The elusive Odderon

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Odderon first motivated in 1973 (Lukaszuk, Nicolescu) by Regge exchange for high-energy cross sections; for example pp and $p\bar{p}$

$$\boxed{A_{\pm} = A(pp) \pm A(p\bar{p})}$$

simple poles $\alpha_{P,O}(0) \sim 1$

$$A_{+}(pp) = A_{+}(p\bar{p}) \quad C = +1$$

$$A_{-}(pp) = A_{-}(p\bar{p}) \quad C = -1$$

Pomeron --- dominately imag

Odderon --- dominately real

Maximal Odderon: odd-sig term as strong as allowed by asymptotic theorems

1. Pomeranchuk theorem $\Delta\sigma \equiv \sigma(\bar{p}p) - \sigma(pp) \sim \mathrm{Im}A_{-} \rightarrow 0 \quad \text{as} \quad s \rightarrow \infty$

2. Generalized Pomeranchuk th: $\dfrac{\sigma(\bar{p}p)}{\sigma(pp)} \rightarrow 1 \quad \text{as} \quad s \rightarrow \infty$

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$\boxed{\text{1 and 2 are not equivalent}}$

$$\sigma(\bar{p}p) = A\ \ln^2 s + B\ \ln s + C$$

$$\sigma(\bar{p}p) = A\ \ln^2 s + B'\ \ln s + C'$$

if $B \neq B'$ then satisfy 2, but not 1

In general $\Delta\sigma \leq c\ \ln s$

No evidence of Odderon from "asymptotic" $\Delta\sigma$ or ρ =Re/Im data

Then in 1980 the Odderon is found to be a firm prediction of QCD

But no evidence of Odderon exchange from HERA data for exclusive photoprod. of C-even mesons $\gamma p \to \pi^0 p, \eta p, f_2 p\ldots$

Discuss evidence from LHC later.

First, explain why Maximal Odderon violates unitarity →

Why the Maximal Odderon violates unitarity

Khoze, Martin, Ryskin
arXiv: 1801.07065

1. Unitarity

$$\mathbf{SS}^\dagger = \mathrm{I} \quad (\text{let} \;\; \mathbf{S} = \mathrm{I} + \mathrm{i}\mathbf{A}) \quad \rightarrow \quad \mathrm{i}(\mathbf{A}^\dagger - \mathbf{A}) \;=\; \mathbf{A}^\dagger\mathbf{A}$$

Unitarity equation

$$2\,\mathrm{Im}A_{\rm el}(b) \;=\; \sum_n |A_{i\to n}(b)|^2 \;=\; |A_{\rm el}(b)|^2 \;+\; G_{\rm inel}(b)$$

$$\text{where} \;\; G_{\rm inel}(b) \;=\; \sum_{n\neq i} |A_{i\to n}(b)|^2 \;<1 \;\;=\; \text{probability of inelastic scatt.}$$

Solution of unitarity eq.

$$A(b) \;\equiv\; A_{\rm el}(b) \;=\; i(1-e^{-\Omega(b)/2}) \quad \text{with} \;\; \mathrm{Re}\Omega(b) \geq \; 0$$

No solution of unitarity eq. if $G_{\rm inel}(b) > 1.$

Let us calculate $G_{\rm inel}(b)$

exp(2iδ$_l$) in terms of partial waves l = b√s/2

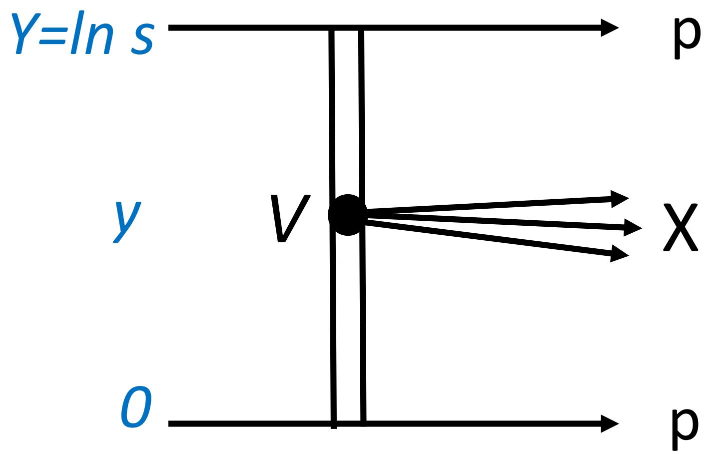
2. Finkelstein-Kajantie problem: $\sigma(\text{diff}^{ve}) > \sigma(\text{total})$ due to $\int_0^{\ln s} dy... \sim \ln s$

Simple example: Central Exclusive Prod. pp → p+X+p

In the Froissart limit $\sigma_{\text{CEP}} \sim ln^5 s$

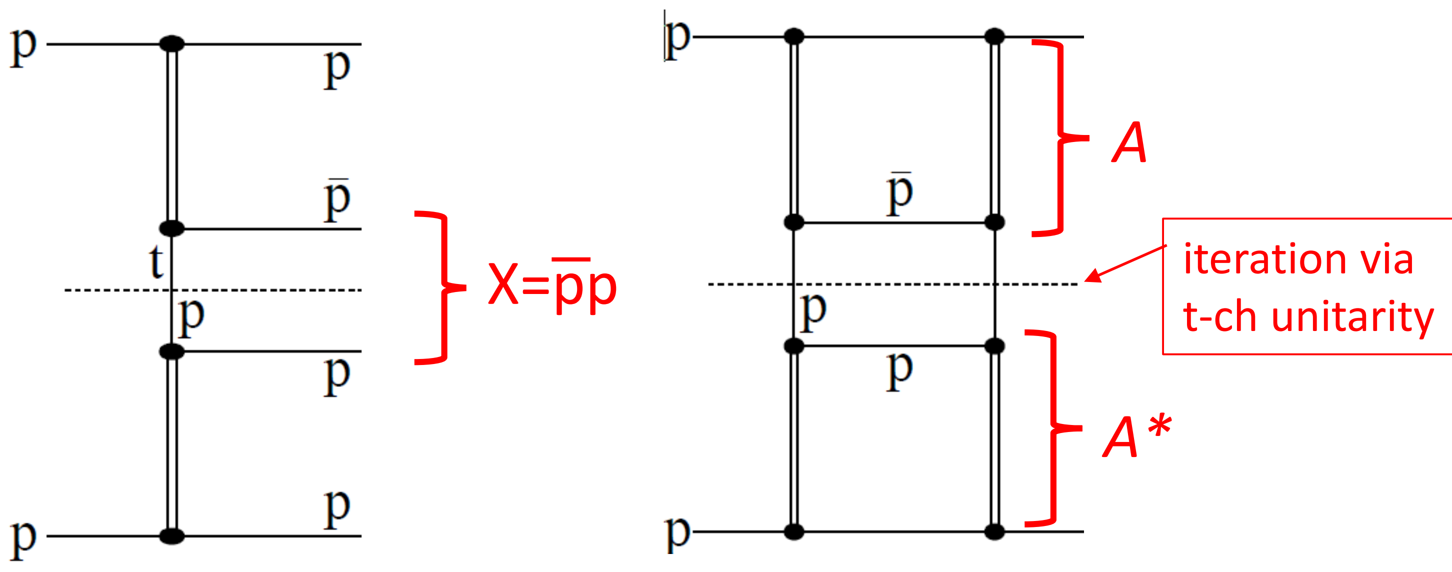
so $\sigma_{\text{CEP}} > \sigma_{\text{tot}} \sim ln^2 s$

Could the explanation be that vertex $V = 0$? **No**



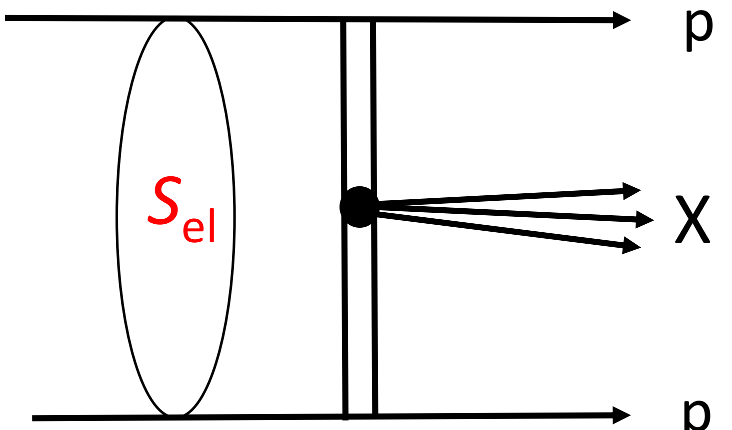
Can show, for example, that the $p\bar{p}$ component of X generated by t-channel unitarity has $V \neq 0$, and cannot be compensated due to the singularity/pole at $t=m_p^2$.

So starting from A_{el} we see t-ch unitarity gives a component of $G_{inel}(b)$ increasing faster than $\int_0^{\ln s} dy.. \sim \ln s$



Figs: amplitude (left) and cross section (right) of $\bar{p}p$ Central Exclusive Prod. generated by t-ch unitarity

3. Solution to the Finkelstein-Kajantie problem



Complete CEP must include rescattering S_{el} (that is the survival probability $S^2 = |S_{el}|^2$ of the rapidity gaps)

$$A_{CEP}(b) = S_{el}(b)\, A_{bare}(b)$$

$$\text{where} \quad |S_{el}(b)|^2 = |1 + iA_{el}(b)|^2 = e^{-\mathrm{Re}\Omega(b)}$$

Black disc asymptotics: $\mathrm{Re}\Omega \to \infty$, $A_{el}(b) \to i$, $\mathbf{S^2(b) \to 0}$ **for** $\mathbf{b < R}$

If σ_{tot} increases, Black disc is the only known solution to the FK problem

To repeat, if at least one component of G_{inel} increases (as $\int dy \sim \ln s$) as $s \to \infty$, violating unitarity, the only way to cancel it is to have $S(b) \to 0$

4. Maximal Odderon contradicts unitarity as s →∞

Maximal Odderon

Asymptotially MO means $\mathbf{Re}A/\mathbf{Im}A \to$ constant $\neq 0$

In this case $\quad S^2(b) = |1 + iA(b)|^2 \geq |\mathrm{Re}A(b)|^2 \neq 0$

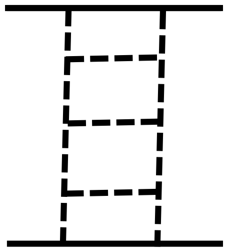
so there is no possibility to compensate the growth of σ_{CEP}.

The Odderon exists in QCD

Need the existence of symmetric tensor d_{abc} of non-Abelian $SU(3)_{col}$ to form colourless ggg exchange with C=-1

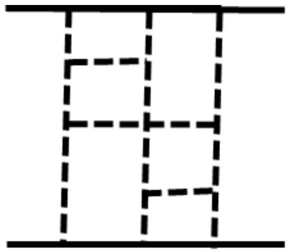
Pomeron (gg)	Odderon (ggg)
BFKL eq.	BKP eq.

Bartels; Kwiecinski, Praszalowicz 1980



resum

$\alpha_P(0) > 1$



resum

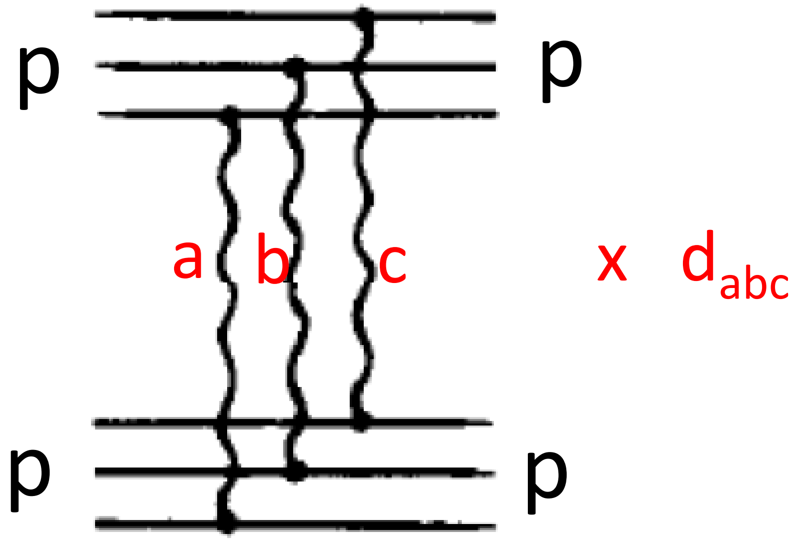
$\alpha_O(0) \approx 1$

Janik-Wosiek solution

Bartels-Lipatov-Vacca solution, 2000

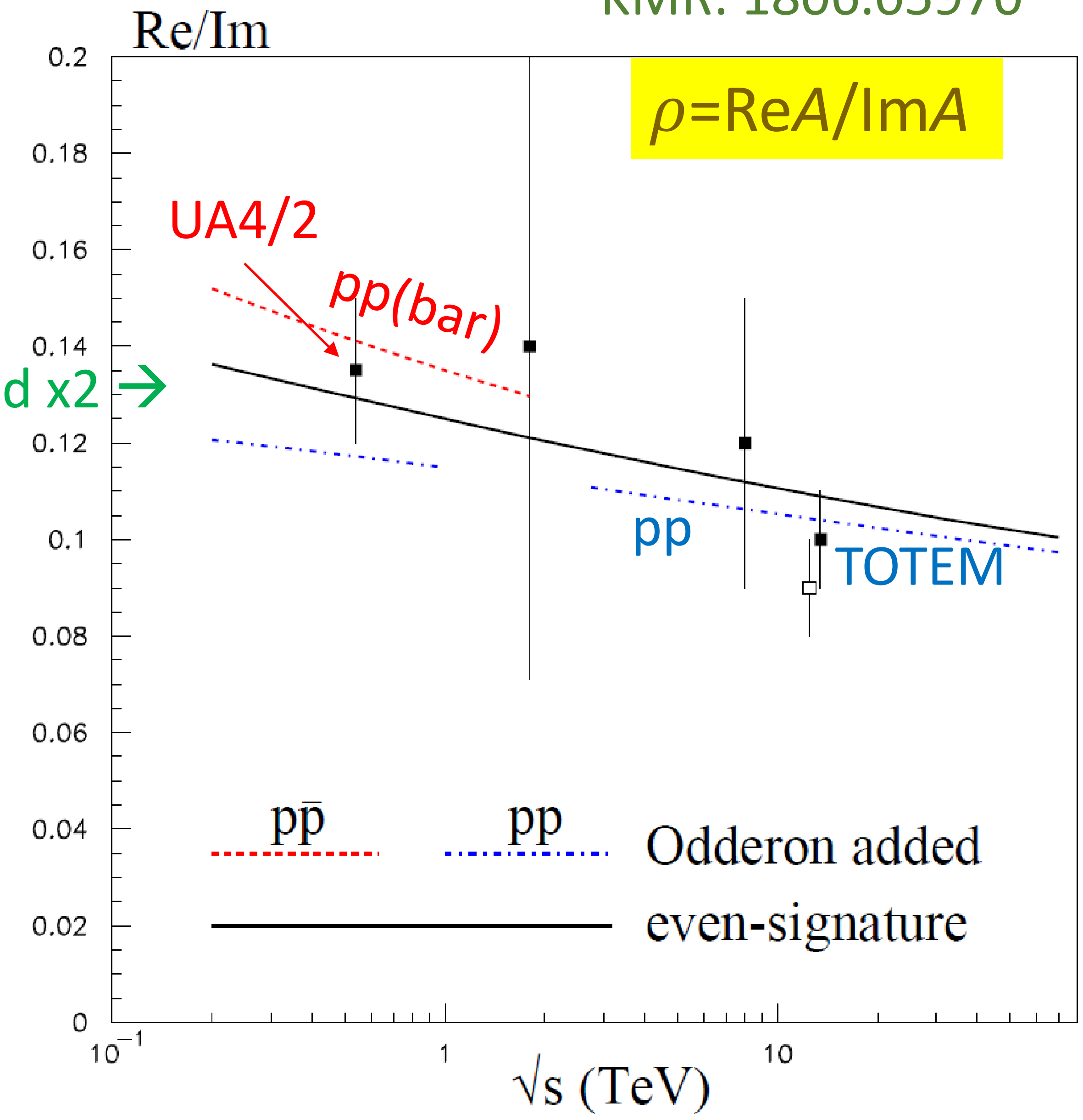
Estimate of Odderon contrib^n

QCD lowest α_s order   Ryskin '87
(Fukugita, Kwiecinski '79;
Kwiecinski,Motyka..'96 (η_c at HERA))



KMR: 1806.05970

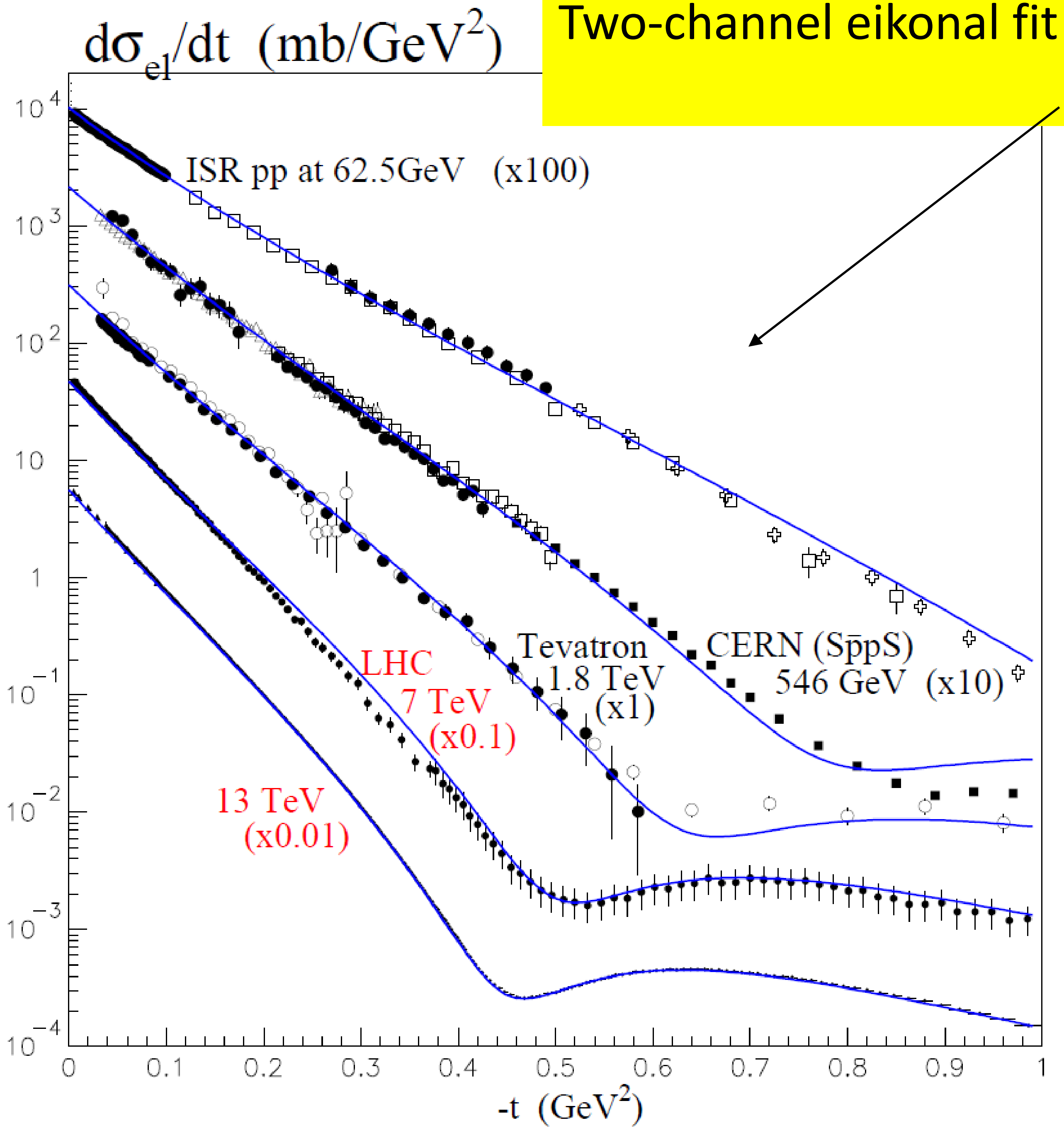
enhanced x2 →



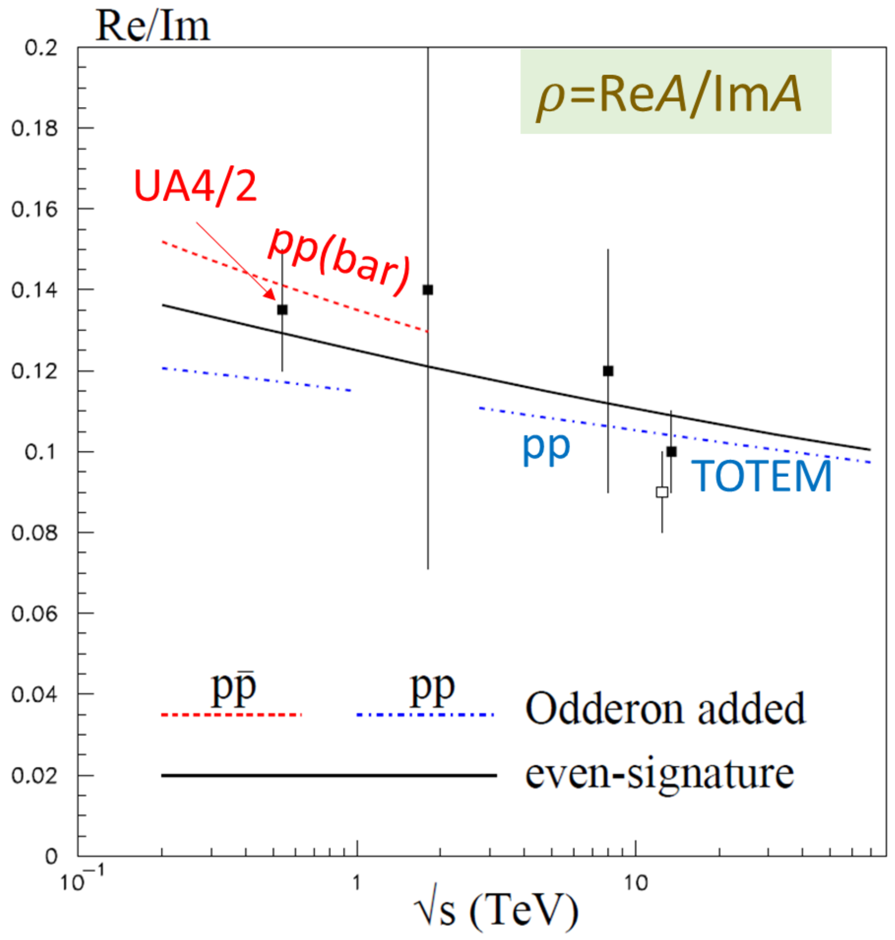
Two-channel eikonal fit to high-energy pp scatt. data

$d\sigma_{el}/dt$, σ_{tot}, $\sigma_{\text{low mass Diffraction}}$

crucial data



Gives acceptable fit to Re*A*/Im*A* without an Odderon



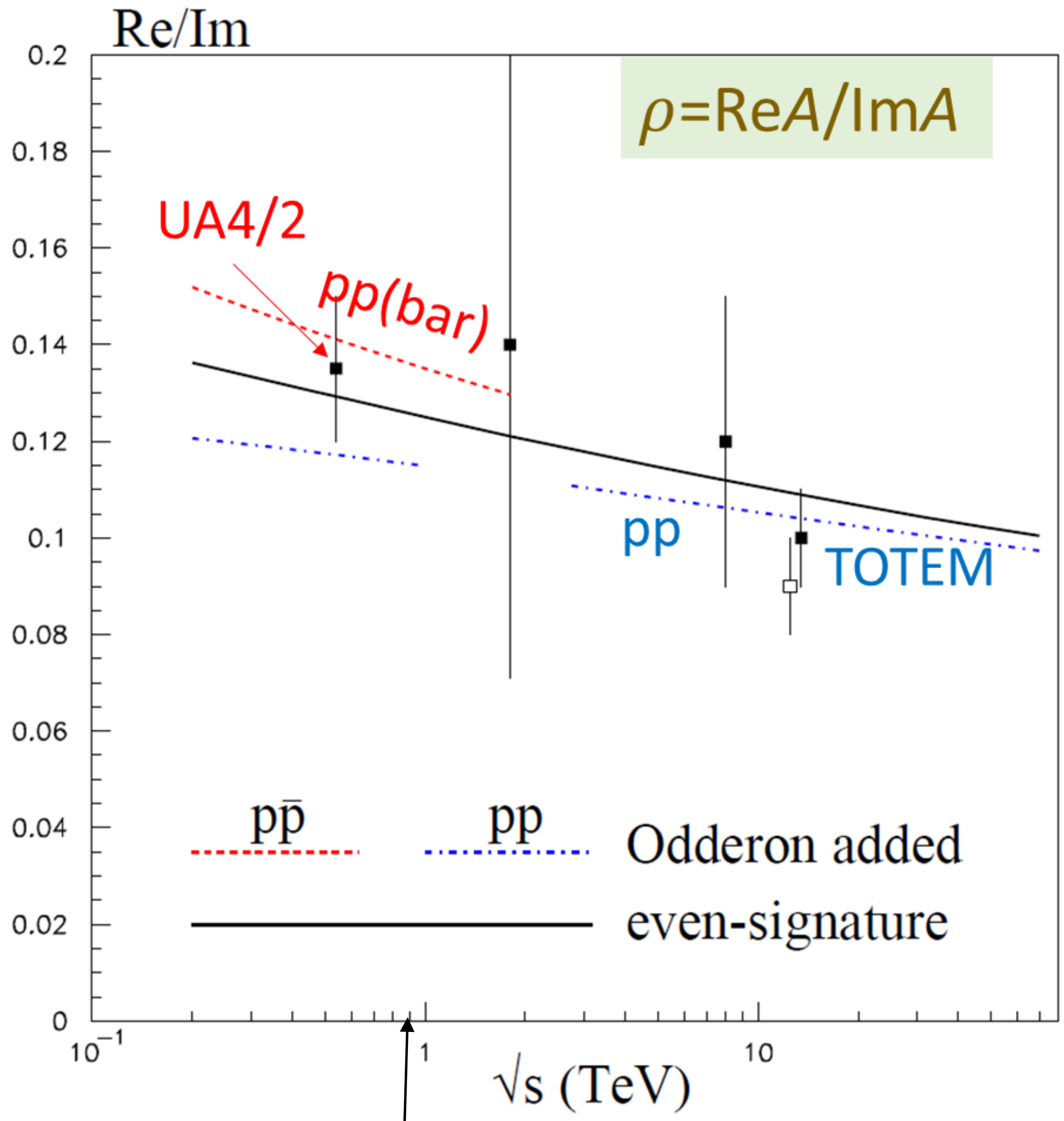
Including the Odderon gives only a marginal improvement

Must include full Ω in amplitude

$$A(b) = i\left(1 - e^{-\Omega(b)/2}\right)$$

with $\Omega = \Omega_{\text{even}} + \Omega_{\text{odd}}$

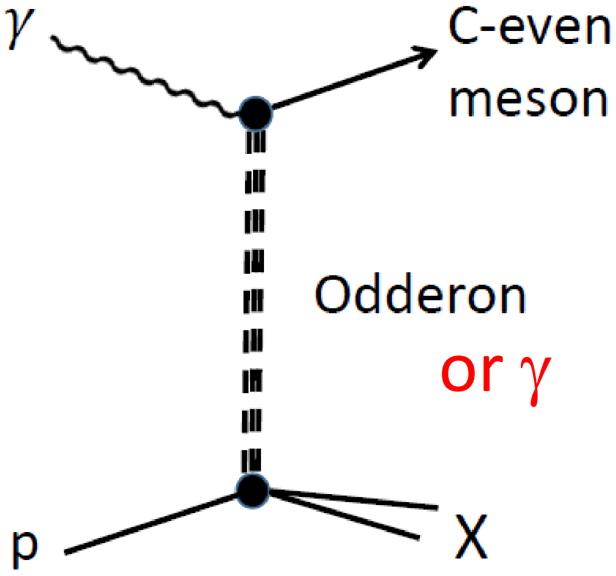
Automatically accounts for absorptive effect caused by elastic rescattering



TOTEM measurement 0.9 TeV would be informative?

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 ...



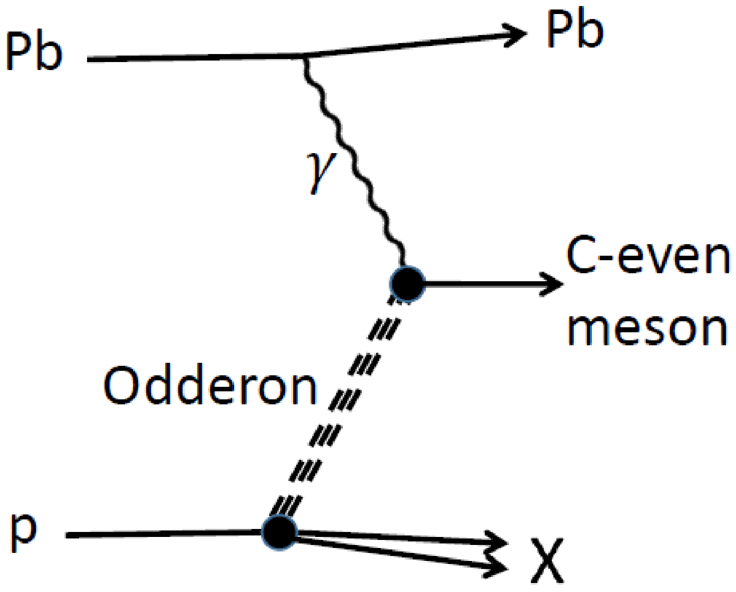
No evidence in HERA data

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

Need to suppress back^{gd} due to γ exchange

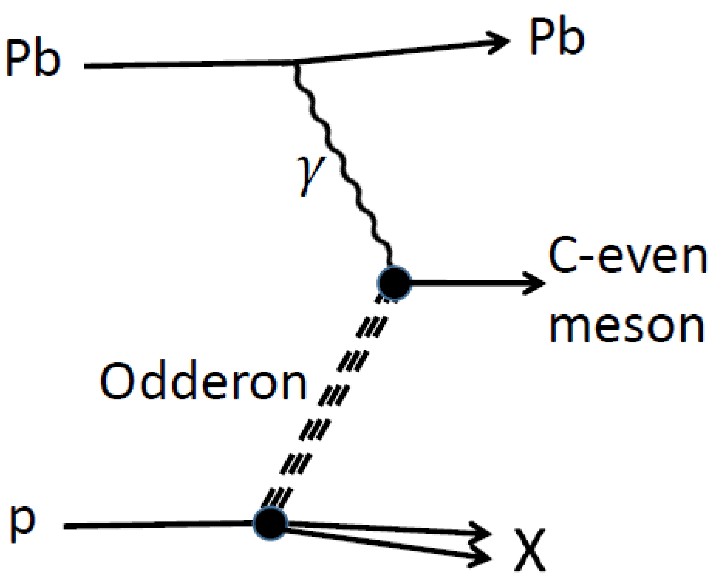
- ultraperipheral production in p-Pb collisions

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

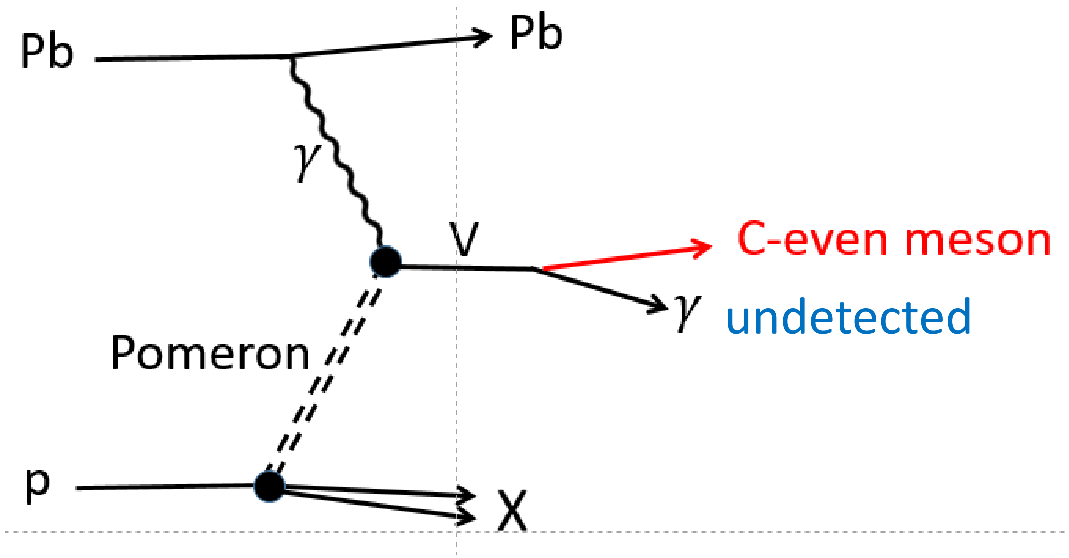


Healthy signal,
but backgrounds
are due to

production of C-even meson by

1. $\gamma\gamma$ fusion
2. Pomeron-Pomeron fusion
3. Via vector meson

   V → C-even meson + undetected γ

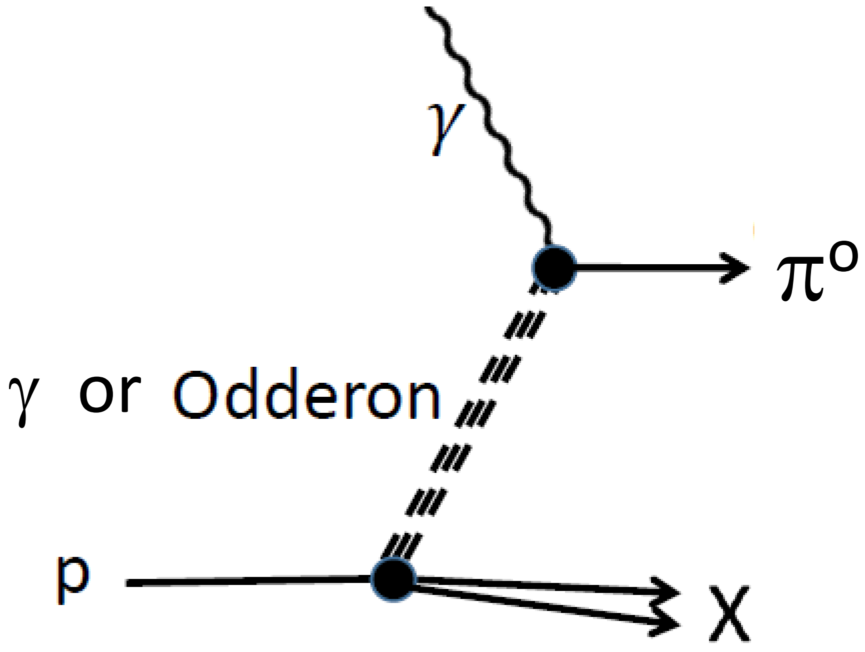


Background due to $\gamma\gamma$ fusion

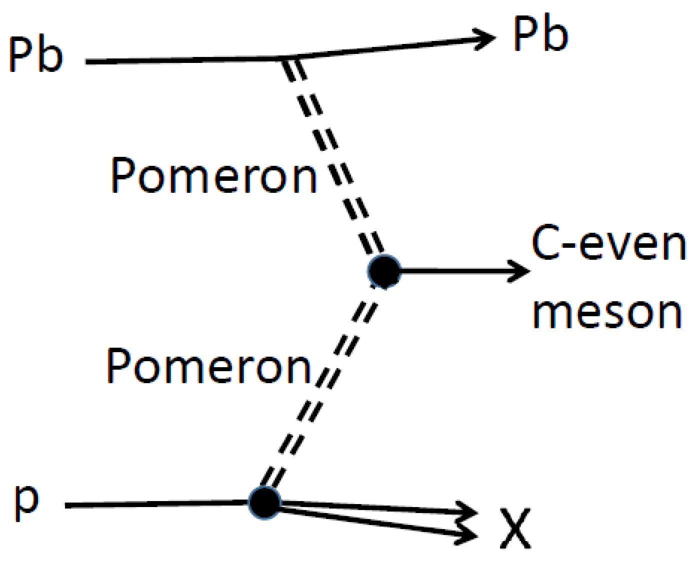
$\sigma(\pi^0)$ from $\gamma\gamma$ fusion is well known.
Estimating the cross section due to Odderon exchange, allowing for the colour factors etc. and integrating over $|t| > 1\ \mathrm{GeV}^2$ we find

$$\sigma_{\mathrm{Odd}}(\gamma p \rightarrow \pi^0 + X) \sim 5(1)\ \mathrm{nb}$$

for the cutoff $\mu = 0.3(0.5)$ GeV.
The t cut adequately suppresses the $\gamma\gamma$ fusion background.



Background due to Pomeron-Pomeron fusion



The only chance to suppress this background is to observe central (semi)exclusive production (CEP*) of C-even mesons in which the proton may break up but the Pb-ion remains intact.
In any nucleon-proton interaction creating the C-even meson there is a large probability of inelastic nucleon-proton interactions which will populate the rapidity gaps. Only in very peripheral ion-proton collisions is there a chance to observe a CEP* event.
Can show the A dependence of CEP* events scales as $A^{1/3}$. Recall the photoprod^{n} cross section (the signal) scales as Z^2, so the expected $A^{1/3}$ back^{gd} scaling is much milder.
Note active nucleon included in calculation of gap survival factor S^2---should therefore be excluded. Calculations show that this increases S^2 by 30-50%

signal and background for $d\sigma(\text{Pb p} \to \text{Pb} + M + X)/dY$ at Y=0

M is C-even meson

suppressed by gap survival for exclusive processes

M	Odderon signal	Pom-Pom bk^{gd}	$V \to M + \gamma$(undetected)
f_2	< 3 μb	3 – 4.5 μb	0.02 μb $(J/\psi \to f_2\gamma)$
π^0	< 7.5 μb	-	30 μb $(\omega \to \pi^0\gamma)$
η	< 3.4 μb	v.small	3 μb $(\phi, \rho \to \eta\gamma)$
η_c	0.1 - 0.5 nb	~ 0.1 nb	12 nb $(J/\psi \to \eta_c\gamma)$

summing over all relevant small BR

$p\,p \to p + M + X$ Pom – Pom background overwhelming

$\text{Pb Pb} \to \text{Pb} + M + \text{Pb}$ $\gamma\gamma$ background overwhelming

Ronan McNulty: Pb-Pb data could check model for Pom-Pom bk^{gd} for f_2; $BR(f_2 \to \gamma\gamma) \sim 10^{-5}$

Conclusion

The Odderon remains elusive

but with experimental ingenuity and precision
it stands a good chance of being cornered