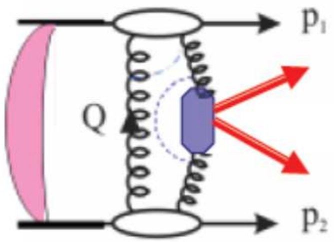
Central Exclusive Processes at Hadron Colliders
(Selected Topics)

V.A. Khoze (IPPP, Durham and PINP)

(in collaboration with Lucian HArland-Lang and Misha RYSkin)

KHARYS

CEP = 



Outline

- **Introduction (why we are interested in collecting CEPs ?)**

- **Standard Candle CEP reactions.**
- **CEP as a way to study old and new heavy resonances**
  - CEP: general theory.
  - χ_c CEP:
    - $\chi_{c(1,2)}$ suppression.
    - χ_c CEP with and without tagged protons.
    - $\chi_c \to \pi\pi, KK \ldots$
  - Don't forget: η_c, χ_b, η_b production...
  - Exotic states: X(3872)...
- **Dimeson and** $\gamma\gamma$ CEP
- **Update on exclusive Higgs production**

- **Summary and Outlook.**

Introduction (why we are interested in CEP ?)

Why are we interested in central exclusive χ_c (χ_b, $\gamma\gamma$, jj) production?

- Driven by same mechanism as Higgs (or other new object) CEP at the LHC.

D0 jj- results, LHCb χ_c
CMS, RHIC data expected

- χ_c, jj and $\gamma\gamma$ CEP has been observed by CDF.

→ Can serve as 'Standard Candle' processes, which allow us to check the theoretical predictions for central exclusive new physics signals at the LHC.

- $\chi_{c,b}$ production is of special interest:
  - Heavy quarkonium production can shed light on the physics of bound states (lattice, NRQCD$\cdots$).
  - Potential to produce different J^P states, which exhibit characteristic features (e.g. angular distributions of forward protons).
  - Possibility to shed light on the various 'exotic' charmonium states observed recently (X,Y,Z) charmonium-like states.

Spin-Parity Analyzer (KMR-00, KKMR-2003)

- Detailed tests of dynamics of soft diffraction (KMR-02)

Why is it interesting?

- '$J_z = 0$ selection rule': production of non-$J_z^{PC} = 0^{++}$ states heavily suppressed, allowing a clean determination of the central object quantum numbers.
  - Higgs CEP: central exclusive $b\bar{b}$ background vanishes at LO (for massless quarks).

- Outgoing proton momenta can be measured by Roman Pot (RP) detectors down the beam line:
  - The proton energy loss is directly related to the central system mass $M_X^2 \approx \xi_1 \xi_2 s$, allowing a high resolution 'missing mass' measurement.
  - Proton tagging can also provide spin and parity information about the central system as well as the structure of the proton and models of soft interactions.

- FP420 R&D collaboration: proposed installation of RP detectors at 420m from ATLAS (AFP) and CMS (PPS) (arXiv:0806.0302), although UK funding of AFP is cut, PPS@CMS and AFP ($\sim$ 220m) both expected to be approved for installation **hopefully**…

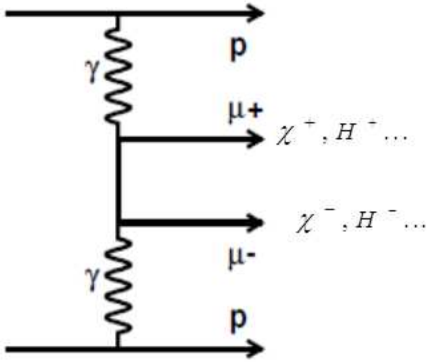
- RP detectors are already installed at RHIC, where data with *pp* collisions are being taken for $\sqrt{s} \leq 500$ GeV.

- Totem-CMS measurements, ongoing discussions in LHCb and Alice NEW!

CENTRAL EXCLUSIVE PRODUCTION PROCESSES

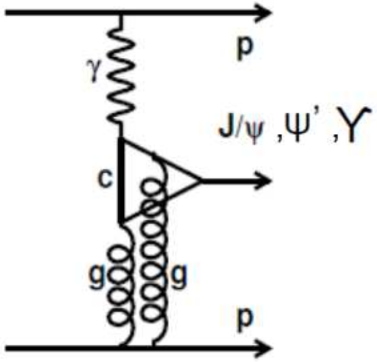
- Elastic process, intact protons continuing down beampipe
- Exchange of colourless objects (photon, pomeron)

diphoton fusion



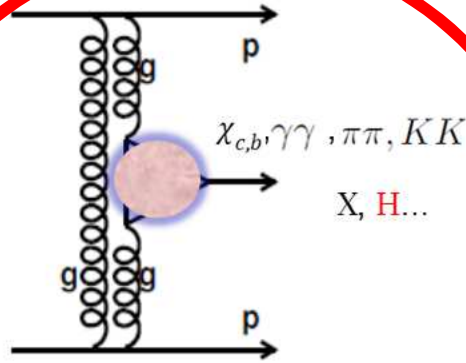
$\chi^+\chi^-$

γ-pomeron fusion



$\psi(3770)\dots$

dipomeron fusion



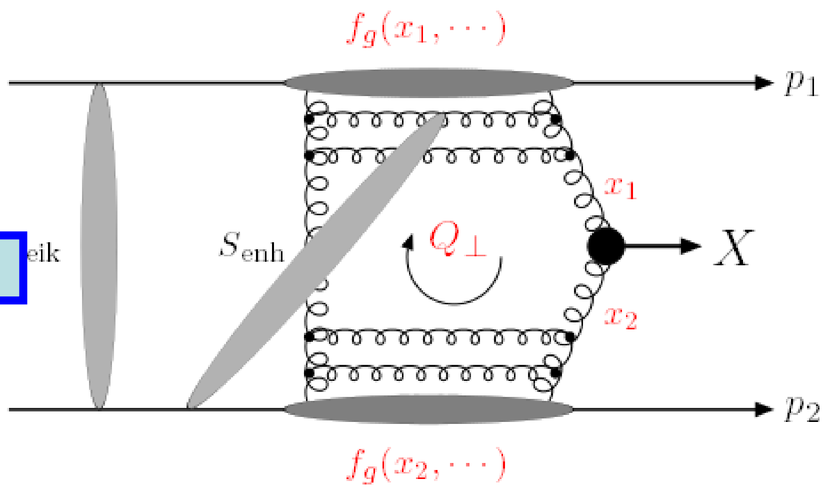
$(c\bar{c}, b\bar{b}, D\bar{D}\dots)$

(odderon searches)

‘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 (a lot of attention, (Asher’s talk))
- In the limit that the outgoing protons scatter at zero angle, the centrally produced state X must have $J_Z^P = 0^+$ quantum numbers.



Calculating CEP : ingredients

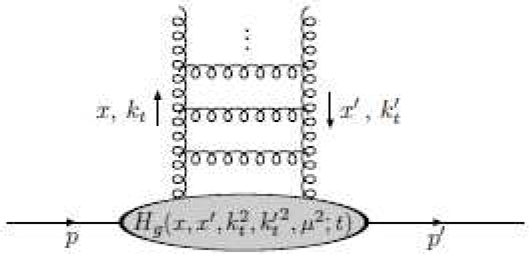
- Soft Survival probability:
  - Non-perturbative object, must take a physical model of hadronic interactions, fitted to soft hadronic data. 'State of the art' models roughly consistent.

Khoze, Martin Ryskin Gotsman, Levin, Maor (S. Ostapchenko)

G. Antchev et al. [TOTEM Collaboration], Europhys. Lett. 101 (2013) 21004 etc

  - Recent TOTEM data on total, elastic and diffractive cross sections has been imporant guide for LHC predictions.

See arXiv:1306.2149 for latest KMR model, accounting for TOTEM



- 'Skewed' PDFs:
  - Correspond to gg coupling to proton for relevant kinematics
  - In the CEP regime can be calculated via usual global PDFs.
- Sudakov factor:

See LHL, PRD 88, 034029 (2013) for latest results.

  - Resums higher order logs in $Q_\perp/M_X$, ensuring IR stable result and validity of perturbative treatment.

Important to include all factors correctly!

One step forward, two steps back (V.I. Lenin)

'Standard Candle' processes

- CEP is a promising way to study new physics at the LHC (light Higgs CEP as well...), but we can also consider the CEP of lighter, established objects : χ_c, $\gamma\gamma$ and jj CEP already observed at the Tevatron, χ_c at the LHC, with more to come... LHCb, CMS, (Totem-CMS)
- 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[2].
- Some examples are:
  - χ_c ($\rightarrow J/\psi\gamma$, $\pi^+\pi^-$, K^+K^-...).
  - Light meson pairs ($\pi\pi$, KK, $\eta(')\eta(')$...). (soon to come CMS, Totem-CMS, LHCb, RHIC)
  - Diphotons $\gamma\gamma$.
  - Dijets jj. (D0, Totem-CMS,....AFP/PPS).

(CDF)

(so far all available CEP data in a good agreement with Durham)

[2] See e.g. LHL, V.A. Khoze, M.G. Ryskin, W.J. Stirling, arXiv:1005.0695, arXiv:1105.1626 arXiv:1204.4803.

New Durham Studies

(known unknowns)

- Account for the b-dependence of the survival factors S^2_{enh}, S^2_{eik}

- NLO effects in the unintegrated parton densities:
  (N)NLO-effects in the hard ME.

- A systematic account of self–energy insertions in the propagator of the screening gluon

- The dependence on the gluon PDF is amplified by the fact that the CEP cross section is essentially proportional to $(xg(x))^4$.

CDF $\gamma\gamma$ data *may* suggest more 'LO–type' PDFs ($\rightarrow$ more optimistic Higgs cross sections) are appropriate.

(Mike's talk)

Improvements of models for soft diffraction: removing tensions with Totem data on σ_{el} and σ_{tot},
agreement with the LHC results on low mass SD,
agreement with the Tevatron/LHC data on CEP processes
subprogram to SuperCHIC to calculate S^2 -KHARYS -13

(KMR, arXiv:1306.2149)

(Asher's talk)

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 photoproduc $+\ \psi(2S)$
  - $\gamma\gamma$ 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.

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

New Dime MC (Harland-Lang, Khoze, Ryskin- 2013)

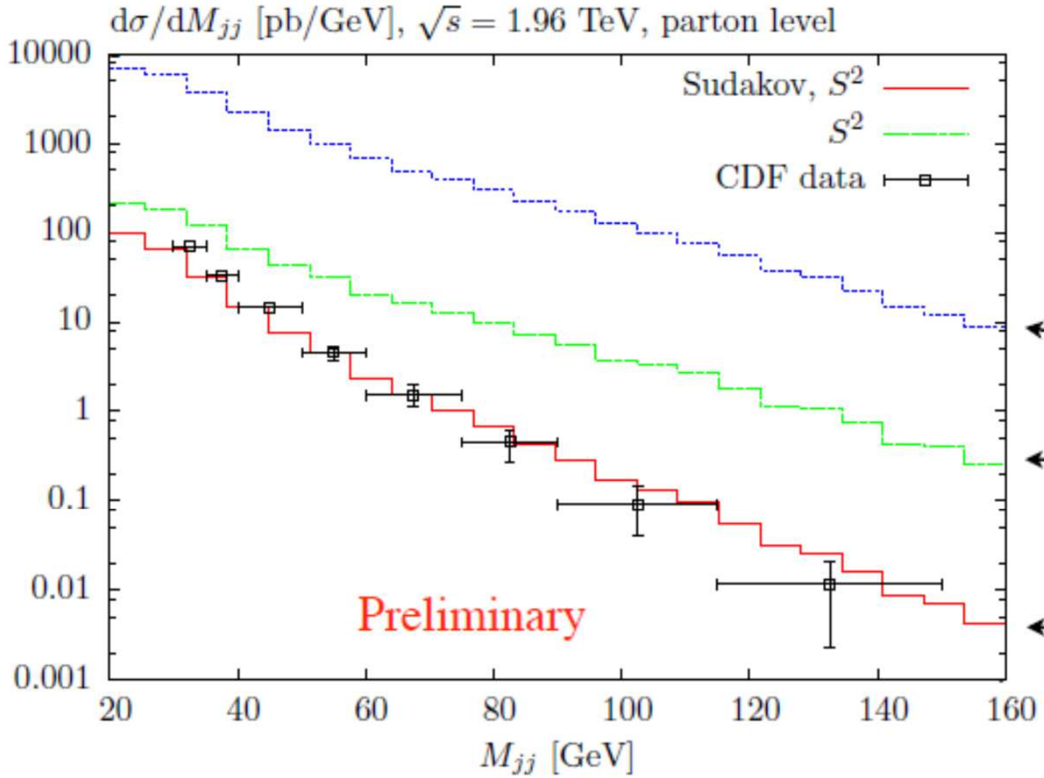
New SuperCHIC MC

Tevatron cross sections

CDF Collab., Phys.Rev.D77:052004,200

- Can compare results of the MC with the CDF measurement.
- See clearly how both soft survival effects and Sudakov factor (non-pert. and pert. physics) are crucial to describe data.

Probability to produce colour singlet dije state drops strongly with M_{jj}



Soft survival not included, scale of Sudakov factor frozen

Soft survival included, scale of Sudakov factor frozen

Soft survival included, scale of Sudakov factor $\sim M_{jj}$

All predictions made with MSTW08LO PDFs

CEP as a way to study old and new heavy resonances.

- Heavy Quarkonia
- Zoo of charmonium –like XYZ states

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 (A. Alekseev-1958-positronium)
- 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 $\chi_{c(1,2)}$

(R.Pasechnik et al, Phys.Lett.B680:62-71,2009; HKRS, Eur.Phys.J.C65:433-448,2010)

(Krakow group)

- The effects of non-zero p_T (especially for 2^+).

...and especially without proton detectors!

Cross section results (1)

- We find the following approximate hierarchy for the spin-summed amplitudes squared (assuming an exponential proton form factor $e^{-b\mathbf{p}_\perp^2}$):

$$|V_0|^2 : |V_1|^2 : |V_2|^2 \sim 1 : \frac{\langle \mathbf{p}_\perp^2 \rangle}{M_\chi^2} : \frac{\langle \mathbf{p}_\perp^2 \rangle^2}{\langle \mathbf{Q}_\perp^2 \rangle^2} . \qquad (2)$$

- This $\sim 1/40$ suppression for the $\chi_{c1,2}$ states will be compensated by the larger $\chi_c \to J/\psi\gamma$ branching ratios, as well as by the larger survival factors $S^2_{\rm eik}$ for the more peripheral reactions.
- An explicit calculation gives (for the perturbative contribution):

$$\frac{\Gamma^{\chi_0}_{J/\psi+\gamma}}{\Gamma^{\chi_0}_{\rm tot}} \frac{{\rm d}\sigma^{\rm pert}_{\chi_{c0}}}{{\rm d}y} : \frac{\Gamma^{\chi_1}_{J/\psi+\gamma}}{\Gamma^{\chi_1}_{\rm tot}} \frac{{\rm d}\sigma^{\rm pert}_{\chi_{c1}}}{{\rm d}y} : \frac{\Gamma^{\chi_2}_{J/\psi+\gamma}}{\Gamma^{\chi_2}_{\rm tot}} \frac{{\rm d}\sigma^{\rm pert}_{\chi_{c2}}}{{\rm d}y} \approx$$ **1 : 0.6 : 0.22**

- Note: these approximate values carry a factor of $\sim \stackrel{\times}{\div} 1.5 - 2$ uncertainty.

- First ‘exclusive’ events now being seen at LHCb. Results suggestive of a sizeable χ_{c2} contribution.

News

From CDF dipion/KK CEP : $< 25\%$ of the $J/\psi + \gamma$ events

(Mike’s talk)

χ_c CEP: data

- In arXiv:0902.1271 CDF reported 65 ± 10 signal χ_c events observed via the $\chi_c \to J/\psi\gamma \to \mu^+\mu^-\gamma$ decay channel. This corresponds to $\mathrm{d}\sigma(\chi_c)/\mathrm{d}y_\chi|_{y=0} = (76 \pm 14)\,\mathrm{nb}$, in good agreement with Durham prediction of ~ 60 nb.
- Recent LHCb data[3]: select 'exclusive' $\chi_c \to J/\psi\gamma$ events by vetoing on additional activity in given η range.
- LHCb see:

	$\frac{\sigma(pp\to pp(\mu^+\mu^-+\gamma))}{\mathrm{Br}(J/\psi\to\mu^+\mu^-)\mathrm{Br}(\chi_{cJ}\to J/\psi\gamma)}$ LHCb (nb)	SuperCHIC (nb)
χ_{c0}	13 ± 6.5	20
χ_{c1}	0.80 ± 0.35	0.49
χ_{c2}	2.4 ± 1.1	0.26

→ See clear suppression in $\chi_{c(1,2)}$ states.

→ Good data/theory agreement for $\chi_{c(0,1)}$ states (within quite large theory uncertainty), but a significant excess of χ_{c2} events above theory prediction for CEP.

[3] LHCb-CONF-2011-022

- A clear way to resolve the issue of χ_c spin-parity identification will be to search for the two-body decays:

KMRS-2004

$$Br(\chi_{c0} \to \pi\pi, K^+K^-) \simeq 1.3\% \qquad \chi_{c1}, \eta_c \not\to \pi\pi, KK \qquad Br(\chi_{c2} \to \pi\pi, K^+K^-) \simeq 0.3\%$$

$$Br(\chi_{c0} \to p\bar{p}) \simeq 2*10^{-4} \qquad Br(\chi_{c1} \to p\bar{p}) \simeq 6.6*10^{-5} \qquad Br(\chi_{c2} \to p\bar{p}) \simeq 6.7*10^{-5}$$

$$Br(\eta_c \to p\bar{p}) \simeq 0.13\%$$

- Tagged forward protons: spin-parity ID of old and new heavy meson states, detailed tests of absorption effects

News

First CDF limits -2013

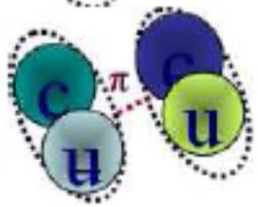
(Mike's talk)

We previously observed [5] exclusive χ_c^0 production in the mode $J/\psi(\to \mu^+\mu^-) + \gamma$, but could not distinguish the three χ_c states. The $\pi^+\pi^-$ and K^+K^- channels have larger branching fractions and enough resolution to separate the χ_c states. We do not see significant signals in this data, and give upper limits (90% C.L.) on $d\sigma/dy|_{y=0}(\chi_{c0}) = 21.4\pm4.2$(syst.)nb (in $\pi^+\pi^-$) and 18.9 ± 3.8(syst.)nb (in K^+K^-). This implies that $< 25\%$ of the $J/\psi + \gamma$ events were $\chi_{c0}(3415)$. Even though the $\chi_{c2}(3556)$ may have a much smaller production cross section its branching fraction is $17\times$ larger.

Zoo of charmonium –like XYZ states

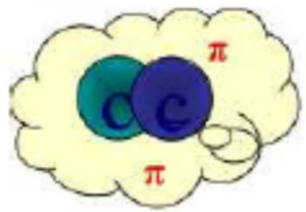
Tetraquark:
four tightly bound quarks

Molecular state:
two loosely bound mesons



Hybrid: states with
excited gluonic degrees of freedom

Hadrocharmonium: charmonium state,
“coated” by excited light-hadron matter



- X(3872) –
- XYZ(3940) & X(3915) –
- Y(4140)/Y(4280) & X(4350)

PDG'12

$M_{X(3872)} - (M_{D^0} + M_{D^{*0}}) = -0.16 \pm 0.32$ MeV

	Relative BF
$J/\psi\,\rho$	1
$J/\psi\,\omega$	0.8 ± 0.3
$J/\psi\,\gamma$	0.21 ± 0.06
$D^0\bar{D}^{*0}$	~ 10

isospin violation

$J^{PC} = 1^{++}$

Most likely interpretation:

DD* molecule with admixture of $\chi_{c1}(2P)$

isospin violation

production at high energy

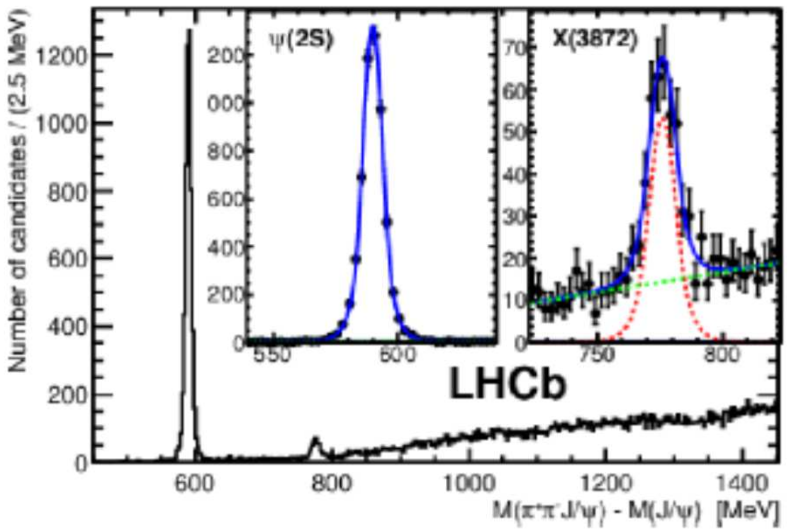
Fractions of admixtures? Bound or virtual?
Dynamical model?

Experimental issues:

- δM (D^0 mass uncertainty dominates)
- $\psi(2S)\,\gamma$ (Belle/BaBar controversy)
- line-shape in $D\bar{D}^*$ (statistics limited)
- absolute BF (inelastic channels?)

The future (?): X(3872)

- Discovered by Belle in 2003, confirmed by Babar, at the Tevatron and the LHC.
- Could be of exotic nature: loosely bound hadronic molecule, diquark-antidiquark ('tetraquark') and hybrid ($\bar{c}cg\cdots$). However, conventional $c\bar{c}$ interpretation is still possible.

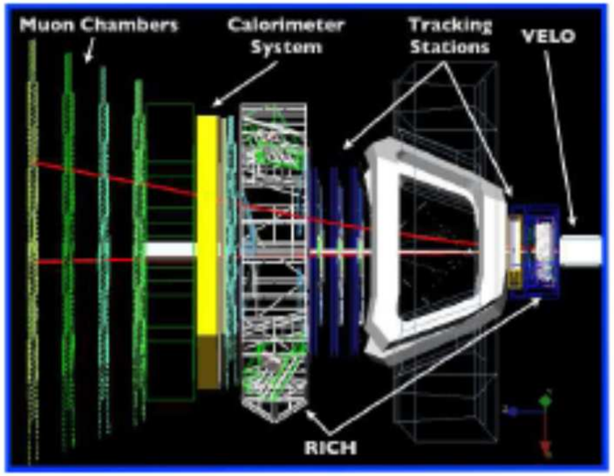


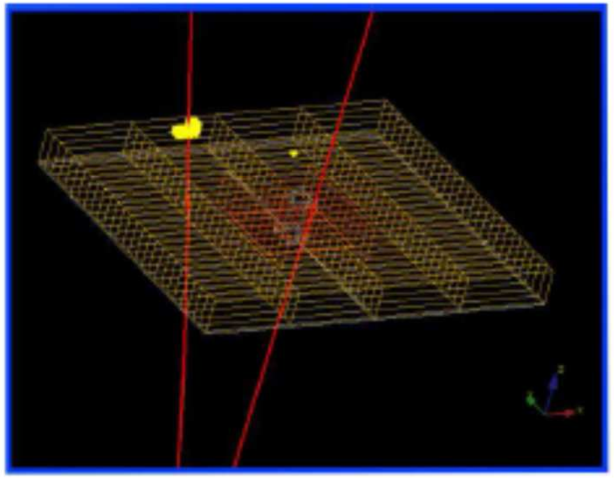
- Possible J^{PC} assignments were 1^{++} or 2^{-+}.
- New LHCb data (arXiv:1302.6269) rejects 2^{-+} at 8 sigma level $\rightarrow \eta_{c2}(1^1D_2)$ ruled out.
- Exotic interpretations still possible or conventional $\chi_{c1}(2^3P_1)$ charmonium? Or admixture?

Insight from CEP

- In CEP the state X is produced directly, i.e. at short distances: $gg \to X(3872)$ and nothing else. $\to$ would be clear evidence of a direct production mode.
- In an inclusive environment, for which additional soft quarks, D–mesons etc can be present/emitted it should be easier to form molecular state. Will expect additional suppression in exclusive case.

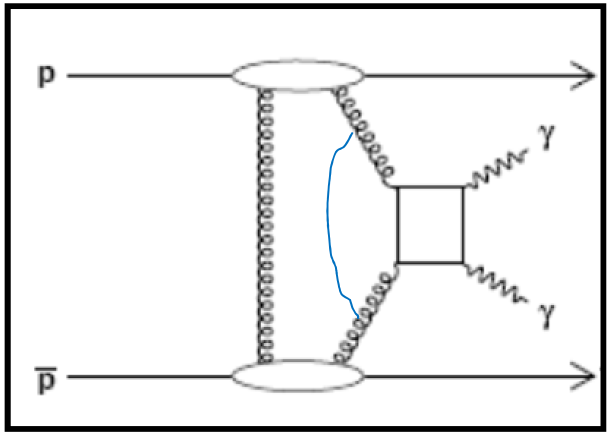
$\to$ Can shed further light by comparing to the rate of $\chi_{c1}(1^3P_1)$ production, as seen by LHCb. Up to mass effects, cross section ratio should be given by ratio of squared wavefunction derivatives at the origin $|\phi'_P(0)|^2$.

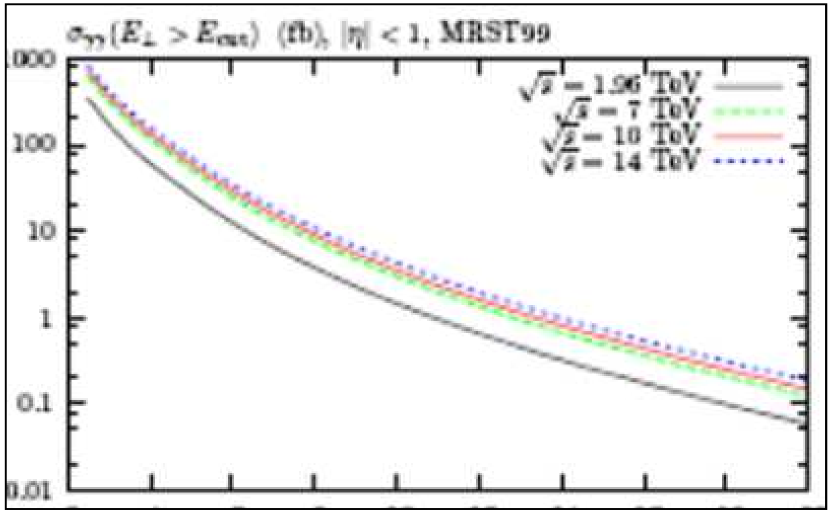




Good Luck to LHCb

- 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.(new LHC results)





- 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.

(LHCb,CMS, Totem+CMS- news)

$\gamma\gamma$ CEP

- Clean probe of theory: ideal 'Standard Candle' for higher mass CEP.
- Highly sensitive probe of gluon density at low x and Q^2 . CDF collaboration, PRL 108, 081801 (2012)
- Measured by CDF: $\sigma_{\gamma\gamma} = 2.48^{+0.40}_{-0.35}$ (stat) $^{+0.40}_{-0.51}$ (syst) pb

for $E_\perp$ >2.5 GeV, $|\eta_\gamma| < 1$ HKRS: EPJC 72 (2012) 2110

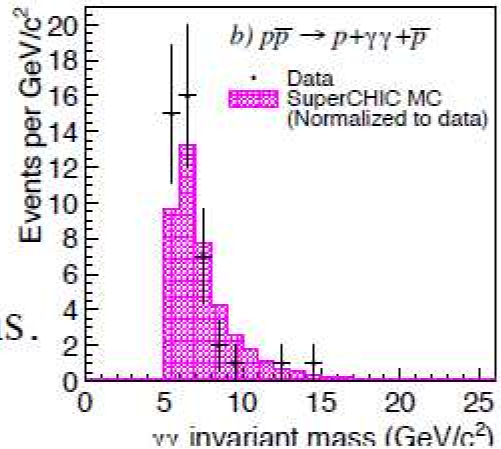
- In good agreement with Durham **pre**dictions:

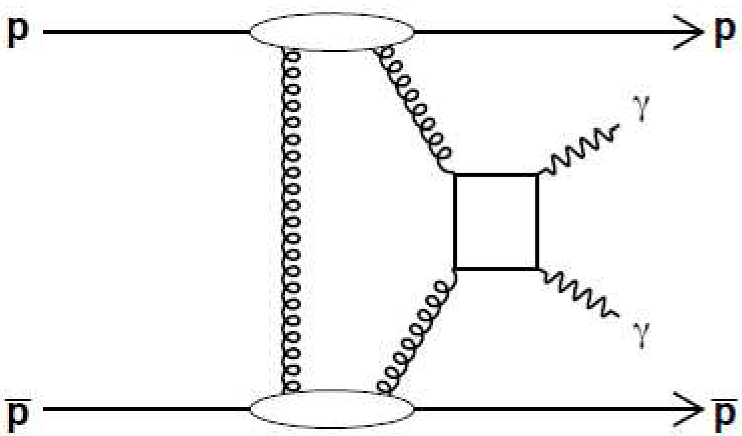
	MSTW08LO	CTEQ6L	GJR08LO
$\sqrt{s} = 1.96$ TeV $(\lvert\eta\rvert < 1)$	1.4	2.2	3.6

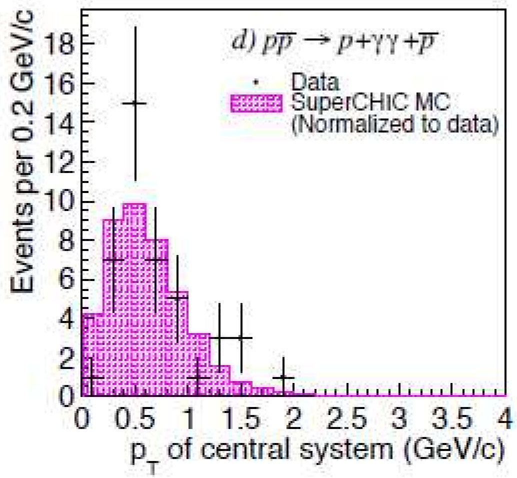
- CMS have set limits close to Durham LHC predictions.

CMS-PAS-FWD-11-004.

$\Rightarrow$ No room for much larger S^2 at the LHC







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 $$M = \pi, K, \rho, \eta, \eta' ...$$

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

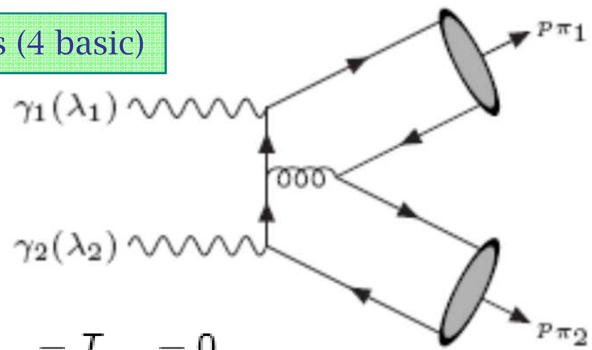
Modeling meson pair CEP perturbatively

- 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 $\phi(x)$

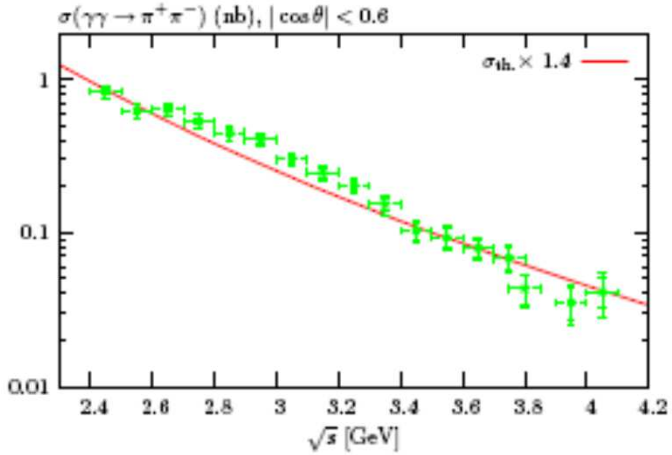
$$\mathcal{M}_{\lambda_1\lambda_2}(s,t) = \int_0^1 \mathrm{d}x\,\mathrm{d}y\,\phi(x)\phi(y)T_{\lambda_1,\lambda_2}(x,y;s,t)$$

where helicity amplitudes $T_{\lambda_1\lambda_2}$ 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)



✳ $T_{++} = T_{--} = 0$



[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

(M.Benayoun,V.Chernyak,-1990)

Flavour non-singlet mesons

HKRS: arXiv:1105.1626

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

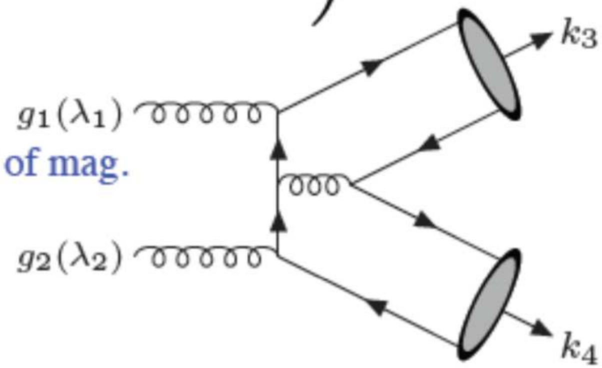
Flavour non-singlets $(\pi^+\pi^-, \pi^0\pi^0, K^+K^-, \rho^0\rho^0...)$: (31 diagrams)

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

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

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, $|\eta| < 1)$

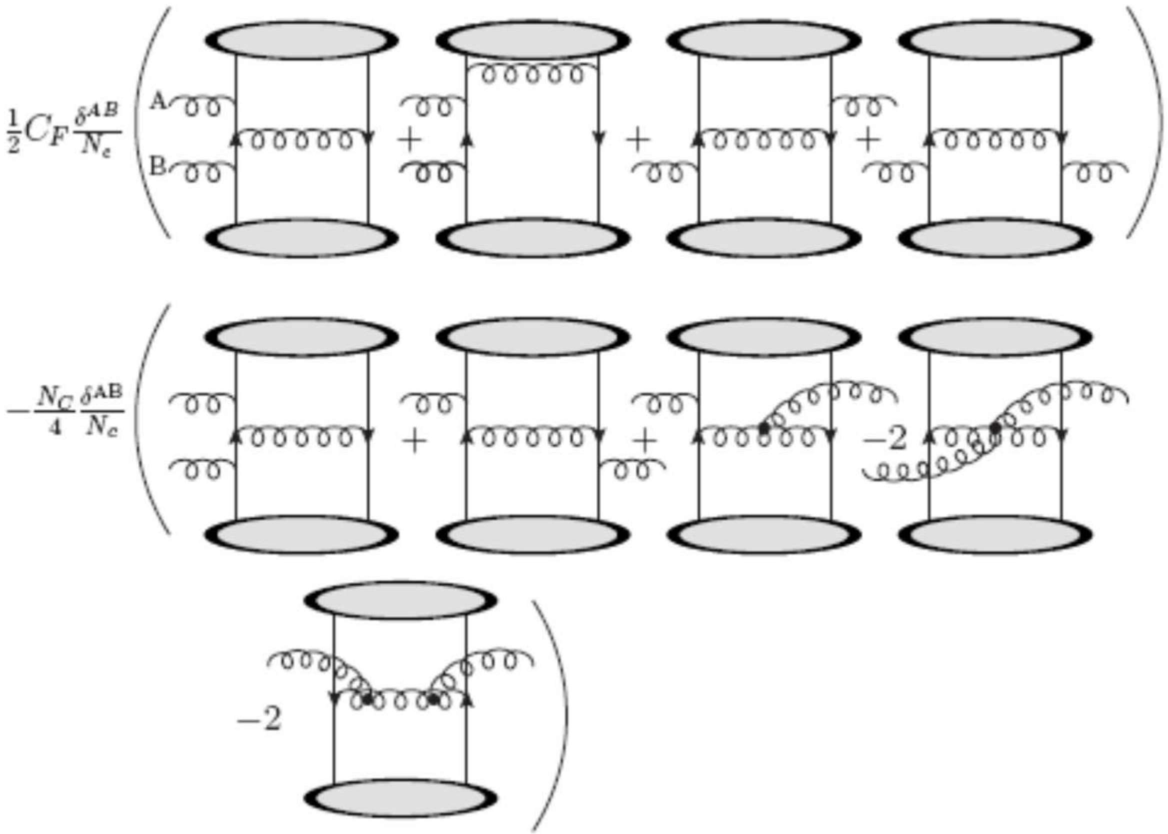
Experiment: $N(\pi^0\pi^0)/N(\gamma\gamma) < 0.35$ @ 95% confidence

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

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

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

is this easy to understand ?

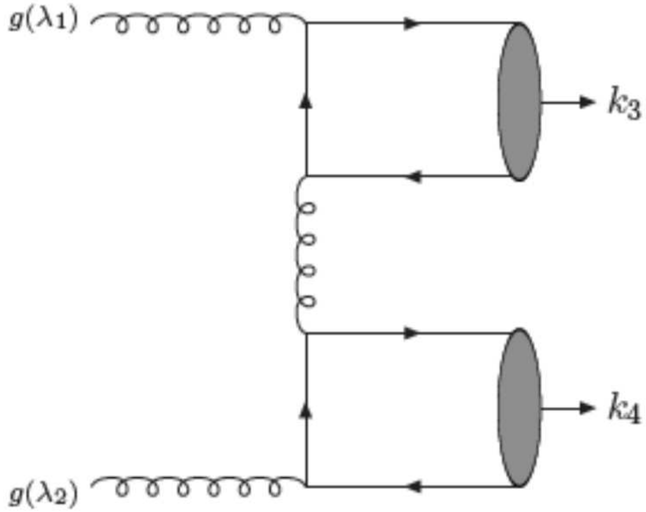


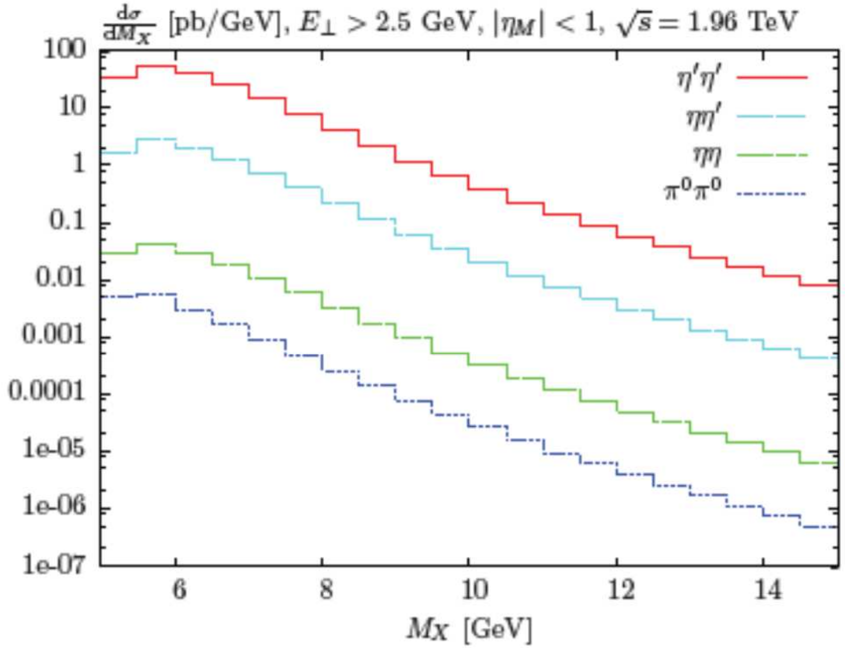
currently popular (among the more formal community) MHV- technique

Flavour singlet mesons

HKRS: arXiv:1105.1626

- 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 (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!





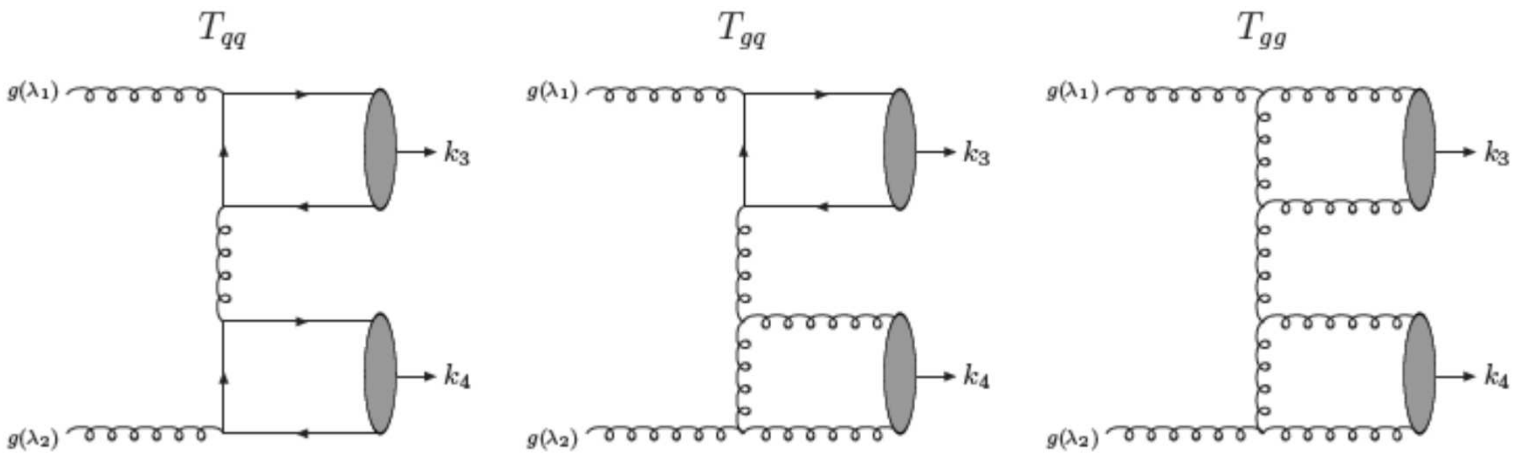
The gluonic component of the $\eta'(\eta)$

HKRS: arXiv:1302.2004

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

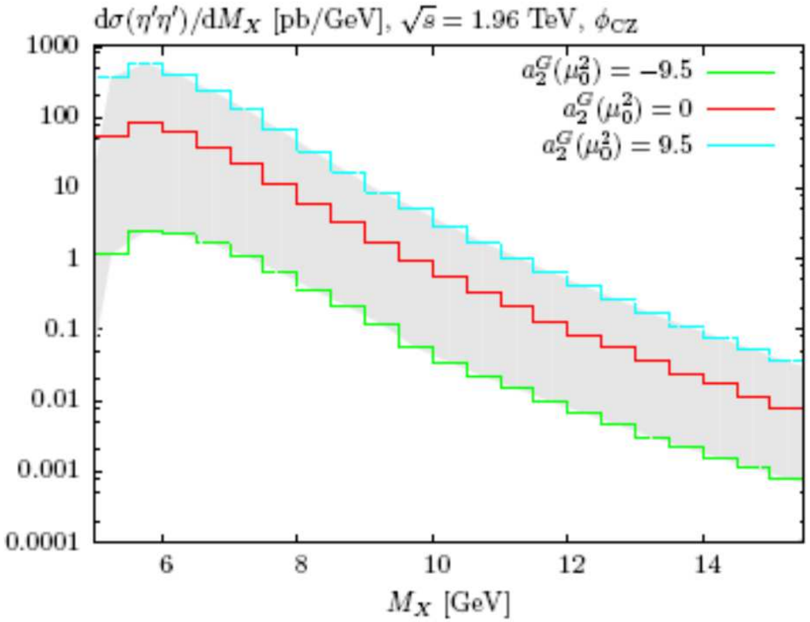
$\longrightarrow$ The $gg \to \eta(')\eta(')$ process will receive a contribution from the $gg \to gg q\overline{q}$ and $gg \to gggg$ parton level diagrams.

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



Taking this envelope of values, we find a $\sim$ 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

(CDF, TOTEM-CMS –prospects)

Forward proton angular distributions (2)

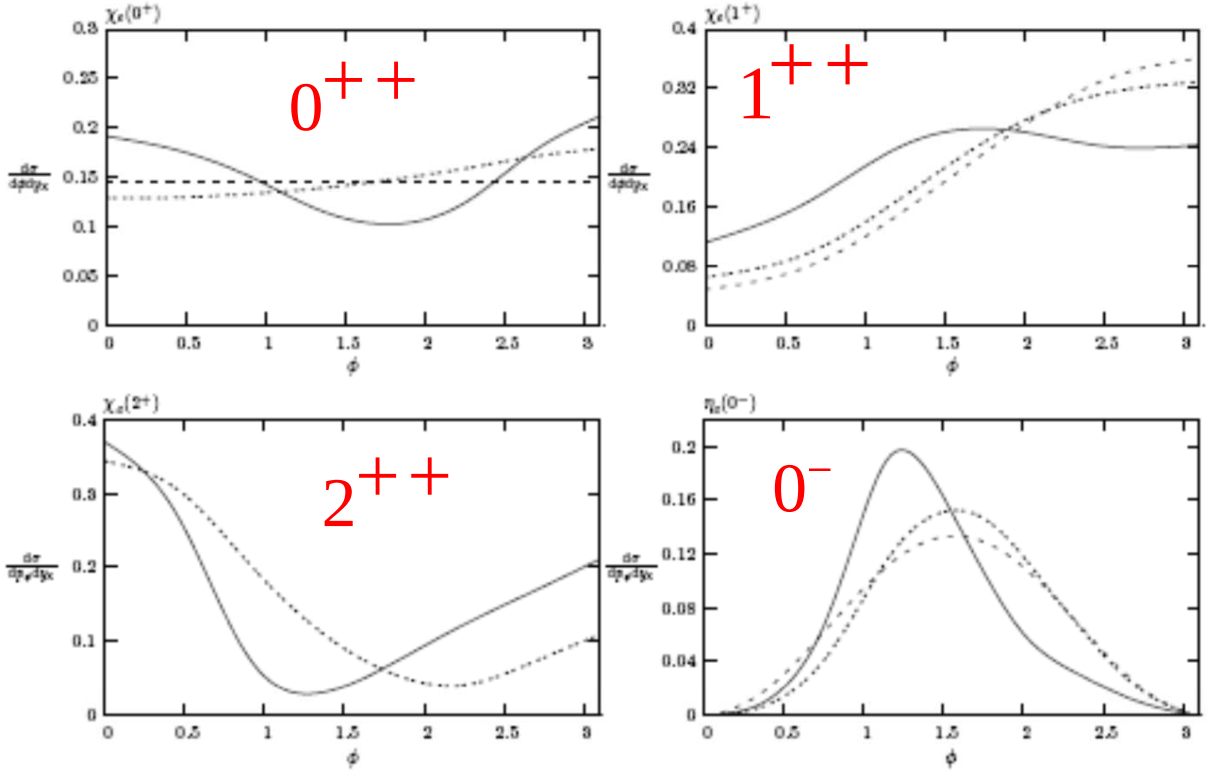


Figure: distribution (in arbitrary units) within the perturbative framework of the difference in azimuthal angle of the outgoing protons for the CEP of different J^P $c\bar{c}$ states at $\sqrt{s} = 14$ TeV. The solid (dotted) line shows the distribution including (excluding) the survival factor, while the dashed line shows the distribution in the small $p_\perp$ limit excluding the survival factor.

$\rightarrow$ Measurement of azimuthal angle, ϕ, between outgoing protons and proton $p_\perp$ distributions via forward proton taggers would allow a clear discrimination between the different J states, as well as possibly probing different models of soft diffraction (which will predict in general different distributions).

THEORY UNCERTAINTIES

Known Unknowns

- N(N)LO- radiative effects (K-factors etc..)
  '…possible inadequancy of PT theory in α_s …' R.Barbieri et al-1980
- ' 'Right' choice of gluon densities, in particular at so low scales as in the χ_c case
  (potentiality of a factor of ~3 rise for the H-case) .
- Complete model for calculation of absorptive corrections.
- Complete theoretical (+MC) treatment of the proton dissociation effects in the RG events.

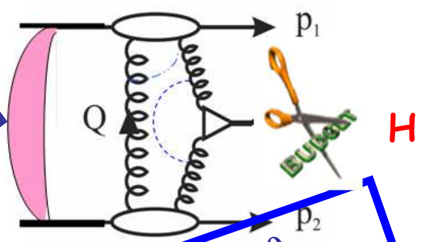
Unknown Unknowns

- Non- pQCD effects in the meson characteristics.
  Currently no complete description of heavy quarkonium characteristics.
  'Two gluon width does not tell the whole story.'
- Gluons at so low scales, surprises are not excluded at all.

Main Goal: KEEP THE Ball ROLLING

Update on Exclusive Higgs Production

The main advantages of CEP Higgs production



- Prospects for high accuracy (~1%) mass measurement

  (irrespectively of the decay mode).

- Quantum number filter/analyser.

  (0++ dominance ;C,P-even)

PRIOR TO THE LHC START-UP

currently ATLAS FP-420
(STFC cutting rule)
CMS-PPS, Totem
ATLAS-AFP

- H ->bb opens up (Hbb Yukawa coupl.)

  (gg)CED ⊘ bb in LO ; NLO,NNLO, b- mass effects – controllable.

(very important feature)

- For some BSM scenarios CEP may become *a* discovery channel

  - A handle on the overlap backgrounds- Fast Timing Detectors (10 ps timing or better).

✳ New leverage -proton momentum correlations (probes of QCD dynamics , CP- violation effects…)

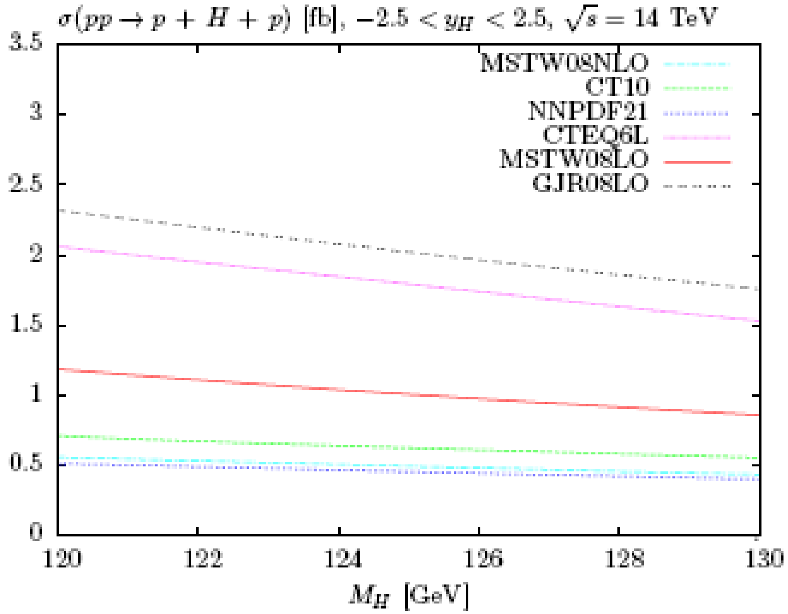
Triple product correlation: $\vec{n}_0 \cdot (\vec{p}_{1\perp} \times \vec{p}_{2\perp}) \sim \sin\varphi$,

Integrated counting asymmetry (~10%)

$$A = \frac{\sigma(\varphi<\pi)-\sigma(\varphi>\pi)}{\sigma(\varphi<\pi)+\sigma(\varphi>\pi)},$$

Higgs Boson: cross section predictions SM

SuperCHIC



- Cross section $\sim$ fbs, i.e. roughly 4 orders of mag. lower than inclusive case (price paid for exclusivity).
- Uncertainties (Survival factors, higher–order corrections, PDFs) exist in theoretical calculation. But $\gamma\gamma$ CEP cross section tends to lie a little above theory estimates $\to$ favours the higher predictions shown.

- Higgs cross section predictions guided in particular by CDF $\gamma\gamma$ data

Data $\sigma_{\gamma\gamma} = 2.48^{+0.40}_{-0.35}$ (stat) $^{+0.40}_{-0.51}$ (syst) pb

Theory

	MSTW08LO	CTEQ6L	GJR08LO
$\sqrt{s} = 1.96$ TeV ($\lvert\eta\rvert < 1$)	1.4	2.2	3.6

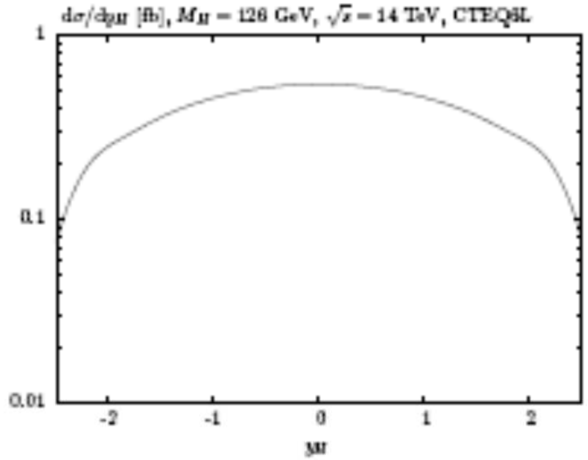
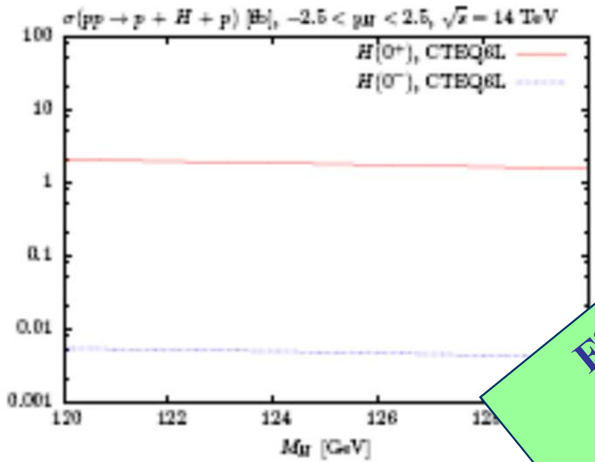


Figure 5: Rapidity distribution $d\sigma/dy_H$ for a $M_H = 126$ GeV SM Higgs boson, using CTEQ6L PDFs.



Find a CEP resonance and you have confirmed its quantum numbers!

Figure 6: Cross sections for the CEP of scalar $J^P = 0^+$ and pseudoscalar $J^P = 0^-$ particles of the Higgs sector as a function of the Higgs mass, M_H, integrated over the rapidity interval $-2.5 < y_H < 2.5$.

MSSM Higgs Summary

CED Higgs production has a great potential compared to the standard LHC searches:

(Marek Taševský)

arXiv:1310.7772 [hep-ph]

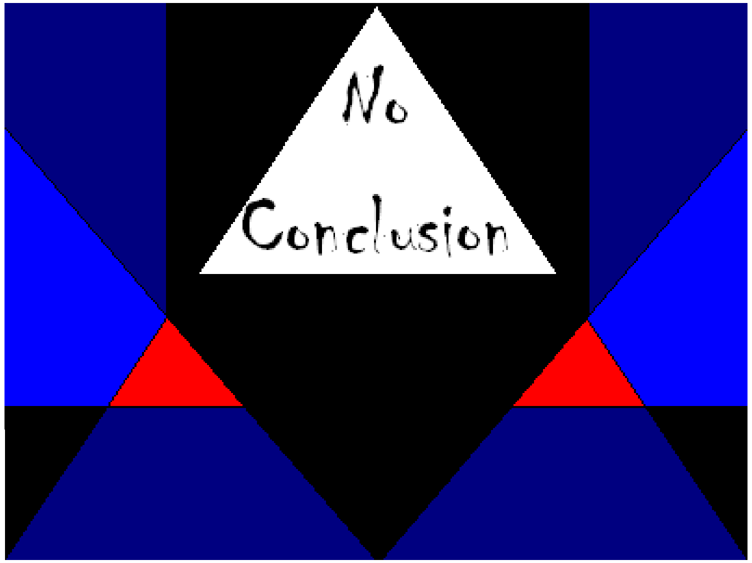
- **excellent mass resolution**
- **good S/B**
- **complementary information about the Higgs sector in MSSM**
- **complementary information about quantum numbers (a few events are enough and no need for coupling to vector bosons)**
- **information about CP-violation effects**
- **information about Yukawa Hbb coupling**

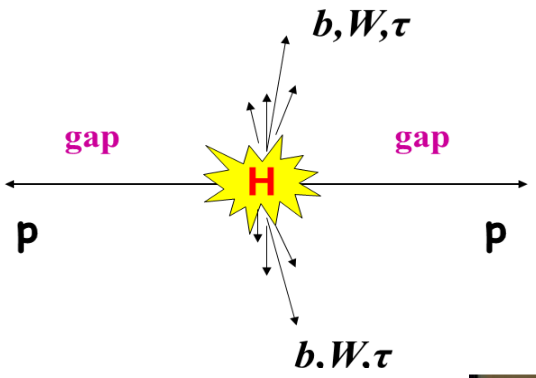
7 new MSSM benchmark scenarios tried out: only LowMH scenario looks promising for CED Higgs.

- This scenario is reachable only using 420+420 because the mass of the searched object is low (80 < M_h < 90 GeV). Big demands on experimental procedure (e.g. L1 trigger).
- AFP/PPS may be the unique way to reach such low-mass Higgs or it may confirm what ATLAS and CMS have already found there.

1) Allowed MSSM phase space is very limited. LHC analyses show that the discovered Higgs is more and more SM like. Event yield for the exclusive SM Higgs is low but can be perhaps increased by tuning the selection procedure (we know the mass of Higgs, gluon-b misidentification improved).

2) Whether Higgs is SM or MSSM, the low-mass exclusive Higgs needs stations at 420 m.





Jury is still out

We are looking forward to new exciting adventures in Exclusiveland

Summary and Outlook

- CEP in hadron collisions offers a promising framework within which to study novel aspects of QCD and new physics signals.
- CEP processes observed at the Tevatron, RHIC and low–luminosity LHC can serve as 'standard candles' for Higgs (and other physics) CEP at the LHC.
- The data are in good overall agreement with the Durham theory $\rightarrow$ supports predictions for e.g. Higgs (and new physics) CEP.
- The CEP of mesons pairs at high invariant masses ($/k_\perp$) is an interesting process, representing a novel application of pQCD framework for describing exclusive processes. Could help probe the gluonic structure of η, η' mesons.
- CEP could help probe the gluonic structure of η, η' mesons.
- Perturbative calculation predicts that $\pi^0\pi^0$ BG to $\gamma\gamma$ CEP is suppressed.
- New CDF $\gamma\gamma$ data gives encouraging results. Could shed light on the gluon density...awaiting CMS results.
- CEP could shed light on the nature of exotic charmonium–like states.
- More CEP results to come from RHIC, Tevatron data analysis and the LHC in the future.

- **'Diffractive Higgs' and new physics CEP (AFP, HPS) -jury is still out.**


THANK YOU


QUESTIONS?

BACKUP

χ_b production

- 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 for χ_c .
- J assignment of χ_{bJ} states still experimentally undetermined: CEP can shed light on this.
- Calculation very similar to χ_c case

$$|V_{0+}|^2 : |V_{1+}|^2 : |V_{2+}|^2 \sim 1 : \frac{\langle \mathbf{p}_\perp^2 \rangle}{M_\chi^2} : \frac{\langle \mathbf{p}_\perp^2 \rangle^2}{\langle \mathbf{Q}_\perp^2 \rangle^2} \sim 1 : \frac{1}{400} : \frac{1}{100}$$

$\chi_b(nP) \to DX$ (about 0.25 of all hadronic decays (CLEO-2009))

$\chi_{b1} \to c\bar{c}X$ (Barbieri et al (1979), NRQCD)

- Measurement of ratio of χ_b to $\gamma\gamma$ CEP rates in same mass region would eliminate certain theory uncertainties (survival factors....).
- Predictions for χ_b CEP via $\Upsilon\gamma$ decay (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

SM Higgs, 125 GeV

Signal-to-Background Ratio (a brief reminder)

$H \to b\bar{b}$

- The largest signal, but large background and (most) difficult trigger
  (other channels –too low rate).
- Major theor. uncertainties cancel in the ratio, in particular survival factors, PDFs,..
- Experimental efficiencies (trigger, b-tagging..) cancel.

Dominant non-PU backgrounds:

[DeRoeck, Orava+KMR, EPJC 25 (2002) 392, EPJC 53 (2008) 231]

1) Admixture of |Jz|=2 production

2) NLO gg→bbg, large-angle hard gluon emission

3) LO gg→gg, g can be misidentified as b

4) b-quark mass effects in dijet processes, HO radiative corrections

Main characteristics:
2007 (HKRTSW) values

Mass window	ΔM	~4 GeV.
g-b misID	$P(g/b)$	~ 1.3%
cone size	ΔR	~0.5.

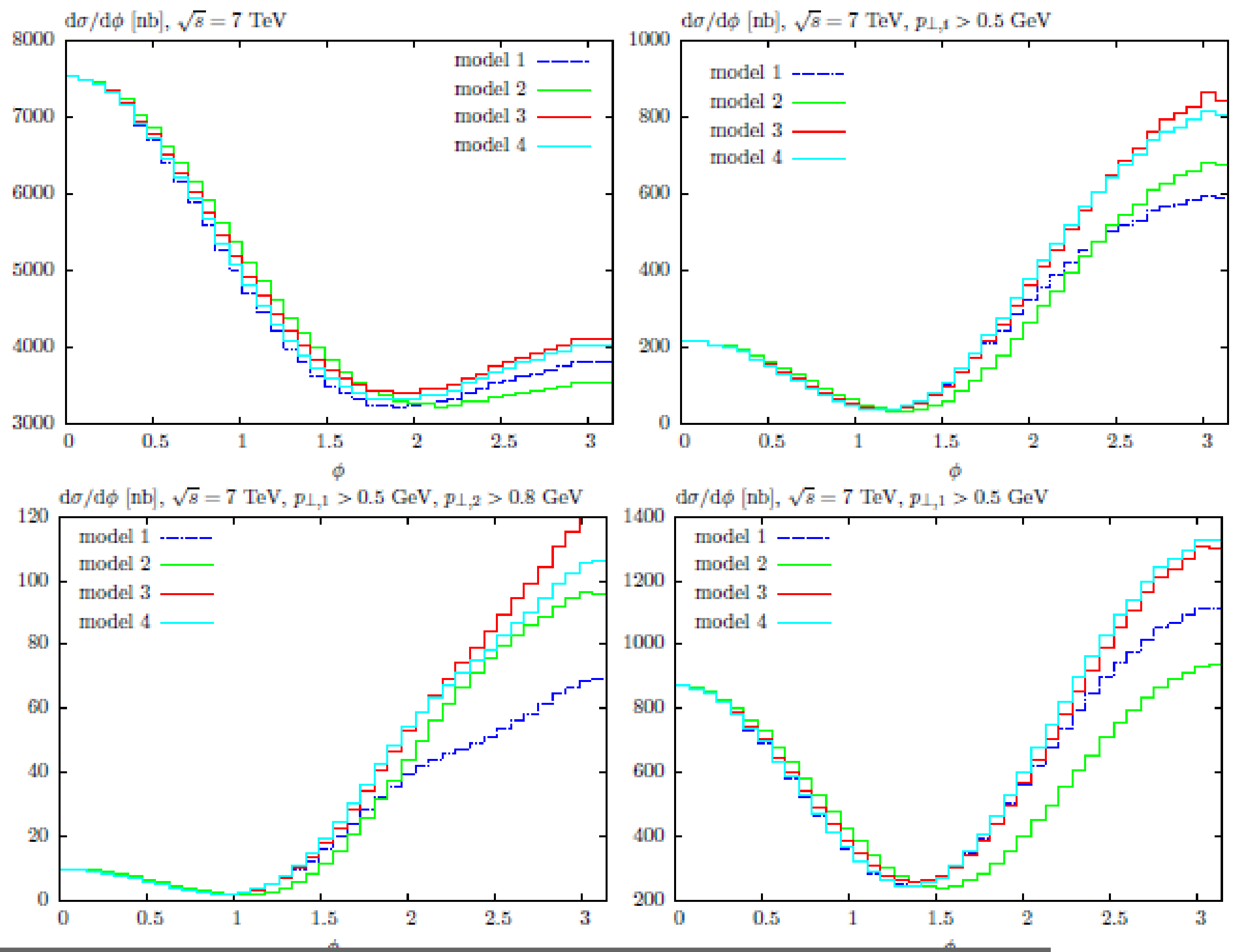
S/B ≈1

(420+420)

Could be improved by a factor of 2 or so.

Proton ϕ distributions for low mass $\pi^+\pi^-$ CEP

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 'diffractiv dip' structure.

Novel probe of the models of soft interaction

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:

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

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

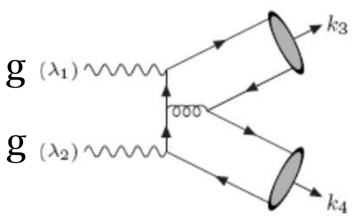
$gg \to M\overline{M}$ amplitude: MHV calculation (1)

- $g(+)g(+) \to q(\pm)\overline{q}(\mp)q(\pm)\overline{q}(\mp)$ amplitude is MHV: maximum $(n-2)$ number of particles have same helicity.
- Such amplitudes known to have remarkably simple forms, and corresponding 'spinor helicity' formalism can greatly simplify calculation.
- T_{++}, T_{--} can be calculated from known Parke-Taylor amplitude[5]

$$M_n \propto \sum_\sigma \frac{\langle k_p\, k_{\overline{q}}\rangle}{\langle k_p\, a_1\rangle \cdots \langle a_l\, k_{\overline{q}}\rangle} \frac{\langle k_q\, k_{\overline{p}}\rangle}{\langle k_q\, b_1\rangle \cdots \langle b_{l'}\, k_{\overline{p}}\rangle} (\lambda^{a_1} \cdots \lambda^{a_l})_{i_1 j_2} (\lambda^{b_1} \cdots \lambda^{b_{l'}})_{i_2 j_1}$$
$$- \frac{1}{N_c} \frac{\langle k_p\, k_{\overline{p}}\rangle}{\langle k_p\, a_1\rangle \cdots \langle a_l\, k_{\overline{p}}\rangle} \frac{\langle k_q\, k_{\overline{q}}\rangle}{\langle k_q\, b_1\rangle \cdots \langle b_{l'}\, k_{\overline{q}}\rangle} (\lambda^{a_1} \cdots \lambda^{a_l})_{i_1 j_1} (\lambda^{b_1} \cdots \lambda^{b_{l'}})_{i_2 j_2} \, .$$

- Making colour singlet identification ($i_1 = j_2$, $i_2 = j_1$) and identifying $q\overline{q}$, $p\overline{p}$ with collinear quarks within mesons

$$k_q = xk_3 \quad k_{\overline{q}} = (1-y)k_4 \quad k_p = yk_4 \quad k_{\overline{p}} = (1-x)k_3 \, ,$$



then amplitude reduces to

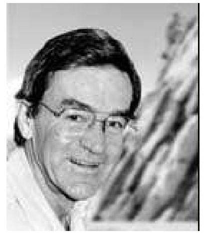
$$M \propto \langle k_3\, k_2\rangle\langle k_1\, k_4\rangle + \langle k_1\, k_3\rangle\langle k_2\, k_4\rangle - \langle k_3\, k_4\rangle\langle k_1\, k_2\rangle = 0 \, ,$$

which vanishes from the Schouten identity.

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

Here the indices $r(\overline{r})$ and $s(\overline{s})$ refer to the quarks (antiquarks) with colour indices $i_1(j_1)$ and $i_2(j_2)$, respectively, and the labels a_i, b_i refer to the gluons, while the standard spinor contraction '$\langle k, l\rangle$'

Towards Full Acceptance Detector at the LHC (bj- 1992)



CMS (& ATLAS) currently blind between $\eta = 6.4$ (CASTOR) and beam rapidity ($y_p = 8.9$ @ 7 TeV) except ZDC (neutrals). Cannot distinguish most diffractive/non-diffractive events.

(uninstrumented regions at LHCb and Alice)

IS THERE A WAY OUT ?

Yes, an addition of Forward Shower Counters around beam pipes- low PU runs

NEW!

first results of combined CMS+ TOTEM measurements with the FSCs on (showers from particles with | η | = 7-9)

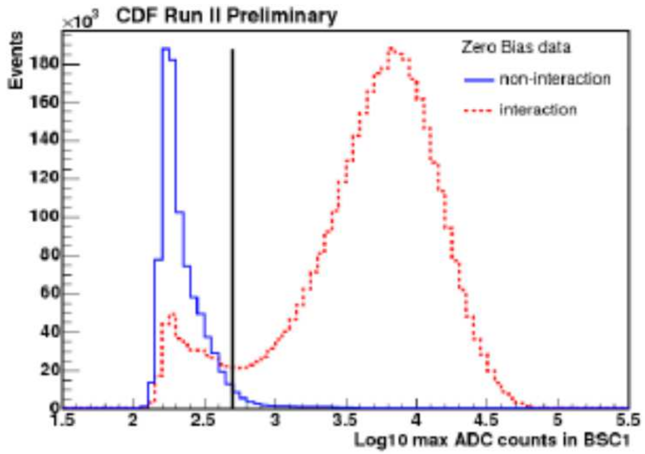
(plans for LHCb and Alice)

BSC very important as rap gap detectors.
All LHC experiments should have them!

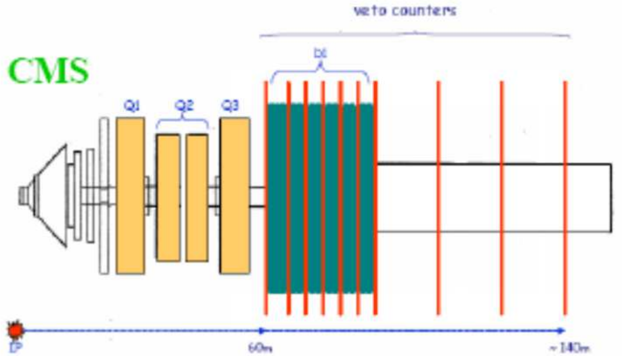
FORWARD PHYSICS WITH RAPIDITY GAPS AT THE LHC

Published in JINST-2009

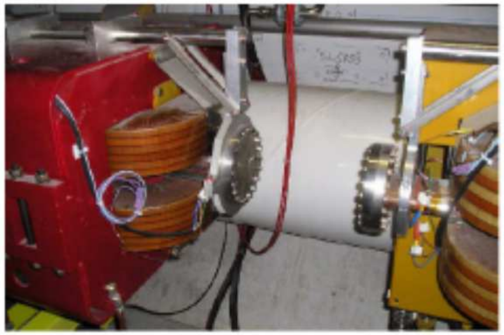
Michael Albrow[1], Albert De Roeck[2], Valery Khoze[3], Jerry Lämsä[4,5], E. Norbeck[6],
Y. Onel[6], Risto Orava[5], and M.G. Ryskin[7]
Sunday, November 09, 2008



Warm accessible vacuum pipe (circular – elliptical)
Do not see primary particles, but showers in pipe ++
Simple scintillator paddles: **Gap detectors in no P-U events**



Take 0-bias events (Essential!)
{1} = prob no interaction
{2} = prob >= 1 interaction
Take hottest PMT of 8 BSC1
Plot log max ADC for {1} and {2}
Separates empty / not empty
Repeat for all detectors



4

(Installed in 2011 at the CMS)

Forward Shower Counters (FSC): extending the CMS η-coverage.

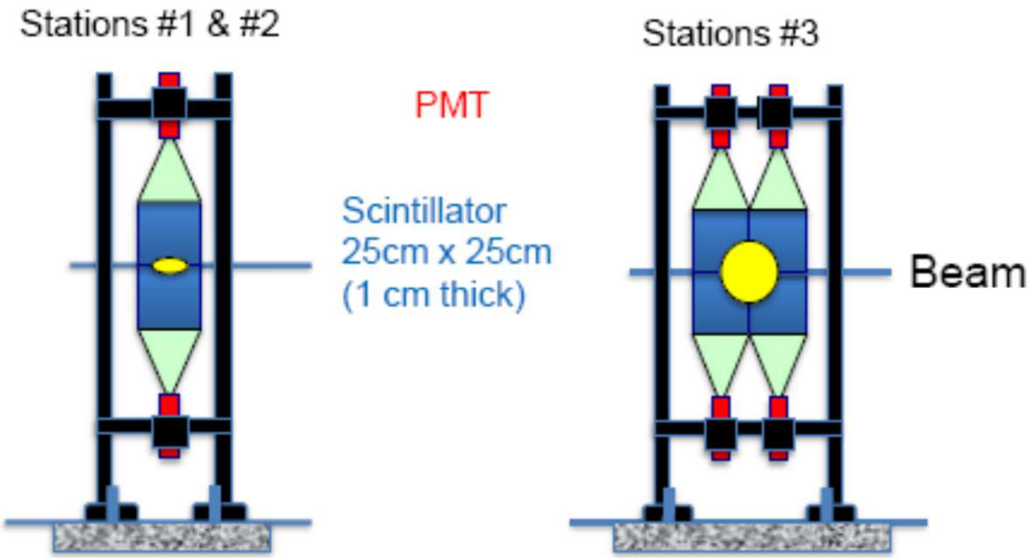
- CMS, as most collider detectors, has excellent hermeticity at low η
- In the forward direction the CMS coverage is extended with different additional detectors: HF + Castor + ZDC (+ TOTEM)
- There may be gaps in the coverage of the forward region (high η)
- The Forward Shower Counters (FSC) system is made of scintillators installed near the LHC beam pipe at 59, 85 and 114 m from IP5, on both sides of CMS
- These counters detect showers produced by very forward hadrons hitting the beam pipe and surrounding materials.

Forward Physics at LHC
Reggio Calabria (15-18 July 2013)

Aldo Penzo (INFN-Trieste)
for the CMS Collaboration
and the FSC Team

Not only CMS…

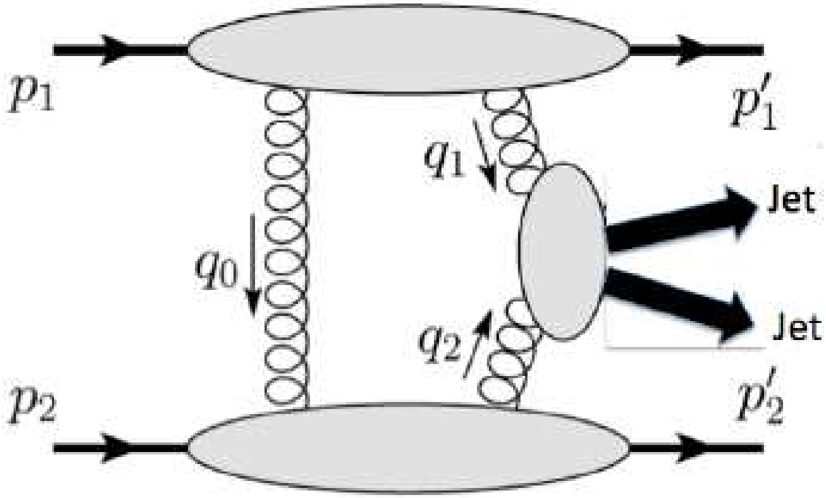
- ***Most LHC experiments*** *plan to use* ***"patch"*** *detectors to bridge their gaps in η-coverage (see Paula Collins' LHCb talk here)*
- *CMS has installed* ***FSC counters*** *since 2011 (used throughout 2012)*



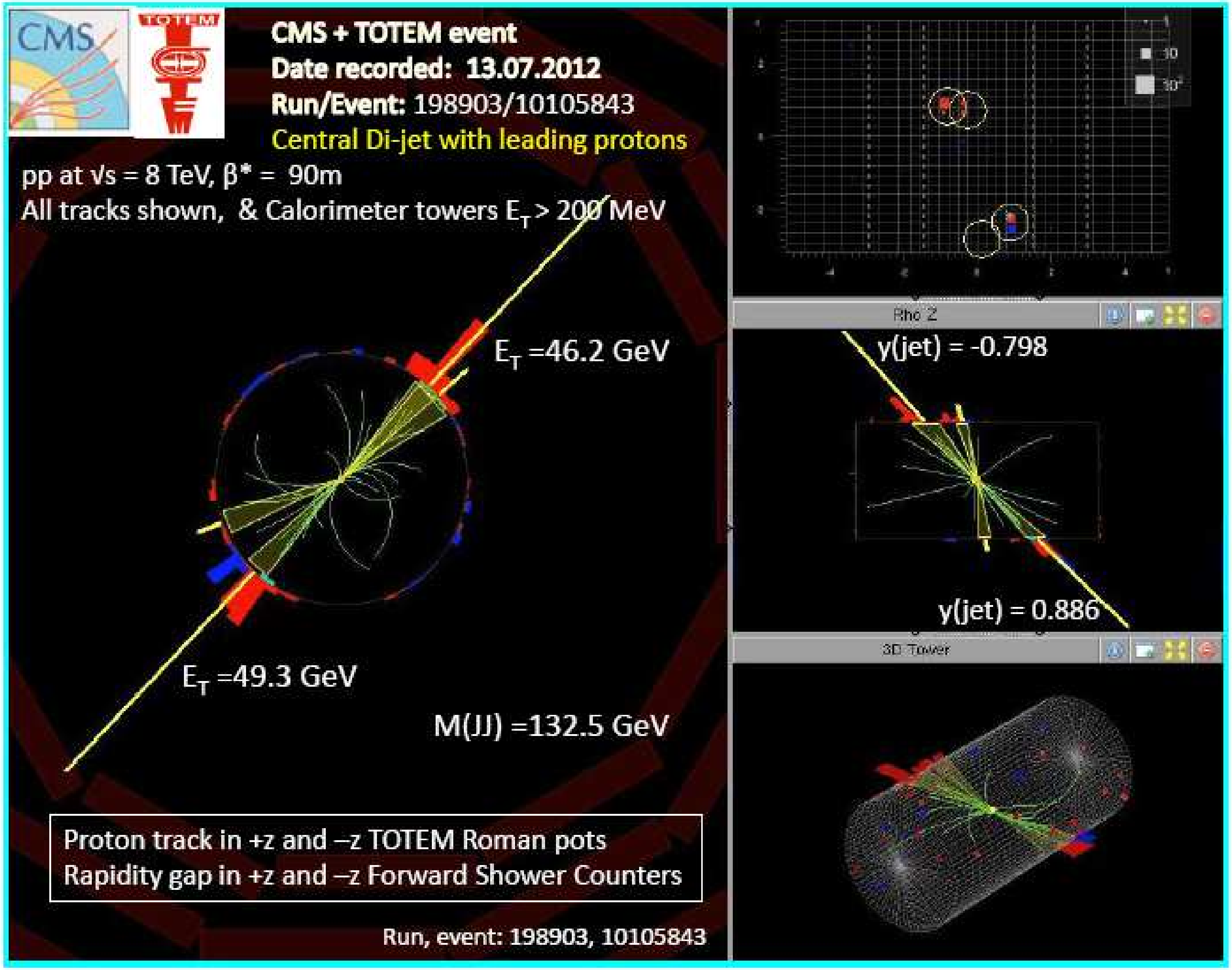
Sector 4-5 Station3

Results from Low PU Runs

- *Data collected during* ***low PU (β* = 90 m) pp at 8 TeV*** *runs in July 2012, with CMS and TOTEM operating with* ***common triggers****, show events consistent with central production of high-pT jets accompanied by two leading protons.*
- *FSC detectors, covering the very forward pseudo-rapidity $6 < |\eta| < 8$, were* ***required to be empty****.*
- *The leading protons were detected as tracks in the TOTEM Roman Pot (RP) stations around the CMS interaction point.*
- *Preliminary results shown in:*
- ***CMS DP -2013/004:*** CMS-TOTEM *events: high-pT jets with two leading protons*
- ***CMS DP -2013/006:*** *Central high-pT jet production during low pile-up, β* = 90m, 8 TeV pp run*



Dipion CEP- coming soon


CMS
TOTEM
CMS + TOTEM event
Date recorded: 13.07.2012
Run/Event: 198903/10105843
Central Di-jet with leading protons
pp at √s = 8 TeV, β* = 90m
All tracks shown, & Calorimeter towers E_T > 200 MeV
E_T =46.2 GeV
E_T =49.3 GeV
M(JJ) =132.5 GeV
Proton track in +z and –z TOTEM Roman pots
Rapidity gap in +z and –z Forward Shower Counters
Run, event: 198903, 10105843
Rho Z
y(jet) = -0.798
y(jet) = 0.886
3D Tower