Exclusive meson pair production and the gluonic component of the η, η' mesons

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Based on work by V.A. Khoze, M.G. Ryskin, W.J. Stirling and L.A. Harland-Lang. (KHRYSTHAL collaboration)

Now KHARYS collaboration!

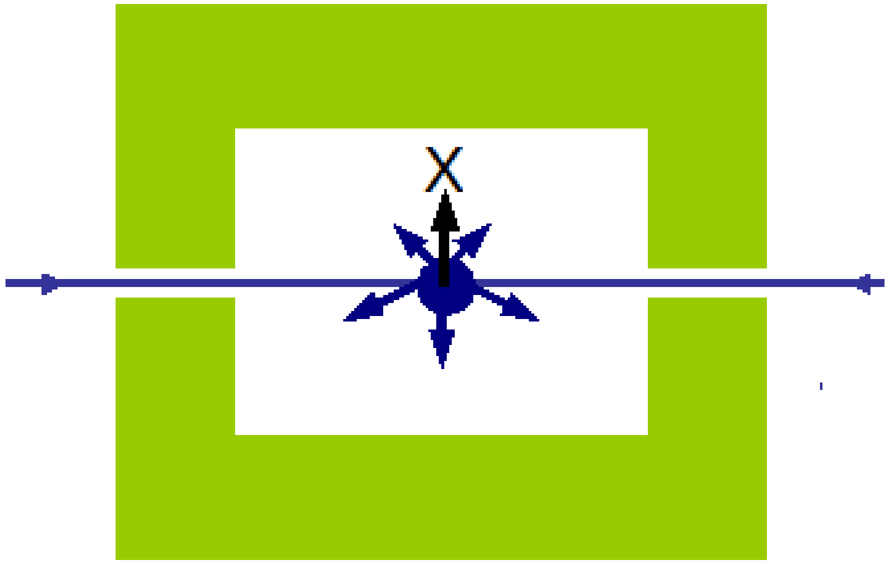
See arXiv:1304.4262, 1302.2004 and 1105.1626

Central Exclusive Diffraction

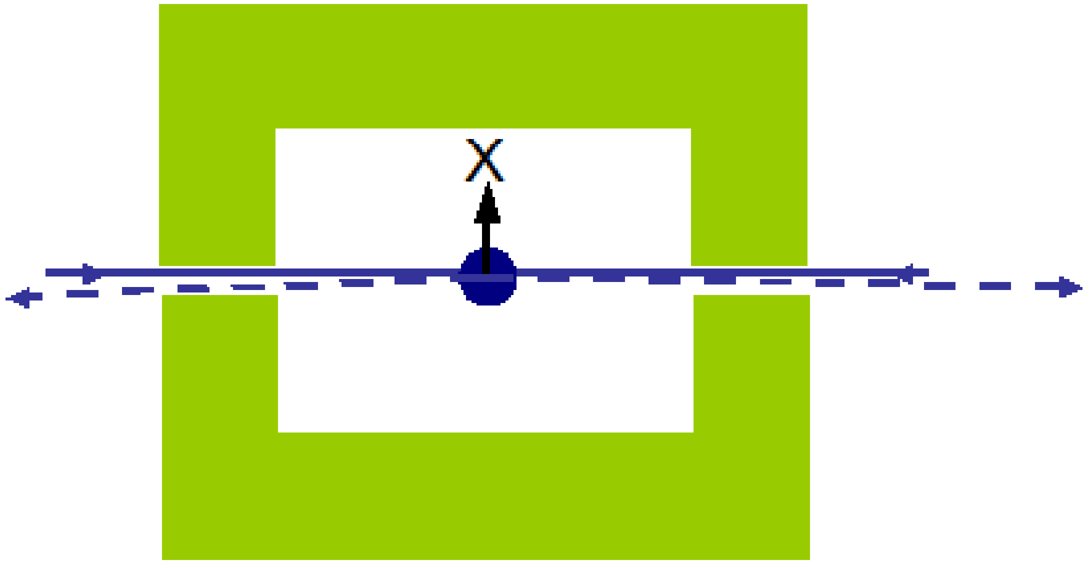
Central exclusive diffraction, or central exclusive production (CEP) is the process

$$h(p_1)h(p_2) \to h(p_1') \; + \; X \; + \; h(p_2')$$

- Diffraction: colour singlet exchange between colliding hadrons, with large rapidity gaps ('$+$') in the final state.
- Exclusive: hadrons lose energy, but remain intact after collision and can in principal be measured by detectors positioned down the beam line.
- Central: a system of mass M_X is produced at the collision point, and *only* its decay products are present in the central detector region.

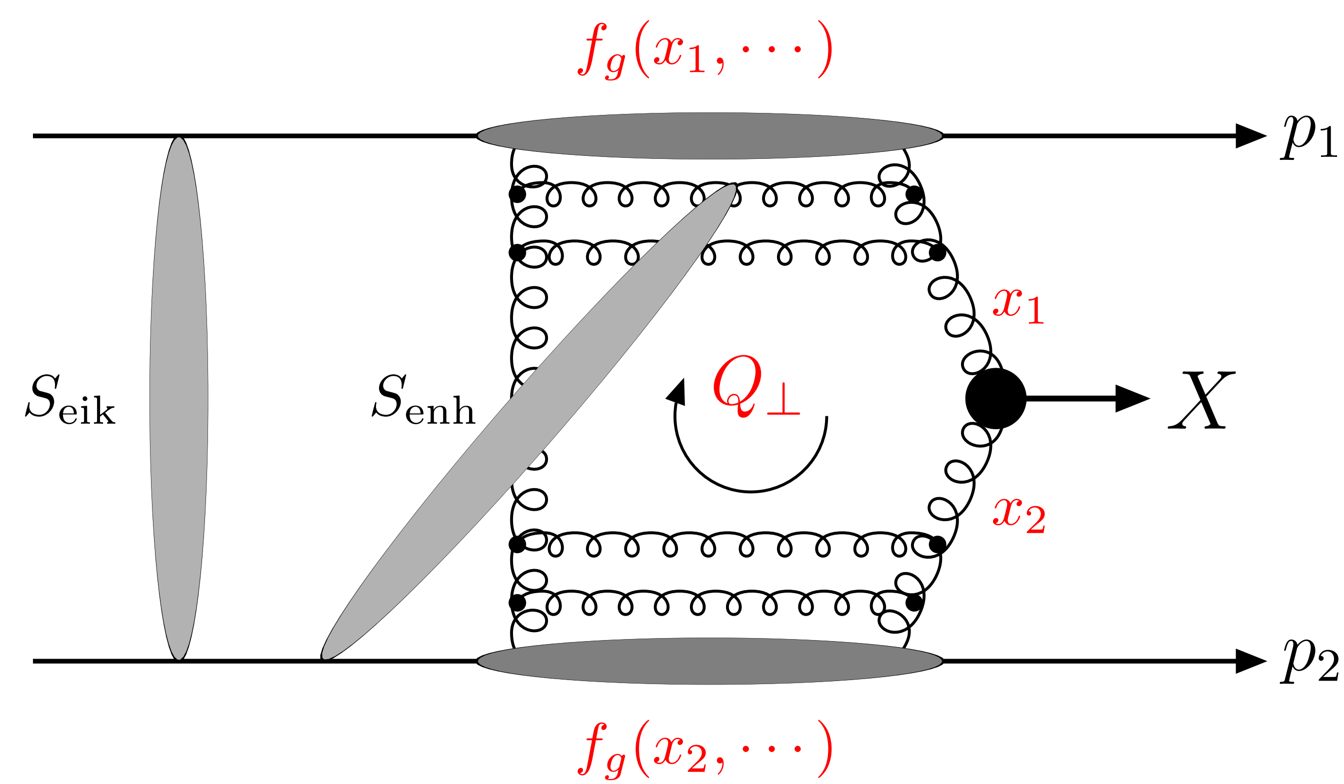


vs.



‘Durham Model’ of Central Exclusive Production

- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons.
- The use of pQCD is justified by the presence of a hard scale $\sim M_X/2$. This ensures an infrared stable result via the Sudakov factor: the probability of no additional perturbative emission from the hard process.
- The possibility of additional soft rescatterings filling the rapidity gaps is encoded in the ‘eikonal’ and ‘enhanced’ survival factors, $S^2_{\rm eik}$ and $S^2_{\rm enh}$.
- In the limit that the outgoing protons scatter at zero angle, the centrally produced state X must have $J_Z^P = 0^+$ quantum numbers.



$J_z = gg$ axis $\approx$ beam axis

- Protons can have some small $p_\perp$ (scatter at non-zero angle), but if this is too big, they break up $\longrightarrow$ strong suppression in non $J_z^P = 0^+$ configuration.

CEP of meson pairs

CEP via this mechanism can in general produce *any* C–even object which couples to gluons: Higgs, BSM objects...but also dijets, quarkonium states, light meson pairs...

i.e consider production of a pair of light mesons

$$h(p_1)h(p_2) \to h(p_1') \; + \; M_1 M_2 \; + \; h(p_2')$$

Where $$M = \pi, K, \rho, \eta, \eta' \ldots$$

For reasonable values of the pair invariant mass/transverse momentum, we can try to model this process using the pQCD-based Durham model.

Lower $k_\perp$ region: use Regge-based model

Lebiedowicz, Pasechnik, Szczurek, PLB 701:434-444, 2011

HKRS: arXiv:1204.4803

$\longrightarrow$ Represents a novel application of QCD, with many interesting theoretical and phenomenological features...

HKRS: arXiv:1304.4262, 1302.2004, 1204.4803, 1105.1626

The perturbative regime

- For reasonable meson $k_\perp$ model $gg \to M_1 M_2$ process using 'hard exclusive' formalism. Amplitude is written as

Brodsky, Lepage: Phys.Rev. D24 (1981) 1808....

$$\mathcal{M}_{\lambda_1\lambda_2}(s,t) = \int_0^1 \mathrm{d}x\,\mathrm{d}y\,\phi(x)\phi(y)T_{\lambda_1\lambda_2}(x,y;s,t)$$

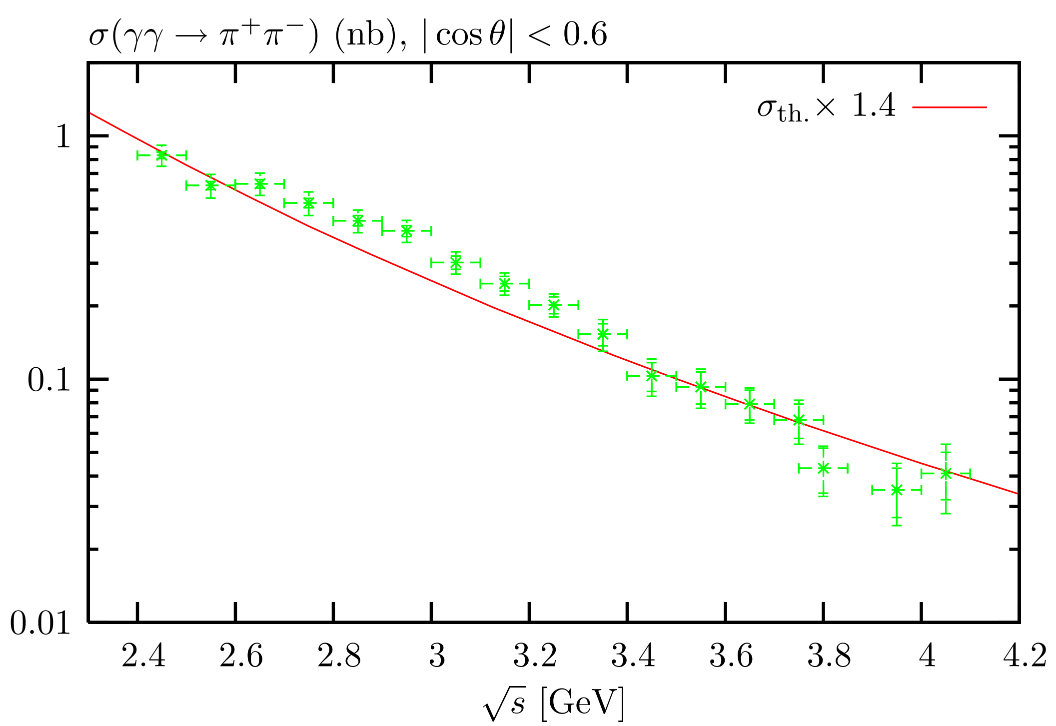
where $T_{\lambda_1\lambda_2}$ is (pert.) parton level amplitude and $\phi(x)$ is (non pert.) wavefunction for collinear partons to form parent meson.

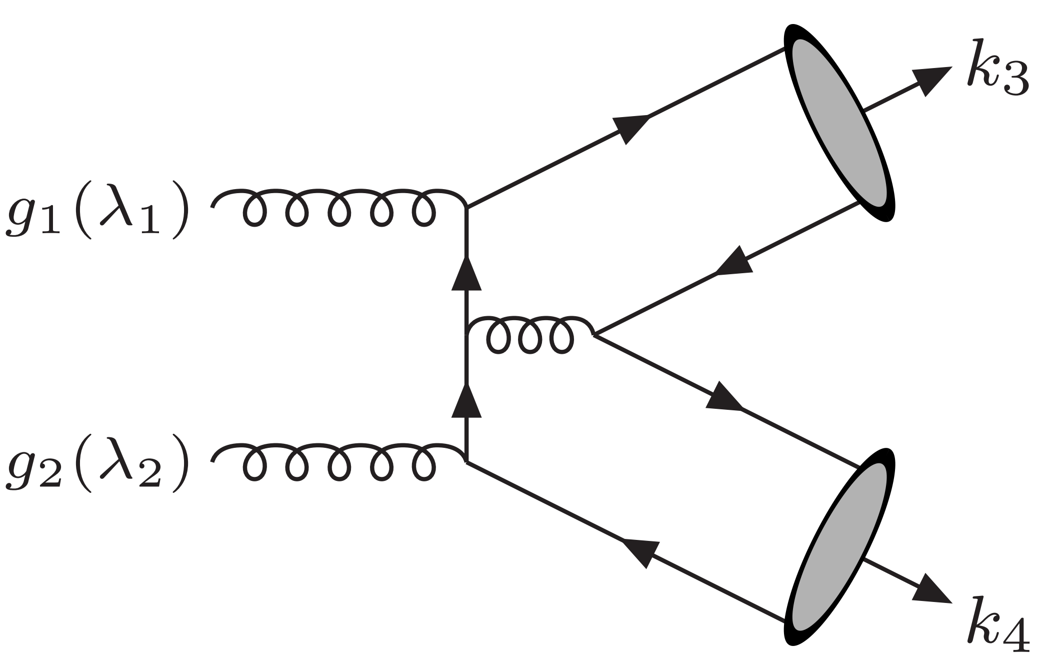
- Shape of $\phi(x,\mu_0)$ fit to data. Take 'CZ' form

V. L. Chernyak, A. R. Zhitnitsky, Nucl. Phys. B201 (1982) 492.

$$\phi_M^{\rm CZ}(x,Q^2=\mu_0^2) = 5\sqrt{3}f_M\,x(1-x)(2x-1)^2$$

but other choices possible (numerical results roughly unchanged).





Flavour non-singlet mesons

HKRS: arXiv:1105.1626

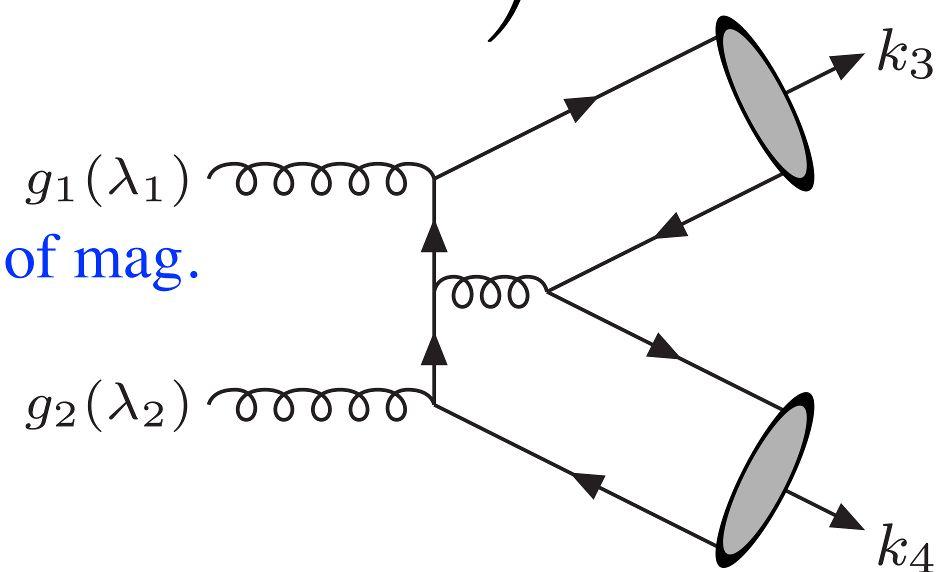
- The allowed parton-level diagrams depend on the meson quantum numbers. Leads to interesting predictions.....

Flavour non-singlets $(\pi^+\pi^-, \pi^0\pi^0, K^+K^-, \rho^0\rho^0 ...)$: (31 diagrams)

$$T_{++} = T_{--} = 0$$

$$T_{-+} = T_{+-} \propto \frac{\alpha_S^2}{a^2 - b^2\cos^2\theta}\left(\frac{N_c}{2}\cos^2\theta - C_F a\right)$$

where $a, b = (1-x)(1-y) \pm xy$



$\rightarrow J_z = 0$ amplitudes vanish. Strong ~2 order of mag. suppression in CEP cross section expected.

Further suppression from radiation zero in $J_z = \pm 2$ amplitude.

T. Aaltonen et al., PRL 108, 081801 (2012), arXiv:1112.0858

Seen in CDF $\gamma\gamma$ data $(E_\perp(\gamma) > 2.5$ GeV, $|\eta| < 1)$

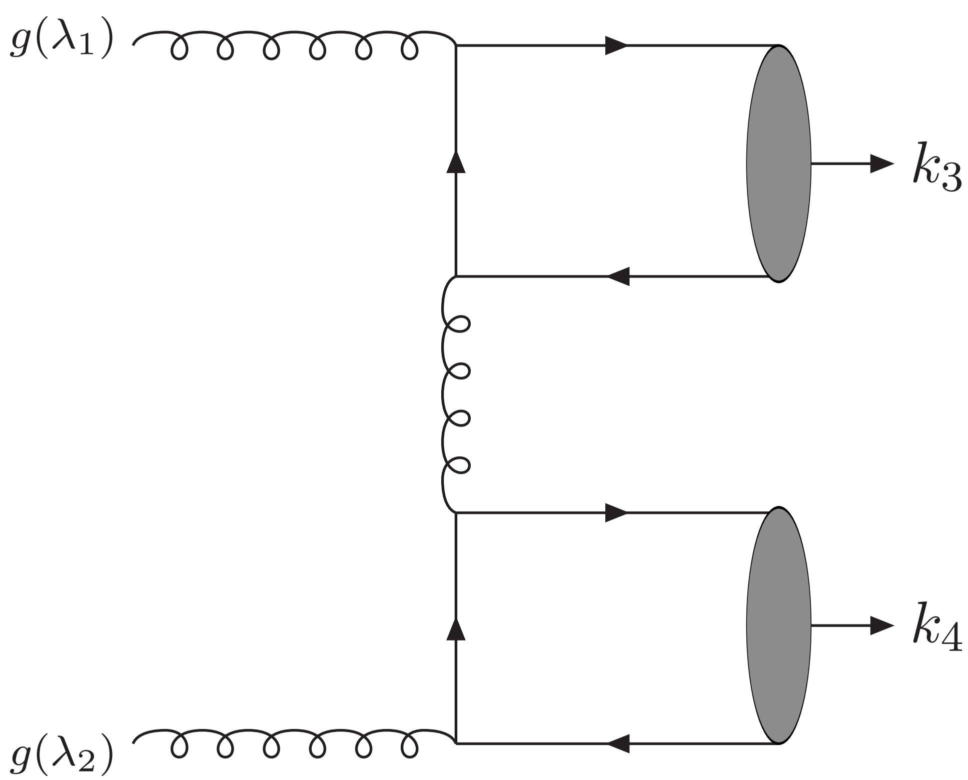
Experiment: $N(\pi^0\pi^0)/N(\gamma\gamma) < 0.35$ @ 95% confidence

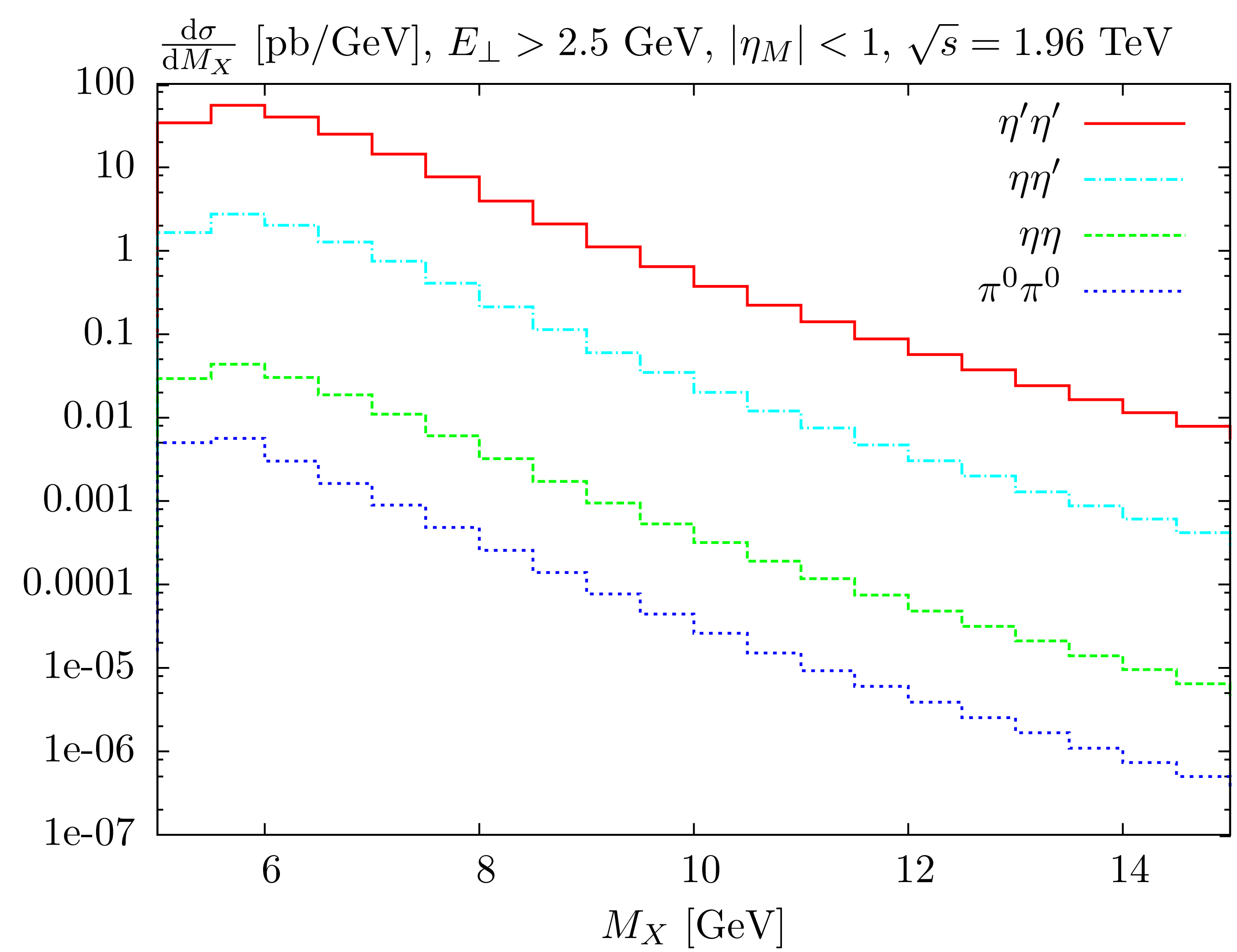
Theory: $\sigma(\pi^0\pi^0)/\sigma(\gamma\gamma) \approx 1\%$

Flavour singlet mesons

HKRS: arXiv:1105.1626

- For flavour singlet mesons a second set of diagrams can contribute, where $q\overline{q}$ pair is connected by a quark line.
- For flavour non-singlets vanishes from isospin conservation ($\pi^{\pm}$ is clear, for π^0 the $u\overline{u}$ and $d\overline{d}$ Fock components interfere destructively).
- In this case the $J_z = 0$ amplitude does not vanish (see later) $\Rightarrow$ expect strong enhancement in $\eta'\eta'$ CEP and (through $\eta - \eta'$ mixing) some enhancement to $\eta\eta'$, $\eta\eta$ CEP. The $\eta'\eta'$ rate is predicted to be large!





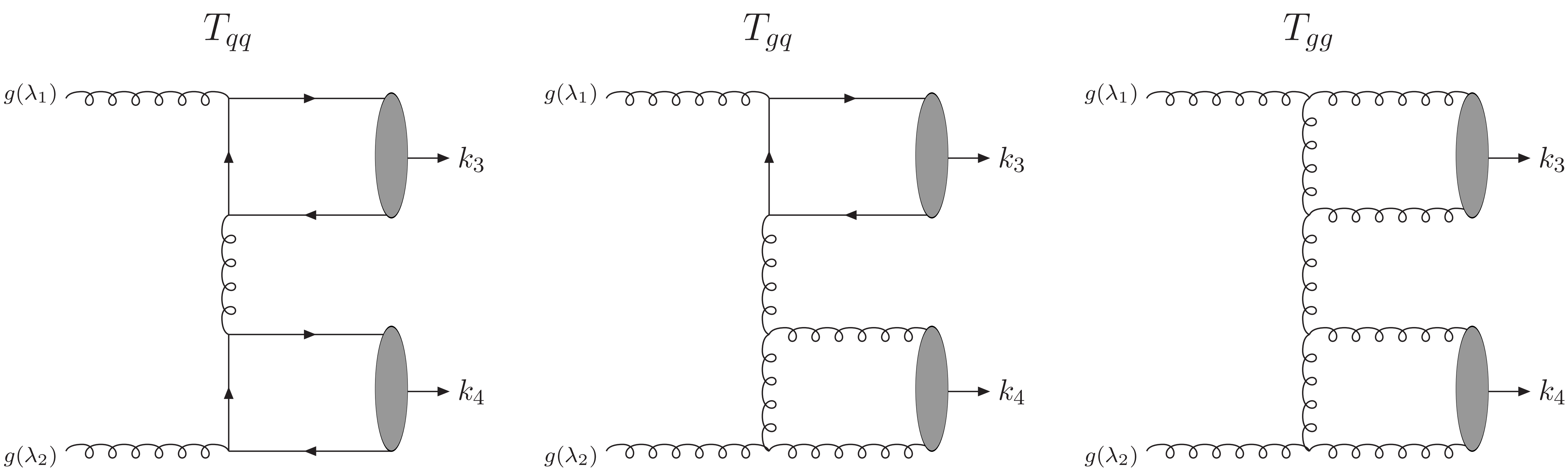
The gluonic component of the $\eta'(\eta)$

HKRS: arXiv:1302.2004

- The flavour singlet η' (and, through mixing η) should contain a gg component. But no firm consensus about its size.

$\longrightarrow$ The $gg \to \eta(')\eta(')$ process will receive a contribution from the $gg \to ggq\bar{q}$ and $gg \to gggg$ parton level diagrams.

$\longrightarrow$ Use $\eta(')\eta(')$ CEP as a probe of the size of this gg component.



• As in the case of flavour non-singlet mesons, the $J_z = 0$ amplitudes have very simple forms. After lengthy calculation, finally get

(8 diagrams)

$$T^{qq\cdot}_{++} = T^{qq\cdot}_{--} = -\frac{\delta^{ab}}{N_C}\frac{64\pi^2\alpha_S^2}{\hat{s}xy(1-x)(1-y)}\frac{(1+\cos^2\theta)}{(1-\cos^2\theta)^2}$$

$$T^{gq\cdot}_{++} = T^{gq\cdot}_{--} = 2\,T^{qq\cdot}_{++}\frac{N_c^2}{\sqrt{N_c(N_c^2-1)}}(2x-1)$$

(130 diagrams)

$$T^{gg\cdot}_{++} = T^{gg\cdot}_{--} = 4\,T^{qq\cdot}_{++}\frac{N_c^3}{N_c^2-1}(2x-1)(2y-1)$$

Not just diagrams of 'ladder type'

Simple, and identical in form, up to overall colour and normalization factors. Feynman diagrams complete distinct and apparently unrelated.

$\longrightarrow$ Unexpected result, but MHV can shed light (see later)

For more details see HKRS: arXiv:1304.4262, PLB 724 (2013) 115-120

Extraction of the gg component

- Two principle ways to extract this:

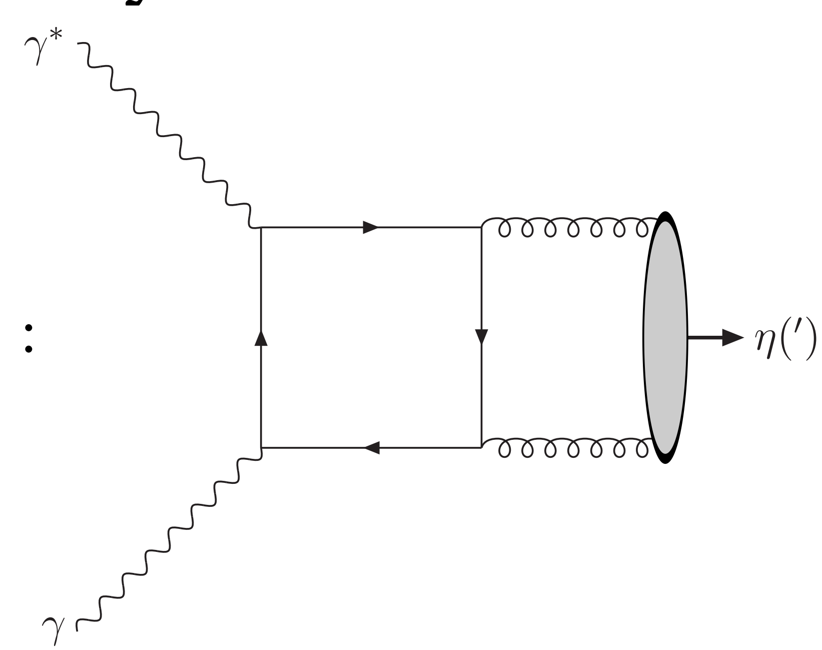
C. E. Thomas, JHEP 0710 (2007) 026. arXiv:1207.1500...

  - Decays: fit to meson branching ratios ($\eta' \to \gamma\gamma$, $\phi \to \eta'\gamma$, $J/\psi \to \eta\gamma$...) hints at small non-zero gluonic component, but results are conflicting. Fits suffer from important theory (and experimental) uncertainties and model dependences (form factors for meson decays...)

P.Kroll, K.Passek-Kumericki, arXiv:1206.4870

  - Form factors: fit to $F_{\eta(\eta'),\gamma}(Q^2)$ for $\gamma^*\gamma \to \eta(\eta')$ process, as measured at e^+e^- colliders. Suggests potentially sizeable gluonic component, however gg only enters at NLO (QED initial state). Requires precision fit in region of Q^2 where theory uncertainties (power corrections...?) may be of similar size.

$F_{\eta(\eta'),\gamma}(Q^2)$:



gg distribution amplitude

Distribution amplitude written as sum over Geigenbaur polynomials:

$$\phi_G(x, \mu_F^2) \propto x(1-x) \sum_{n=2,4,\cdots} a_n^G(\mu_F^2) C_{n-1}^{5/2}(2x-1)$$

dominant contribution given by $n = 2$ term.

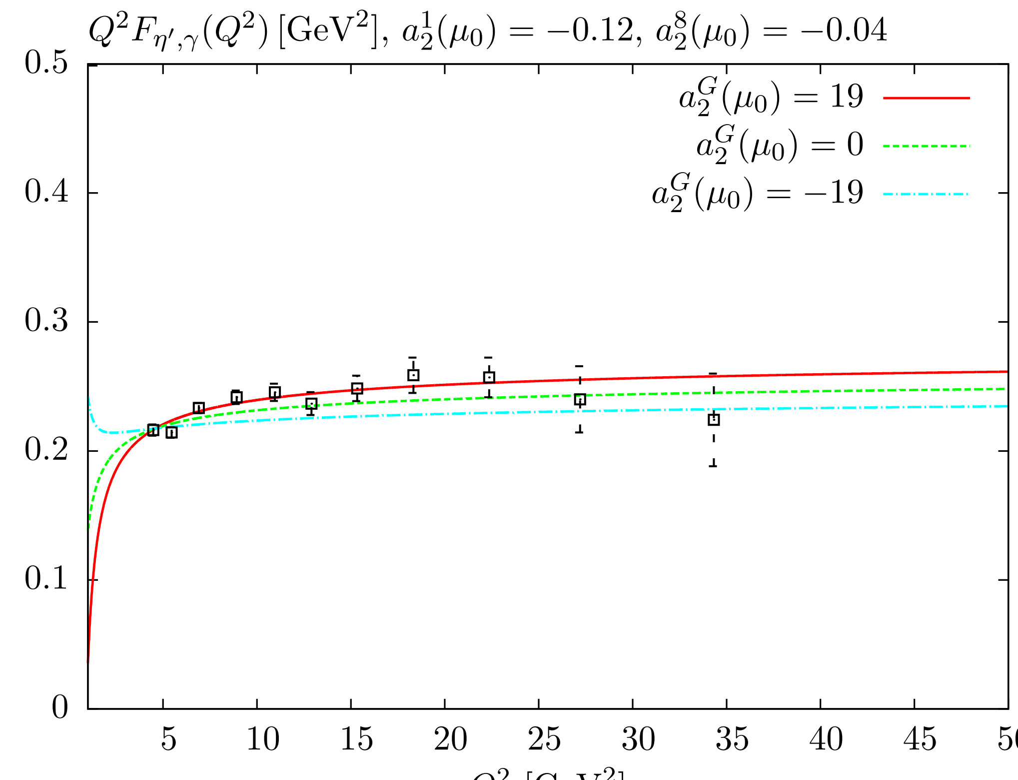
Fit of arXiv:1206.4870 :

$$a_2^G(\mu_0 = 1\mathrm{GeV}) = 19 \pm 5$$

Guided by this, we take conservative band:

$$-9.5 < a_2^G(\mu_0 = 1\mathrm{GeV}) < 9.5$$

Sign not known $\qquad$ $a_2^G \approx 0$ not excluded!



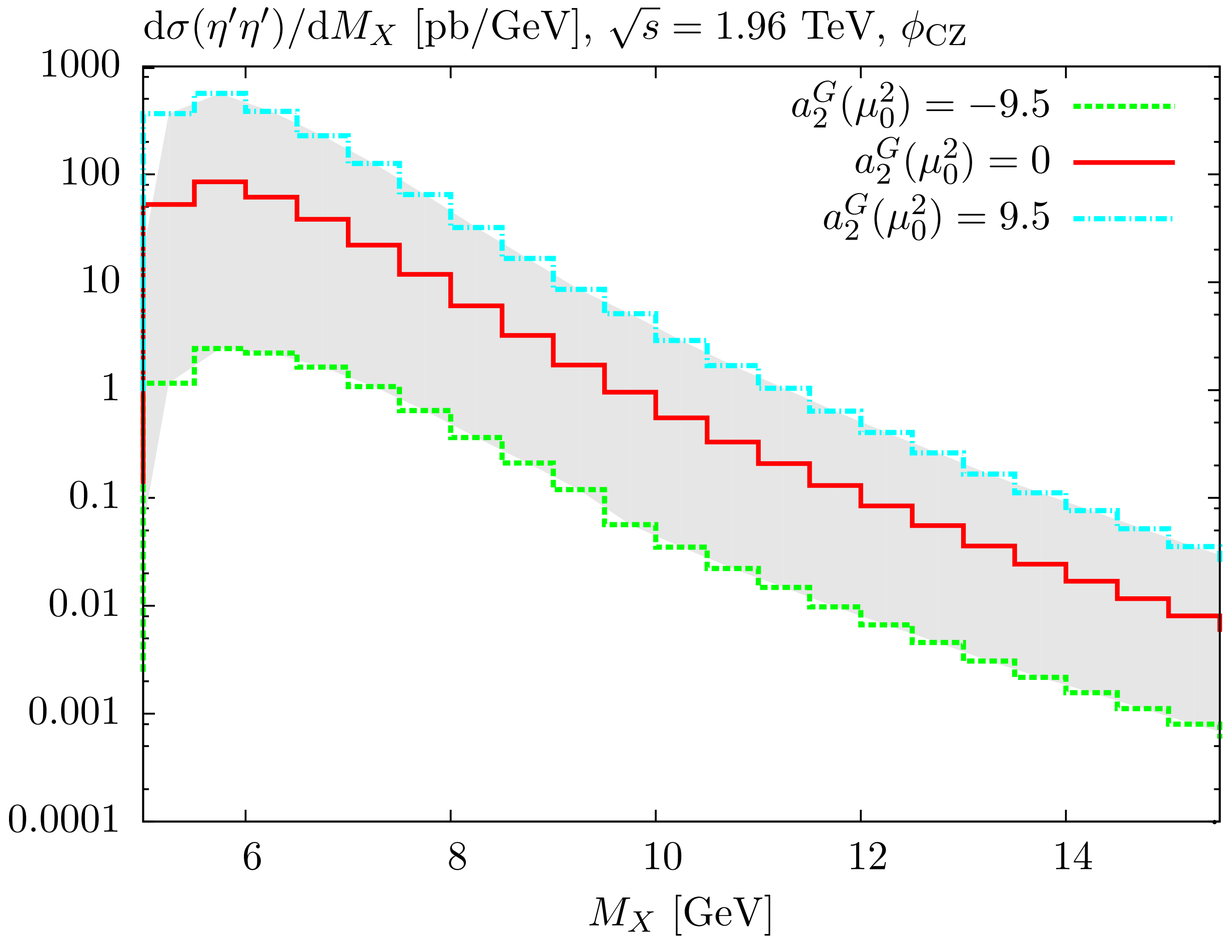
NLO contribution to $\gamma^*\gamma \to \eta(')$

P.Kroll, K.Passek-Kumericki, arXiv:1206.4870

Remarks	χ^2	a_2^8	a_2^1	a_2^g	(41)
default	37.7	-0.05 ± 0.02	-0.12 ± 0.01	19 ± 5	0.03

Taking this envelope of values, we find a ~ order of magnitude variation in the $\eta(')\eta(')$ cross section!
gg contribution enters at same (LO) order as $q\overline{q}$, and is not dynamically ($J_z = 0$) or colour suppressed.

$\longrightarrow$ CEP provides a potentially sensitive probe of the gg component of the η, η' mesons. Cross section ratios can pin this down further/ reduce uncertainties.



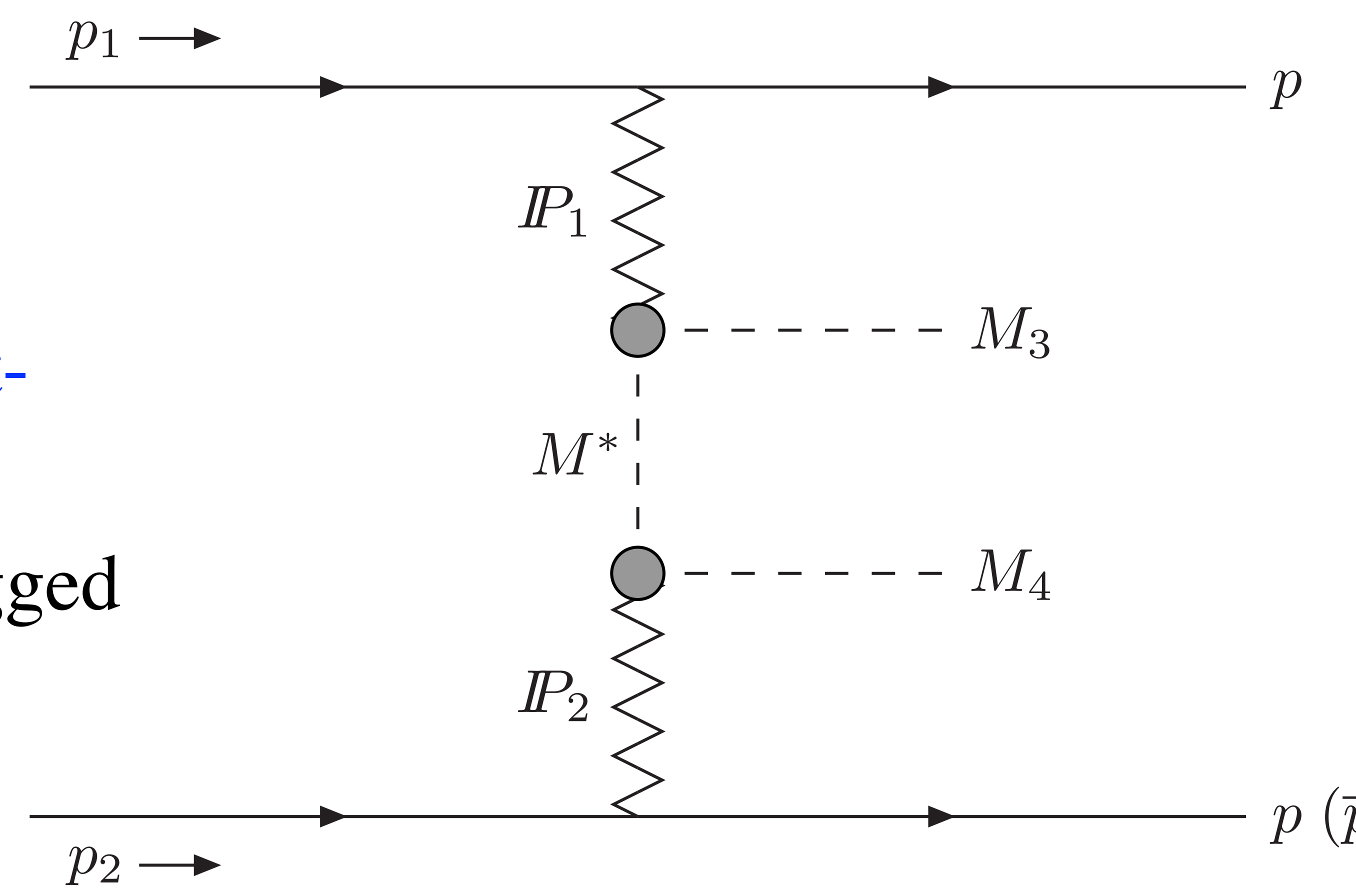
$a_2^G(\mu_0^2)$	-9.5	0	9.5
$\sigma(\eta\eta)/\sigma(\pi^0\pi^0)$	2.7	12	66
$\sigma(\eta'\eta')/\sigma(\pi^0\pi^0)$	570	16000	100000
$\sigma(\eta'\eta')/\sigma(\gamma\gamma)$	3.5	100	660
$\sigma(\eta'\eta' \to 4\gamma)/\sigma(\gamma\gamma)$	0.0017	0.049	0.33
$\sigma(\eta\eta \to 4\gamma)/\sigma(\gamma\gamma)$	0.0025	0.012	0.066

HKRS: arXiv:1302.2004

Meson pair CEP at low $k_\perp$....

• The scale of the meson pair production process is set by the meson $k_\perp$. At lower $k_\perp$ ($\lesssim 2\ \mathrm{GeV}$) a perturbative treatment can't be used.

$\longrightarrow$ Use tools of Regge theory to model process - Double $I\!P$ exchange.



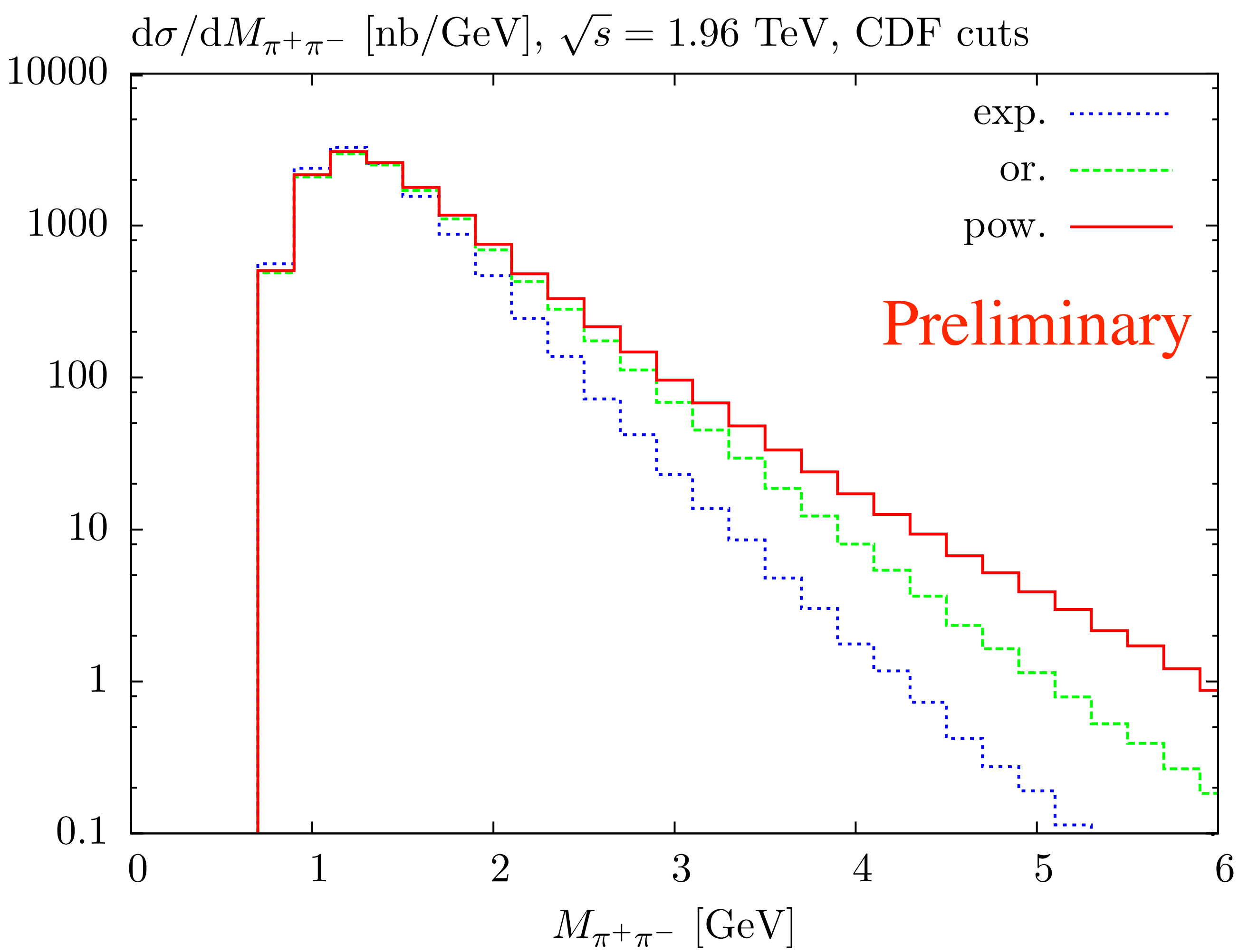
‣ Many ingredients to such a model ($I\!P \to MM^*$ form factor, rescattering corrections, additional exchanges in the t-channel...).

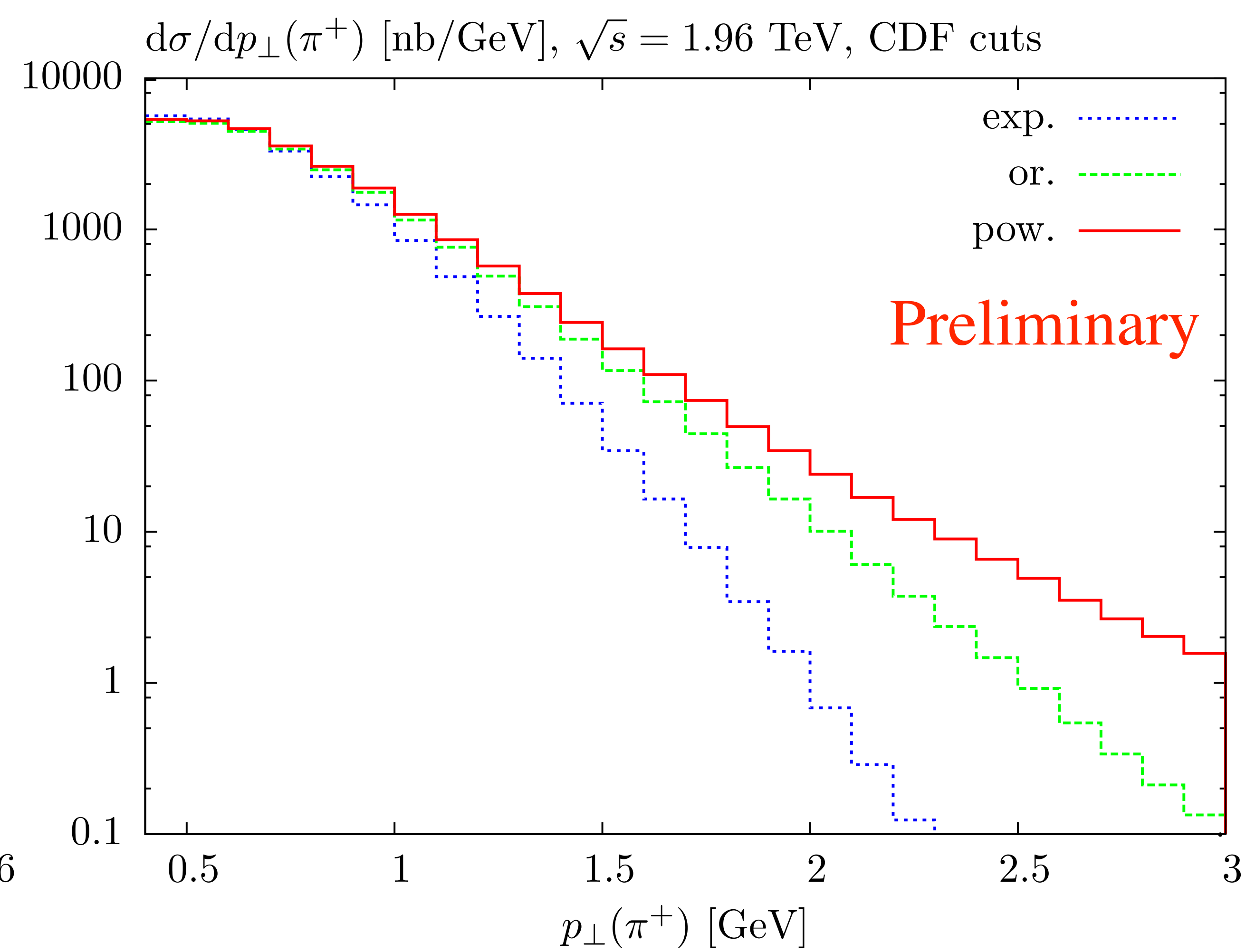
‣ Large ($\sim \mu$bs) cross sections. With tagged protons can probe survival effects....

Available on request, on Hepforge soon - paper in prep.

$\longrightarrow$ New Dime MC for meson pair production ($\pi\pi$, KK, $\rho\rho$...) via DPE. Latest models of survival effects included exactly.

Dime MC : distributions





- Use Dime MC to give distributions for CDF kinematics.
- Take different forms for $I\!P\pi\pi^*$ form factor $F_\pi(\hat{t})$

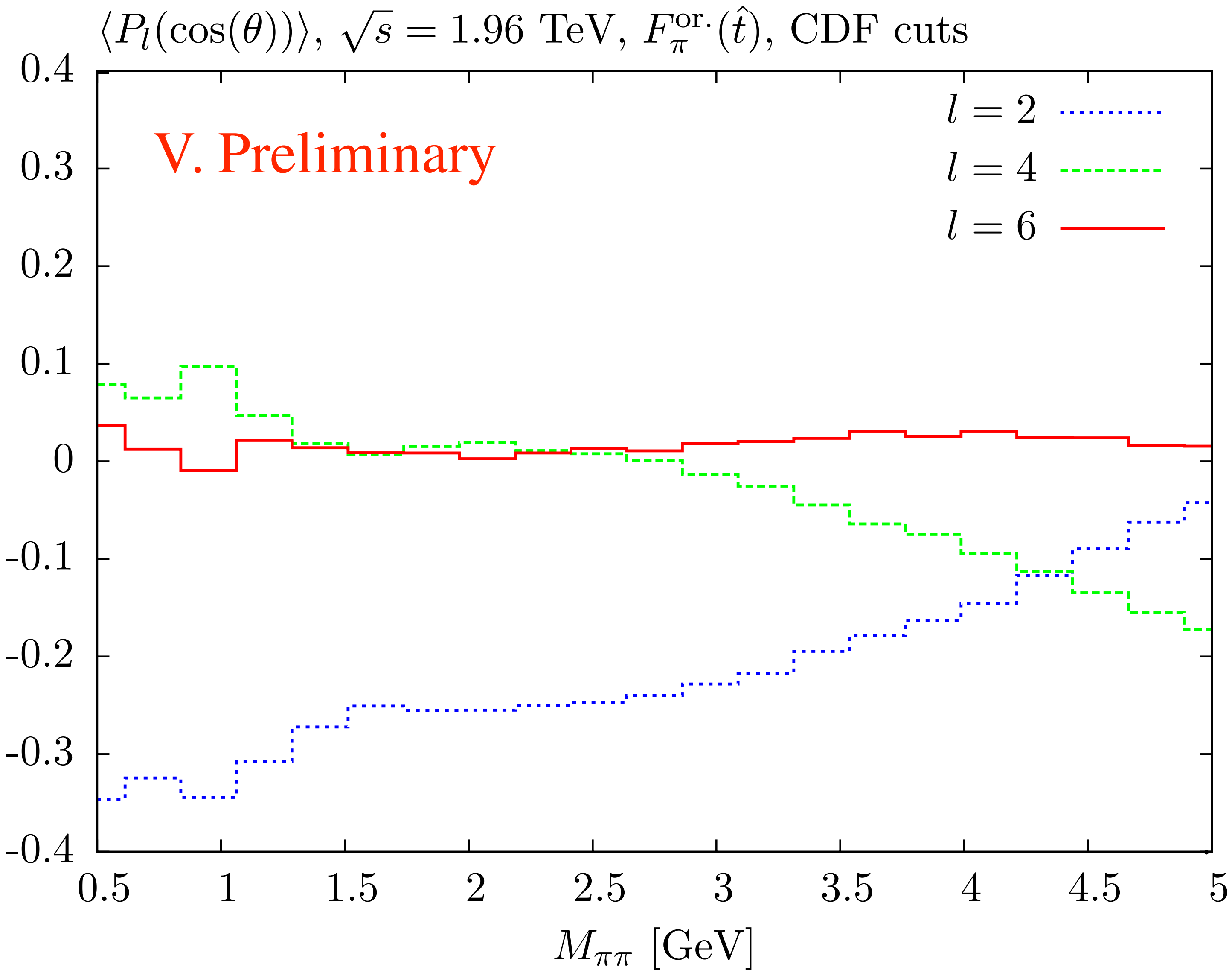
See Mike Albrow's talk

Exp. : $\sim \exp(b_{\rm exp}t)$ Orear : $\sim \exp(b_{\rm or}\sqrt{-t})$ Power : $\sim 1/(1-t/b_{\rm pow})$

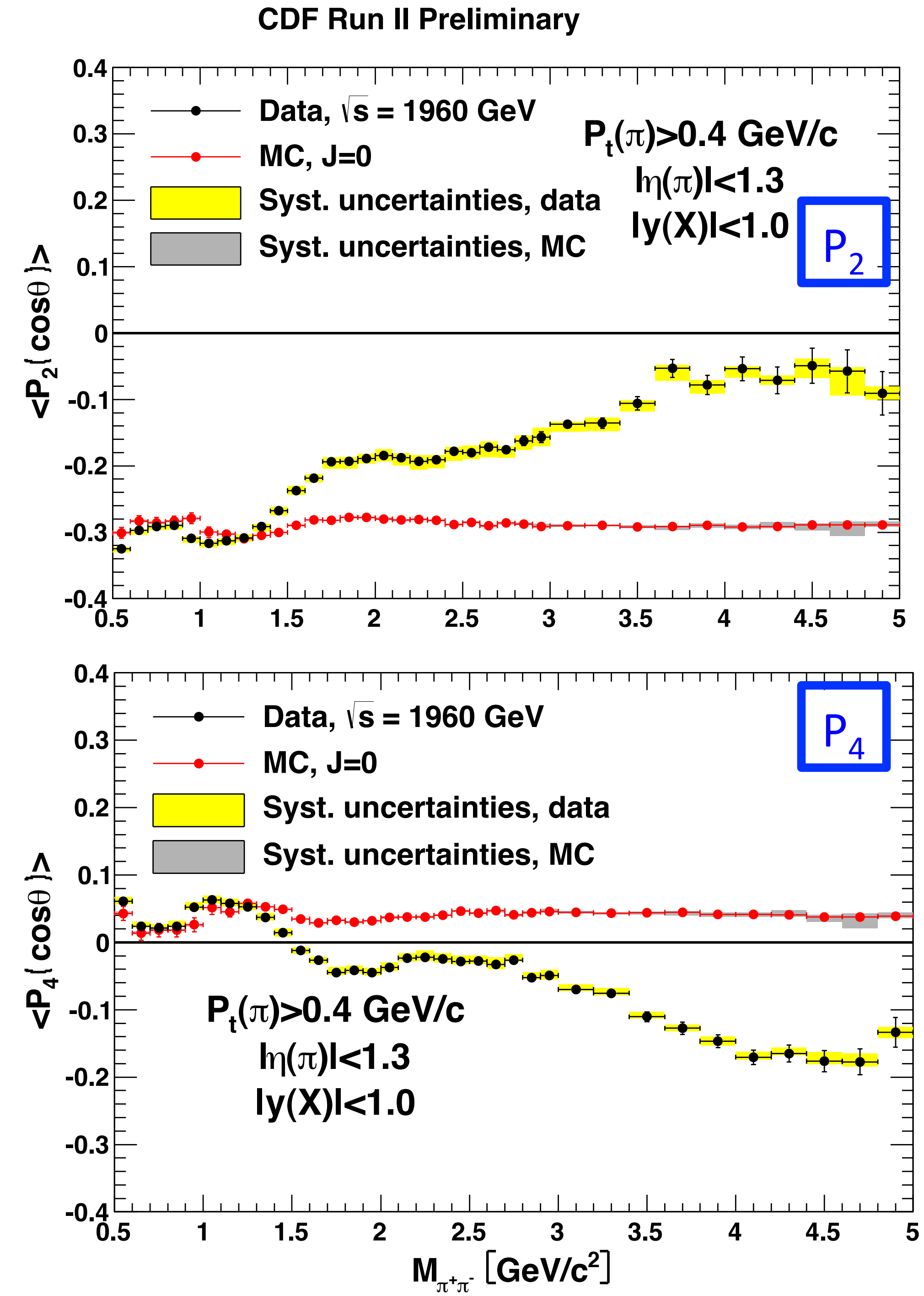
- Work underway: these plots are for CEP- how will proton dissociation affect them?

More distributions...

CDF data *may* prefer Orear form



Mike Albrow's talk



- Consider other variables, e.g. Legendre coefficients for $\pi^+\pi^-$ distribution w.r.t. $\cos\theta$

π^+ w.r.t. incoming proton in $\pi^+\pi^-$ R.F.

CEP with tagged protons

- Structure of $gg \to X$ vertex gives characteristic proton distributions:

$$\mathrm{d}\sigma(0^+)/\mathrm{d}\phi \approx \text{const.}\ ,$$
$$\mathrm{d}\sigma(1^+)/\mathrm{d}\phi \approx (p_{1_\perp} - p_{2_\perp})^2\ ,$$
$$\mathrm{d}\sigma(0^-)/\mathrm{d}\phi \approx p_{1_\perp}^2 p_{2_\perp}^2 \sin^2(\phi)\ .$$

ϕ : azimuthal angle between outgoing proton $p_\perp$ vectors

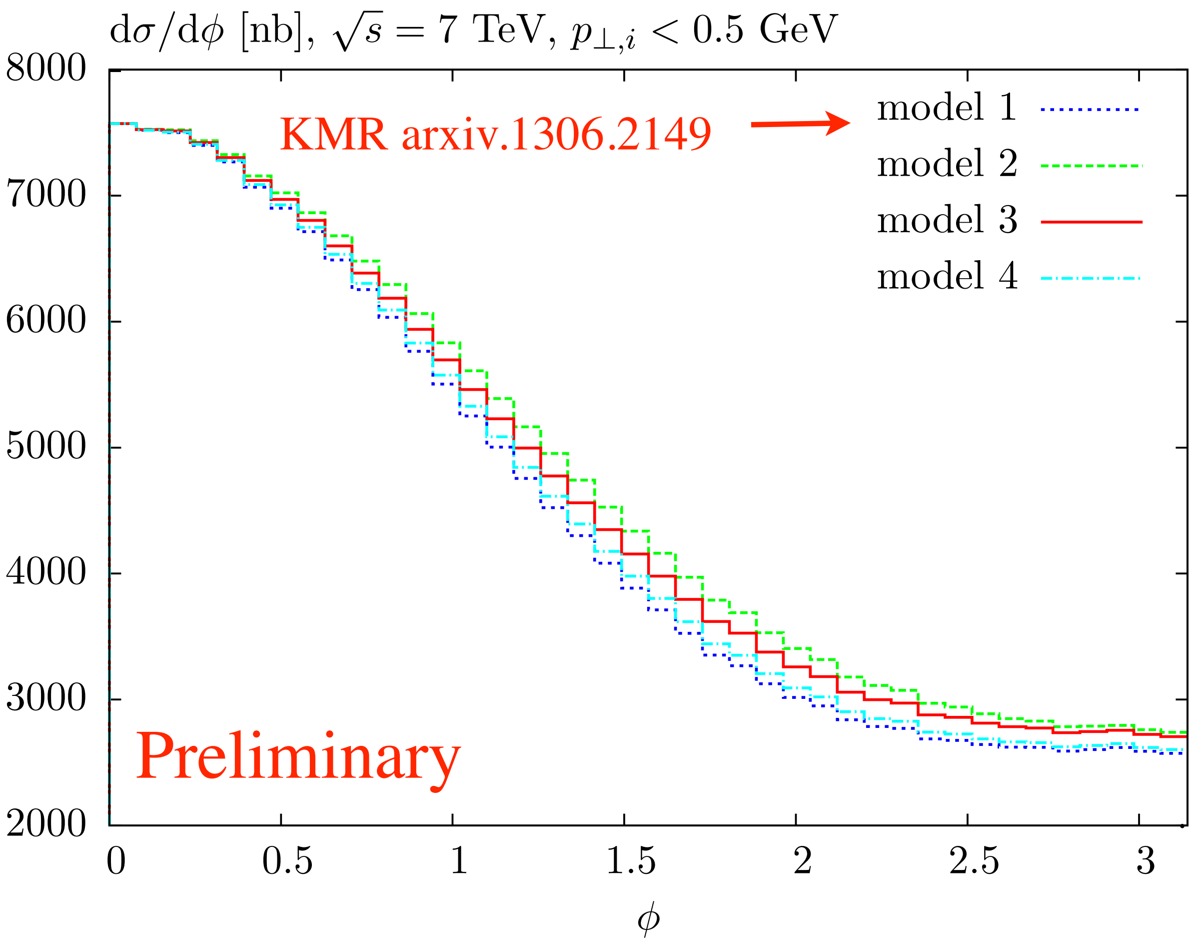
- These are strongly affected by the absorptive corrections: the amount of soft rescattering is strongly dependent on the impact parameter b_t.
- The full cross section is given by

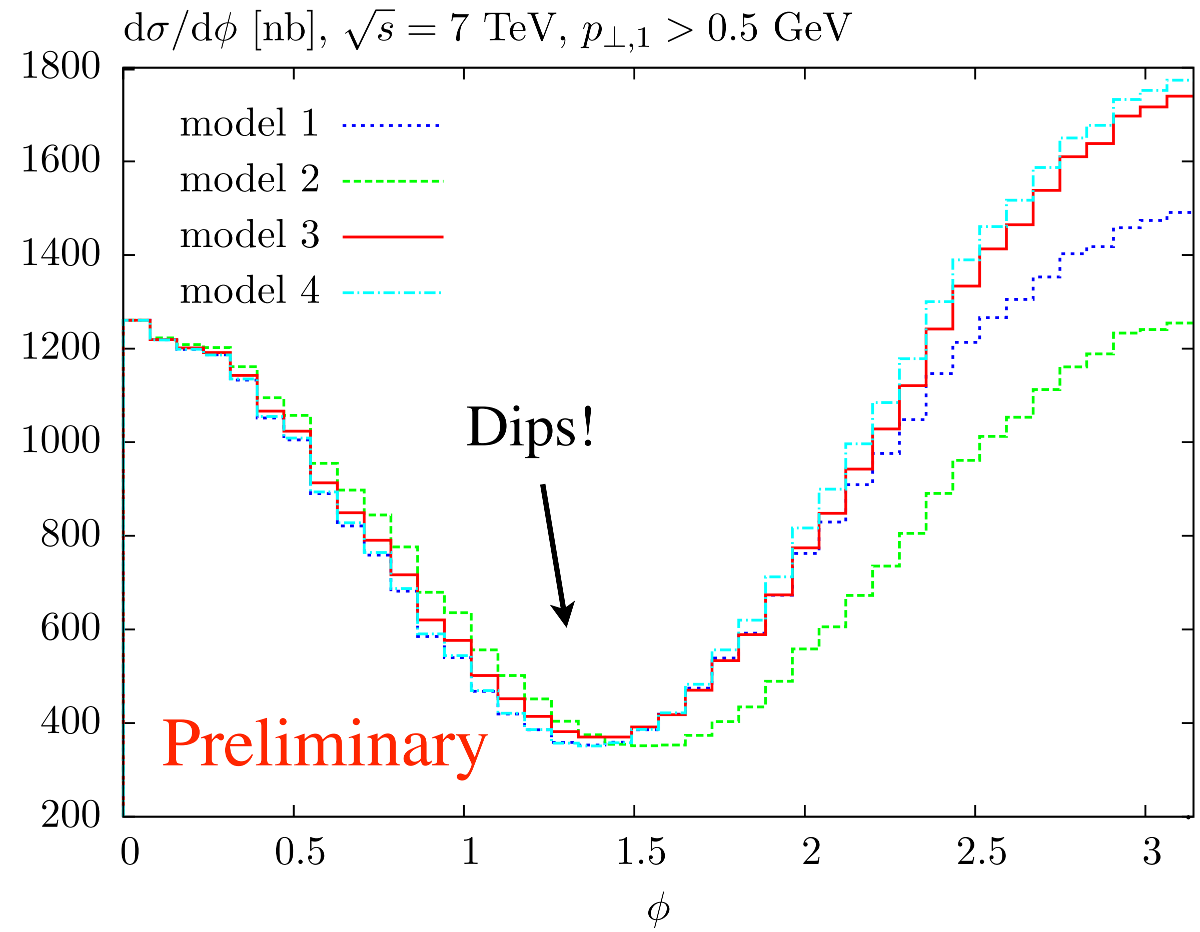
$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_X} \propto \int \mathrm{d}^2\mathbf{p}_{1_\perp}\mathrm{d}^2\mathbf{p}_{2_\perp} |T(\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp}))|^2 S^2_{\mathrm{eik}}(\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp})$$

where T is the perturbative CEP amplitude, excluding survival effects.
S^2_{eik} is the 'survival factor' ~ probability of no additional rescaterring

• Consider, e.g. $\pi^+\pi^-$ production, with tagged protons. TOTEM, ALFA

R. Staszewski et al., arXiv:1104.3568





Proton ϕ distributions for low mass $\pi^+\pi^-$ CEP, using Dime MC

• Distributions in angle ϕ between outgoing protons strongly affected by soft survival effects, in model dependent way.

• This is in particular true when larger values of $p_\perp$ are selected. Cancellation between screened and unscreened amplitudes results in characteristic 'diffractive dip' structure. V. A. Khoze, A.D. Martin and M.G. Ryskin, hep-ph/0203122

LHL, V.A. Khoze, M.G. Ryskin and W.J. Stirling, arXiv:1011.0680

The SuperCHIC MC

A MC event generator including[8]:

- Simulation of different CEP processes, including all spin correlations:
  - $\chi_{c(0,1,2)}$ CEP via the $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ decay chain.
  - $\chi_{b(0,1,2)}$ CEP via the equivalent $\chi_b \to \Upsilon\gamma \to \mu^+\mu^-\gamma$ decay chain.
  - $\chi_{(b,c)J}$ and $\eta_{(b,c)}$ CEP via general two body decay channels
  - Physical proton kinematics + survival effects for quarkonium CEP at RHIC.
  - Exclusive J/ψ and Υ photoproduction. $+\ \psi(2S)$
  - $\gamma\gamma$ CEP.
  - Meson pair ($\pi\pi$, KK, $\eta\eta$...) CEP.
- More to come (dijets, open heavy quark, Higgs...?).

Plans to develop further: Herwig++, updated survival factors....

$\longrightarrow$ Via close collaboration with experimental collaborations, in both proposals for new measurements and applications of SuperCHIC, it is becoming an important tool for current and future CEP studies.

Suggestions for additional modes etc to include/study are welcome!

Summary and Outlook

• CEP in hadron collisions offers a promising and complementary way to study Standard Model and new physics signals.

• Exclusive processes observed at the Tevatron, RHIC and low pile-up/luminosity LHC can serve as 'standard candles' for the exclusive Higgs, and other new physics, but are of interest in their own right.

• Concentrated in this talk on the case of meson pair at sufficiently high invariant mass ($k_\perp$) that a perturbative approach can be used. Represents a novel and interesting application of pQCD framework:

- Highly non-trivial hierarchy in cross sections ($\pi\pi$ vs. $\eta'\eta'$)
- Interesting theoretical features of helicity amplitudes (MHV)
- Sensitive probe of the gg component of the η', η
- Background to $\gamma\gamma, \chi_c \to \pi^+\pi^-$... CEP

• $\pi\pi$, KK... CEP at lower invariant mass ($k_\perp$) : test of Regge-based models and soft survival effects.

• Many other channels not discussed today are possible, and hopefully many more CEP results to come in the future!

Back up

MHV approach

= Maximally Helicity Violating $\quad gg \to q\bar{q}q\bar{q}, ggq\bar{q}, gggg \ldots$

- For meson pair production interested in 6 parton helicity amplitudes.
- Scalar mesons: outgoing partons have $+-$ helicity. Representative helicity configuration for $J_z = 0$ gluons:

$$\underset{1}{g(+)}\,\underset{2}{g(+)} \to \underset{3}{q(+)}\,\underset{1}{\bar{q}(-)}\,\underset{4}{q(+)}\,\underset{2}{\bar{q}(-)}$$

These LO amplitudes are MHV: maximum ($n-2=4$) number of partons have same helicity. Known to have very simple form: n-parton MHV amplitude can be written down analytically, often in one line.

$\Rightarrow$ Not suprising that previous $J_z = 0$ amplitudes are so simple

Meson pair production amplitudes represent a novel application of MHV formalism. Take general MHV expressions for n-parton amplitudes, and consider specific (6-parton) kinematics... Colour singlet Collinear

$$\underbrace{\mathcal{M}_n(\{p_i, h_i, c_i\})}_{\text{Total}} = \sum_\sigma \underbrace{T_n(\{c_{\sigma(i)}\})}_{\text{colour}} \underbrace{A_n(\{k_{\sigma(i)}, h_{\sigma(i)}\})}_{\text{kinematic}}$$

one for each non-cyclic ordering

Flavour non-singlets ($\pi\pi, KK...$): $J_z = 0$ amplitude shown to vanish after 1 page of trivial algebra. 31 Feynman diagrams! HKRS: arXiv:1105.1626

Flavour singlets ($\eta(')\eta(')$): relevant MHV kinematic amplitudes are

$$A(g_1^+, g_2^+, ..., g_i^-, ..., g_j^-, ..., g_n^+) = \frac{\langle i\, j\rangle^4}{\prod_{k=1}^n \langle k\, k+1\rangle}$$

$$\langle k_i\, k_j\rangle = \overline{u}_-(k_i)u_+(k_j) = \overline{v}_+(k_i)v_-(k_j)$$

$$A(g_1^+, g_2^+, ..., g_i^-, ..., \overline{q}_j^-, q_{j+1}^+, ..., g_n^+) = \frac{\langle i\, j\rangle^3 \langle i\, j+1\rangle}{\prod_{k=1}^n \langle k\, k+1\rangle}$$

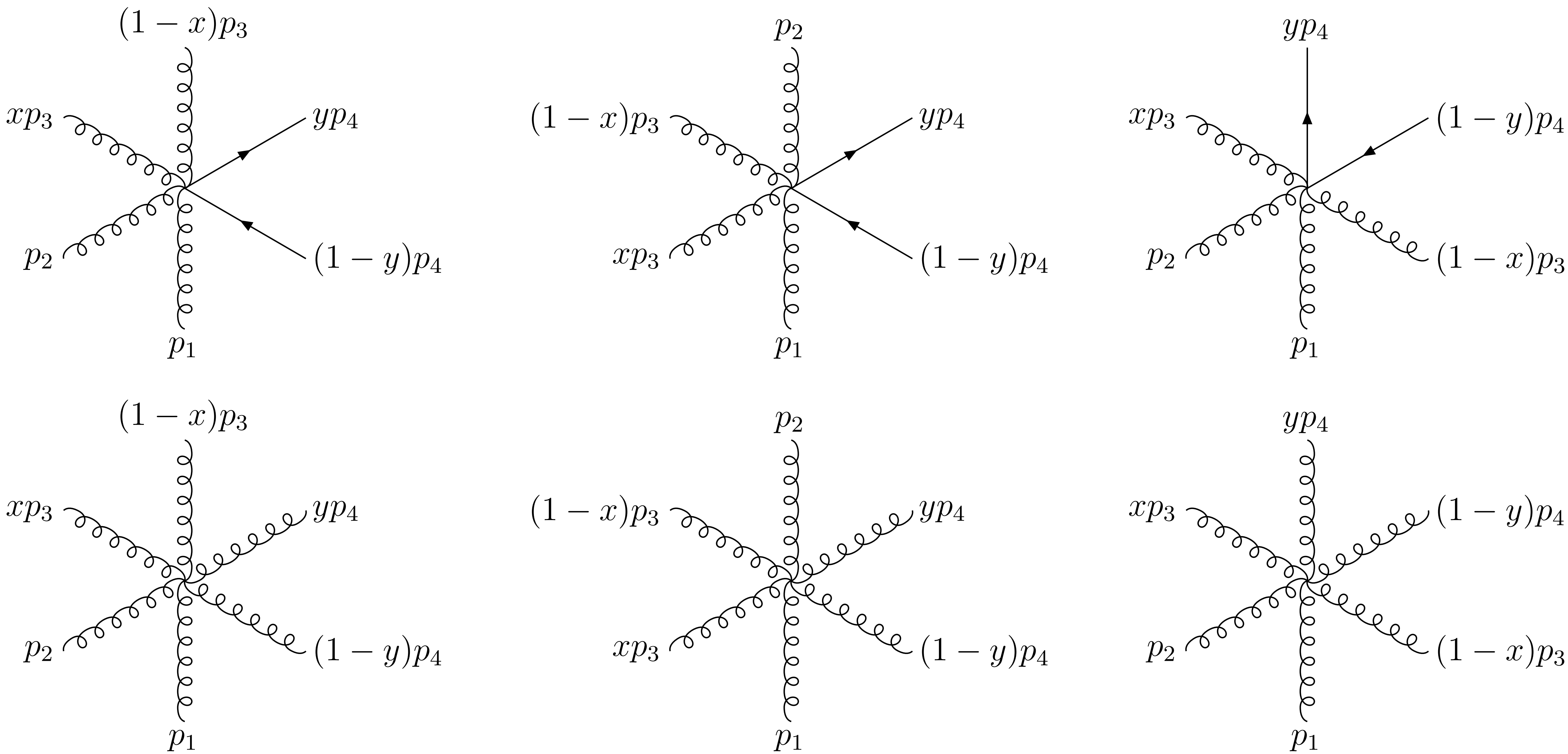
Denominators same in both cases $\rightarrow$ determined by particle ordering

Numerator given by relevant spin projection, e.g.

$$(g^-(l_3)g^+(l_4) - g^+(l_3)g^-(l_4))(g^-(l_5)g^+(l_6) - g^+(l_5)g^-(l_6))$$
$$\rightarrow \langle l_4 l_6\rangle^4 + \langle l_3 l_5\rangle^4 - \langle l_3 l_6\rangle^4 - \langle l_4 l_5\rangle^4 = s^2(2y-1)(2x-1)$$

and by inspection only leading-N_c terms contribute to amplitudes $T^{gg.}_{\pm\pm}$ and $T^{qg.}_{\pm\pm}$

$$T_n((n-2)g + q\overline{q}) = \mathrm{Tr}\,(\lambda^1 \cdots \lambda^{n-2})$$
$$T_n(ng) = \mathrm{Tr}\,(\lambda^1 \cdots \lambda^n)$$



Find that the same particle orderings contribute in three cases. Therefore the denominator factors are the same.

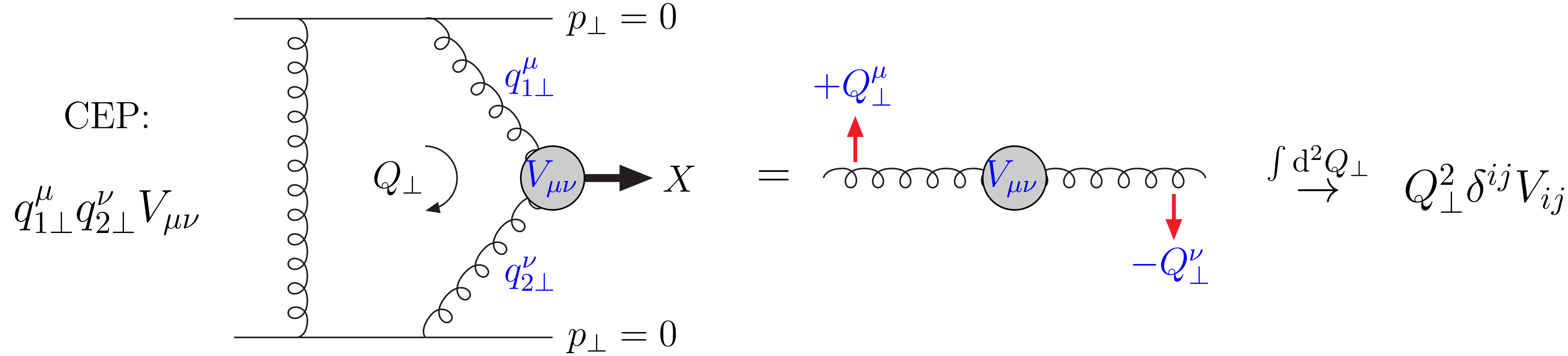
$\Longrightarrow$ So are the amplitudes, up to overall colour factors and factors from numerator (different spin projector between gg and $q\bar{q}$)

$gg \to q\bar{q}q\bar{q}$ case follows in a similar way

Some remaining subtleties: see arXiv:1302.2004 for more details

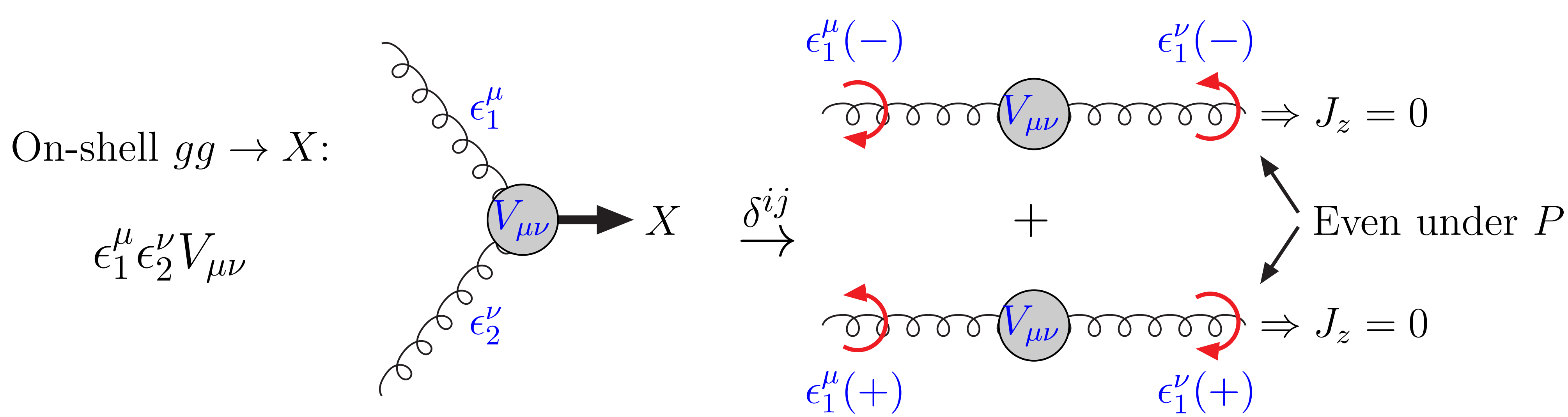
$J_z^P = 0^+$ selection rule (2)

- In the limit of forward protons ($p_\perp = 0$), the CEP subamplitude becomes



- If we consider the on–shell $gg \to X$ vertex $V_{\mu\nu}$, then we have the equality

$$\delta^{ij} V_{ij} = V_{xx} + V_{yy} = (\epsilon_1^\mu(+)\epsilon_2^\nu(+) + \epsilon_1^\mu(-)\epsilon_2^\nu(-))V_{\mu\nu} \equiv V_{++} + V_{--} \ ,$$



$\rightarrow$ Fusing gluons/object X have zero J_z along gg axis, and are in an even parity state. Only $J_z = 0$ on–shell helicity amplitudes V_{++}, V_{--} will contribute (up to small $O(Q_\perp^2/M_X^2)$ corrrections fusing gluons are on–shell).