\sigma(s, Q^2, t, m_{2\pi}^2, y, \alpha, \theta, \lambda)} = \frac{\int d\cos \theta \cos \theta N_{charge}}{\int d\cos \theta D}$$

N.B. linear with amplitude

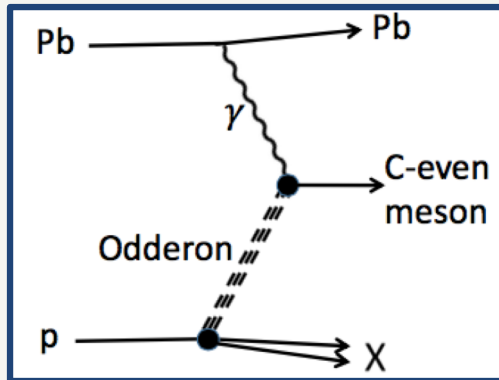


Need to tag outgoing proton to define production plane?



Method 4: Photoproduction of C+

Search in CEP photoproduction where quantum numbers inconsistent with pomeron



Czyzewski, Kwiecinski, Motyka, PLB398 (1997) 400.

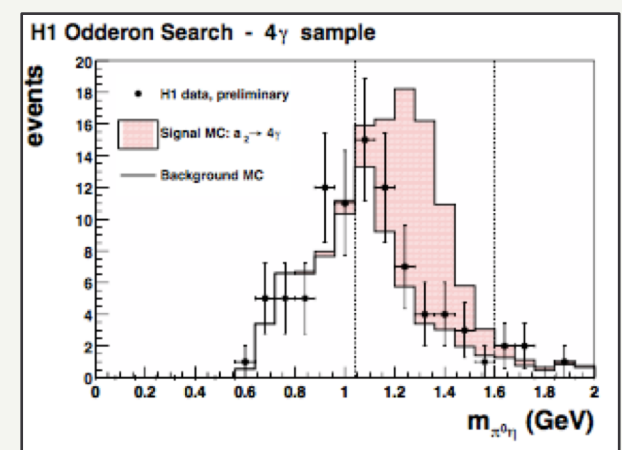
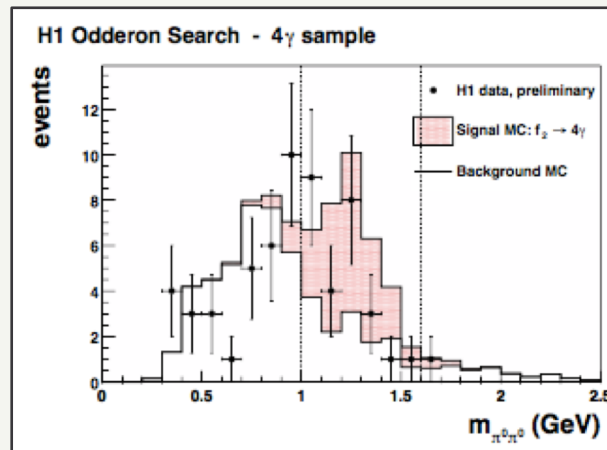
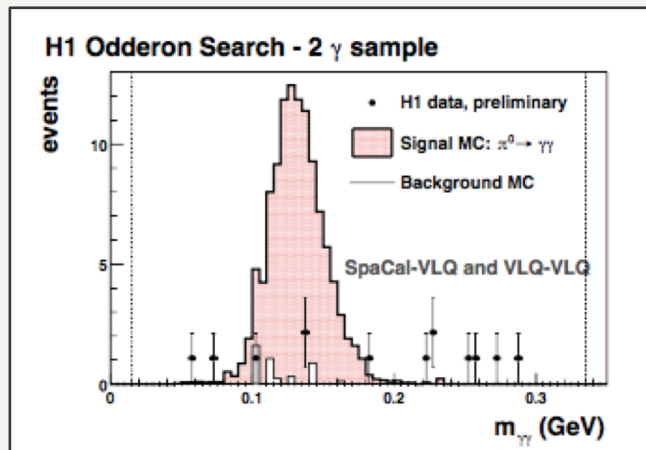
Berger, Donnachie, Dosch, Kilian, Nachtmann, EPJ C9 (1999) 491.

Ryskin EPJ C2 (1998) 339.

Kilian & Nachtmann, EPJ C5 (1998) 317.

Harland-Lang, Khoze, Martin, Ryskin PRD 99 (2019) 3, 034011

Acta Phys. Polon. B33, 3499 (2002). (Conference proceeding.)



Direct observation at LHC?

Harland-Lang, Khoze, Martin, Ryskin PRD 99 (2019) 3, 034011

$d\sigma/dy|_{y=0}$ for PbP collisions

C-even meson (M)	Odderon Signal		Backgrounds		
	Upper Limit	QCD Prediction	$\gamma\gamma$	Pomeron-Pomeron	$V \rightarrow M + \gamma$
π^0	7.4	0.1 - 1	0.044	—	30
$f_2(1270)$	3	0.05 - 0.5	0.020	3 - 4.5	0.02
$\eta(548)$	3.4	0.05 - 0.5	0.042	negligible	3
η_c	—	$(0.1 - 0.5) \cdot 10^{-3}$	0.0025	$\sim 10^{-5}$	0.012

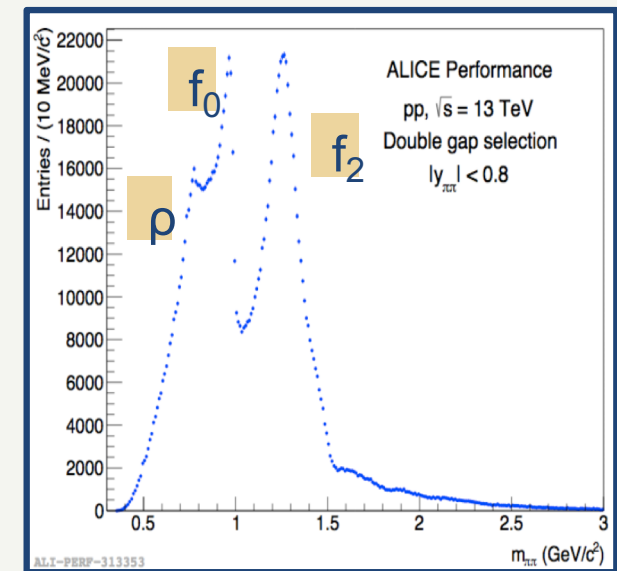
Note: Background processes are always much bigger

Which modes can provide significant signal?
How can you be sure any excess is due to odderon?

Go forward

Photoproduction of C+ meson

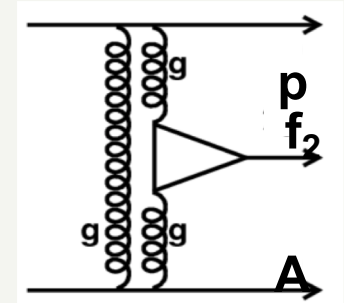
- To enhance the photon flux consider heavy ion collisions
 - Proton-ion (pA)
 - Ion-ion (AA*)
- Compared to pp collisions:
 - SIGNAL: For Pb, photon flux is $\sim Z^2=6700$ greater and **strongly peaked to backward rapidities**
 - Pomeron-pomeron BKG: cross-section is factor 2-5 greater than for protons
 - $\gamma\gamma$ BKG: Z^2 enhanced in pA. Z^4 in AA! (Z^2 in AA*)



arXiv:1912.00611

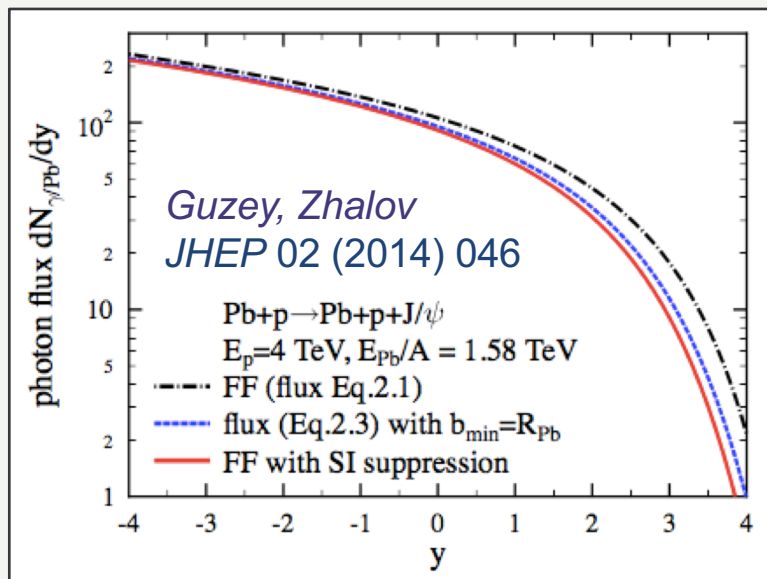
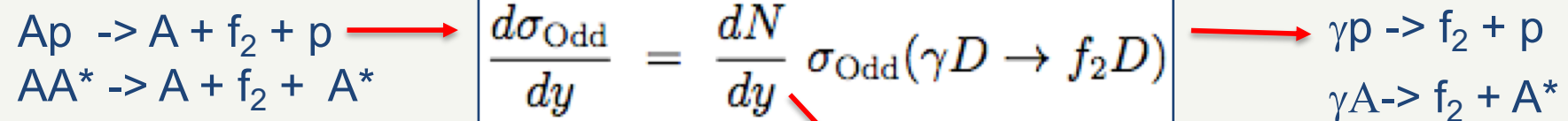
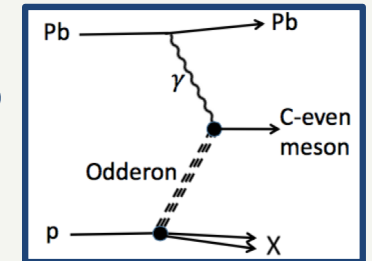
Key idea

C+ mesons dominantly produced by Double Pomeron Exchange: roughly flat with rapidity



SIGNAL PROCESS:

C+ production by photoproduction is peaked towards low rapidities due to energy dependence of photon flux



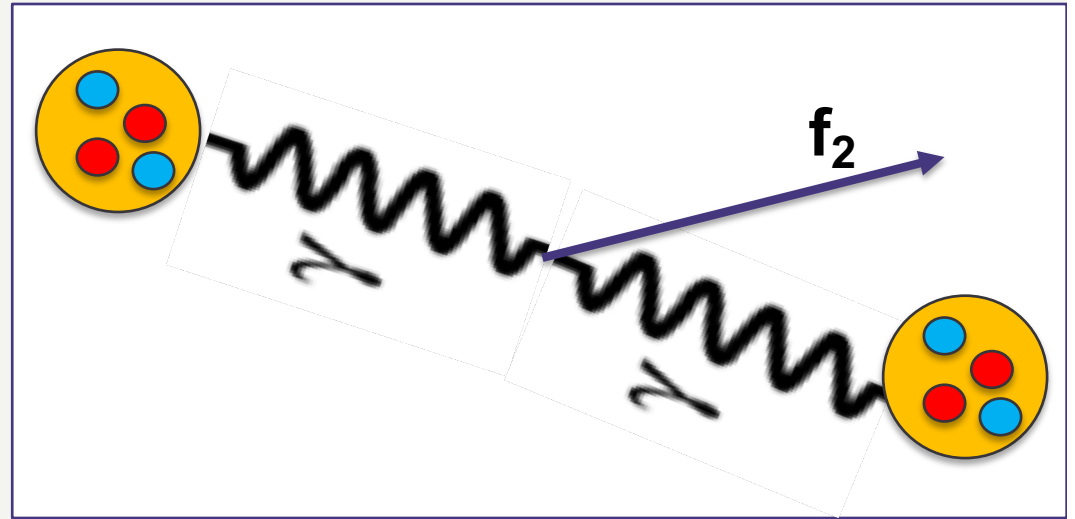
$$x = M_V e^{-y}$$

$$\frac{d^3 N_\gamma}{dx d^2 b_\gamma} = \frac{Z^2 \alpha^{\text{QED}}}{x \pi^2 b_\gamma^2} (x m_n b_\gamma)^2 K_1^2(x m_n b_\gamma)$$

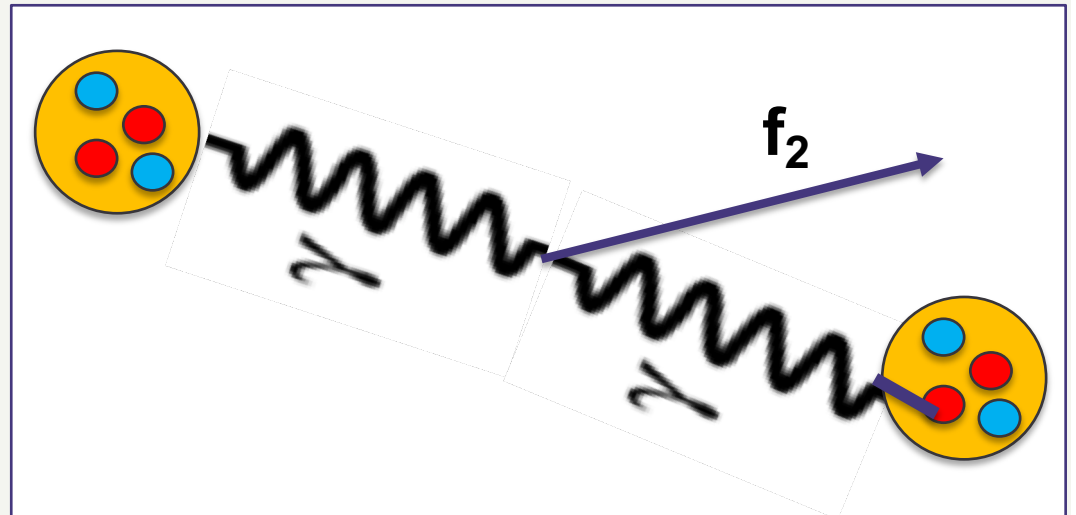
$b > R_A + R_p$ for pA
 $b > 2R_A$ for AA

AA collisions

Coherent $\gamma\gamma$ production enhanced by Z^4 compared to pp collisions.



Incoherent production enhanced by Z^2 .
To suppress $\gamma\gamma$ production, require that ONE of the ions breaks up.



Pomeron-pomeron process in pA

$$\frac{d\sigma_{pp}^{\text{CEP}}(y)}{dy} = \frac{C^2}{16^2\pi^3} \frac{e^{2\epsilon(y_1-y_2)}}{4(B + \alpha'_P(y_1 - y))(B + \alpha'_P(y - y_2))}$$

$B \sim 8 \text{ GeV}^{-2}$, $\alpha_P \sim 0.25 \text{ GeV}^{-2}$, $\epsilon = 1.08$, thus \sim flat with y

For pA collisions

Interaction with one nucleon $pA \rightarrow p + f_2 + A^*$

$$\frac{d\sigma_{pA}^{\text{incoh}}}{dy} = \frac{d\sigma_{pp}^{\text{CEP}}}{dy} \int d^2b T_A(b) S_{f_2N}^2(b) S_{pN}^2(b)$$

Survival factor

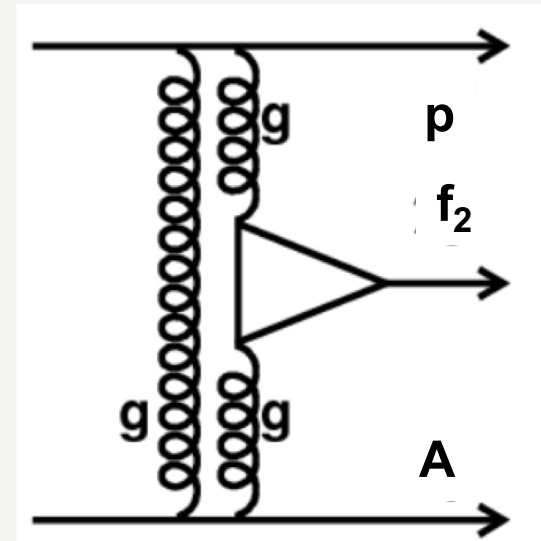
$$S_{pN}^2(b_t) = \exp(-\sigma_{\text{tot}}(pN) T_A(b_t))$$

optical density

$$T_A(b) = \int_{-\infty}^{\infty} dz (\rho_p(z, b) + \rho_n(z, b))$$

Interaction with whole nucleus $pA \rightarrow p + f_2 + A$

$$\frac{d\sigma_{pA}^{\text{coh}}}{dy} = \frac{d\sigma_{pp}^{\text{CEP}}}{dy} 8\pi(B + \alpha'_P(y - y_2)) \int d^2b T_A^2(b) S_{f_2N}^2(b) S_{pN}^2(b)$$



Results for p-Pb collisions

Pomeron-Pomeron production is flat and scaled to p-p results
(CMS arXiv:1706.08310)

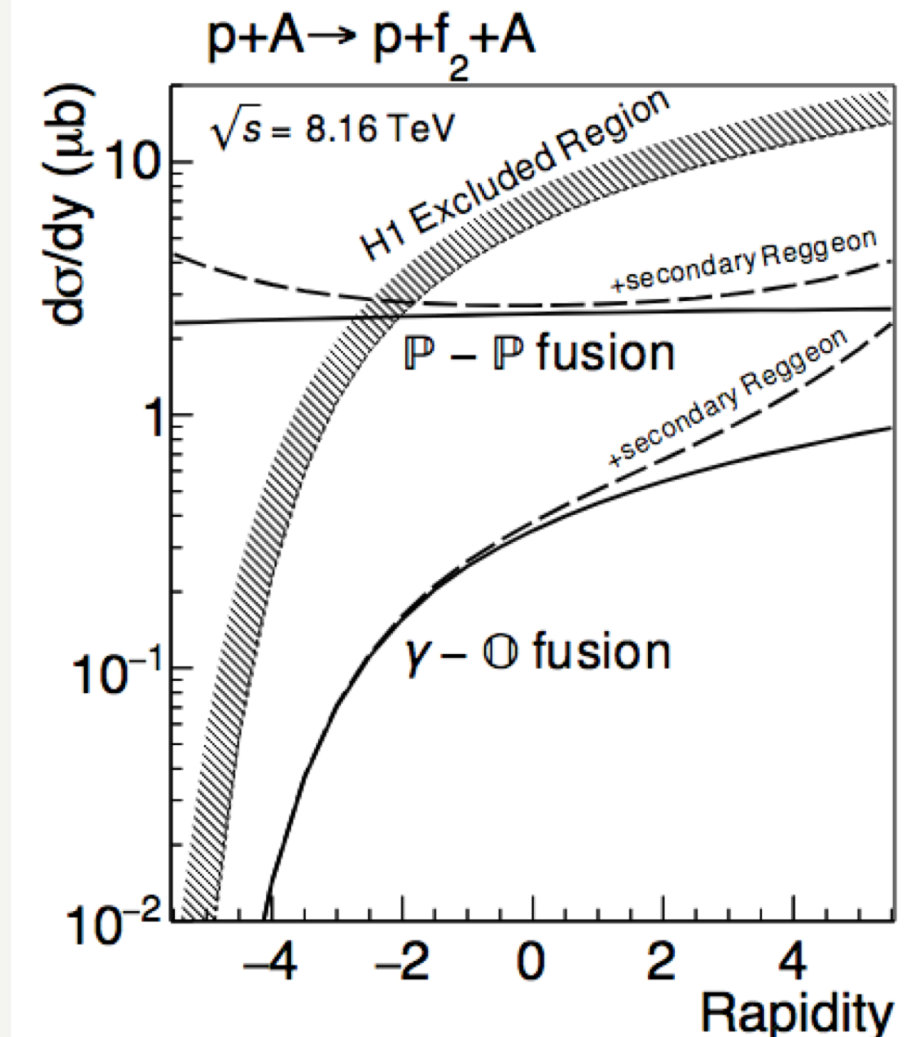
Gamma-Odderon is forward peaked.
Value unknown. Assume nominal 1nb photoproduction cross-section.

The excluded region comes from preliminary H1 result
(Acta Phys. Polon. B33, 3499 (2002))

Greater sensitivity than previous result.

An excess of events would be seen, but only in the forward region
i.e. for LHCb in pA and not Ap.

Distinctive signature

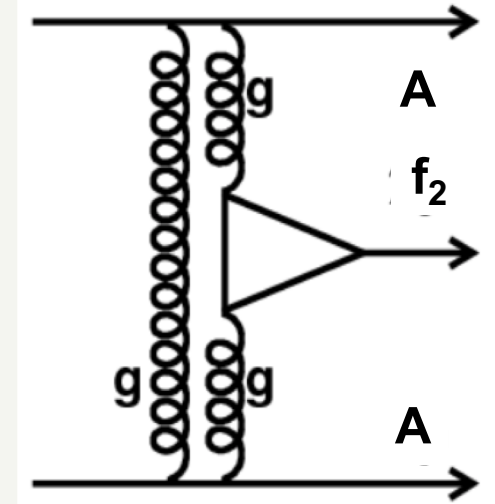


Pomeron-pomeron process in AA

$$\frac{d\sigma_{pp}^{\text{CEP}}(y)}{dy} = \frac{C^2}{16^2\pi^3} \frac{e^{2\epsilon(y_1-y_2)}}{4(B + \alpha'_P(y_1 - y))(B + \alpha'_P(y - y_2))}$$

$B \sim 8 \text{ GeV}^{-2}$ while $\alpha_P \sim 0.25 \text{ GeV}^{-2}$ thus \sim flat with y

For AA collisions



Interaction with one nucleon in both ions $AA' \rightarrow A^* + f_2 + A'^*$

$$\frac{d\sigma_{AA'}^{\text{incoh}}}{dy} = \frac{d\sigma_{pp}^{\text{CEP}}}{dy} \int d^2b_1 d^2b_2 T_A(b_1) T_{A'}(b_2) S_{f_2N}^2(b_1) S_{f_2N'}^2(b_2) S_{NN'}^2(|\vec{b}_1 - \vec{b}_2|)$$

Coherent interaction with one nucleon $AA' \rightarrow A + f_2 + A'^*$

$$\frac{d\sigma_{AA'}^{\text{coh}}}{dy} = \frac{d\sigma_{pp}^{\text{CEP}}}{dy} 8\pi(B + \alpha'_P(y_1 - y)) \int d^2b_1 d^2b_2 T_A^2(b_1) T_{A'}(b_2) S_{f_2N}^2(b_1) S_{f_2N'}^2(b_2) S_{NN'}^2(|\vec{b}_1 - \vec{b}_2|)$$

$$S_{NN'}^2(b) \simeq \theta(b - 17 \text{ fm})$$

Results for (incoherent) AA^* collisions

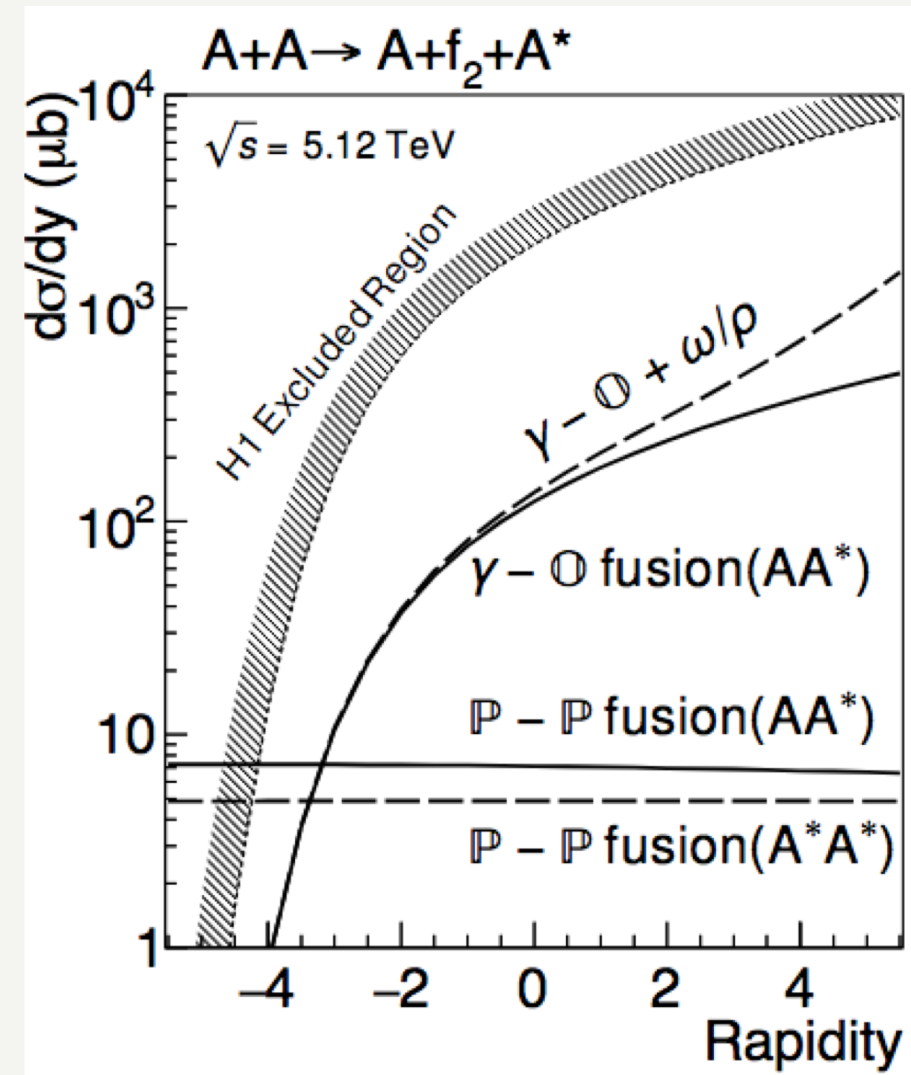
Pomeron-Pomeron production is flat and scaled to p-p results

Gamma-Odderon is forward peaked but **one needs to know which ion emitted the photon**. Detecting break-up allows us do this.

1nb photoproduction cross-section assumed again.

Cross-section is \sim factor 100 greater than in pA. However, luminosity at LHC for AA is \sim factor 100 lower.

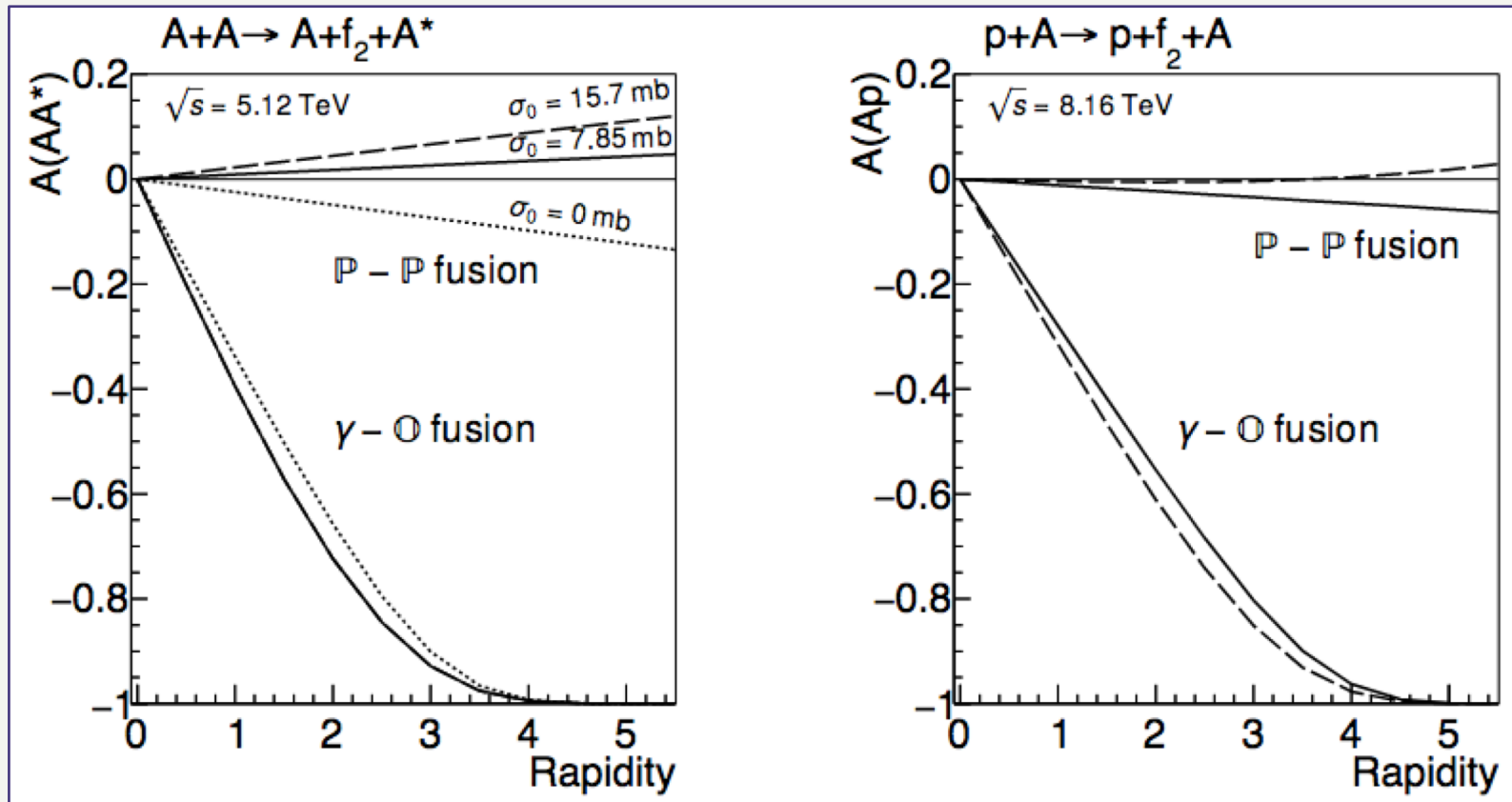
Relative background is **much lower** than in pA collisions.



Asymmetry

$$A(Ap) = \frac{\sigma(pA) - \sigma(Ap)}{\sigma(pA) + \sigma(Ap)}$$

$$A(AA^*) = \frac{\sigma(A^*A) - \sigma(AA^*)}{\sigma(A^*A) + \sigma(AA^*)}$$



Asymmetry in pA/Ap would be most clearly seen in forward/backward detectors.
 Note: LHC has runs where they swap the direction of the projectiles

Asymmetry in AA requires you 'tag' the photon emitter: the ion that doesn't break

Conclusions

- Enhanced C+ meson production (f_2 , η , η' , η_c) would be consistent with odderon production
- Depending on the (unknown) cross-section, this may be observable in heavy-ion collisions at LHC or at EIC
- The backgrounds in AA collisions appear particularly small.
- The observation of an **asymmetry** would guarantee it was photo-production and thus require an additional C-propagator

Backup

f_2 interaction with nucleon

$$\sigma_{\text{tot}}(f_2 N) = \sigma_0 (s/1 \text{ GeV}^2)^\epsilon \quad \sigma_0 = 13.6 \text{ mb} \quad \epsilon = 0.0808$$

$$\sigma_{\text{tot}}(f_2 N) = \sigma_{\text{tot}}(\rho N) \quad \sigma_0 = 15.7 \text{ mb} \quad \epsilon = 0.055$$

The absorptive cross section $\sigma_{\text{tot}}(f_2 N)$ is chosen in three different ways: via the VDM approach (17) with $\sigma_0 = 15.7 \text{ mb}$, with a twice smaller $\sigma_0 = 15.7/2 \text{ mb}$ (taking $\epsilon = 0.055$), and with no absorption inside the heavy ion ($\sigma_0 = 0$).

Including secondary Reggeon contributions

Besides f_2 production by Pomeron-Pomeron fusion there are production amplitudes in which one or both Pomerons in the amplitude (2) can be replaced by a secondary Reggeon⁴ of the form

$$A_R(p_1, p_2, y) = C_R \exp(B't_1 + B''t_2) e^{\alpha_R(t_1)(y_1-y)} e^{\alpha_P(t_2)(y-y_2)}. \quad (18)$$

Rapidity dependence of Pomeron-pomeron contribution

Let us start with the pure exclusive $pp \rightarrow p + f_2 + p$ reaction. The cross section as a function of the rapidity of the f_2 meson has the form

$$\frac{d\sigma_{pp}^{\text{CEP}}}{dy} = \frac{1}{16^2\pi^5} \int d^2p_1 d^2p_2 |A(p_1, p_2, y)|^2 e^{-2(y_1 - y_2)} \quad (1)$$

where y_1 (y_2) and y are the rapidities of the beam (target) protons and f_2 meson respectively ($y_1 > y > y_2$); and p_1 (p_2) are the transverse momenta of the outgoing protons; $t_1 = -p_1^2$, $t_2 = -p_2^2$. The amplitude is dominated by double Pomeron exchange and reads

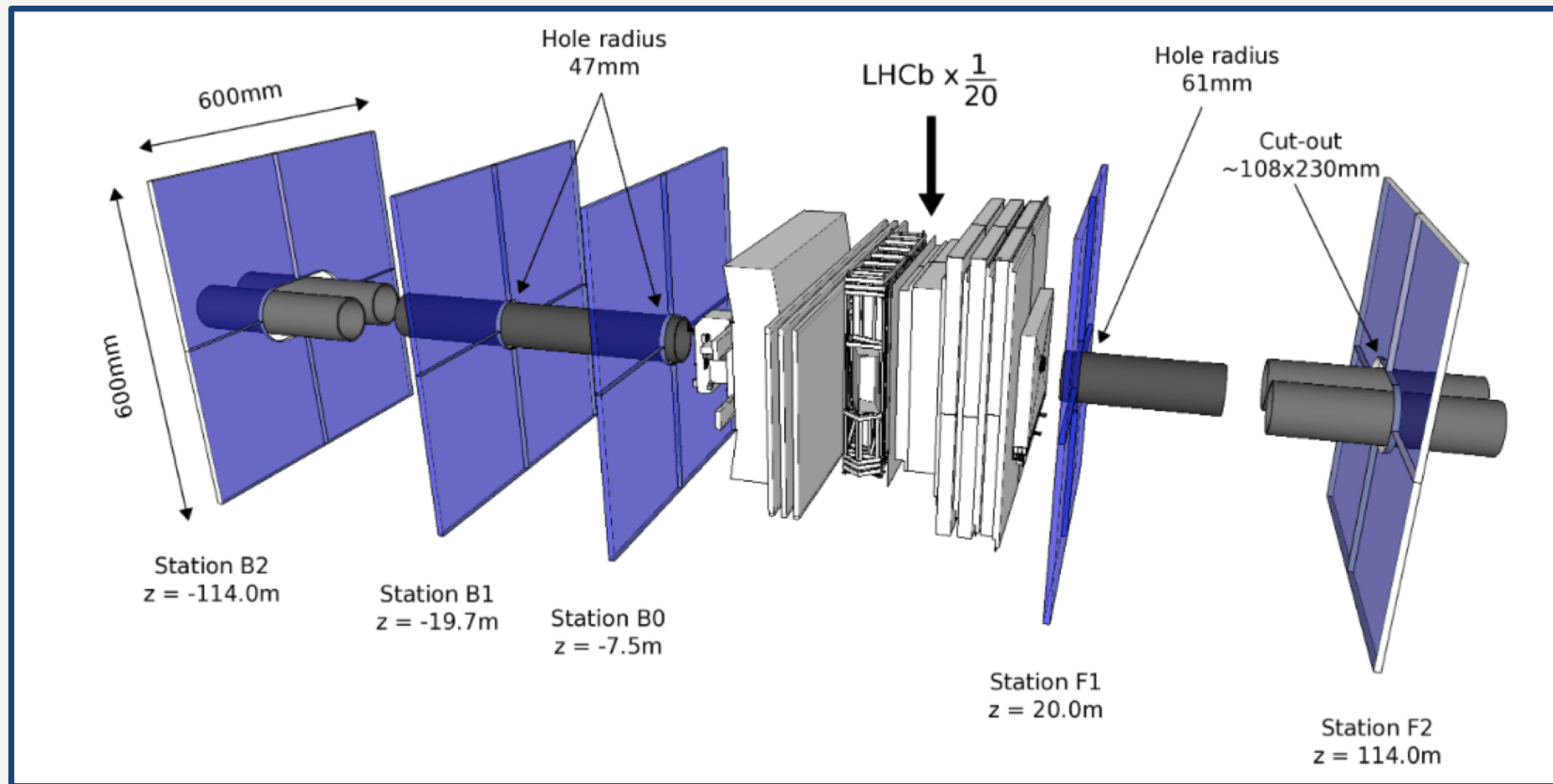
$$A(p_1, p_2, y) = C \exp(Bt_1 + Bt_2) e^{\alpha_P(t_1)(y_1 - y)} e^{\alpha_P(t_2)(y - y_2)}, \quad (2)$$

where $\alpha_P(t)$ is the Pomeron trajectory; B accounts for the slope of the vertices and C is the product of the coupling constants (two Pomeron-proton couplings times the Pomeron-Pomeron-to- f_2 fusion constant). For the Pomeron trajectory we use the simple form $\alpha_P(t) = 1 + \epsilon + \alpha'_P t$ with $\alpha'_P = 0.25 \text{ GeV}^{-2}$ and $\epsilon = 0.0808$ (corresponding to the Donnachie-Landshoff (DL) parametrization [17]). After integration over the transverse momenta in (1) the cross section becomes

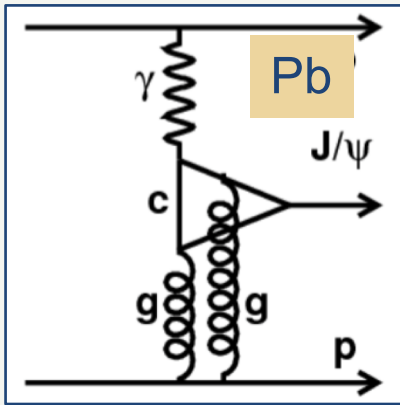
$$\frac{d\sigma_{pp}^{\text{CEP}}(y)}{dy} = \frac{C^2}{16^2\pi^3} \frac{e^{2\epsilon(y_1 - y_2)}}{4(B + \alpha'_P(y_1 - y))(B + \alpha'_P(y - y_2))}. \quad (3)$$

The LHCb detector

JINST 13 (2018) no.04, P04017



Fully instrumented: $2 < \eta < 5$
Veto region (Run 1): $-3.5 < \eta < -1.5$
Veto region (Run 2): $-10 < \eta < -5, 5 < \eta < 10$

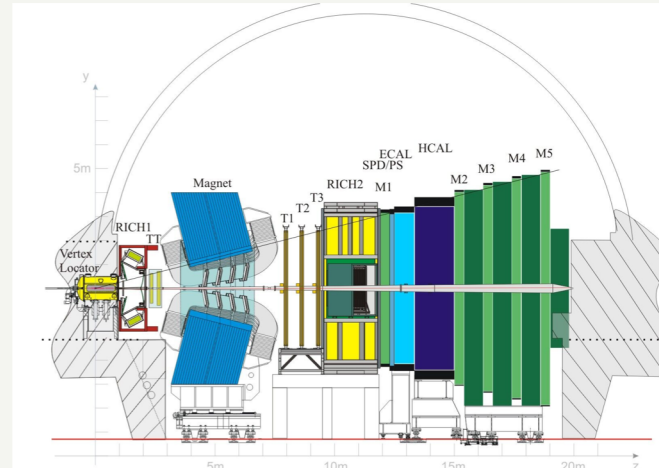


Which projectile produced the photon?

pomeron



pPb collisions



pomeron

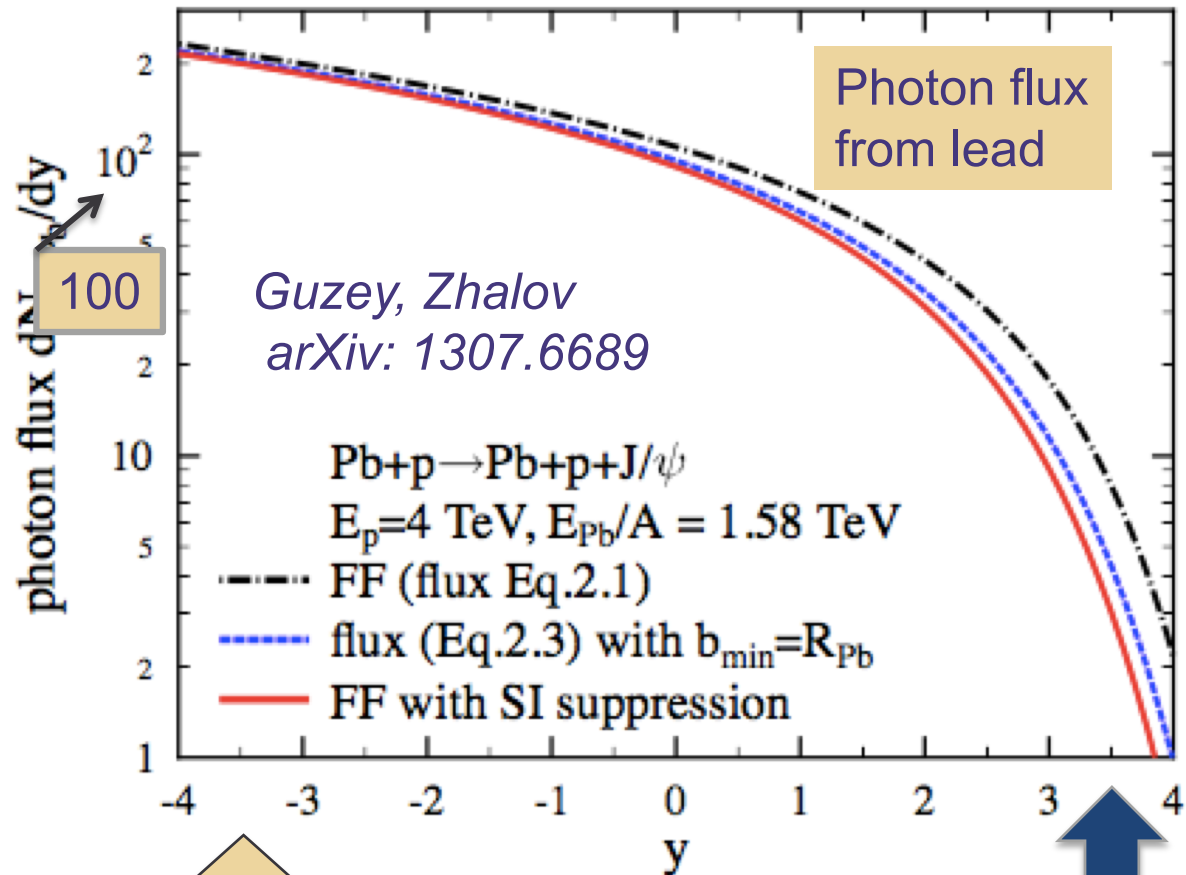
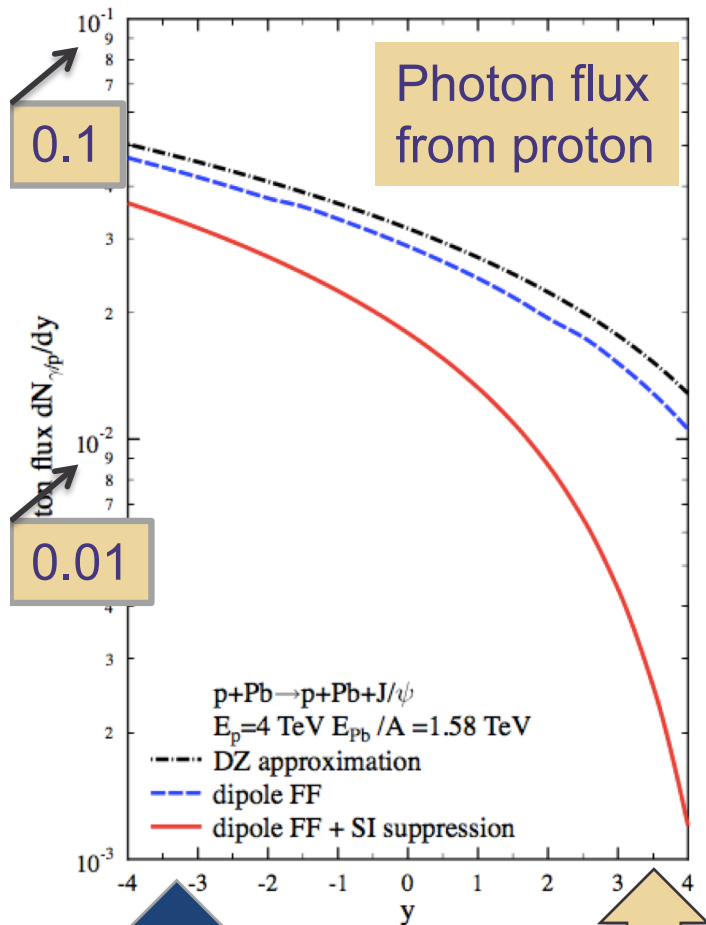


Pbp collisions



Which projectile produced the photon?

At $y \sim 0$, photon comes from lead (Z^2 enhancement)

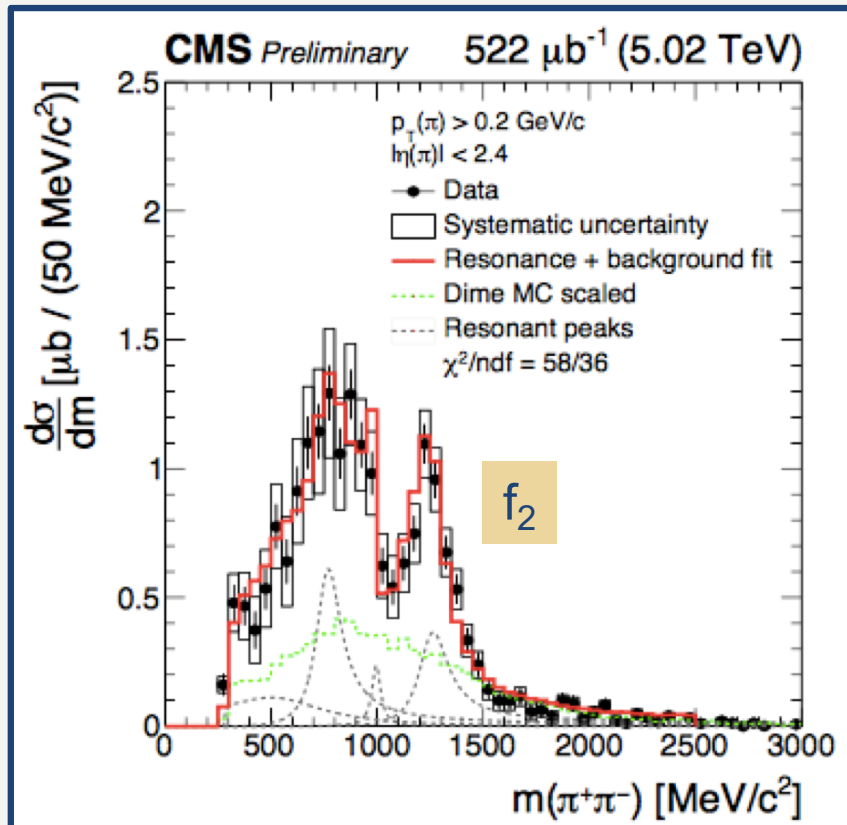


For LHCb, In pPb collisions,
 photon comes from lead

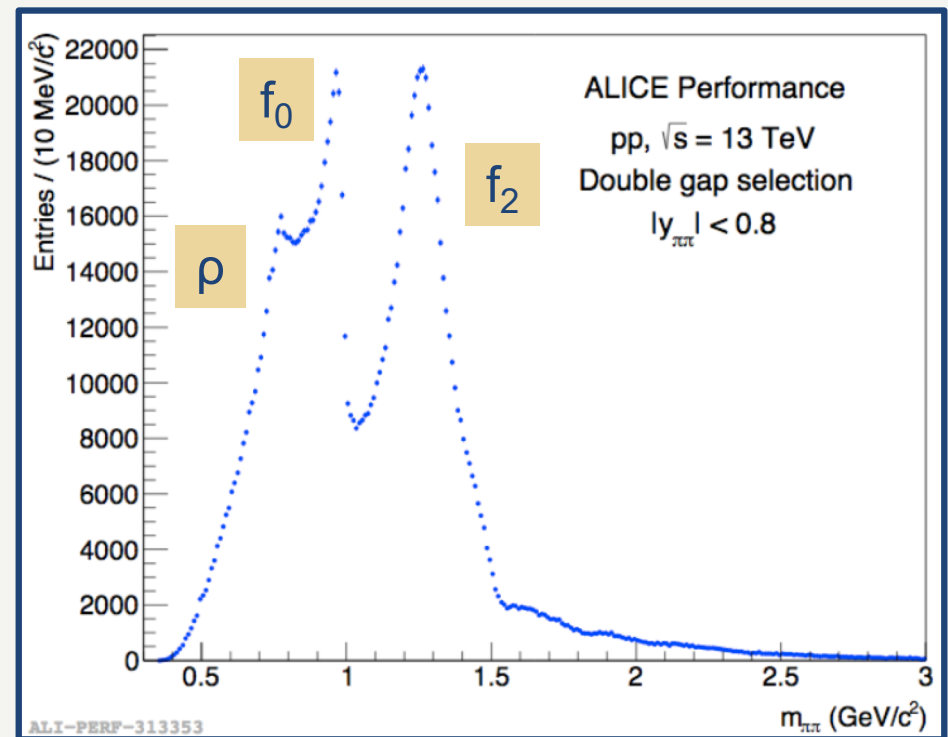
For Pb-p collisions,
 ~1% comes from p

$\pi\pi/KK$ final state in pp collisions

CMS-PAS-FSQ-16-006



arXiv:1912.00611

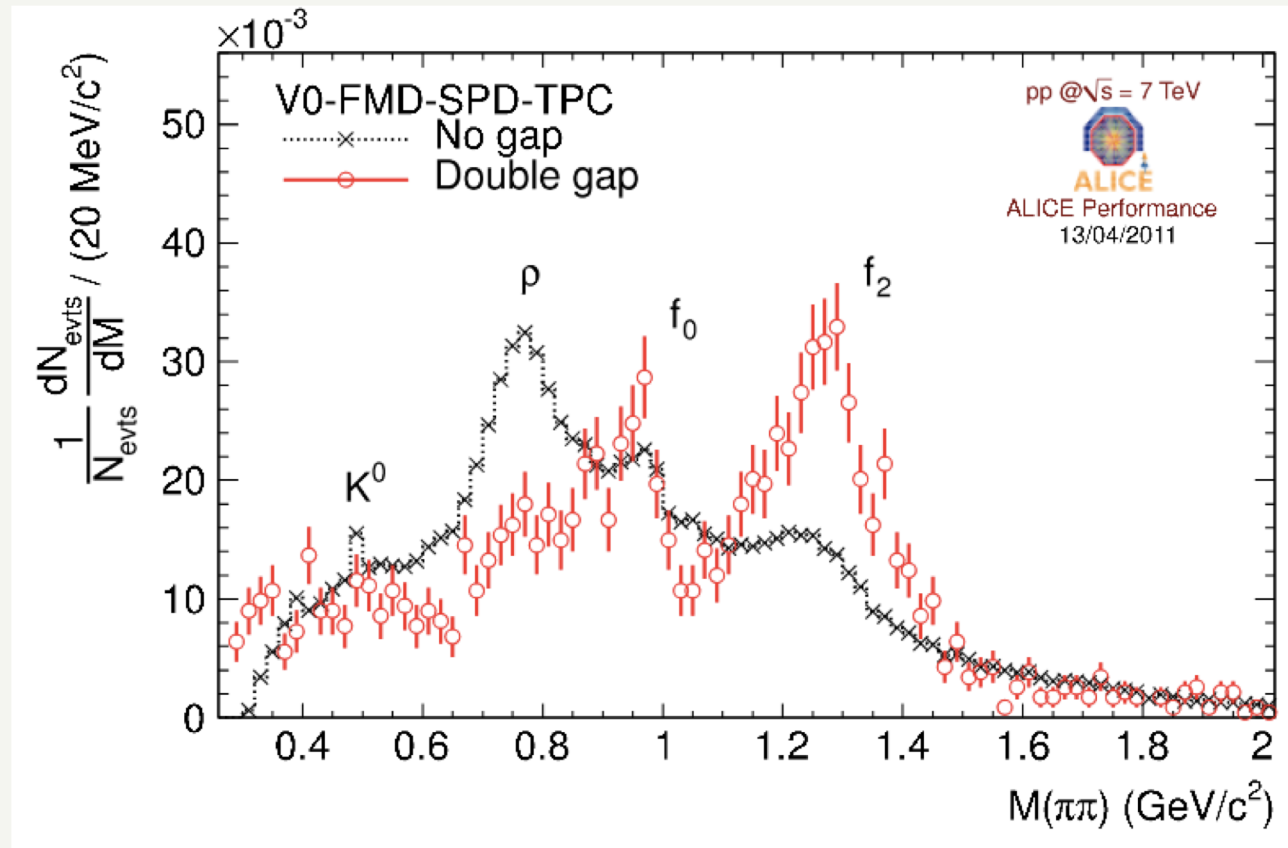


LHC sees similar structures.

Note photo-production competes with DPE, especially as you go forward

$\pi\pi$ final state in pp collisions

arXiv: 1208.2588



Resonance at $\sim 1250 \text{ MeV}$ seems enhanced in CEP and DPE processes
Characteristic of DPE ?