Central Exclusive Production @ LHC (Selected Topics)

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| Reviews

Central exclusive production within the Durham model: A Review

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LHC Forward Physics

LHC Forward Physics Working Group • K. Akiba (Rio de Janeiro State U.) et al. (Oct 17, 2016)

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Experiment

Paul Newman
Christoph Royon

Outline

- Introduction (why we are interested in CEP processes?)
  CEP and Large RAP GAPS.
- QCD-induced CEP mechanism.
- CEP as a spin-parity analyzer
- 'Diffractive Higgs' revisited.
- Standard Candle CEP reactions and experimental tests.
- Gluon –gluon vs photon-photon fusion.
- Dimeson Saga.
- Other selected CEP topics
- Summary and Outlook

CEP and RAP GAPs

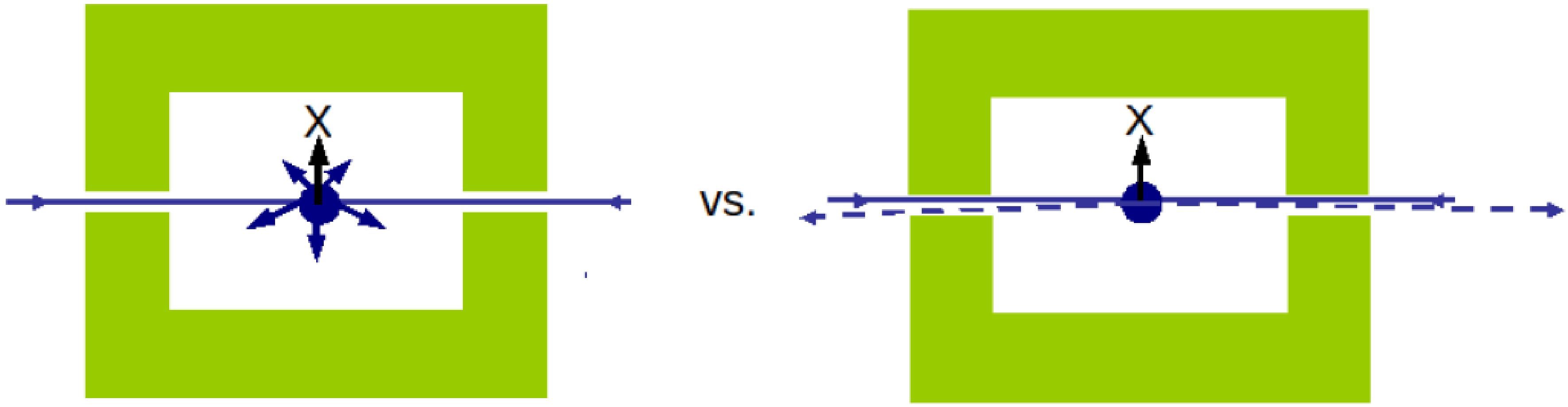
Central Exclusive Production

LRGs caused by Pomeron, photon (W,Z) or Odderon exchanges

Central Exclusive Production (CEP) is the interaction:

$$pp \rightarrow p^{(*)} + X + p^{(*)}$$

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



Why is it interesting?

- Clean:
  - Experimentally clean signal: low multiplicity ($\longrightarrow$ low background) process,* not typically seen in hadronic collisions.
  - Theoretically modeling such exclusive processes requires novel application of pQCD, quite different to inclusive case.
- Quantum number selection:
  - Demanding exclusivity strongly selects certain quantum numbers for produced object - the '$J_z^{PC} = 0^{++}$' selection rule for certain processes.
- Proton tagging:
  - Outgoing protons can be measured by tagging detectors installed at CMS (CT-PPS) and ATLAS (AFP). Handle to select events and provides additional event information (missing mass/proton correlations).

ALFA/TOTEM

(Radiation tolerance)

$\longrightarrow$ Clean production environment and selection rules provide potentially unique handle on QCD physics, but also BSM objects. Threshold scan.

*In absence of pile-up

Measuring CEP

- Two methods to select exclusive events:

★ **Proton tagging:** $\boxed{pp \to p + X + p}$

- Dedicated detectors close to beam line and ~200m from IP.
- With timing $\longrightarrow$ can select CEP during regular HL running.

$$\boxed{pp \to p^{(*)} + X + p^{(*)}}$$

(LHC runs 1,2)

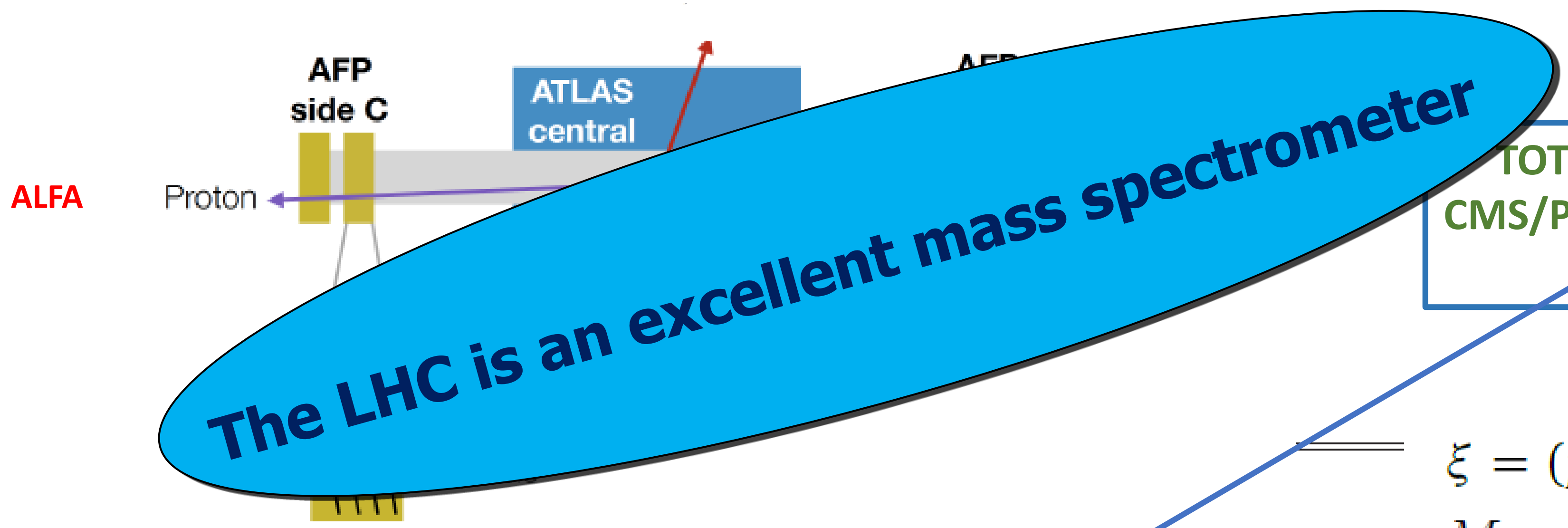
AFP/PPS

★ **Gap vetoing:** no activity between system and beam directions. More suitable for low lumi/pile-up (possible at high pile up with vertex vetoes).

- No activity between system and beam directions.
- More suitable for low lumi/pile-up: ALICE prospects.

(ALICE-double Gap trigger, Runs 1 and 2)

- If proton remains intact will continue down the beam line but with lower energy $E < \sqrt{s}/2$: will be bent out of beamline by LHC magnets.
- Can measure with dedicated detectors ~ 200m (+): proton taggers.



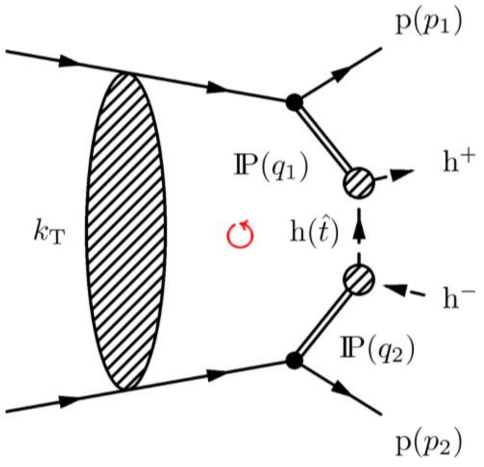
TOTEM & ALFA
CMS/PPS & ATLAS/AFP

$$\xi = (p_{nom} - p)/p_{nom},$$
$$M_X = \sqrt{\xi_1 \cdot \xi_2 \cdot s}.$$
$$y_M = \frac{1}{2}\ln\left(\frac{\xi_1}{\xi_2}\right)$$

- Allows exclusive events to be selected, and momentum reconstructed.
- These are installed and running in association with ATLAS and CMS.

- ALFA/TOTEM- radiation tolerance → low PU special runs

•e-Print: [2401.14494](2401.14494) [hep-ex]



0.35 < m< 0.65 GeV

1.8 < m < 2.0 GeV/c^2

Central exclusive production (nonresonant processes)

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for the CMS and TOTEM Collaborations

EPS-HEP 2023, Hamburg

August 21, 2023

CMS Physics Analysis Summary

Contact: cms-pag-conveners-smp@cern.ch 2023/08/15

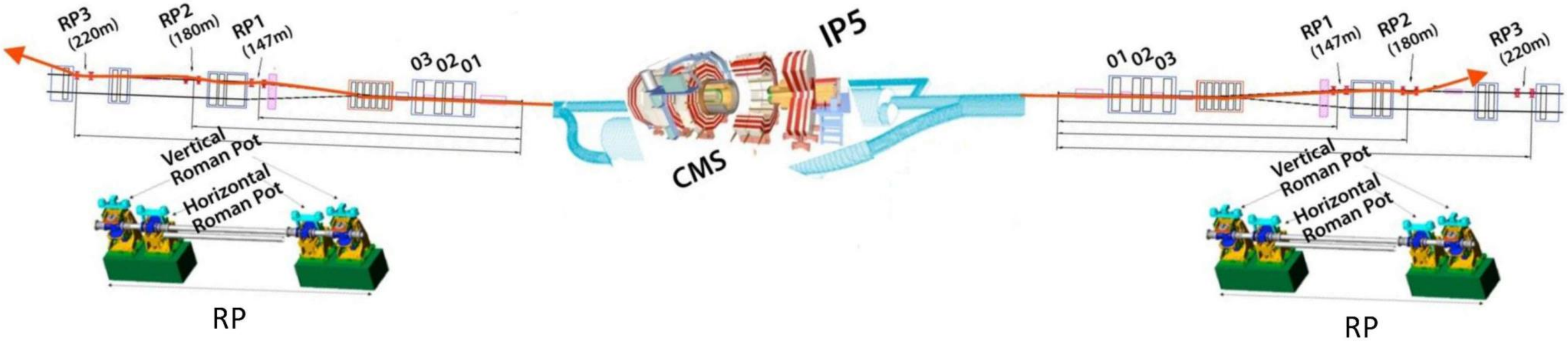
Nonresonant central exclusive production of charged hadron pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV

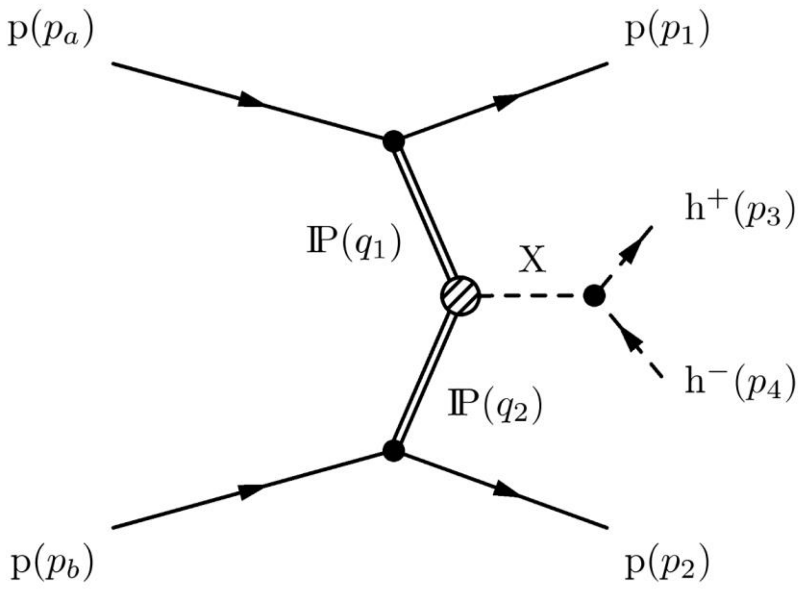
The CMS and TOTEM Collaborations

Abstract

The central exclusive production of charged hadron pairs in pp collisions at a centre-of-mass energy of 13 TeV is examined, based on data collected in a special high-β^* run of the LHC. Events are selected by requiring both scattered protons detected in the TOTEM Roman pots, exactly two oppositely charged identified particles in the CMS silicon tracker, and the energy-momentum balance of these four particles. The nonresonant continuum processes are studied with the invariant mass of the centrally produced two-pion system in the resonance-free region, $m < 0.7$ GeV or $m > 1.8$ GeV. Differential cross sections as functions of the azimuthal angle between the surviving protons, squared four-momenta, and two-hadron invariant mass are measured in a wide region of scattered proton transverse momenta $0.2\text{ GeV} < p_{1,T}, p_{2,T} < 0.8$ GeV and for hadron rapidities $|y| < 2$. A rich structure of interactions related to double pomeron exchange emerges. The parabolic minimum in the distribution of the two-proton azimuthal angle is observed for the first time. It can be understood as an effect of additional pomeron exchanges between the protons from the interference between the bare and the rescattered amplitudes. After model tuning, various physical quanti-

Central exclusive production – data





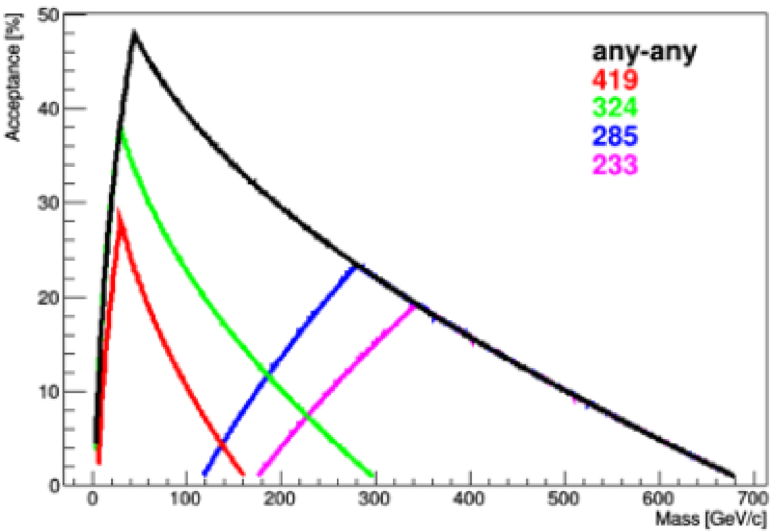
- CMS+TOTEM dataset ($\beta^* = 90\,\mathrm{m}$, 2018)
  - about 80 M events with **two scattered protons** and only **two reconstructed central tracks**
  - part of those is double pomeron exchange (DPE), where a central system (X) was created
  - decayed to particle-antiparticle pair $\mathrm{h}^+\mathrm{h}^-$, mostly $\pi^+\pi^-$or $\mathrm{K}^+\mathrm{K}^-$, but some $\mathrm{p}\overline{\mathrm{p}}$
  - invariants: $p_{1,\mathsf{T}}, p_{2,\mathsf{T}}, \phi$; $m_{\mathrm{h}^+\mathrm{h}^-}$

$\mathbb{P}\mathbb{P}$ collider $\rightarrow$ gluon-rich initial state

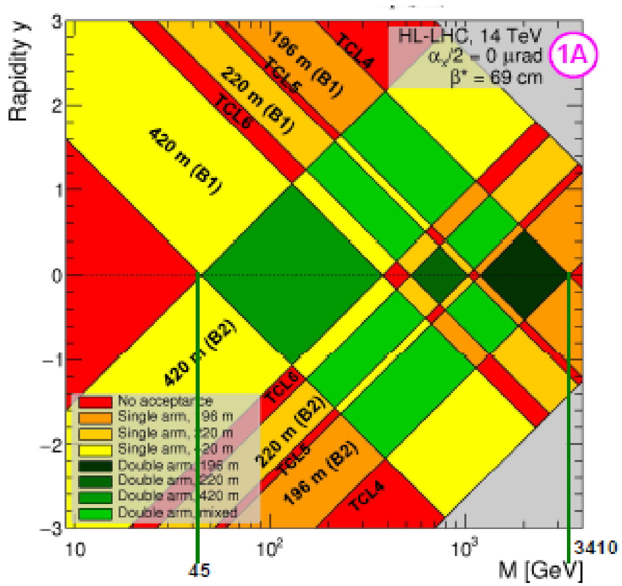
Proton Tagging at HL-LHC AFP & PPS

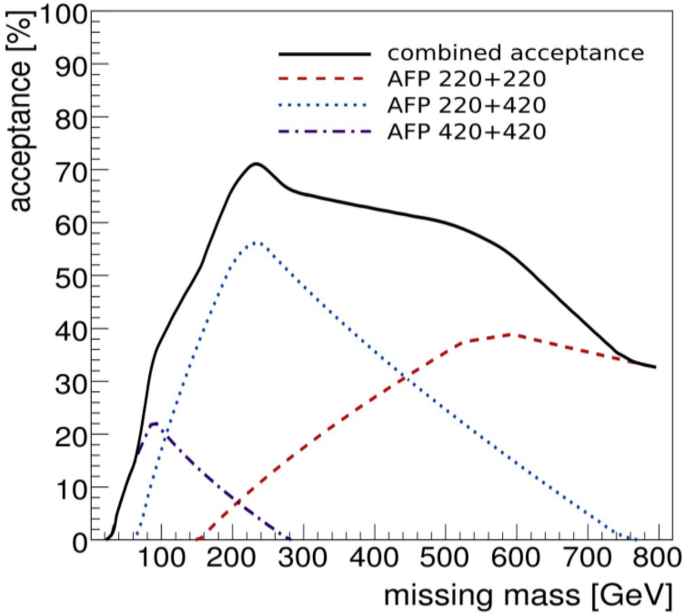
- Range of detector positions, from ~ 200 m (higher mass $M_X \gtrsim 300\,\mathrm{GeV}$) to ~ 400 m (lower mass $M_X \gtrsim 20 - 50\,\mathrm{GeV}$) considered.
- Physics possibilities driven by these: exciting potential to probe **wide range** of **masses**, from low to high.

ATLAS



CMS (CT-PPS)





- Standard HL runs. With precision tracking and timing detectors.

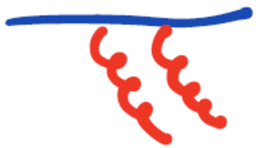
$$\text{approximately } 0.02 < \xi < 0.1$$

(0.02-0.15)

What can generate CEP?

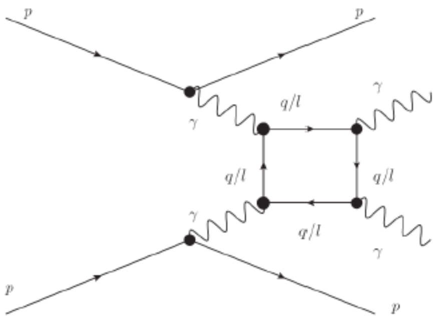
- Generated by t-channel exchange with no colour flow - can occur in pure QED and QCD interaction:

(ZZ, mixed,...)



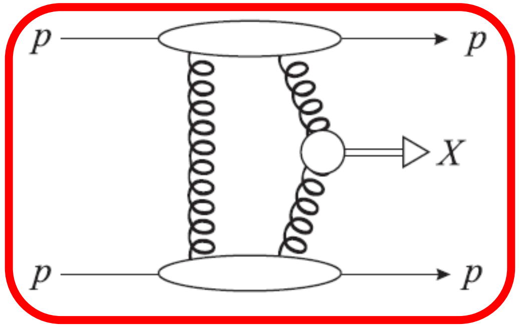
- Combination of these leads to three principle classes of process:

C-even, Couples to photons



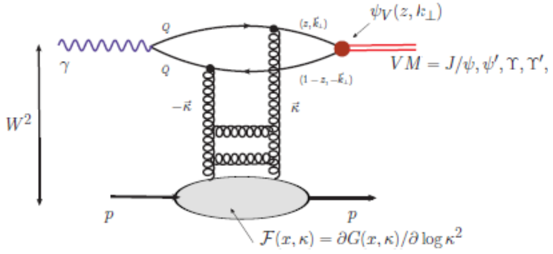
Photon-induced

C-even, couples to gluons

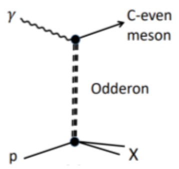


QCD-induced

C-odd, couples to photons + gluons



Photoproduction

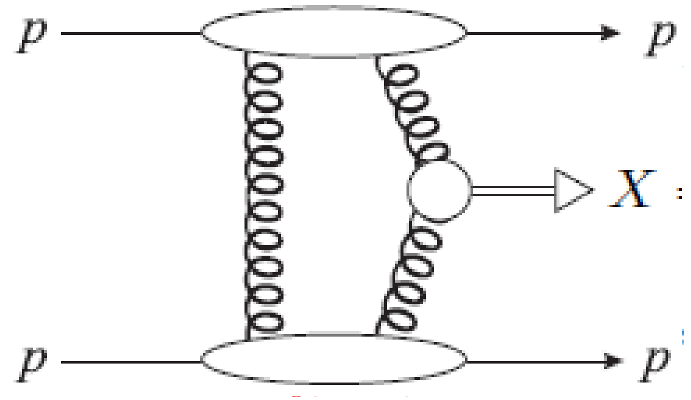


QCD-induced CEP

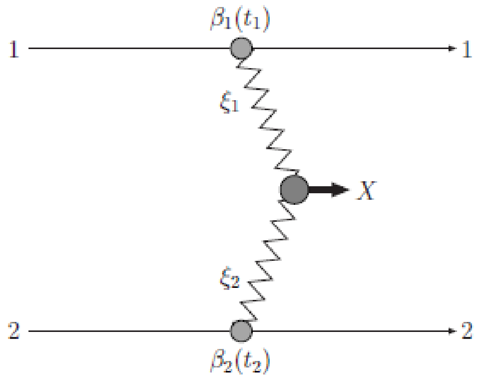
QCD-Induced CEP

- Dominant mechanism for states that couple via strong interaction. How do we model it? Answer depends on scale of production:

  - For sufficiently large scale (~ object mass M_X), apply **perturbative** '**Durham**' model.
  - Mediated via colour-singlet gg exchange.



  - At lower scales (~ object mass M_X) pQCD description will break down.
  - Diffractive, so can apply well established tools of Regge theory **Double Pomeron Exchange** (**DPE**).

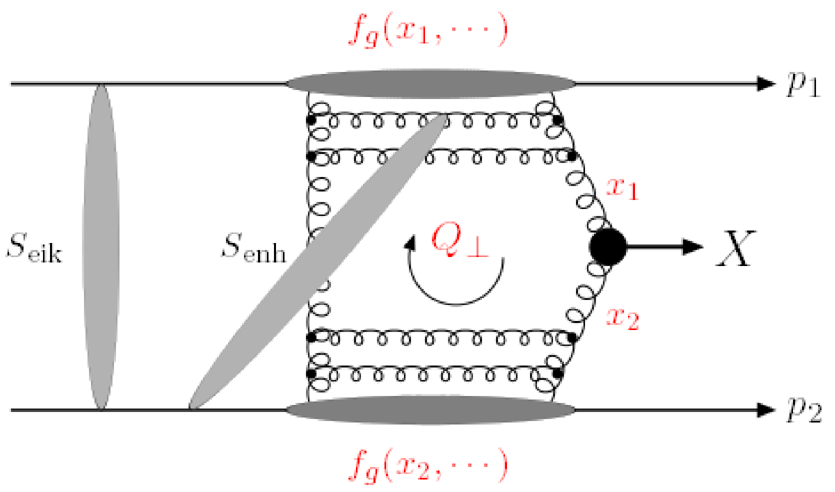


- Exactly where transition from DPE to pQCD picture occurs is open question. **Glueballs** ($M_G \sim 1-2\,\mathrm{GeV}$) - expect to be in **DPE regime**.

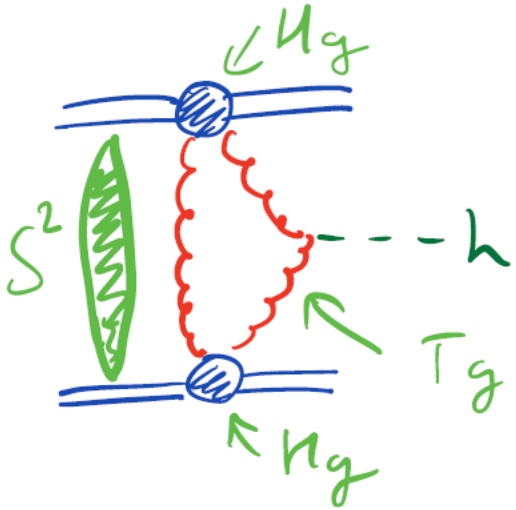
'Durham Model' of central exclusive production

KMR-1997-2001

- 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.

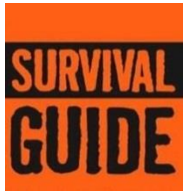


- Long established, remains 'the' model of high scale QCD-induced CEP. In brief, cross section given in terms of:



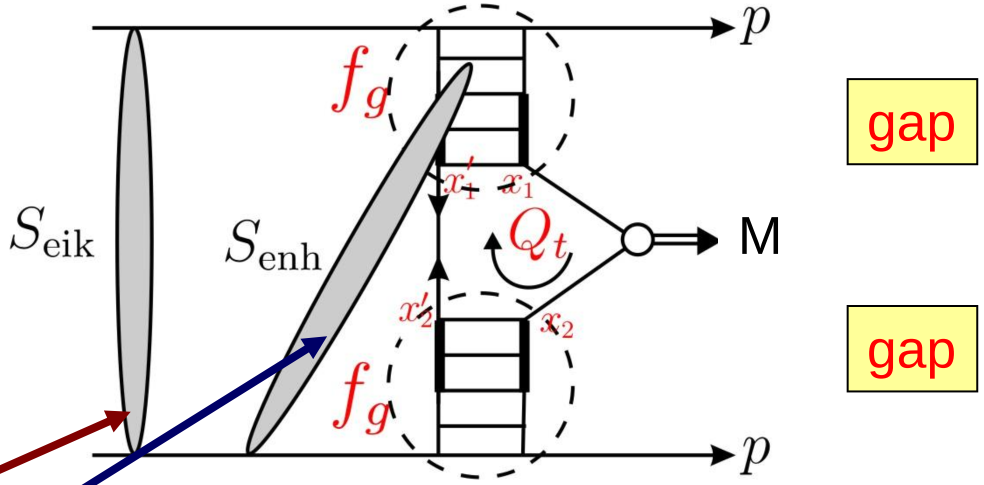
  - ★ Generalised gluon PDFs H_g - relatable to collinear gluon for CEP kinematics.
  - ★ Sudakov factors $T_g(Q_\perp, \mu_F^2)$ - probability of no gluon emission.
  - ★ `Survival factor' probability of no soft proton-proton interactions (no MPI).
  - ★ $gg \to X$ amplitudes, but dominantly only for $g(\pm)g(\pm) \to X$.

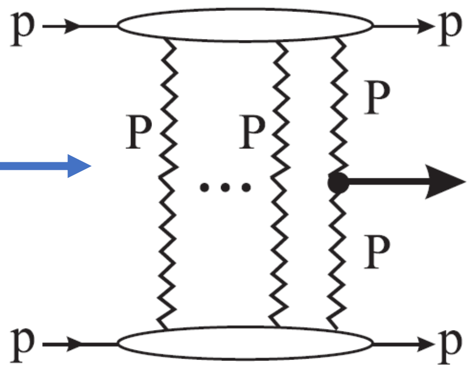
$$T = \pi^2 \int \frac{d^2\mathbf{Q}_\perp \overline{\mathcal{M}}}{\mathbf{Q}_\perp^2(\mathbf{Q}_\perp - \mathbf{p}_{1_\perp})^2(\mathbf{Q}_\perp + \mathbf{p}_{2_\perp})^2} f_g(x_1, x_1', Q_1^2, \mu_F^2; t_1) f_g(x_2, x_2', Q_2^2, \mu_F^2; t_2) ,$$



"soft" scattering can easily destroy the gaps

S^2 → absorption effects -necessitated by unitarity





Eikonal rescatt: between protons

Semi-enhanced rescatt: involving intermediate partons

$$1 > S^2_{\rm enh} \gg S^2_{\rm elk}$$

Survival factor

- Survival factor, $S^2_{\rm eik}$: probability of no additional soft proton-proton interactions, spoiling exclusivity of final-state.

- Not a constant: depends sensitively on the outgoing proton $\mathbf{p}_\perp$ vectors. Physically- survival probability will depend on impact parameter of colliding protons. Further apart $\longrightarrow$ less interaction, and $S^2_{\rm eik} \to 1$.
  b_t and $p_\perp$: Fourier conjugates.

Process dependence

$\longrightarrow$ Need to include survival factor differentially in MC.

First fully differential implementation of soft survival factor – **SuperChic 2** MC event generator- HKR, ArHiv:1508.02718

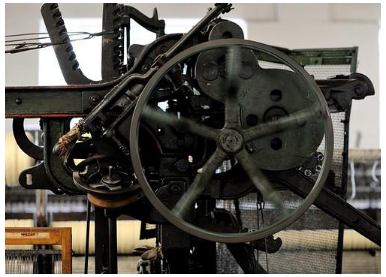
SC-3,4

The survival factor is conventionally written in terms of the proton opacity $\Omega(s, b_t)$. The proton opacity is related via the usual elastic unitarity equations to such hadronic observables as the elastic and total cross sections as well as, combined with some additional physical assumption about the composition of the proton, the single and double diffractive cross sections. Thus, while the survival factor is a soft quantity which cannot be calculated using pQCD, it may be extracted from soft hadronic data. Although there is some uncertainty in the precise level of suppression (in particular in its dependence on the c.m.s. energy $\sqrt{s}$), this is found to be a sizeable effect, reducing the CEP cross section by about two orders of magnitude.

Well developed machinery

KMR (2000-2013)

GLM, **FS**, **Ostapchenko**



The survival factor is not a simple multiplicative constant,[11] but rather depends on the distribution in impact parameter space of the colliding protons. In particular, in the simplest 'one–channel' model, which ignores any internal structure of the proton, we can write the average suppression factor as

$$\langle S^2_{\rm eik}\rangle = \frac{\int {\rm d}^2\mathbf{b}_{1t}\,{\rm d}^2\mathbf{b}_{2t}\,|T(s,\mathbf{b}_{1t},\mathbf{b}_{2t})|^2\exp(-\Omega(s,b_t))}{\int {\rm d}^2\,\mathbf{b}_{1t}{\rm d}^2\mathbf{b}_{2t}\,|T(s,\mathbf{b}_{1t},\mathbf{b}_{2t})|^2}\,, \tag{11}$$

where $\mathbf{b}_{it}$ is the impact parameter vector of proton i, so that $\mathbf{b}_t = \mathbf{b}_{1t} + \mathbf{b}_{2t}$ corresponds to the transverse separation between the colliding protons, with $b_t = |\mathbf{b}_t|$. $T(s, \mathbf{b}_{1t}, \mathbf{b}_{2t})$ is the CEP amplitude (10) in impact parameter space,

exp(−Ω(s, but)) probability that no inelastic scattering occurs at impact parameter bt, depends only on proton transverse separation

In such events we produce a colour-singlet state M which is practically free from soft secondary particles. Moreover, if forward going protons are tagged we can reconstruct the 'missing' mass M with good resolution, and so have an ideal means to search for new resonances and to study threshold behaviour phenomena. We have to pay a price for ensuring such a clean diffractive signal. In particular, the diffractive event rate is suppressed by the small probability, $\hat{S}^2$, that the rapidity gaps survive soft rescattering effects between the interacting hadrons, which can generate secondary particles which populate the gaps

In general, we may write the survival factor $\hat{S}^2$ in a multi-channel eikonal framework in the form

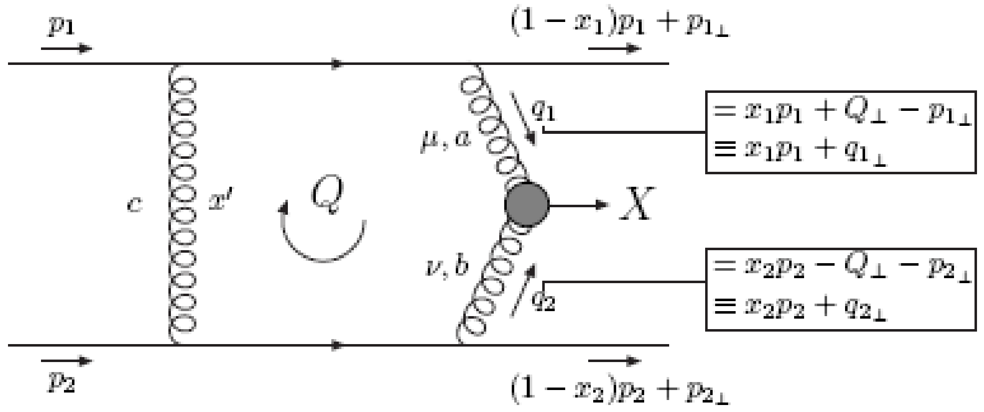
$$\hat{S}^2 = \frac{\int \sum_i |\mathcal{M}_i(s, b_t^2)|^2 \exp\left(-\Omega_i(s, b_t^2)\right) d^2b_t}{\int \sum_i |\mathcal{M}_i(s, b_t^2)|^2 d^2b_t} \qquad (2)$$

where the incoming proton is decomposed into diffractive eigenstates, each with its own opacity[1] Ω_i. The amplitudes $\mathcal{M}_i(s, b_t^2)$ of the process of interest may be different in the different diffractive eigenstates. They are expressed in impact parameter b_t space at centre-of-mass energy $\sqrt{s}$. It is important to recall that the suppression factor $\hat{S}^2$ is not universal, but depends on the particular hard subprocess, as well as on the kinematical configurations of the parent reaction,

the possibility of (low mass) diffractive dissociation p → N* .

Theory: parton level amplitude

- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons in a colour singlet state[1].



eikonal approximation for the qg vertices,

$$\frac{iA}{s} = \alpha_S^2 C_F^2 \int \frac{d^2 Q_\perp}{Q_\perp^2 q_{1\perp}^2 q_{2\perp}^2} \mathcal{M} ,$$

where $\mathcal{M}$ is the normalised, colour averaged subamplitude, written in terms of the $gg \to X$ vertex V as

$$\mathcal{M} \equiv \frac{2}{M_X^2} \frac{1}{N_C^2 - 1} \sum_{a,b} \delta^{ab} q_{1\perp}^{\mu} q_{2\perp}^{\nu} V_{\mu\nu}^{ab} .$$

$J_z^P = 0^+$ selection rule

- Consider the limit $p_{1_\perp} = p_{2_\perp} = 0$, i.e. exactly forward scattering. Have

$$q_{1_\perp} = -q_{2_\perp} = Q_\perp \; ,$$
$$\epsilon_1 = -\epsilon_2 \; ,$$

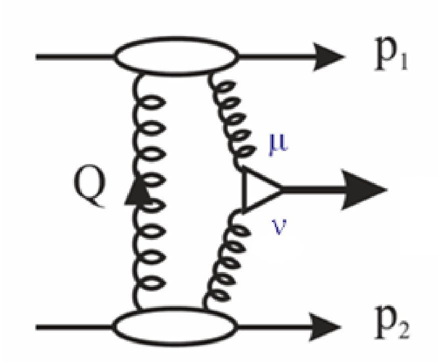
i.e. $gg \to X$ subamplitude is given by

$$\mathcal{M} \sim Q_\perp^i Q_\perp^j V_{ij} \qquad (i/j = 1,2)$$
$$\to \frac{1}{2} Q_\perp^2 (V_{++} + V_{--})$$

i.e. fusing gluons have equal (transverse) polarisations $\lambda_1 = \lambda_2 = \pm$.

$\to$ In exact forward limit, fusing gluons are in a $J_z = 0$ state along beam axis.

- For general proton $p_\perp \neq 0$, non-$J_z^P = 0^+$ states contribute, but these will be sub-leading (as $p_\perp \approx 0$ in general) and can be efficiently suppressed with proton tagging.



$$M_{\mu\nu}(gg^{PP}) \sim (p_{t,1} - Q_t)_\mu (p_{t,2} + Q_t)_\nu$$

after $(\vec{Q}_t)$ angular integration at $p_{t,i} = 0$ ➔ $-\delta^{(2)}_{\mu\nu} Q_t^2 / 2$

in terms of helicity amplitudes . $1/2\{(++;f) + (--;f)\}$ ➔ Jz=0, P-even state

at non-zero $p_{t,i}$ - an admixture of Jz=2 ➔ $\frac{(2p_{1,t}p_{2,t})^2}{Q_t^4}$

Important consequences for $H \to b\bar{b}$

Symmetry properties of the $\gamma(\lambda_1, k_1) + \gamma(\lambda_2, k_2) \to q(h, p) + \bar{q}(\bar{h}, \bar{p})$. amplitude (FKM-97)

$J_Z = 0$ (nullifies in the massless limit) → (++,+-) (--,+-) (++,-+) (--,-+)

in terms of the **MHV rules** the only nonzero amplitudes gg→qq

(S .Parke, T.Taylor (1986))

(+ - ; + -) J_z=2, **HCA**

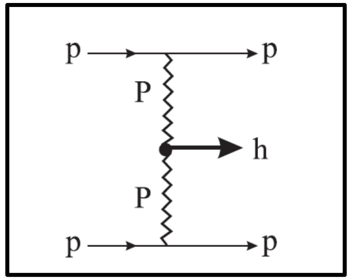
(-+ ; -+ /+-)

'An Amplitude for *n* Gluon Scattering'

CEP AS A SPIN-PARITY ANALYZER

What is known from Regge Theory

$$\boxed{1+2 \;\to\; 3+h+4}$$



$$T^{\lambda_3\lambda_h\lambda_4}_{\lambda_1\lambda_2}(s_1,s_2,t_1,t_2,\phi) = \sum_{i,k} g_{\lambda_1\lambda_3}(t_1)g_{\lambda_2\lambda_4}(t_2)\left(\frac{s_1}{s_0}\right)^{\alpha_i(t_1)}\left(\frac{s_2}{s_0}\right)^{\alpha_k(t_2)}\eta(\alpha_i(t_1))\eta(\alpha_k(t_2))g^{\lambda_h}_{ik}(t_1,t_2,\phi)$$

K.Boreskov, 68

Kaidalov. Karnakov, 66,70

$$g_{\lambda_1\lambda_3}(t) \sim (-t)^{|\lambda_1-\lambda_3|/2}, \quad \text{as } t\to 0. \quad g^{\lambda_h}_{ik} = \sum_{m_2=-\infty}^{\infty} e^{im_2\phi}\,\gamma^{\lambda_h}_{m_1m_2}, \quad \text{with } m_1+m_2=\lambda_h,$$

$$\gamma^{\lambda_h}_{m_1m_2} = (-1)^{\lambda_h}\xi_3\,\gamma^{-\lambda_h}_{-m_1-m_2}, \quad \xi_3 = \eta_h(-1)^{S_h}, \quad \text{for small } t_1,t_2 \quad \gamma^{\lambda_h}_{m_1m_2} \sim (-t_1)^{|m_1|/2}(-t_2)^{|m_2|/2}, \quad \text{with } m_1+m_2=\lambda_h$$

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

$\boxed{J^P(h)=0^-}$ $\qquad g^h_{ik} = f_{0^-}(p^2_{3\perp},p^2_{4\perp},\vec p_{3\perp}\cdot\vec p_{4\perp})\,\varepsilon_{ikl}(p_{3\perp})_i(p_{4\perp})_k(n_0)_l$

all amplitudes with $m_1, m_2 = 0$ are zero, and so $|m_1| = |m_2| = 1$ $\longrightarrow$ $d\sigma(0^-)/d\phi \approx p^2_{1\perp}p^2_{2\perp}\sin^2\phi$,

observed by the WA102 Collaboration for η, and η'

$\boxed{J^P(h)=1^+}$ $\qquad g^h_{ik} = f^0_{1^+}\,\varepsilon_{ikl}(p_{3\perp})_i(p_{4\perp})_k e_l + \left(f^1_{1^+}\,(p_{3\perp})_i + \tilde f^1_{1^+}\,(p_{4\perp})_i\right)\varepsilon_{ikl}(n_0)_k e_l,$

for small $\vec p_{i\perp}$ $\qquad f^0_{1^+} \sim (p^2_{3\perp}-p^2_{4\perp}), \qquad f^1_{1^+} = -\tilde f^1_{1^+}.$

$$g_{PP} = a_{\lambda=0}(p^2_{3t}-p^2_{4t})/M^2(\vec p_{3t}\times\vec p_{4t})\vec e + f_{\lambda=1}(K\times\vec n)\vec e/M, \quad K=(\vec p_3-\vec p_4$$

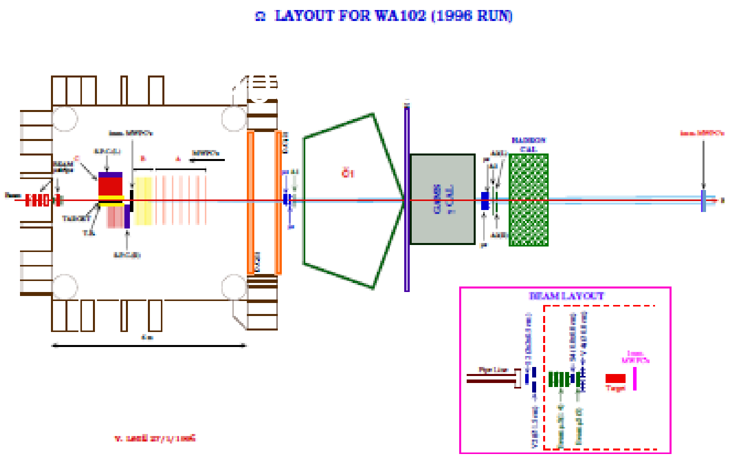
- Coincide with the NCVC model expectation by F. Close et al (1999)
- Agree with the WA102 data on $f_1(1420)$ and $f_1(1285)$

Follows from general principles

Pre-LHC studies

review: A. Kirk. 1408.1196[hep-ex]

- Fixed-target pp experiments in 80s and 90s. Most significantly at CERN Omega spectrometer (WA76, 91, 102).
- Many final states $(\pi, K, \eta('), \phi, \omega \ldots)$ looked at, and resonances identified.
- But $\sqrt{s} \lesssim 30\,\text{GeV}$ **not high enough** for pure DPE.



Scalar	$\pi\pi/K\bar{K}$	$\pi\pi/\eta\eta$	$\eta\eta/K\bar{K}$	$\rho\rho/2[\pi\pi]_S$	$\rho\rho/4\pi$	$\sigma\sigma/4\pi$
$f_0(1370)$	2.17 ± 0.90		0.35 ± 0.21		~ 0.9	~ 0
$f_0(1500)$	3.13 ± 0.68	5.5 ± 0.84		$2.6 \pm 0.4\,^1$ $3.3 \pm 0.5\,^2$	0.74 ± 0.03	0.26 ± 0.03
$f_0(1710)$	0.20 ± 0.03		0.48 ± 0.14			

V. Crede and C. A. Meyer, Prog. Part. Nucl. Phys. 63 (2009) 74-116

- Pre-LHC, highest energy glueball searches only up to $\sqrt{s} = 63\,\text{GeV}$, and with limited statistics when in DPE regime.

$\longrightarrow$ **Clear motivation** to use LHC to bring something new to table.

$$\frac{|T(|J_z|=2)|^2}{|T(J_z=0)|^2} \sim \frac{\langle p_\perp^2 \rangle^2}{\langle Q_\perp^2 \rangle^2}$$

- In Regge theory there does not exist a simple closed form for the χ_2 case.

- Within the PT approach forward CEP of non-relativistic heavy 2++ quarkonium is strongly reduced because of the suppression of the 2 ++ → 2g transition for the Jz = 0 on-mass-shell two-gluon state

KMR-2001

- Note these will receive corrections of $O(p_\perp^2/\langle Q_\perp^2\rangle)$.
- These distributions are strongly affected by absorptive corrections, through their dependence on the proton distribution in impact parameter *b* space.
- Forward proton detection would allow a clear discrimination between the different *J* states.

Jz = 0 amplitude vanishes for the γγ decay of the 2++ 3P2 positronium (Tumanov, 53;Alekseev, 58)

Glueball filter ?

Lattice results

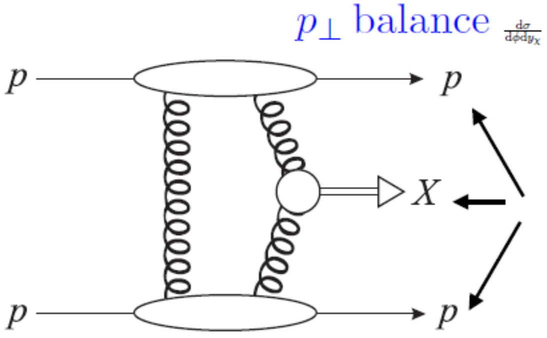
J^{PC}	mass
0^{++}	1730 ± 80 MeV/c^2
2^{++}	2400 ± 120 MeV/c^2
0^{-+}	2590 ± 130 MeV/c^2

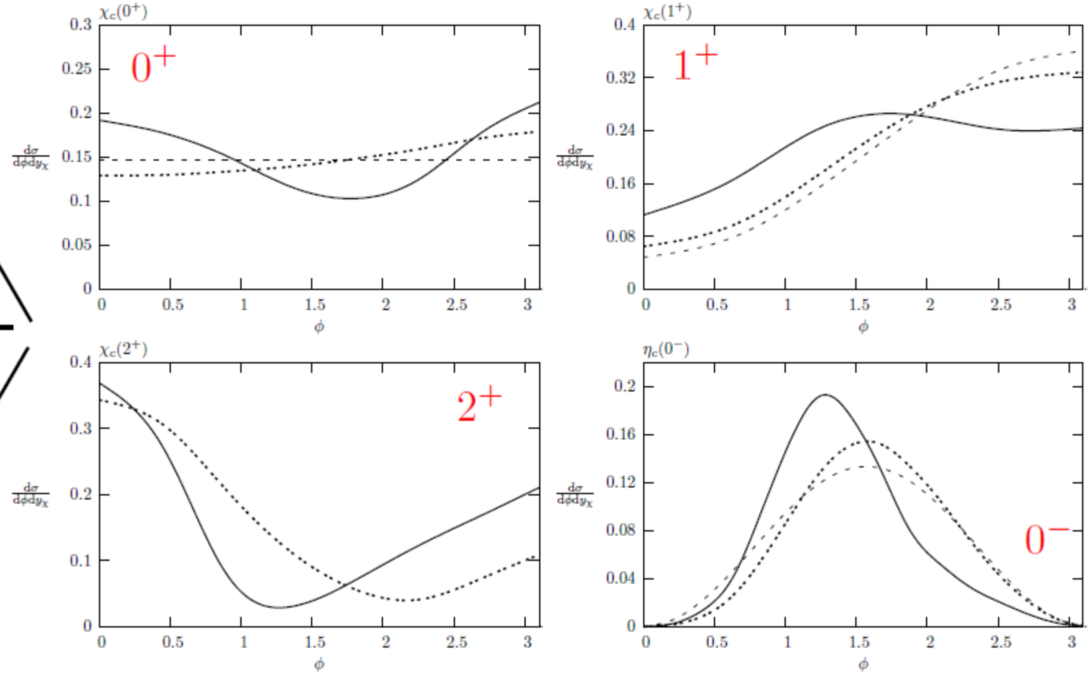
Eur.Phys.J.C 80 (2020) 11, 1077

X(2370) @ BESIII strong evidence in favour of 0^-

CEP and Tagged Protons

- For different object spin-parities, expect **distinct distributions** in the azimuthal angle ϕ between the outgoing proton $p_\perp$ vectors.





dotted curve- no S^2

$\longrightarrow$ **Additional handle** for spin-parity analysis.

- In addition 'missing mass' of system M_X can be reconstructed from protons.

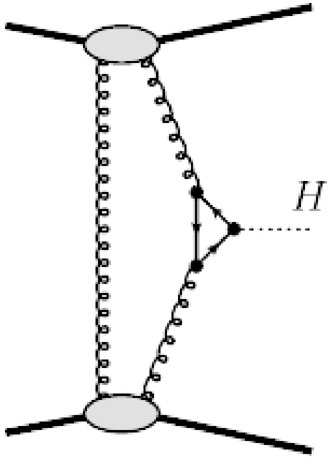
Life, Death and “Ressurection “ of ‘Diffractive Higgs

Physics with tagged protons - QCD

The early 2000s

★ **Exclusive Higgs:**

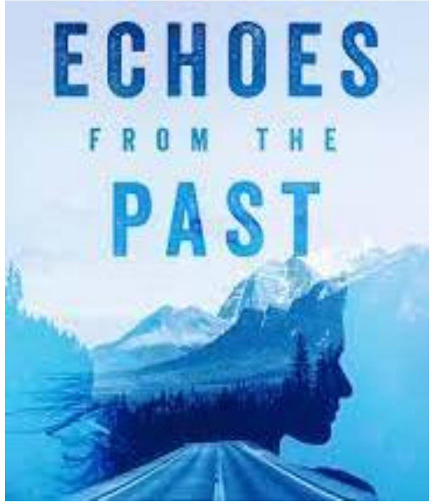
- Completely novel (and so far unseen) production channel.
- $H \to b\bar{b}$: QCD $gg \to b\bar{b}$ background dynamically suppressed.
- Combined with proton tagging: handle on CP.
- Cross section $O(\text{fb}) \Rightarrow$ clear benefit from higher lumi.



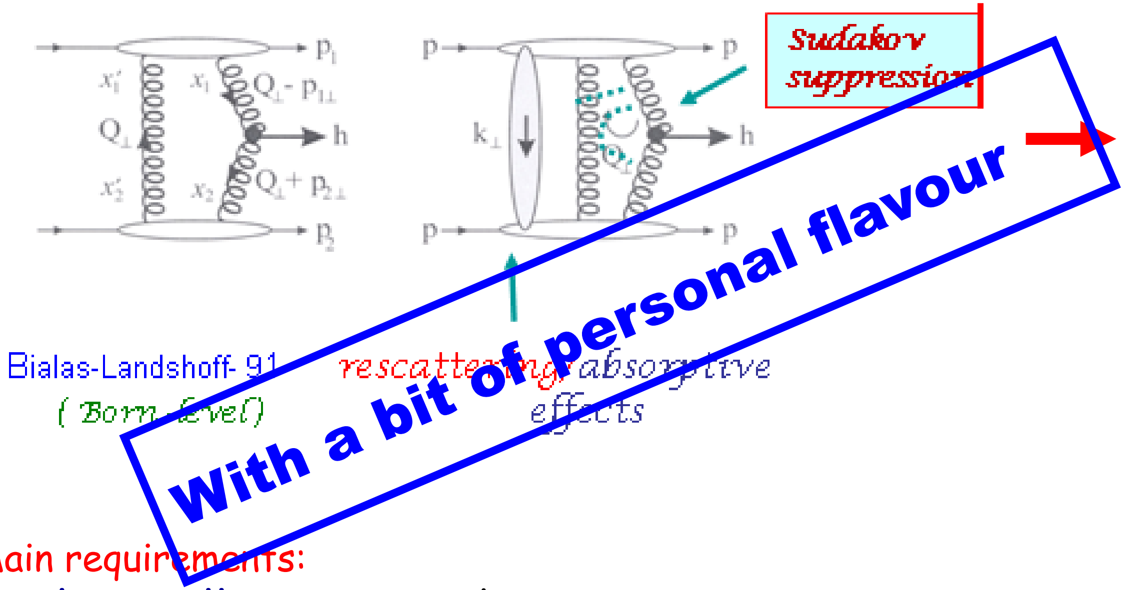
- Lower mass acceptance highly desirable for jets and essential for Higgs $\Rightarrow$ detectors at $\gtrsim 300$m needed.

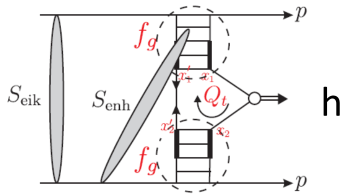
The basic ingredients of the thery approach

(interplay between the soft and hard dynamics)



RG signature for Higgs hunting (DKT-1987). Bjorken (1992-93)



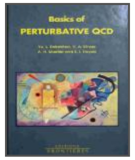


Main requirements:

•inelastically scattered protons remain intact

•active gluons do not radiate in the course of evolution up to the scale M

•<Qt> >>Λ_{QCD} in order to go by pQCD book



$$\sigma(\text{CDPE}) \sim 10^{-4} * \sigma\ (\text{incl})$$

High price to pay for such a clean exclusive environment:

$\sigma_H(\mathrm{CEP}) \sim 10^{-4} * \sigma_H(\text{inclus.})$

Rapidity Gaps should survive **hostile** hadronic *radiation damages* and *'partonic pile-up'*

symbolically $W = S^2 T^2$

Colour charges of the 'digluon dipole' are screened only at $r_d \geq 1/(Q_t)_{ch}$

GAP Keepers (Survival Factors) , protecting RG against:

- the debris of QCD radiation with $1/Q_t \geq \lambda \geq 1/M$ **(T)**
- soft rescattering effects (necessitated by unitarity) **(S)**

A. Bialas and P.V. Landshoff, Phys. Lett. B256 (1991) 540.

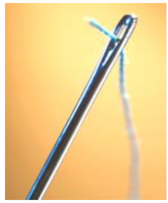
Excitement of the Tevatron community-

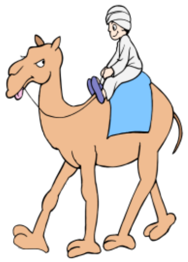
Theory spread of 11 orders

KMR 1997

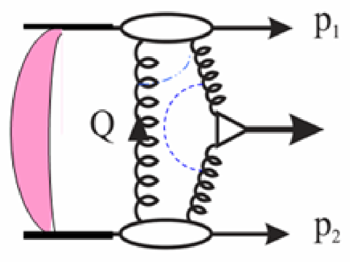
Factor ~3 since then

Forcing two camels to go through the eye of a needle





P **H** **P**



$$\sigma_{pp}(M^2,\ldots) = L_{eff}(M^2, y) * \sigma_{hard}(M^2,\ldots)$$

$$\frac{\partial^2 L_{eff}}{\partial y \partial M^2} M^2 = S^2 * L(M^2)$$

$\sigma(CEP) \sim 10^{-4}\ \sigma\ (incl)$

focus on $\sigma^{bgd}_{hard}(M^2,\ldots)$

$L_{eff}(M^2, y)$ → the same for Signal and Bgds

Roughly $L_{eff} \sim \frac{\hat{S}^2}{b^2} \left| N \int \frac{dQ_t^2}{Q_t^4} f_g(x_1, x_1', Q_t^2, \mu^2) f_g(x_2, x_2', Q_t^2, \mu^2) \right|^2$

contain Sudakov factor T_g which exponentially suppresses infrared Q_t region → pQCD

$$\langle Q_t \rangle_{SP} \simeq M/2 * \exp(-1/\bar{\alpha}_s) \approx 2GeV \gg \Lambda_{QCD},$$

$$\bar{\alpha}_S \simeq (N_c/\pi) * \alpha_s(M) * C_\gamma$$

Tg + anom .dim. → *IR filter*

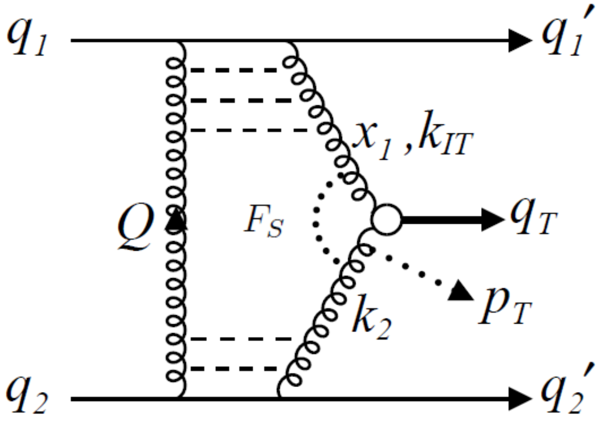
S^2 is the prob. that the rapidity gaps survive population by secondary hadrons → soft physics

9

The Born amplitude

$$M(qq \to qHq) = \frac{2}{9} 2A \int \frac{d^2Q_T}{Q^2 k_1^2 k_2^2} 4\alpha_S^2(Q^2)\, (\boldsymbol{k}_1.\boldsymbol{k}_2)$$

$$\boxed{\frac{4\alpha_S(Q^2)}{3\pi} \to f(x,Q^2) = \frac{\partial(xg(x,Q^2))}{\partial \ln Q^2}}$$



Sudakov F_S probability not emitting gluons with $Q_T \lesssim p_T \lesssim M_H/2$

$\boxed{\text{no emission when } \lambda \simeq 1/p_T \text{ is larger than the separation, } \Delta\rho \sim 1/Q_T}$ $F_S = \exp\left(-\frac{\alpha_s N_c}{4\pi}\ln^2\left(\frac{Q_\perp^2}{M_X^2}\right)\right)$ **DL**

$$\boxed{M(pp \to pHp) = A\pi^3 \int \frac{dQ^2}{Q^4}\, e^{-S(Q_T^2, M_H^2)}\, f(x_1, Q_T^2)\, f(x_2, Q_T^2)}$$

- no infrared divergency
- $\langle Q_\perp^2 \rangle = O(\text{GeV}^2)$, safely in the perturbative regime.
- $\langle \bar{Q}_\perp^2 \rangle$ increases with mass M_H and $\sqrt{s}$,

saddle point given by $\ln(M_H^2/4Q^2) = (2\pi/N_c\alpha_S(Q^2))\,(1-2\gamma)$

γ is the anomalous dimension of the gluon, $g(x,Q^2) \propto (Q^2)^\gamma$.

$\boxed{\frac{\alpha_S C_F}{\pi} \to f_g(x, x', Q_\perp^2, \mu^2)}$ 'skewed' unintegrated PDF $x' \ll x$ regime relevant to CEP

FP420 AND RESURRECTION OF 'DIFFRACTIVE HIGGS' (20 YEARS ON)

- searching for lower mass new objects in

MANCHESTER 1824

The University of Manchester

The FP420 R&D project (2004

- FP420 was a joint R&D collaboration between CMS and AT proton detector system to tag outgoing protons.
- Key questions:
  - Can suitable forward detectors be placed close to the
  - What is the physics potential of these detectors?
  - Will they cover an interesting region of Higgs mass?
- Final report is available at JINST 4:T10001,2009 [arXiv:080

❖ QCD-initiated production: potential for e.g. studies analysed (though there are more).

★ **Jets**: gg colour-singlet initial state range of unique QCD studies.

★ **Higgs**: completely unseen mode, Higgs properties (CP, couplings) via independent method.

p -

p -

96 GeV-'light Higgs' indications

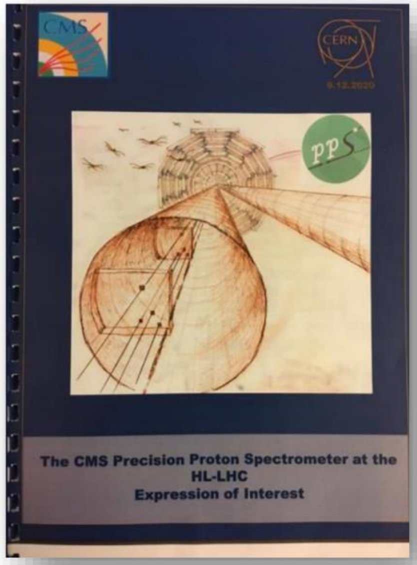
PPS/AFP- new proposals

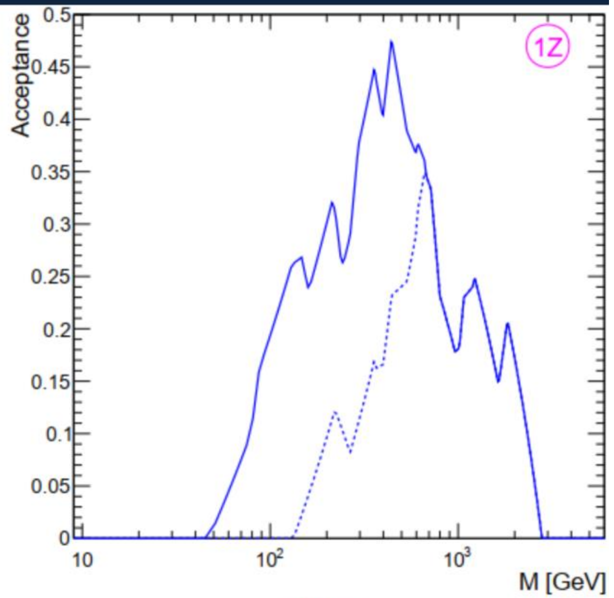
PPS in HL-LHC

CMS-NOTE-2020-008, arxiv:2103.02752

- New proposal with extended mass range:
  - 133 GeV – 2.7 TeV for the first 3 stations
  - 43 GeV – 2.7 TeV for all stations

Run 2+3 acceptance between 350 and 2 TeV





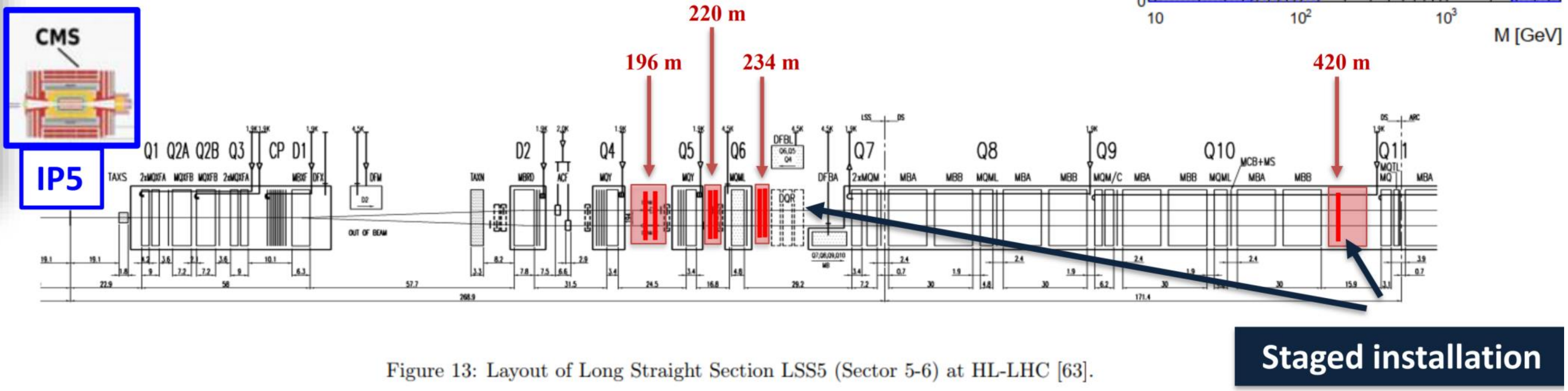
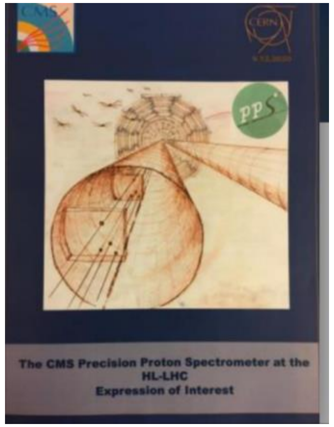


Figure 13: Layout of Long Straight Section LSS5 (Sector 5-6) at HL-LHC [63].

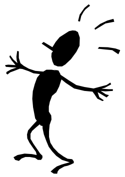
Extends current LHC physics program (WW, di-τ, top, ALPs, SUSY, etc…)



- New proposal with extended mass range:

  133 GeV – 2.7 TeV for the first 3 stations ($0.0142 < \xi < 0.1967$)

  43 GeV – 2.7 TeV for 4 stations ($0.00325 < \xi < 0.1967$)

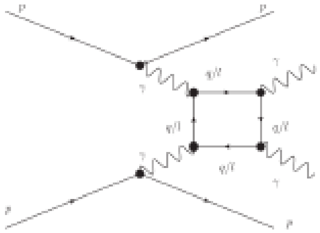


- PPS2 starting with 200m during LHC Run 4 (PPS2-EOI), while the 420m station is planned for Run5+

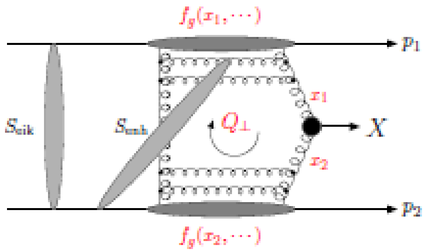
Photon vs Gluon fusion

$\gamma\gamma$ vs. gg collisions at high mass

- Naively, $\alpha_S \gg \alpha$ and so expect gg to dominate (where possible).



vs.



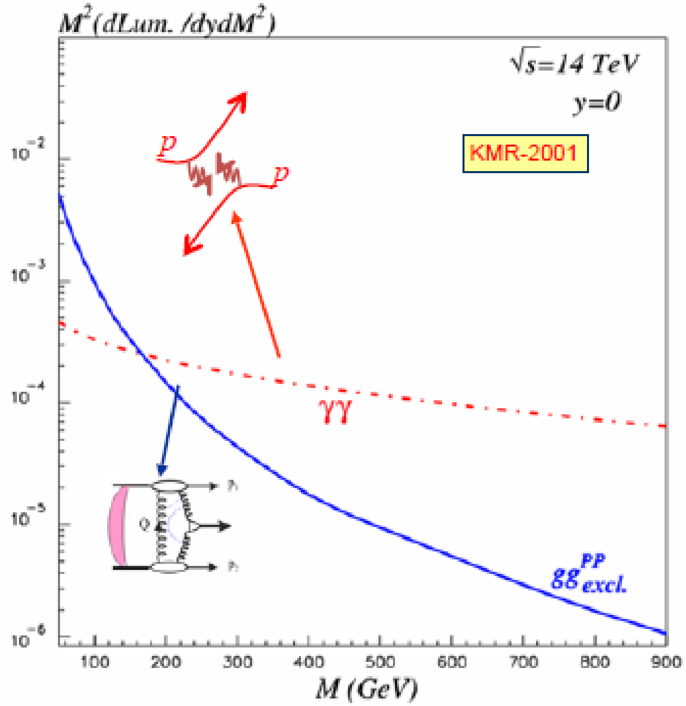
- But QCD enhancement can also be weakness: exclusive event $\Rightarrow$ no additional gluon radiation in final state.

- As system mass M_X increases, phase space for extra gluon emission $\uparrow$ and $\sigma \downarrow$. Gluons like to radiate!

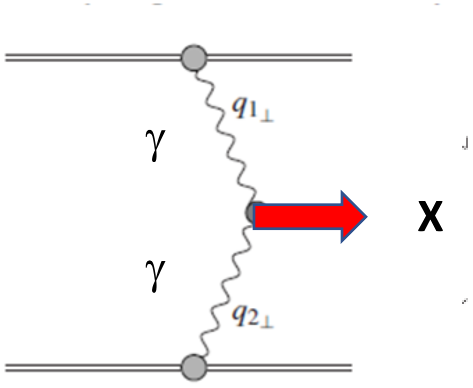
- Expect cross over where $\gamma\gamma$ collisions dominate as $M_X \uparrow$ (all thing equal).

- In $\gamma\gamma$ vs. gg luminosities, occurs before AFP acceptance, $M_X \sim 200\,\text{GeV}$. More precisely expect α from $\hat{\sigma}$, so moves to higher M_X .

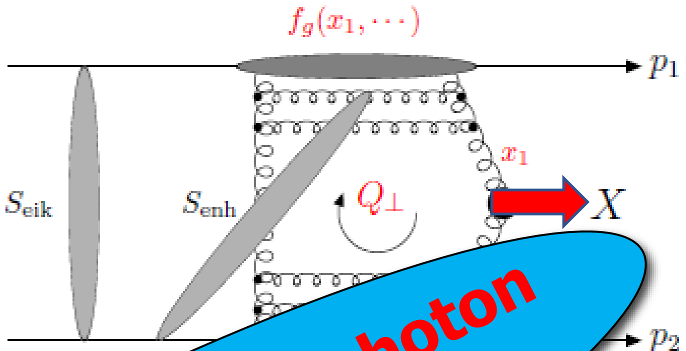
PPS



In addition - S^2 much lower for and suppression from $1/N_c^2$.



VS.



The LHC is the high energy photon collider

- Naively expect strong interacti … α.
- However QCD enhanc … akness: exclusive event requires no ext … to final state. Requires introduction of S … ng factor:

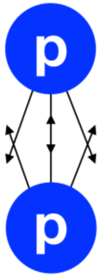
'Large' Pomeron size in the production of the small size objects.

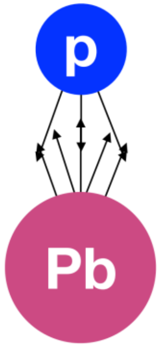
$$T_g(Q_\perp^2,\mu^2) = \exp\left(-\int_{Q_\perp^2}^{\mu^2} \frac{d\mathrm{k}_\perp^2}{\mathrm{k}_\perp^2}\frac{\alpha_s(k_\perp^2)}{2\pi}\int_0^{1-\Delta}\left[zP_{gg}(z)+\sum_q P_{qg}(z)\right]dz\right)$$

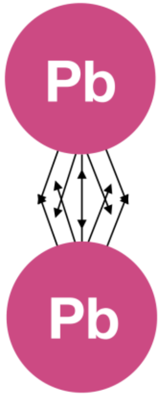
- Increasing M_X $\Rightarrow$ larger phase space for extra gluon emission stronger suppression in exclusive QCD cross section. Gluons like to radiate!

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

The LHC is also a photon collider







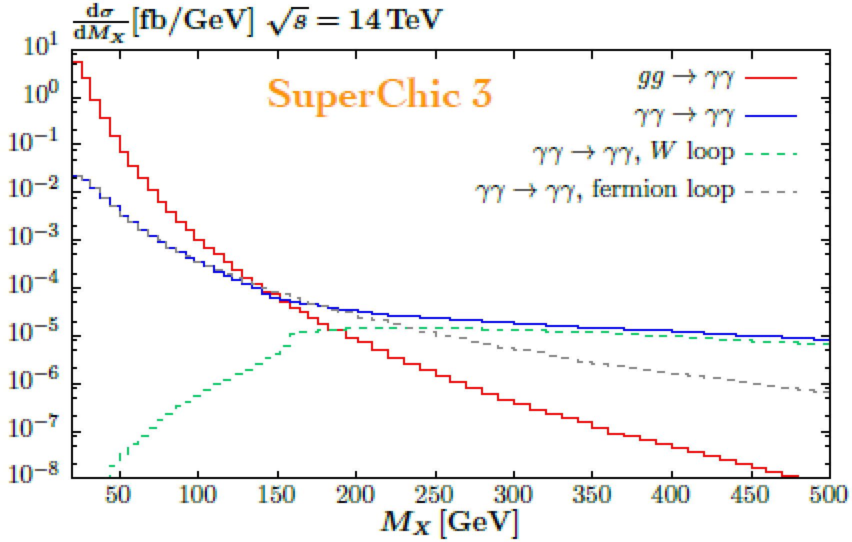
$\sqrt{s}$	13 TeV	8.16 TeV	**5.02 TeV**
$\mathscr{L}$	~140 fb^{-1}	~170 nb^{-1}	**~2 nb^{-1}**
σ	-	$\propto Z^2$	**$\propto Z^4$**

Z = 82 for Pb

1

★ As mass of central system M_X increases, QCD-initiated production cross section suppressed by no radiation probability $\Rightarrow$ BG often low*.

- Example of $\gamma\gamma$ production:



- CEP: unique possibility to observe photon-initiated production of states with EM coupling in clean/well understood environment.

$\sqrt{s_{\gamma\gamma}}$ up to 1-2 TeV

- However typically considering high mass region (RPs) and relatively low cross sections (EM couplings). **Statistics limited**.

$\longrightarrow$ Increased statistics from HL-LHC running offer **clear advantage** here, in particular in terms of pushing to higher mass.

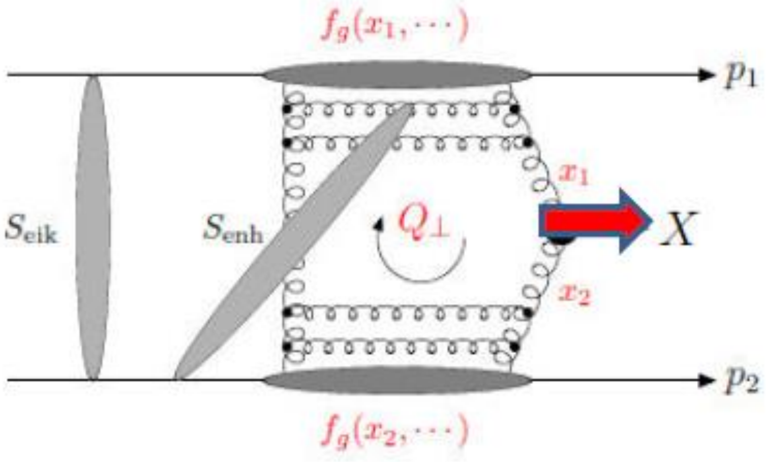
*Precise level depends on particular process.

Currently, pure CEP studies at the LHC are $\gamma\gamma$ dominated (also HIC-UPC)

STANDARD CANDLES

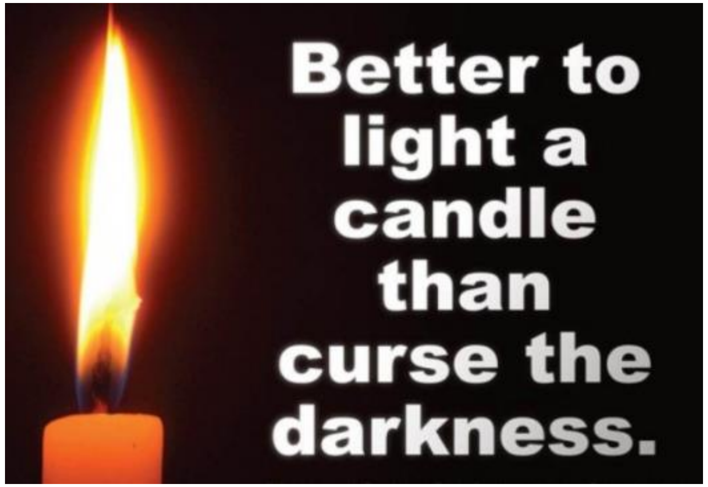
Standard candle central exclusive processes at the Tevatron and LHC

Eur. Phys. J. C (2010) 69: 179–199
DOI 10.1140/epjc/s10052-010-1404-5



(spread of theory predictions)

Exclusive Processes pp→γγ/jj, χ_c, χ_b are standard candles for new physics searches @CEP



K'ung Fu-tzu
Confucius
551 - 479 B.C.E.
Links, Quotes, Bibliography, Sayings, Notes

(Cannot detect p/pbar, down beam pipe, but BSC → η = 7.4 empty)

- CEP is a promising way to study new physics at the LHC, but we can also consider the CEP of lighter, established objects : χ_c, $\gamma\gamma$ and *jj* CEP already observed at the Tevatron. (LHCb RG results)
  - Can serve as 'Standard Candle' processes, which allow us to check the theoretical predictions for central exclusive new physics signals at the LHC, as well as being of interest in their own right[1].
  - the CEP of $\gamma\gamma$ **and light** meson pairs, $M\overline{M}$, at sufficiently high invariant mass for perturbative formalism to be applicable:
    - Provides novel application/test of hard exclusive formalism, complementary to more standard photon-induced processes ($\gamma\gamma \to M\overline{M}$, $\gamma\gamma^{(*)} \to M$ etc[2]).
    - Demonstrates application of MHV formalism to simplify/check calculations.
    - $\pi^0\pi^0$ CEP a possible background to $\gamma\gamma$ CEP.
    - Could probe the $q\overline{q}$ and gg content of η, η' mesons
    - An interesting potential observable @ RHIC, Tevatron and LHC: meson pair CEP data (at lower $p_\perp$) already being taken by ALICE and CDF.

$\gamma\gamma$ production

- 3 candidate events observed by CDF (arXiv:0707.237),

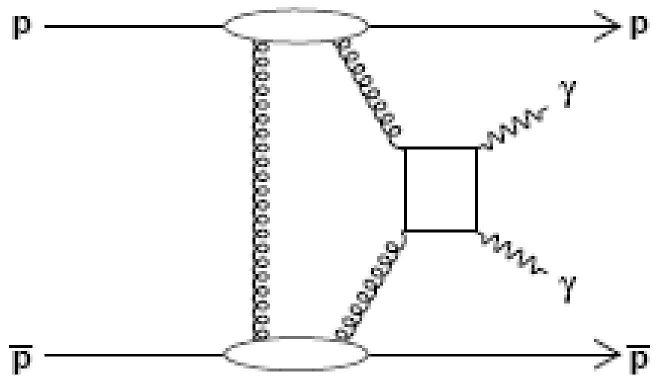
T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. 108, 081801 (2012)

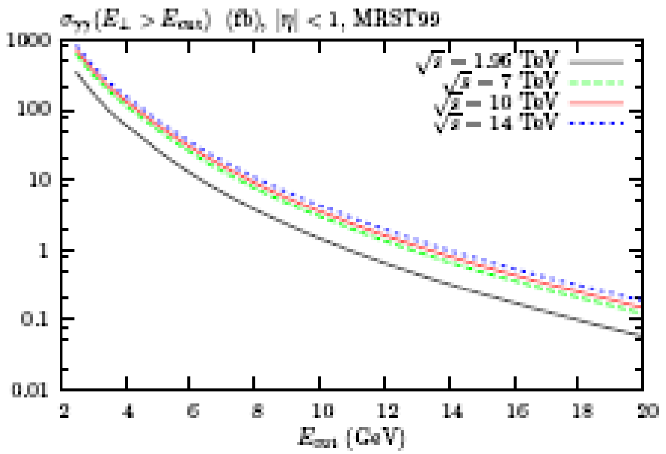
43 events

- Similar uncertainties to χ_c case for low $E_{\perp_\gamma} < E_{\rm cut}$ scale, but this decreases for higher scales.

Et>2.5 GeV

- More CDF events allow us to probe scaling of σ with cut on photon $E_\perp$ ($\lesssim M_{\gamma\gamma}/2$): strong predicted fall-off with $M_{\gamma\gamma}$ driven by Sudakov factor (already seen in dijet data).





(KMRS-04)
(HKRS-10)

- **However**: $\pi^0\pi^0(\eta\eta)$ production, with one photon from each decay either undetected or two photons merging, is a potentially important background (pure QCD process).

proved to be very small (CDF) (in agreement with expectations)

χ_{c1} and χ_{c2}: general considerations

- General considerations tell us that χ_{c1} and χ_{c2} CEP rates are strongly suppressed:
  - χ_{c1}: Landau-Yang theorem forbids decay of a $J = 1$ particle into on-shell gluons.
  - χ_{c2}: Forbidden (in the non-relativistic quarkonium approximation) by $J_z = 0$ selection rule that operates for forward ($p_\perp$=0) outgoing protons. KMR-01 (Tumanov-1953,A. Alekseev-1958-positronium)

RC-numerically suppressed

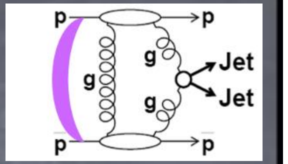
Glueball Filter ??

- However the experimentally observed decay chain $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ strongly favours $\chi_{c(1,2)}$ production, with:

$$\mathrm{Br}(\chi_{c0} \to J/\psi\gamma) = 1.1\% \,,$$
$$\mathrm{Br}(\chi_{c1} \to J/\psi\gamma) = 34\% \,,$$
$$\mathrm{Br}(\chi_{c2} \to J/\psi\gamma) = 19\% \,.$$

- We should therefore seriously consider the possibility of $\chi_{c(1,2)}$

Comparison with KMR



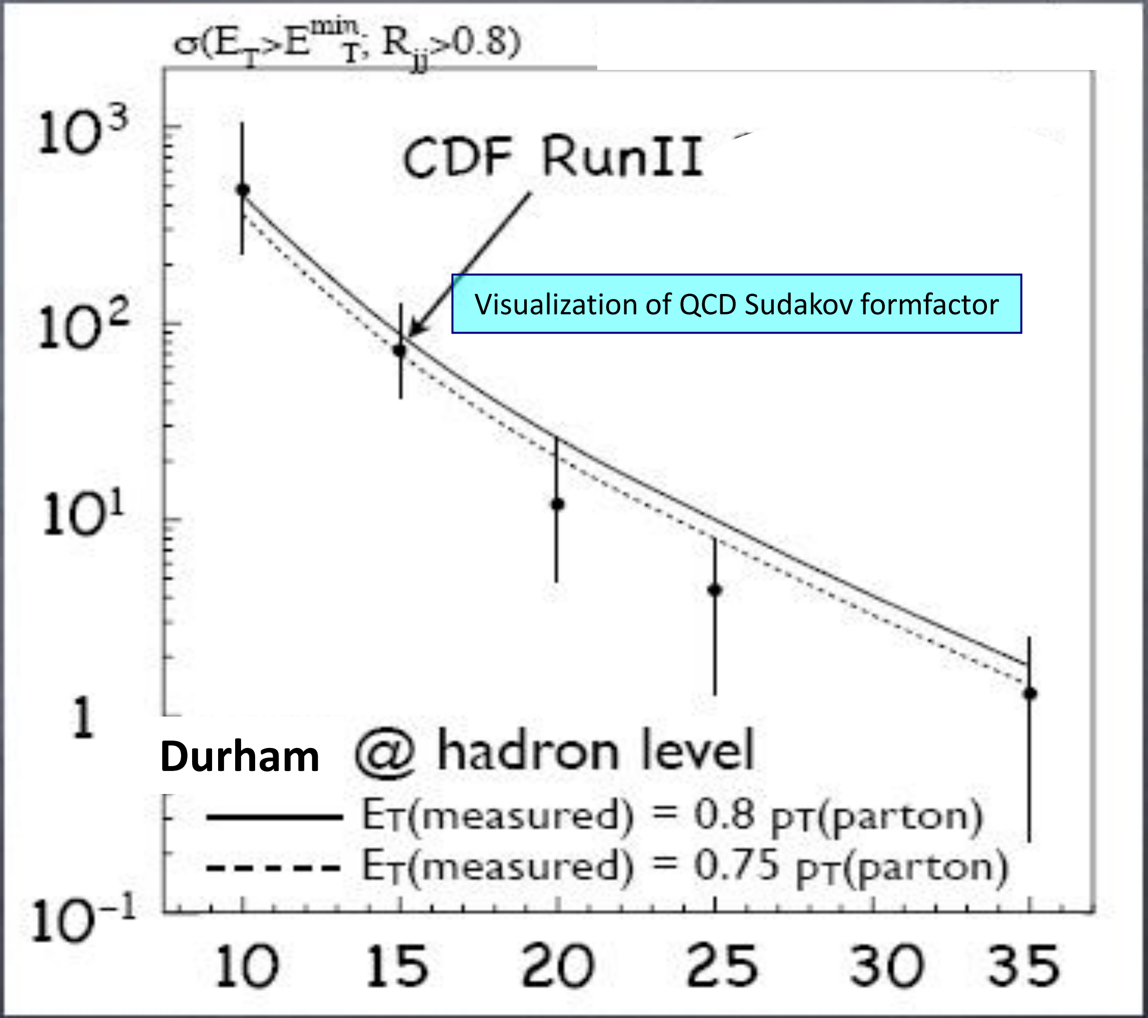
CDF PRD-2008

D0-2010

More direct comparison with KMR calculations including hadronization effects preferred

CDF out-of-cone energy measurement (cone R=0.7) :
- 20-25% at E_T^{jet}=10-20 GeV
- 10-15% at E_T^{jet}=25-35 GeV

Good agreement with data found by rescaling parton p_T to hadron jet E_T



Evidence for exclusive di-jets, with suggestion of depletion of exclusive b-bbar dijets as expected.

Dimeson SAGA

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

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

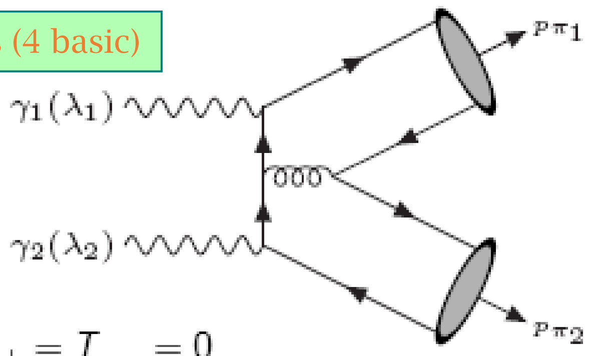
Modeling meson pair CEP perturbatively

- Simpler exclusive process $\gamma\gamma \to M\overline{M}$ $(= \pi^0\pi^0, \pi^+\pi^-, K^+K^-...)$ at large angles was calculated ~30 years ago[3].
- Total amplitude given by convolution of parton level $\gamma(\lambda_1)\gamma(\lambda_2) \to q\overline{q}q\overline{q}$ amplitude with non-perturbative pion wavefunction $\phi(x)$

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

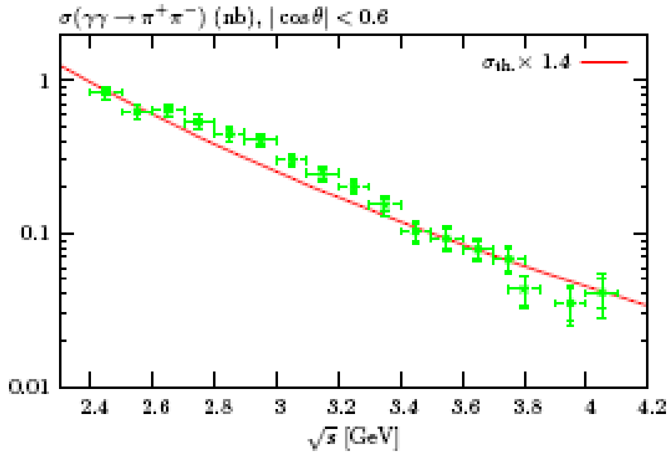
where helicity amplitudes T_{λ_1,λ_2} can be calculated perturbatively.
- With suitable choice of $\phi(x)$ shape, $\gamma\gamma \to M\overline{M}$ data are described quite well (see plot[4].).

40 diagrams (4 basic)



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

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



[3] S. J. Brodsky and G. P. Lepage, Phys. Rev. D 24 (1981) 1808.
[4] Data taken from Belle Collaboration, Phys. Lett. B615 (2005) 39

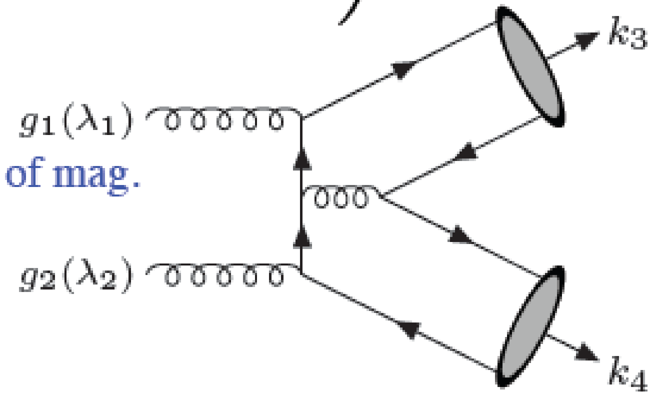
Flavour non-singlet mesons

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



$\longrightarrow J_z = 0$ 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, $|\eta| < 1)$

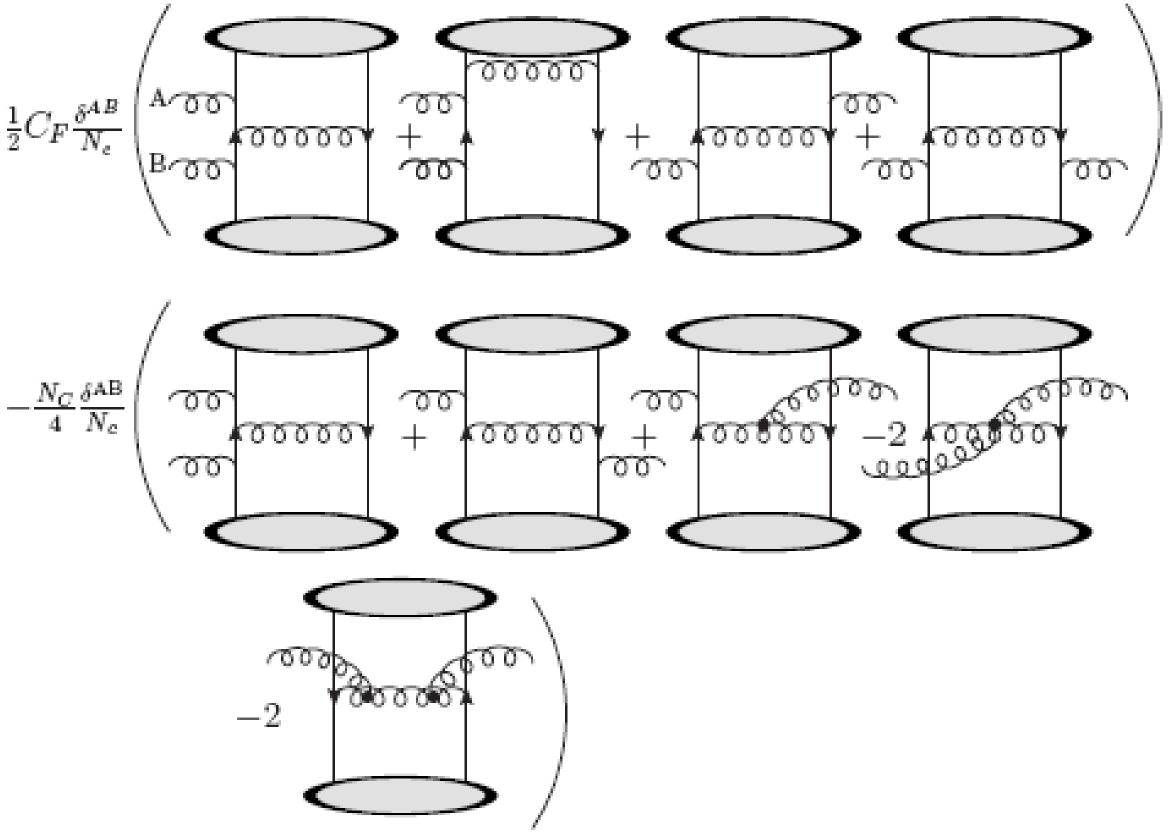
Experiment: $N(\pi^0\pi^0)/N(\gamma\gamma) < 0.35$ @ 95% confidence

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

$gg \to M\overline{M}$ amplitude: Feynman diagrams

Vanishing of T_{++}, T_{--} follows after calculating:

is this easy to understand ?



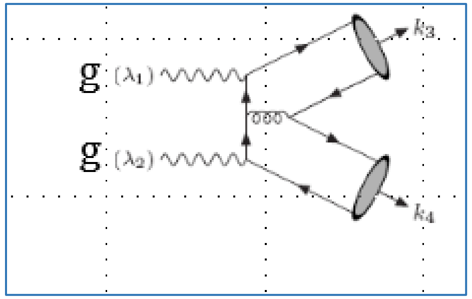
Was popular (among the more formal community) MHV- technique
Nowadays the enthusiasm has a bit faded away- other approaches

[5] M. L. Mangano, S. J. Parke, Phys. Rept. 200 (1991) 301-367

MHV approach

= Maximally Helicity Violating

$gg \to q\bar{q}q\bar{q}, ggq\bar{q}, gggg\ldots$



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

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

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

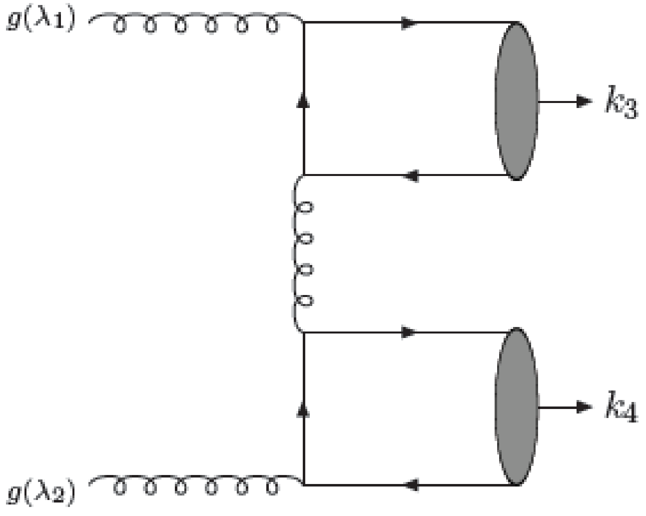
Meson pair production amplitudes represent a novel application of MHV formalism. Take general MHV expressions for n-parton amplitudes, and consider specific (6-parton) kinematics... Colour singlet Collinear

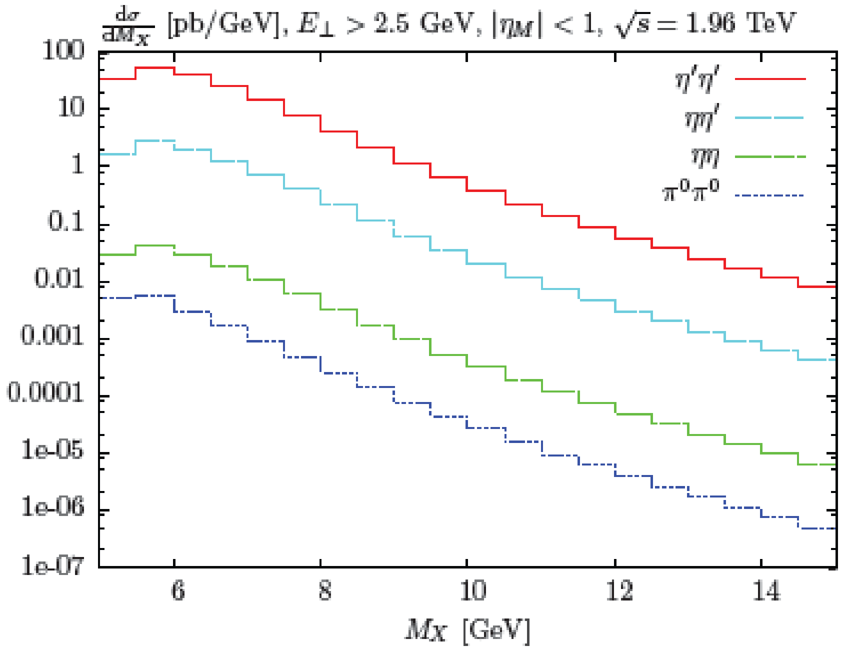
$$\underbrace{\mathcal{M}_n(\{p_i, h_i, c_i\})}_{\text{Total}} = \sum_\sigma \underbrace{T_n(\{c_{\sigma(i)}\})}_{\text{colour}} \underbrace{A_n(\{k_{\sigma(i)}, h_{\sigma(i)}\})}_{\text{kinematic}}$$

one for each non-cyclic ordering

Flavour singlet mesons

- For flavour singlet mesons a second set of diagrams can contribute, where $q\bar{q}$ pair is connected by a quark line.
- For flavour non-singlets vanishes from isospin conservation ($\pi^{\pm}$ is clear, for π^0 the $u\bar{u}$ and $d\bar{d}$ Fock components interfere destructively).
- In this case the $J_z = 0$ amplitude does not vanish $\Rightarrow$ 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!





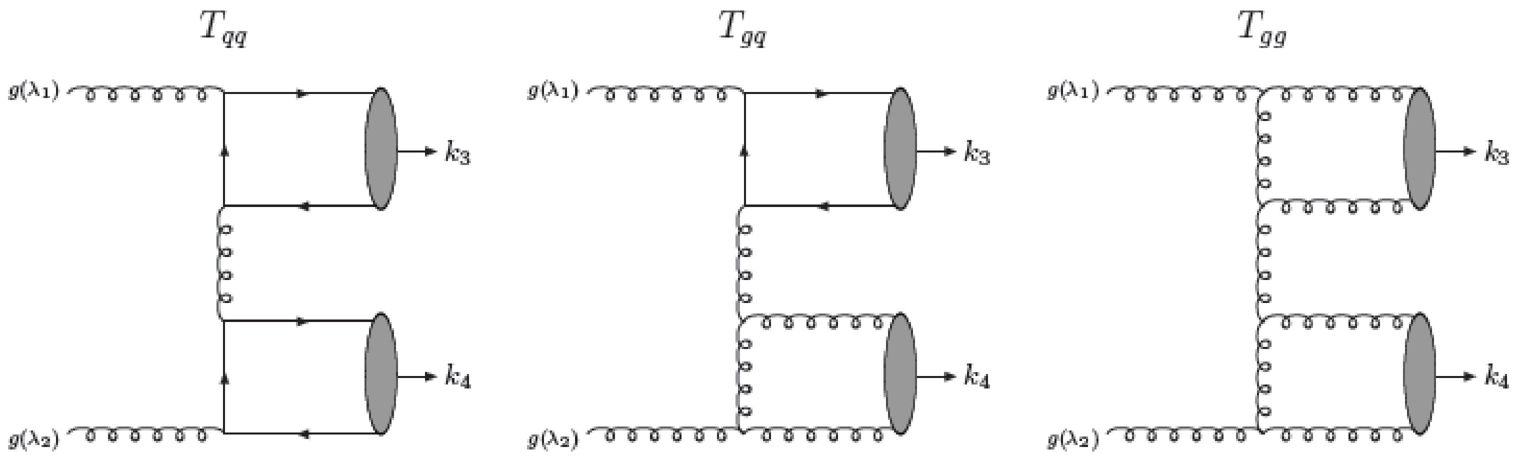
The gluonic component of the $\eta'(\eta)$

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 $gg \to gg q\bar{q}$ and $gg \to gggg$ parton level diagrams.

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



$\longrightarrow$ 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.

$$a^G_{2,\text{fit}}(\mu_0^2) = 19 \pm 5$$

extracted from the transition form factors $F_{\eta(\prime)\gamma}(Q^2)$

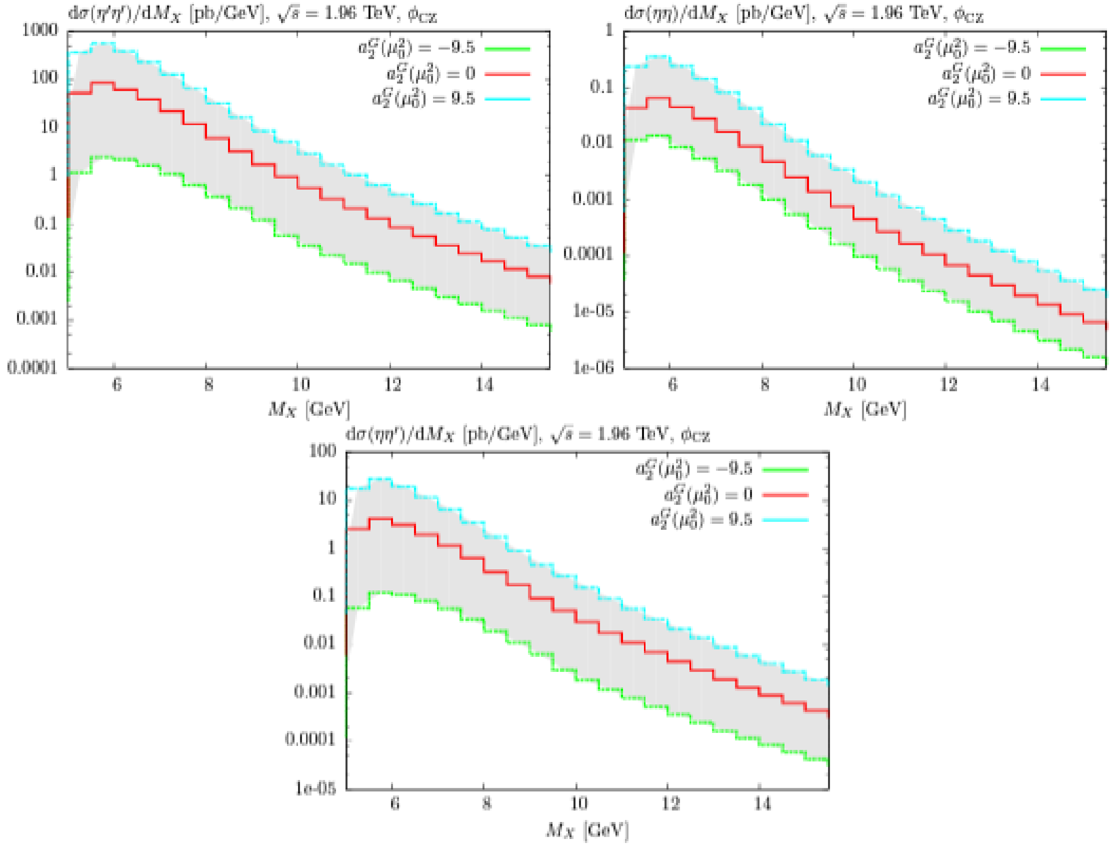


Figure 6: Differential cross section $d\sigma/dM_X$ for $X = \eta'\eta', \eta\eta, \eta\eta'$ production at $\sqrt{s} = 1.96$ TeV with MSTW08LO PDFs [53], taking the CZ form (3.4) for the quark distribution amplitude, and for a band of $a_2^G(\mu_0^2)$ values for the gg distribution amplitude. The mesons are required to have transverse energy $E_\perp > 2.5$ GeV and pseudorapidity $|\eta| < 1$.

OTHER SELECTED CEP TOPICS

χ_b CEP

- Higher χ_b mass means cross section is more perturbative and so is better test of theory, although rate is ~ 3 orders of magnitude smaller than χ_c.
- J assignment of χ_b states still experimentally undetermined: CEP could shed light on this.
- Calculation exactly analogous to χ_c case

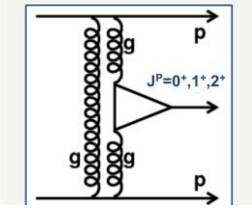
$$|V_{0+}|^2 : |V_{1+}|^2 : |V_{2+}|^2 \sim 1 : \frac{\langle \mathbf{p}_\perp^2 \rangle}{M_\chi^2} : \frac{\langle \mathbf{p}_\perp^2 \rangle^2}{\langle \mathbf{Q}_\perp^2 \rangle^2} \sim 1 : \frac{1}{400} : \frac{1}{36}$$

$\rightarrow$ Do not expect to see χ_{b1}, which is strongly suppressed by χ_b mass.

- Measurement of ratio of χ_b to $\gamma\gamma$ ($E_\perp = 5$ GeV) CEP rates would eliminate certain uncertainties (i.e. dependence on survival factors).
- Predictions for χ_b CEP via the $\Upsilon\gamma$ decay chain (at $y_\chi = 0$):

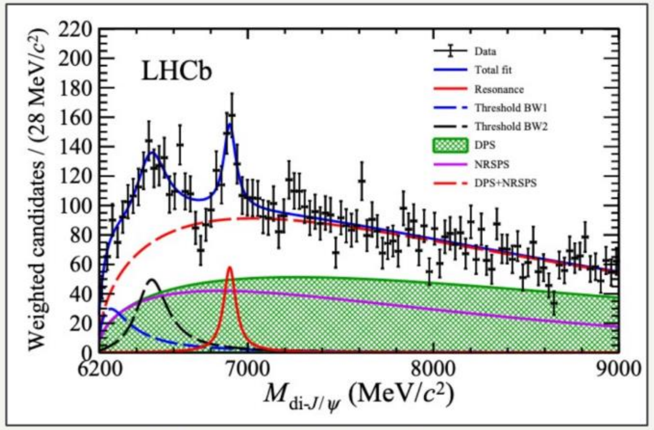
$\sqrt{s}$ (TeV)	1.96	7	10	14
$\frac{d\sigma}{dy_{\chi_b}}(pp \to pp(\Upsilon + \gamma))$ (pb)	0.60	0.75	0.78	0.79
$\frac{d\sigma(1^+)}{d\sigma(0^+)}$	0.050	0.055	0.055	0.059
$\frac{d\sigma(2^+)}{d\sigma(0^+)}$	0.13	0.14	0.14	0.14

Tetraquarks in Central Exclusive Production



J/ψJ/ψ: search for exotica

Structure seen in **inclusive** production of J/ψ+ϕ.



Sci.Bull. 65 (2020) 23, 1983-1993

Tetraquarks in CEP

Today from **inclusive** measurements we know there is significant structure and tetraquark candidates

Diffractive measurements are cleaner and help identify quantum numbers

What is production mechanism for tetraquark states ?

Can molecular states be produced in CEP?

Can tightly bound 4-quark states be produced in CEP?

$c\bar{c}c\bar{c}$. v $c\bar{c}s\bar{s}$

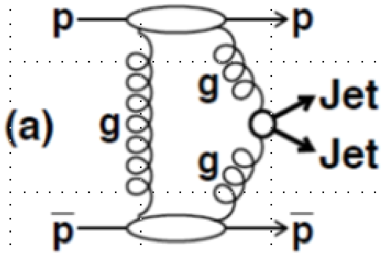
Dijet CEP as a ‘Gluon Factory’

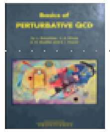
Dijet-monitor for new physics

- QCD-induced baseline high mass channels- exclusive jets and Higgs.

★ **Exclusive jets:**

- Exclusive jets: CEP theory: dominantly gg colour singlet dijets. Large numbers of essentially pure gluon jets in a clean environment





(~20 mln pure q-jets vs 417 ‘tagged’ g at LEP)

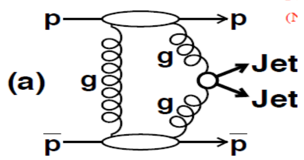
- New QCD regime - data from Tevatron

First ATLAS ST results.

$p_\perp^j > 25\,\mathrm{GeV}$

M_{jj} [GeV]	$\sigma(gg)$ [pb]
100	35
200	1
300	0.14
400	0.024
500	0.0053
600	0.0014

EXCLUSIVE JET PRODUCTION



- **Precisely defined** CEP mechanism $\longrightarrow$ colour singlet gg initial-state with certain $(++/--)$ helicity configurations ($J_z = 0$). In CEP:

$gg \to q\overline{q}$: **Vanishes** for massless quarks - suppressed as $\sim m_q^2/M_{jj}^2$

$gg \to gg$: **Unsuppressed** $\longrightarrow$ gluon dominated jets.

- Possibility to study dominantly **isolated** gg jet production at LHC.

- Taking e.g. $m_b = 4.5$ GeV and $M_X = 40$ GeV we then get

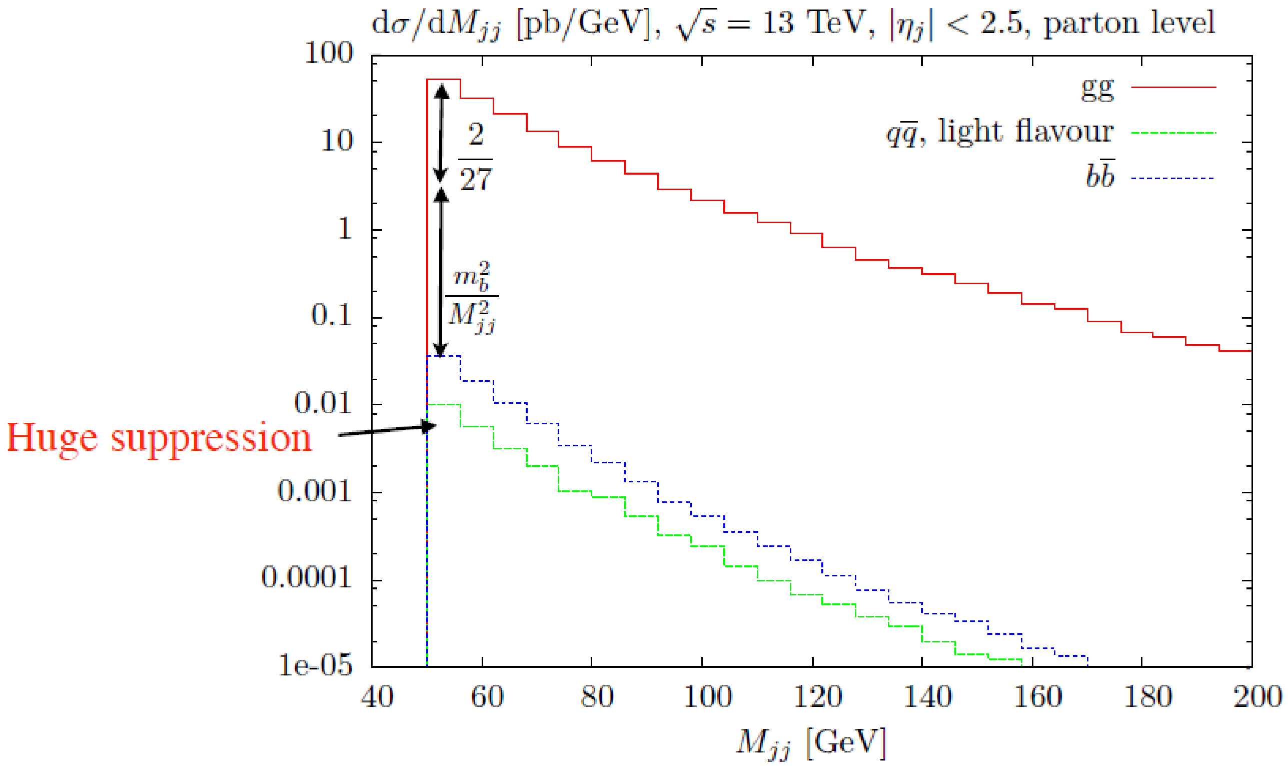
$$\frac{\mathrm{d}\sigma(b\overline{b})/\mathrm{dt}}{\mathrm{d}\sigma(gg)/\mathrm{dt}} \approx 10^{-3}$$

(CDF-2008)

$\longrightarrow$ Huge suppression in b quark jets (increasing with M_X). Completely unlike inclusive case.

LHC cross sections

As expected from above discussion, expect strong gg dominance:



SuperChic-2

Summary & Conclusions

- **F**orward **P**roton **T**agging significantly could extend the physics reach of the ATLAS and CMS detectors by giving access to a wide range of exciting new physics channels.

- **FPT** has the potential to make measurements that are unique at LHC.

- **FPT** *could* serve as a spin-parity analyser and offers a sensitive probe of the CP structure of the new states.

- There are a number of important measurements to be performed in the RG environment at LHCb and ALICE at low μ.

- The theory of the CEP is in a reasonably healthy shape, and dedicated MCs (such as SCs) are well developed

- The predictions are backed by the series of CDF/D0 CEP-like measurements as well as the RAP GAP measurements by the LHCb and ALICE +CEP results from ATLAS& CMS

10ps in Run 4

- The dedicated AFP and PPS detectors allow uinge the timing.
  The main issue is PU suppression, though some progress is foreseen,
  in particular with the addition of timing from the CD.

But ATLAS has already decided not to run AFP at HL-LHC
(at least not in the foreseeable future)

- At large M_{Mmis}> 150-200 GeV the photon-photon fusion dominates over the gg. LHC is the photon-photon collider!

- Such important measurements as the searches for the new Higgs-like states (e.g. resolving the 96 GeV puzzle) , as well as the moderately-heavy instantons, would require the 420 m stations.

- The bulk of important physics (such as glueball,instantons and other new state searches) would require low luminosity runs.