XXII. INTERNATIONAL WORKSHOP ON DEEP-INELASTIC SCATTERING AND RELATED SUBJECTS

DIS 2014

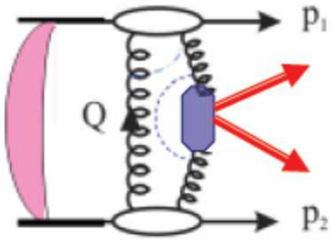
Warsaw, 28 April - 2 May 2014

Central Exclusive Processes at Hadron Colliders
(Selected Topics)

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

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

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:
  - Exotic states: X(3872)...
- **Dimeson** CEP
- **Exclusive jet production**
  (preliminary results).
- **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.
- χ_c, jj and $\gamma\gamma$ CEP has been observed (CDF, D0, LHCb, 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.

- $\chi_{c,b}$ 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)

This is all about QCD with all its beauty and complexities

What are the problems with this? …..
….it is not at all evident to experimentalists, who nowadays tend to prefer mining gold to going fishing.
(J.D. Bjorken, Int.J.Mod.Phys. A7 (1992) 4189-4258)

in the CEP case: …..mining gold to mushroom picking.

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). (in the low PU runs –Rapidity Gap signature)

- 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)

  $\boxed{\text{approved} \rightarrow}$ PPS@CMS and AFP ($\sim$ 220m)

  (Rafal)

- RP detectors are already installed at RHIC, where data with *pp* collisions are being taken for $\sqrt{s} \leq 500$ GeV.
  - Totem-CMS first measurements-2012, upgrade program. MoU (Valentina)

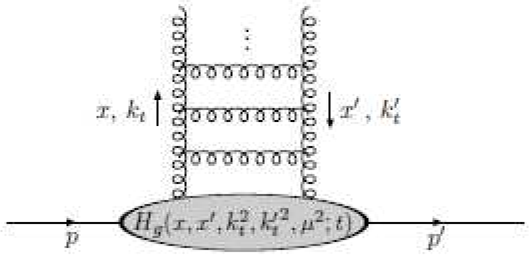
Calculating CEP : ingredients

- 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 ($\to J/\psi\gamma$, $\pi^+\pi^-$, K^+K^-...).
  - Light meson pairs ($\pi\pi$, KK, $\eta(')\eta(')$...). (soon to come CMS, Totem-CMS, LHCb, RHIC)
  - Diphotons $\gamma\gamma$. (CMS-limits)
  - 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.

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 $\chi_{c(1,2)}$

- The effects of non-zero p_T (especially for 2^+). …and especially without proton detectors!

LHCb 2010 LHCb-CONF-2011-022

2011-2012 dataset ~ 80 times more lumi

Move to 25 ns running doubles usable luminosity

HKRS: arXiv:0909.4748

	$\frac{\sigma(pp\to pp(\mu^+\mu^-+\gamma))}{\mathrm{Br}(J/\psi\to\mu^+\mu^-)\mathrm{Br}(\chi_{cJ}\to J/\psi\gamma)}$ 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.

Do not expect to see (or find) in inclusive production.

LHCb Collaboration, arXiv:1307.4285

Measurement of the relative rate of prompt χ_{c0}, χ_{c1} and χ_{c2} production at $\sqrt{s} = 7$ TeV

$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.27\,(\mathrm{stat}) \pm 0.29\,(\mathrm{syst}) \pm 0.16\,(p_T\,\mathrm{model}) \pm 0.09\,(\mathcal{B}),$$

$$\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0.787 \pm 0.014\,(\mathrm{stat}) \pm 0.034\,(\mathrm{syst}) \pm 0.051\,(p_T\,\mathrm{model}) \pm 0.047\,(\mathcal{B})$$

KMRS-2004

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

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

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

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

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

News

First CDF limits -2013

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 $d\sigma/dy|_{y=0}(\chi_{c0}) = 21.4 \pm 4.2$(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× larger.

- Good data/theory agreement for $\chi_c(0,1)$ states (within quite large theory uncertainty), but significant χ_c2 excess...

Theory corrections?

Bad guys-diffractive dissociation

FSCs- to veto proton dissociation-next run

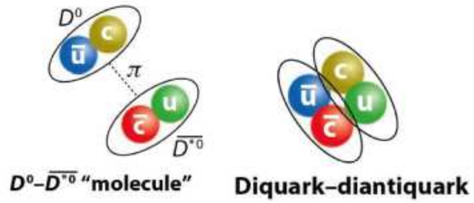
X(3872) analysis: motivation

X(3872) is "a riddle, wrapped in a mystery, inside an enigma; but perhaps there is a key" [1]

What is it? LHCb $J^{PC}=1^{++}$ determination leaves $\chi_{c1}(2^3P_1)$ available as well as D^oD^{*o} molecule, tetraquarks, ccg hybrids + combinations…

Observation of CEP X(3872) could lend weight to charmonium interpretation:

- Prediction possible for ratio of CEP cross sections $\sigma(\chi_{c1}(2P))/\sigma(\chi_{c1}(1P))$
- Tetraquark/molecule interpretation requires additional quarks or D mesons - available to inclusive processes only
- If the X(3872) is a combination of these the proportion can be probed by the CEP cross-section measurement

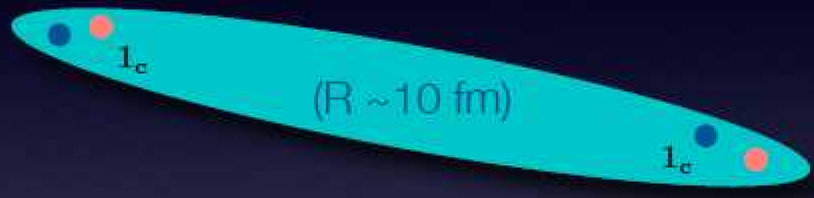


Most likely interpretation:
DD* molecule with admixture of $\chi_{c1}(2P)$
isospin violation
production at high energy

(if it is not χ'_{c1}, where is χ'_{c1}?)

[1] Winston Churchill, 1939

Extreme Interpretations



A compact ‘tetraquark’ e.g. dq-dq*

Maiani, Piccinini, Polosa, Riquer ‘2005
Terasaki; Ali; Ebert; Vijande; Nielsen & collab. …

Approach based on symmetry

A *loosely* bound molecule

Tornqvist; Braaten, Kusinoki; Voloshin; Barnes; Swanson; Close; Mehen, Fleming; Hanhart, Guo, Meissner very long list…’2005 —

Based on strong hadron dynamics

Mixed Charmonium/Molecular interpretations

X at LHCb

Very recent arXiv:1404.0275

$$\frac{\mathcal{B}(X(3872) \to \psi(2S)\,\gamma)}{\mathcal{B}(X(3872) \to J/\psi\,\gamma)} = 3.4 \pm 1.4$$

"…The measured value agrees with expectations for a pure charmonium interpretation of the X(3872) state and a mixture of charmonium and molecular interpretations. However, *it does not support a pure DD* molecular interpretation of the X(3872) state* …"

yet I wuold continue, citing Eichten, Lane & Quigg hep-ph/0511179

" …but the mass of X (3872) is too low to be gracefully identified with the 2^3P_1 charmonium state, especially if Z(3931) is to be identified as the 2^3P_2 level…"

- Loosely bound molecules promptly produced at high energy hadron colliders require a miracle in final state interactions. Close-to-threshold-hadrocharmonia should also be very unlikely formed in such collisions.

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 *may* be easier to form molecular or 4–quark states.

$\to$ 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 $|\phi'_P(0)|^2$.

- Also, can consider e.g. the $Z(3930) \equiv \chi_{c2}(2P)$:
  - Above threshold: decays to $D\overline{D}$, D^+D^- and $D^0\overline{D^0}$ seen.
  - With vertex detection at LHCb and RHIC $\to$ exclusive open charm ($D\overline{D}$...) production.
  - Theory: roughly the same cross section and distributions as $\chi_{c2}(1P)$.

Good Luck to LHCb

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

Flavour non-singlet mesons

HKRS: arXiv:1105.1626

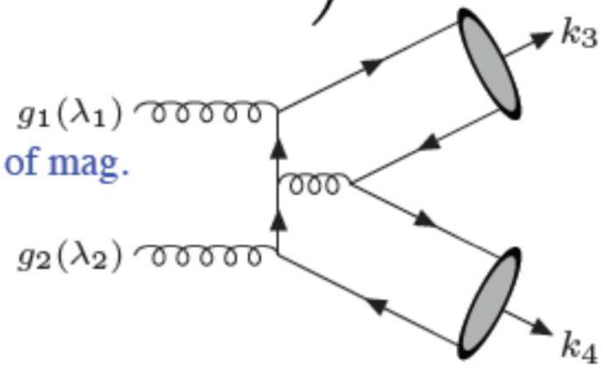
- The allowed parton-level diagrams depend on the meson quantum numbers. Leads to interesting predictions.....

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

(MHV-technique)

$$T_{++} = T_{--} = 0$$
$$T_{-+} = T_{+-} \propto \frac{\alpha_S^2}{a^2 - b^2\cos^2\theta}\left(\frac{N_c}{2}\cos^2\theta - C_F a\right)$$

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, $|\eta| < 1)$

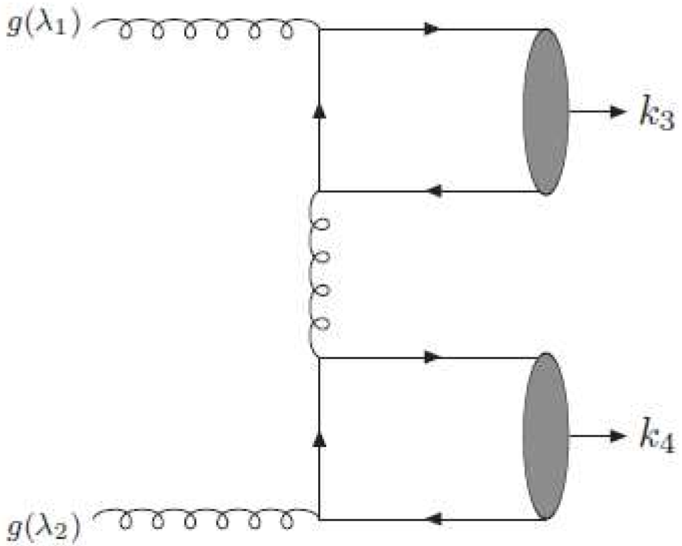
Experiment: $N(\pi^0\pi^0)/N(\gamma\gamma) < 0.35$ @ 95% confidence

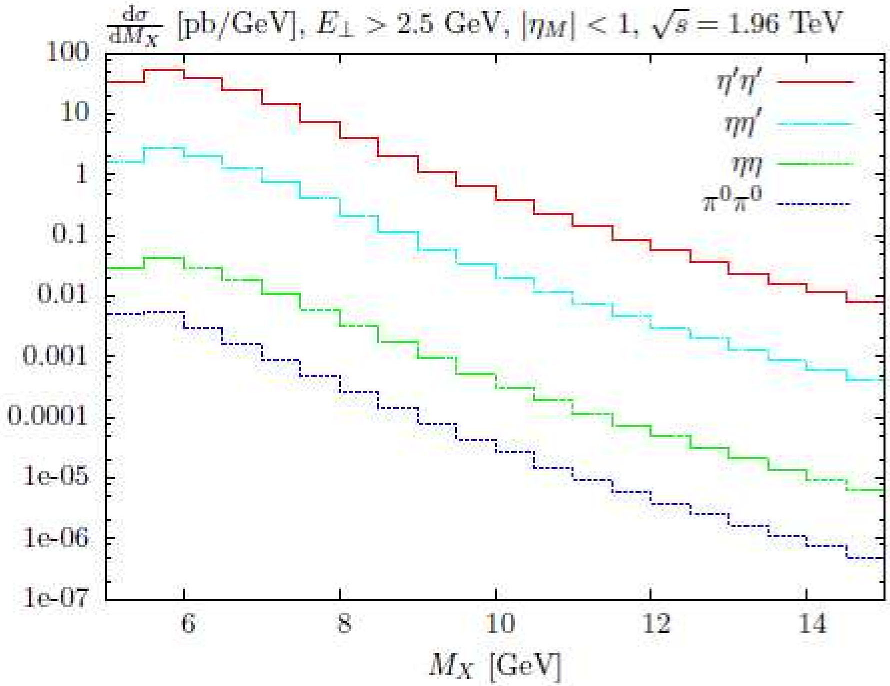
Theory: $\sigma(\pi^0\pi^0)/\sigma(\gamma\gamma) \approx 1\%$

More results are expected to come from CDF

Flavour singlet mesons

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



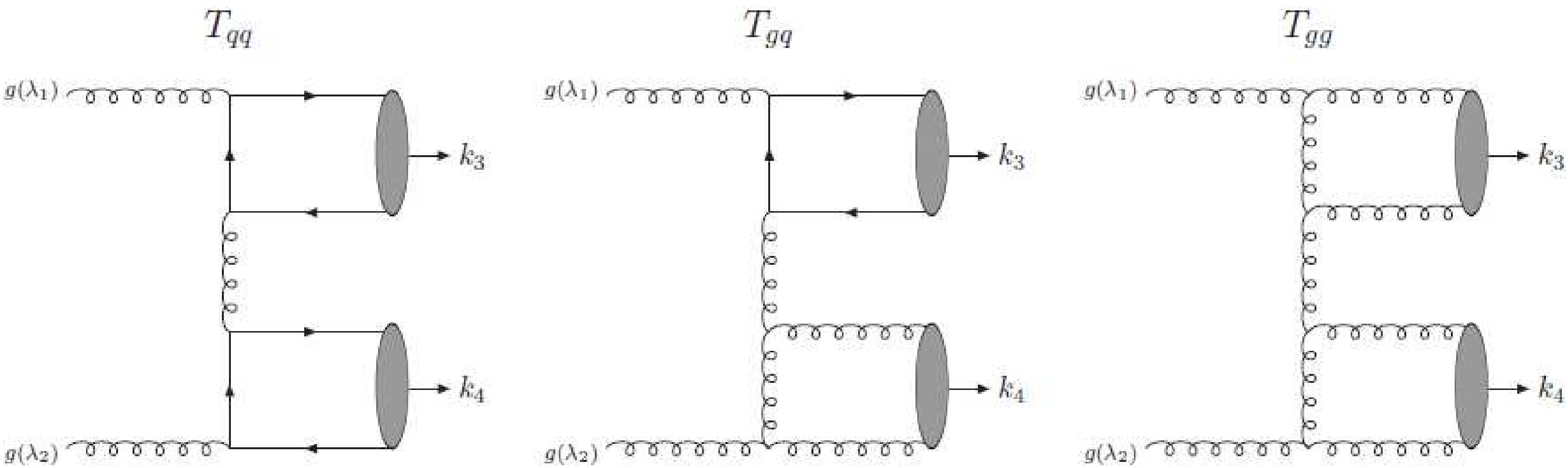


The gluonic component of the $\eta'(\eta)$

- The flavour singlet η' (and, through mixing η) should contain a gg component. But no firm consensus about its size. Thomas, arXiv: 0705.1500...

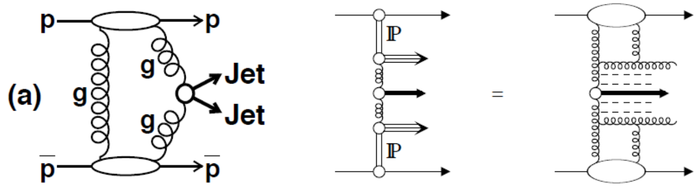
$\longrightarrow$ The $gg \to \eta(')\eta(')$ process will receive a contribution from the $gg \to gg q\bar{q}$ and $gg \to gggg$ parton level diagrams.

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



HKRS: arXiv:1302.2004

Theoretically: two different processes will in general contribute to signal.



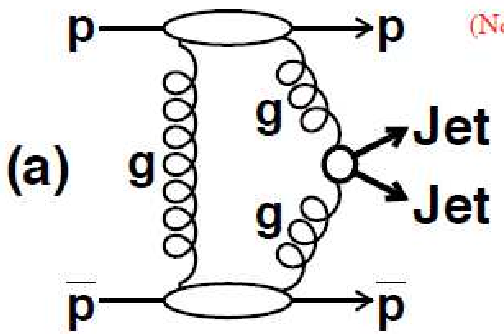
'Exclusive' 'Inelastic DPE'

Exclusive jet production: theory

- We are interested in the exclusive signal, in which case we have

For inelastic DPE: e.g. POMWIG, B.E. Cox and J.R. Forshaw, Comput.Phys.Commun. 144 (2002) 104-110

(Note does not include survival factor)



- The parton-level dijet amplitude is given by the usual Durham expression:

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

Where $X = gg, q\bar{q}$

Production subprocess

- If we consider the exclusive cross section ratio, we find

$$\frac{d\sigma(q\bar{q})/dt}{d\sigma(gg)/dt} \approx \frac{N_c^2-1}{4N_c^3}\frac{m_q^2}{M_X^2} = \frac{2}{27}\frac{m_q^2}{M_X^2}$$

Additional suppression from colour and spin 1/2 quarks

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

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

$\longrightarrow$ Huge suppression in b quark jets (increasing with M_X). Completely unlike inclusive case. See also: $H \to b\bar{b}$

CDF-2008

$$\boxed{\frac{\sigma(|J_z|=2)}{\sigma(J_z=0)} \sim \frac{\langle p_\perp^2\rangle^2}{\langle Q_\perp^2\rangle^2} \sim 10^{-2}}$$

Average outgoing proton transverse momentum (sub-GeV^2)

Average gluon transverse momentum in loop $\sim$ several GeV^2

$$\frac{d\sigma^{J_z=\pm 2}(q\bar{q})/dt}{d\sigma(gg)/dt} \approx \frac{N_c^2-1}{16N_c^3}\frac{\langle p_\perp^2\rangle^2}{\langle Q_\perp^2\rangle^2} \sim 10^{-4}$$

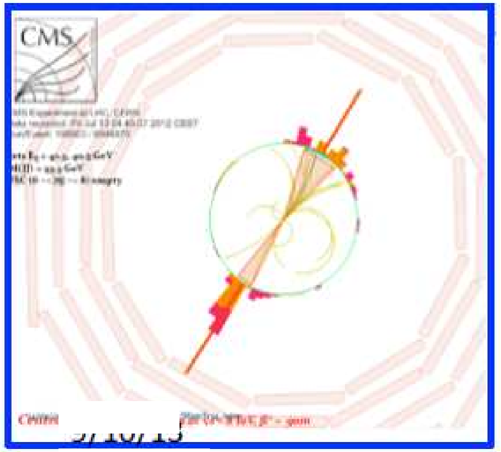
For one flavour $\Rightarrow$ multiply by $n_f = 4$

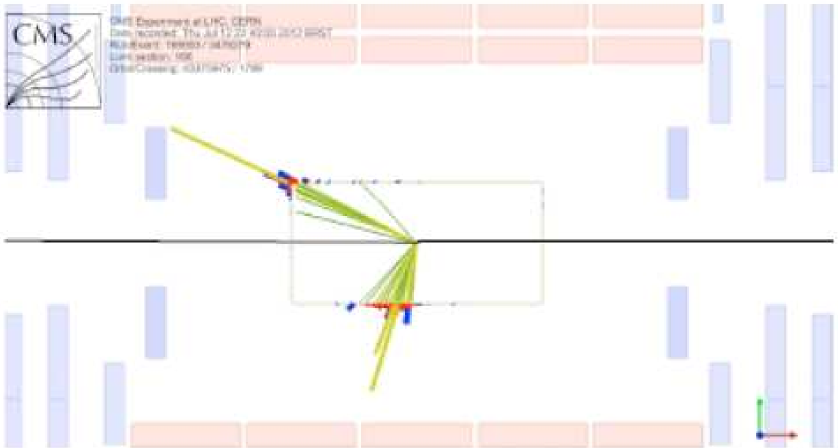
$\longrightarrow$ Huge suppression in light quark jets

Gluon jet dominance

From the above considerations, we expect dijet events to be almost entirely (colour singlet) gg

$\longrightarrow$ CEP of dijets offers the possibility of observing the isolated production of gluon jets at the LHC.





CMS + TOTEM event displays (2012)

These dijet and trijet events are the cleanest ever seen at a hadron collider, and remind one of LEP events. But these dijets are nearly all gg, while at LEP there were all $q\bar{q}$.

$\longrightarrow$ Clean probe of properties of gluons jets (multiplicity, particle correlations...)

Dijet CEP as a gluon factory

Trijet production

• Consider three-jet production, proceeds via $gg \to ggg$ and $gg \to q\bar{q}g$

• $q\bar{q}g$: configuration with g becoming soft/collinear to $q/\bar{q}$ driven by two-jet $q\bar{q}$ amplitude, which vanishes for $J_z = 0$ gluons and $m_q = 0$.

• More precisely, according to 'Low-Burnett-Kroll' theorem, the radiative amplitude $M_{q\bar{q}g}$ can be expanded in powers of $x_g = \frac{2E_g}{\sqrt{\hat{s}}}$ as

$$M_{q\bar{q}g} = \frac{1}{x_g} \sum_{n=0}^{\infty} C_n x_g^n$$

Vanishes

where C_0 and C_1 are given in terms of the Born-level amplitude $M_{q\bar{q}}$

$\Rightarrow$ First non-vanishing term is $n = 2$ giving

$$\frac{\mathrm{d}\sigma^{q\bar{q}g}}{\mathrm{d}E_g} \sim E_g^3 \qquad \text{while} \qquad \frac{\mathrm{d}\sigma^{ggg}}{\mathrm{d}E_g} \sim \frac{1}{E_g}$$

For $J_z = 0$ incoming gluons

Usual (singular) IR behaviour

See also V.A. Khoze, M.G. Ryskin , W.J. Stirling, Eur.Phys.J. C48 (2006) 477-488, hep-ph/0607134

New Monte Carlo implementation

J. Monk and A. Pilkington, Comput.Phys.Commun. 175 (2006) 232   Boonekamp et al.arXiv:1102.2531

- Dijet production previously implemented in Exhume and FPMC

- However, there have been a number of theoretical developments:
  - Correct inclusion of Sudakov factor → Correct limit 'Δ' on z integration: T.D. Coughlin and J.R. Forshaw, JHEP 1001 (2010) 121 (HKRS-10)
  - Consistent treatment of 'skewed' gluon PDFs → R_g factor dependent on gluon $Q_\perp$ LHL, Phys. Rev. D88 (2013) 034029
  - Latest model of soft survival effects → As in V.A. Khoze, A.D. Martin, M.G. Ryskin, Eur.Phys.J. C73 (2013) 2503

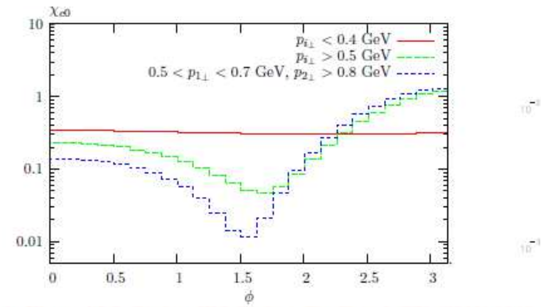
- Most importantly, neither of these include survival effects in a complete way:

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

- Survival factor is not constant, but depends on (and effects) the distribution of the outgoing proton $p_\perp$ vectors.

→ Expected suppression will depend on specific process, and soft survival factors can have a dramatic effect on the predicted distributions

(Recent KHARYS papers (2013-2014)



LHL, V.A. Khoze, M.G. Ryskin, W.J. Stirling, Eur.Phys.J. C71 (2011) 1545

New MC (under development) includes all of these updates and a full treatment of soft survival effects.

SuperCHIC 2

SuperCHIC 2

New MC for CEP under development. Based on original SuperCHIC, but with significant extensions.

- Theoretical developments:
  - Correct inclusion of Sudakov factor
  - Consistent treatment of 'skewed' gluon PDFs
  - Full (differential) treatment of soft survival effects
- LHAPDF interface.
- Complete calculation performed 'on-line', and structured so that additional processes can be easily added.
- Processes include: $\chi_{c,b}$, $\gamma\gamma$, meson pairs $(\pi\pi,\ \rho\rho,\ \eta(')\eta(')...)$, Higgs, jets...

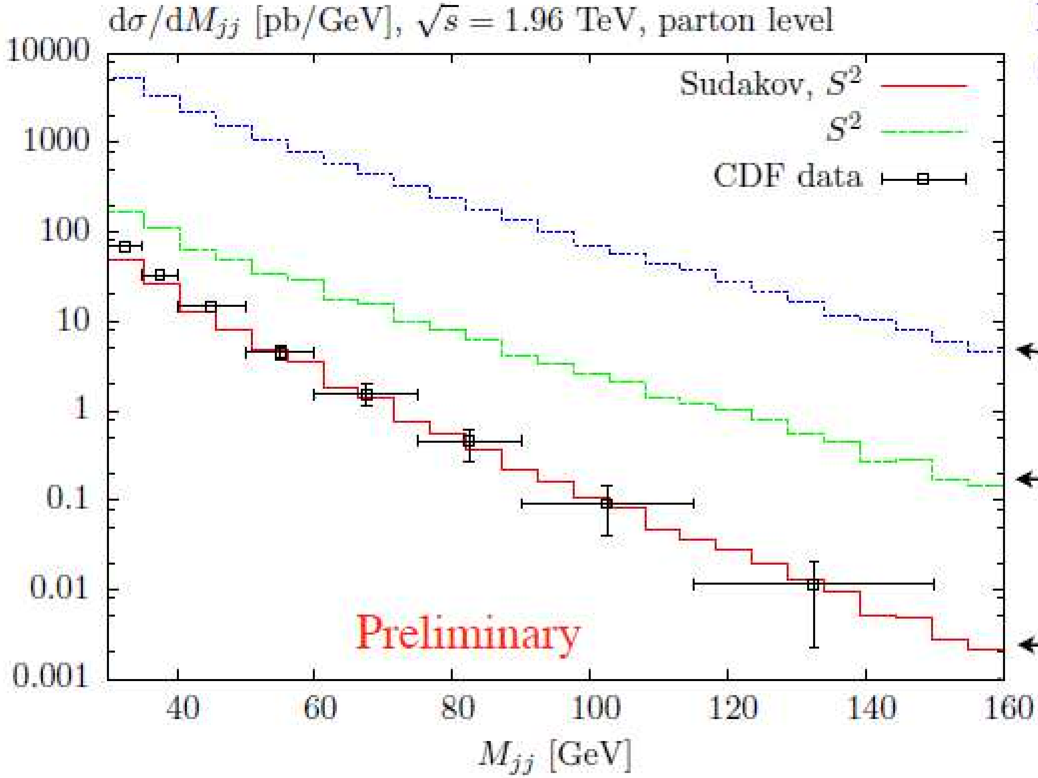
and photoproduction $(J/\psi,\ \Upsilon...)$ as in original SuperCHIC

Dijets $(gg \to gg, q\overline{q})$ and trijets $(gg \to ggg, gq\overline{q})$ included

CDF Collab., Phys.Rev.D77:052004,2008

Tevatron cross sections

- 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 dijet state drops strongly with M_{jj}

All predictions made with MSTW08LO PDFs, parton level

Soft survival not included, scale of Sudakov factor frozen

Soft survival included, scale of Sudakov factor frozen

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

Made with particular choice of S^2 model and PDFs $\Rightarrow$ more measurements (different $\sqrt{s}$...) needed to test theory further...

Also, caveat: only parton level!

LHC cross sections

- Consider two scenarios for observing exclusive jets at the LHC :
  - Low luminosity (CMS + TOTEM), special runs, lower M_X
  - High luminosity (ALFA, PPS), no need for special runs, but M_X must be larger (ξ acceptance of proton taggers)

Dijet predictions for both scenarios: $|\eta_j| < 2.5 \quad |p_{\perp,j}| > 20\,\text{GeV} \quad \sqrt{s} = 13\,\text{TeV}$

	$M_X\,(\text{min})$ [GeV]	gg	$q = b$	$q = c, s, u, d$
	50	620	1.1	2.6
Low Lumi	75	120	0.15	0.44
	100	30	0.031	0.10
	250	0.15	1.1×10^{-4}	4.0×10^{-4}
High Lumi	500	1.9×10^{-3}	8.6×10^{-7}	3.3×10^{-6}

σ [pb]

$n_f = 4$

$q\bar{q}$

Preliminary

$\sqrt{s} = 13\,\text{TeV}$

- Low luminosity CMS + TOTEM, event selection:

Central: $|\eta_j| < 4.4$, $|p_\perp^j| > 30$ GeV   Protons: $|p_\perp^y| >$ 0.1 GeV, $p_{1\perp}^y * p_{2\perp}^y > 0$

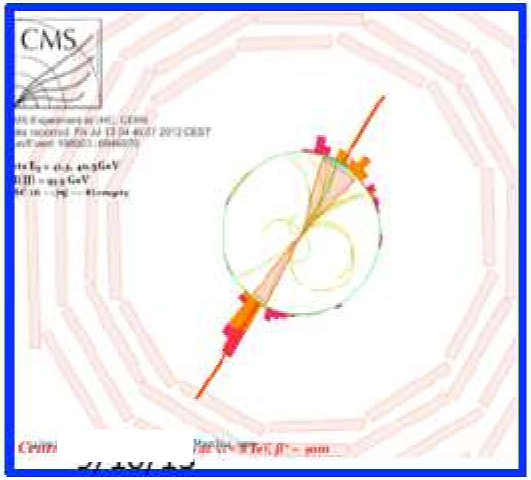
$$\Rightarrow \sigma(gg) \approx 100 \text{ pb}$$

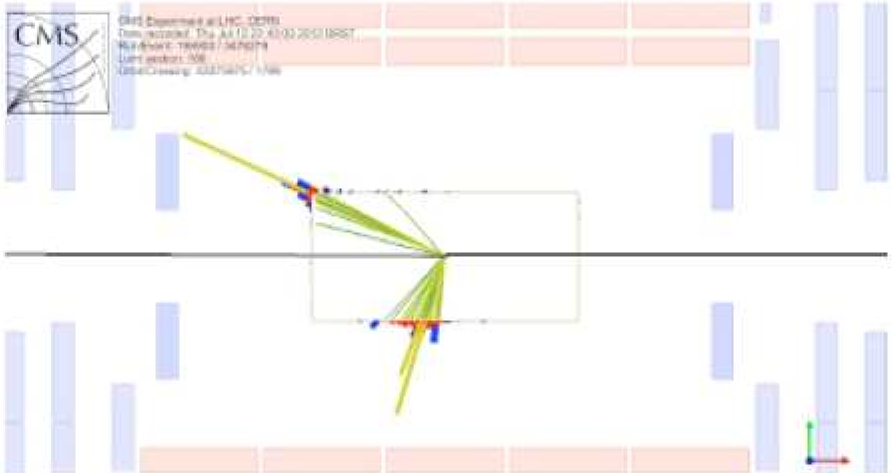
- High luminosity CMS + TOTEM ('CT PPS') event selection:

Central: $|p_\perp^j| > 120$ GeV, $|\eta_j| < 2.5$ Protons: $\xi > 0.03$

$$\Rightarrow \sigma(gg) \approx 0.5 \text{ fb}$$

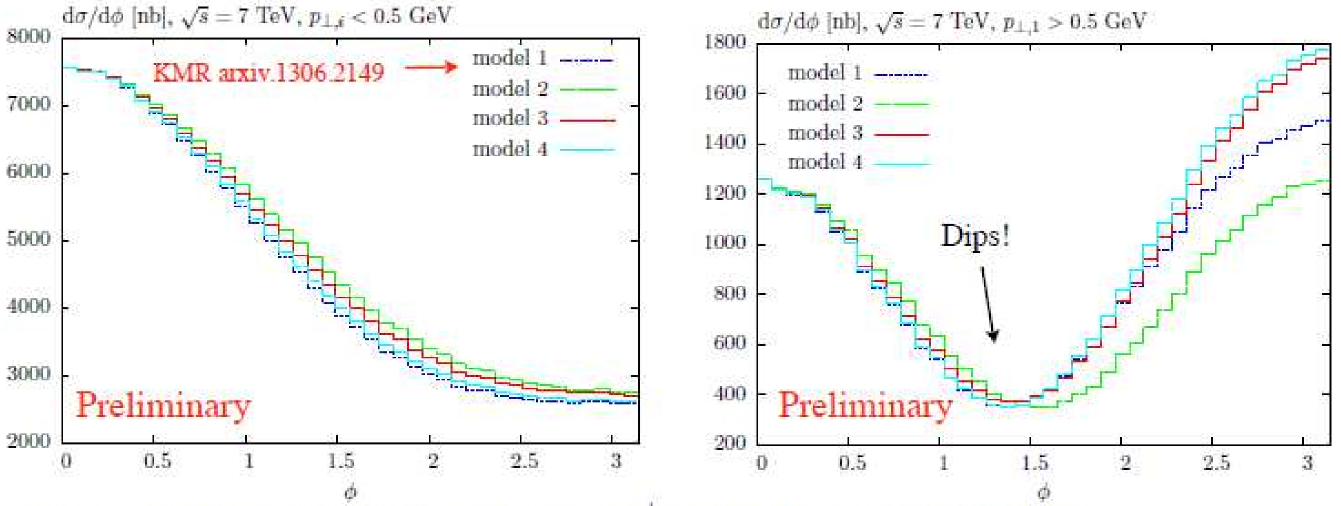
$M_X > 390$ GeV





CMS + TOTEM event displays (2012)

- The observation of exclusive jets (and other processes) with tagged protons also provides additional information....
  - Consider, e.g. $\pi^+\pi^-$ production, with tagged protons. TOTEM, ALFA
    R. Staszewski et al., arXiv:1104.3568



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

- Distributions in angle ϕ between outgoing protons strongly affected by soft survival effects, in model dependent way.
- This is in particular true when larger values of $p_\perp$ are selected. Cancellation between screened and unscreened amplitudes results in characteristic 'diffractive dip' structure. V.A. Khoze, A.D. Martin and M.G. Ryskin, hep-ph/0203122
  LHL, V.A. Khoze, M.G. Ryskin and W.J. Stirling, arXiv:1011.0680

Plots for $\pi^+\pi^-$ but similar effect seen in dijet production

Novel probe of the models of soft interaction

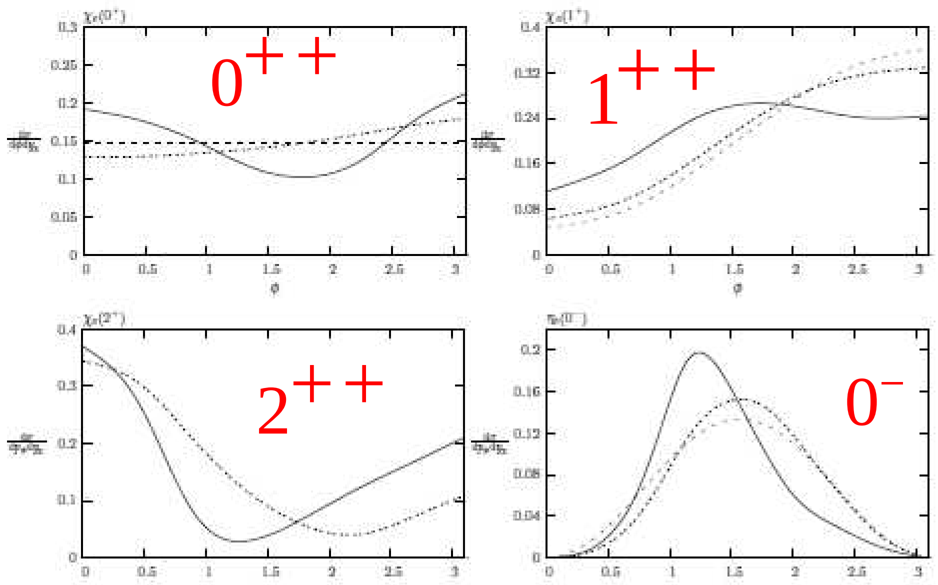
HKRS: arXiv:1005.0695, 1011.0680

Other observables

- χ_b production: also for $J=1,2$ ⟶ $I^G(J^{PC}) = 0^+(0^{++})$ J needs confirmation.
  - Smaller cross sections ($\sim$ pb)...
  - ...but smaller theoretical uncertainty (higher M_X)

- $\eta_{c,b}$ production:
  - Odd parity $\Rightarrow$ suppressed
  - $\eta_c \sim 0.1$ nb, $\eta_b \sim 0.1$ pb

- CEP with tagged protons: distributions of outgoing protons sensitive to spin/parity of production state.



EXCLUSIVE JET PRODUCTION

$\longrightarrow$ Strong motivation for programme of CEP measurements, with tagged protons at the LHC, both at low (TOTEM+CMS, ALFA+ATLAS) and high (PPS, AFP...) luminosity. (Valentina, Rafal)

- Work underway on `SuperCHIC 2`, new MC for CEP, including exclusive two and three jet production.

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.
- Exclusive jet production at the LHC presents an interesting and potentially unique probe of QCD.

  • The Durham perturbative approach (already supported by Tevatron measurements) makes very clear predictions, which are quite different from 'standard' inclusive case:

    - Isolated gg dominance (LO $gg \rightarrow q\overline{q}$ vanishes for massless quarks and $J_z = 0$ gluons). See also: $H \rightarrow b\overline{b}$
    - 'Mercedes' configuration for $gq\overline{q}$ favoured. ggg vs $gq\overline{q}$ topologies

  • Correlations between outgoing proton momenta sensitive to model of soft proton-proton interactions.

We are looking forward to new exciting adventures in Exclusiveland


THANK
YOU

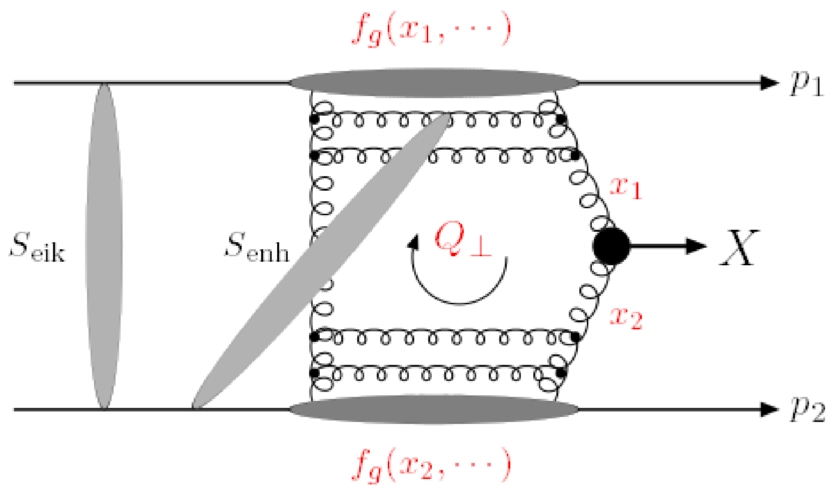

QUESTIONS?

BACKUP

'Durham Model' of central exclusive production

- The generic process $pp \to p + X + p$ is modeled perturbatively by the exchange of two t-channel gluons.
- The use of pQCD is justified by the presence of a hard scale $\sim M_X/2$. This ensures an infrared stable result via the Sudakov factor: the probability of no additional perturbative emission from the hard process.

- The possibility of additional soft rescatterings filling the rapidity gaps is encoded in the 'eikonal' and 'enhanced' survival factors, $S^2_{\rm eik}$ and $S^2_{\rm enh}$.
- In the limit that the outgoing protons scatter at zero angle, the centrally produced state X must have $J_Z^P = 0^+$ quantum numbers.



KMR-2000

$\gamma\gamma$ 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: $\sigma_{\gamma\gamma} = 2.48^{+0.40}_{-0.35}\,(\text{stat})\,^{+0.40}_{-0.51}\,(\text{syst})$ pb for $E_\perp > 2.5$ GeV, $|\eta_\gamma| < 1$

HKRS: EPJC 72 (2012) 2110

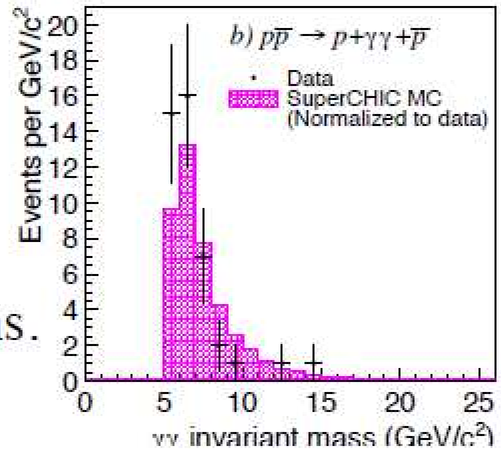
- In good agreement with Durham **pre**dictions:

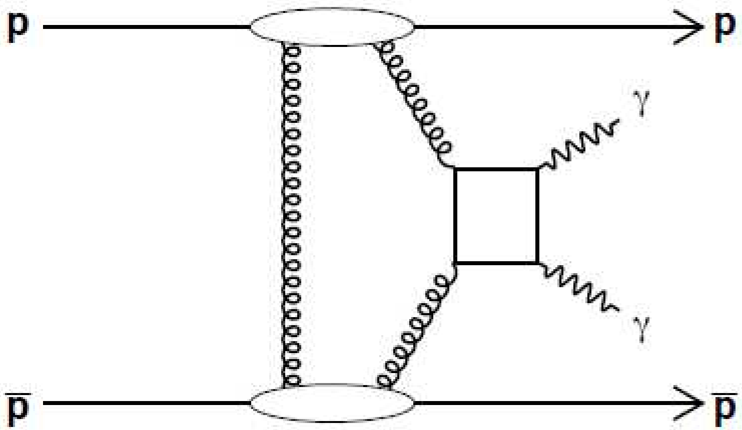
	MSTW08LO	CTEQ6L	GJR08LO
$\sqrt{s} = 1.96$ TeV $(\lvert\eta\rvert < 1)$	1.4	2.2	3.6

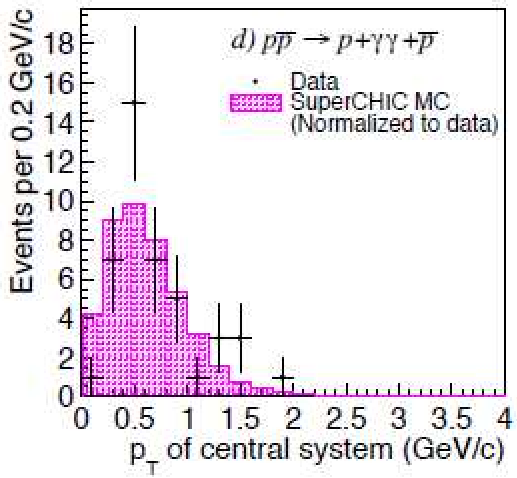
- CMS have set limits close to Durham LHC predictions.

CMS-PAS-FWD-11-004.

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







The $gg \to q\bar{q}g, ggg$ amplitudes for a given helicity config. are known, and have (relatively) simple forms (can be written down in ~ 3 - 4 lines) MHV

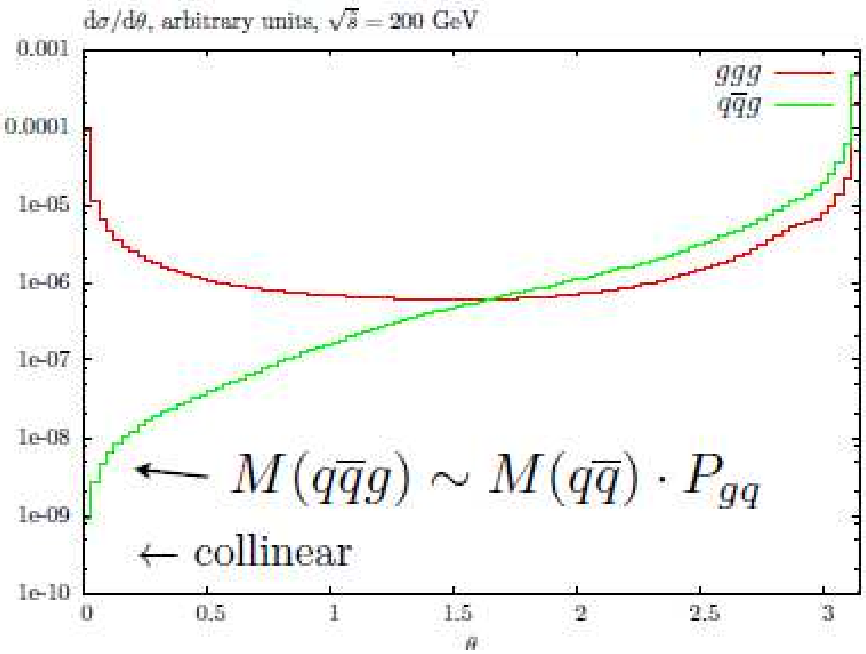
Consider amplitudes for $J_z = 0$ colour-singlet gluons (and massless quarks for simplicity)...

$|y_i| < 5$ $\sqrt{\hat{s}} = 200$ GeV

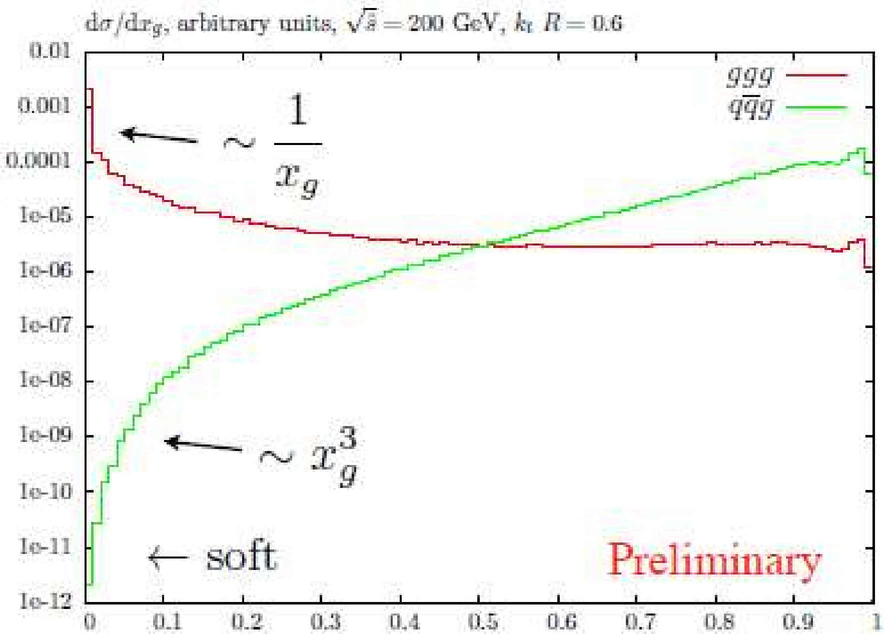
$q\bar{q}g$, ggg normalised to each other

θ: g–b quark angle

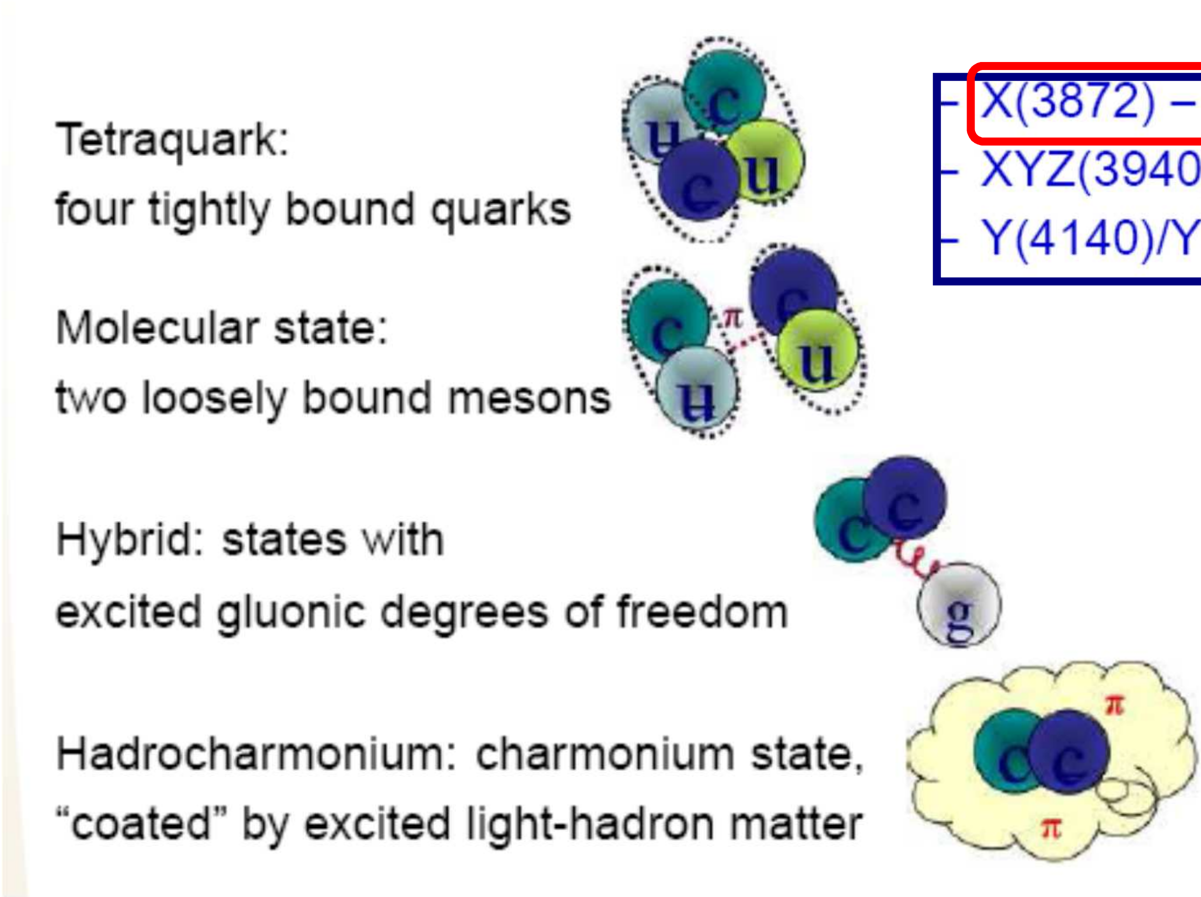
$\mathrm{d}\sigma/\mathrm{d}\theta$ (for ggg between arbitrary gluons)



$\mathrm{d}\sigma/\mathrm{d}x_g$



Zoo of charmonium –like XYZ states



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

X captured attention...

Top Cited Articles of All Time (2013 edition) in hep-ex

The 100 most highly cited papers of All Time (2013 edition) in the hep-ex archive

22. 844 citations up to the end of 2013
Observation of a narrow charmonium - like state in exclusive B+- ---> K+- pi+ pi- J / psi decays
Belle Collaboration (S.K. Choi (Gyeongsang Natl. U.) *et al.*). Sep 2003. 10 pp.
Published in **Phys.Rev.Lett. 91 (2003) 262001**
DOI: 10.1103/PhysRevLett.91.262001

61. 506 citations up to the end of 2013
Observation of the narrow state $X(3872) \to J/\psi \pi^+ \pi^-$ in $\bar{p}p$ collisions at $\sqrt{s} = 1.96$ TeV
CDF Collaboration (D. Acosta (Florida U.) *et al.*). Dec 2003. 6 pp.
Published in **Phys.Rev.Lett. 93 (2004) 072001**
FERMILAB-PUB-03-393-E

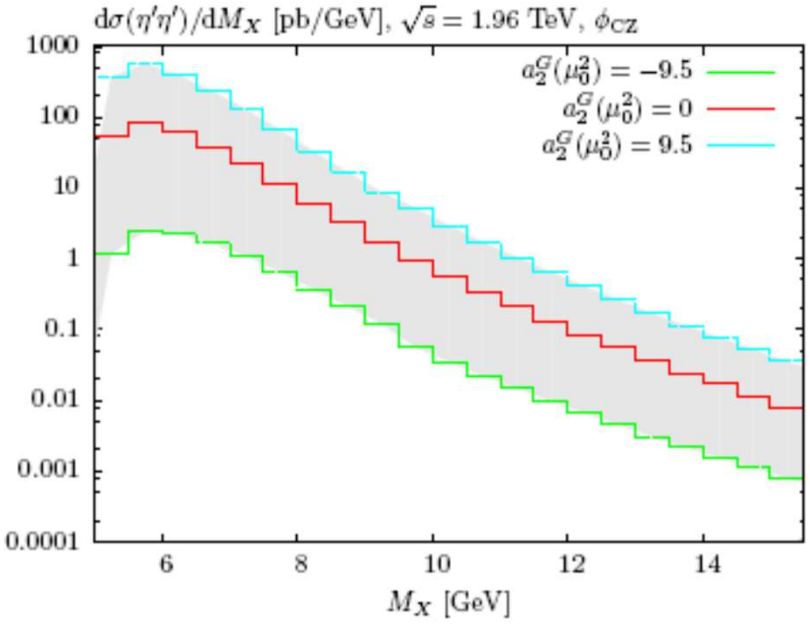
Also its vector cousin got much attention

64. 495 citations up to the end of 2013
Observation of a broad structure in the $\pi^+ \pi^- J/\psi$ mass spectrum around 4.26-GeV/c^2
BaBar Collaboration (Bernard Aubert (Annecy, LAPP) *et al.*). Jun 2005. 7 pp.
Published in **Phys.Rev.Lett. 95 (2005) 142001**
BABAR-PUB-05-29, SLAC-PUB-11320
DOI: 10.1103/PhysRevLett.95.142001

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 $q\bar{q}$, 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)

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 $y_\chi = 0$):

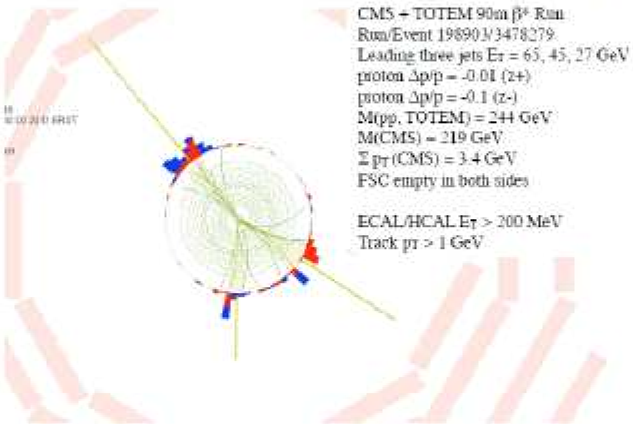
$\sqrt{s}$ (TeV)	1.96	7	10	14
$\frac{d\sigma}{dy_{\chi_b}}(pp \to pp(\Upsilon + \gamma))$ (pb)	0.60	0.75	0.78	0.79
$\frac{d\sigma(1^+)}{d\sigma(0^+)}$	0.050	0.055	0.055	0.059
$\frac{d\sigma(2^+)}{d\sigma(0^+)}$	0.13	0.14	0.14	0.14

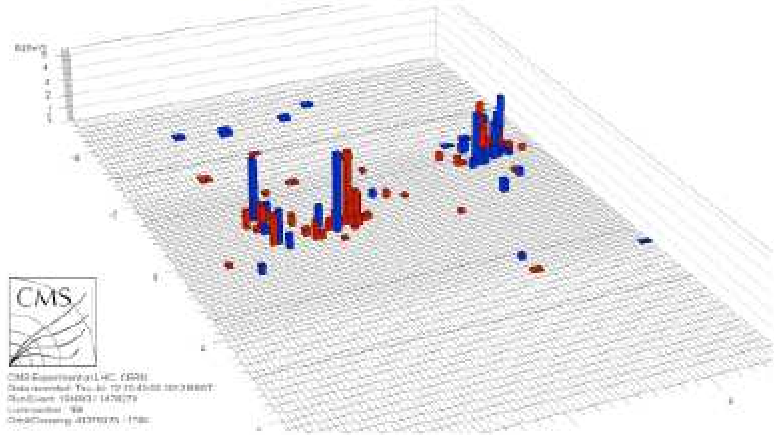
- Trijet cross sections: $|\eta_j| < 2.5$ anti–k_t; Δ R=0.6

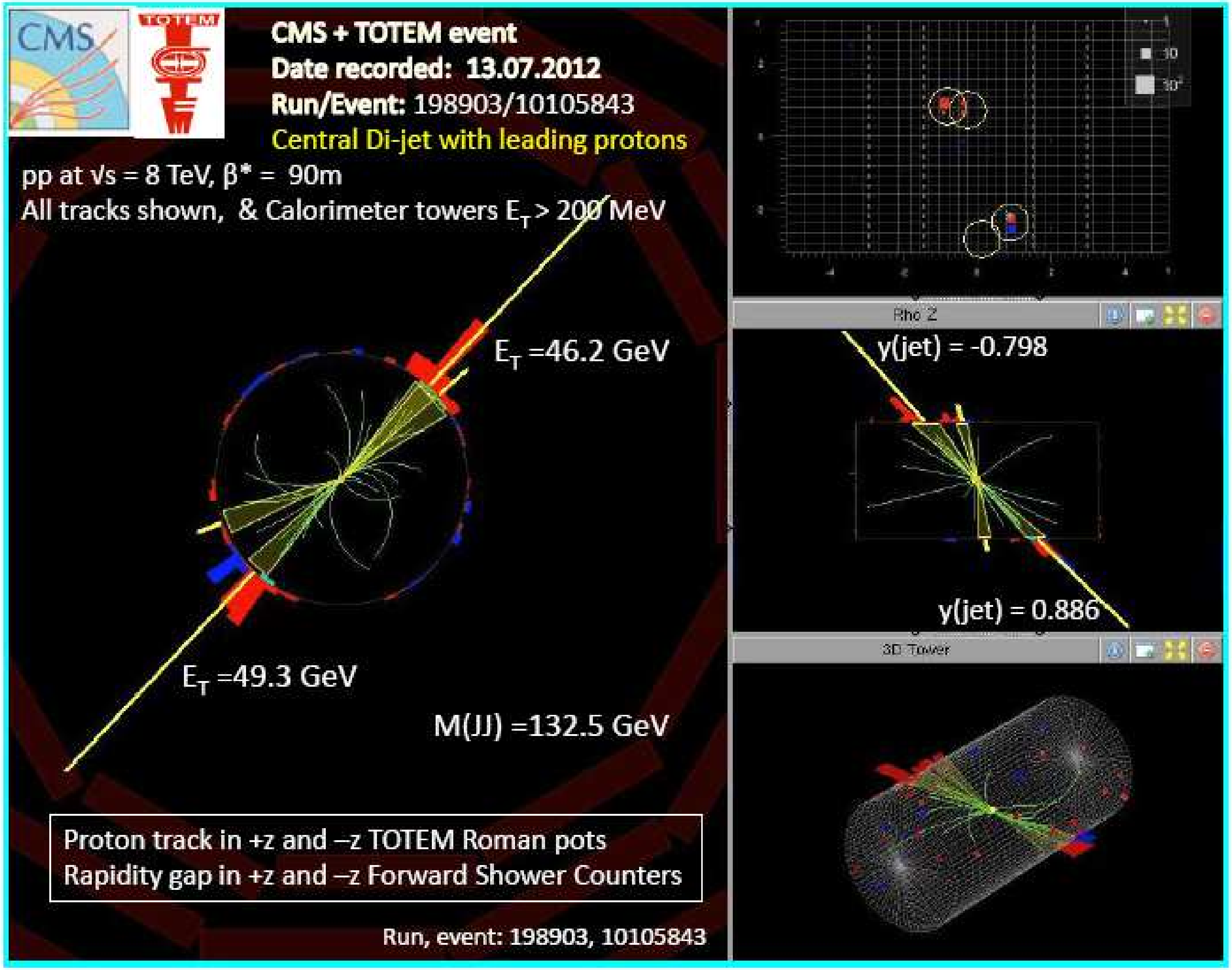
$b\bar{b}g$
~ factor of 4
$(= n_f)$ smaller

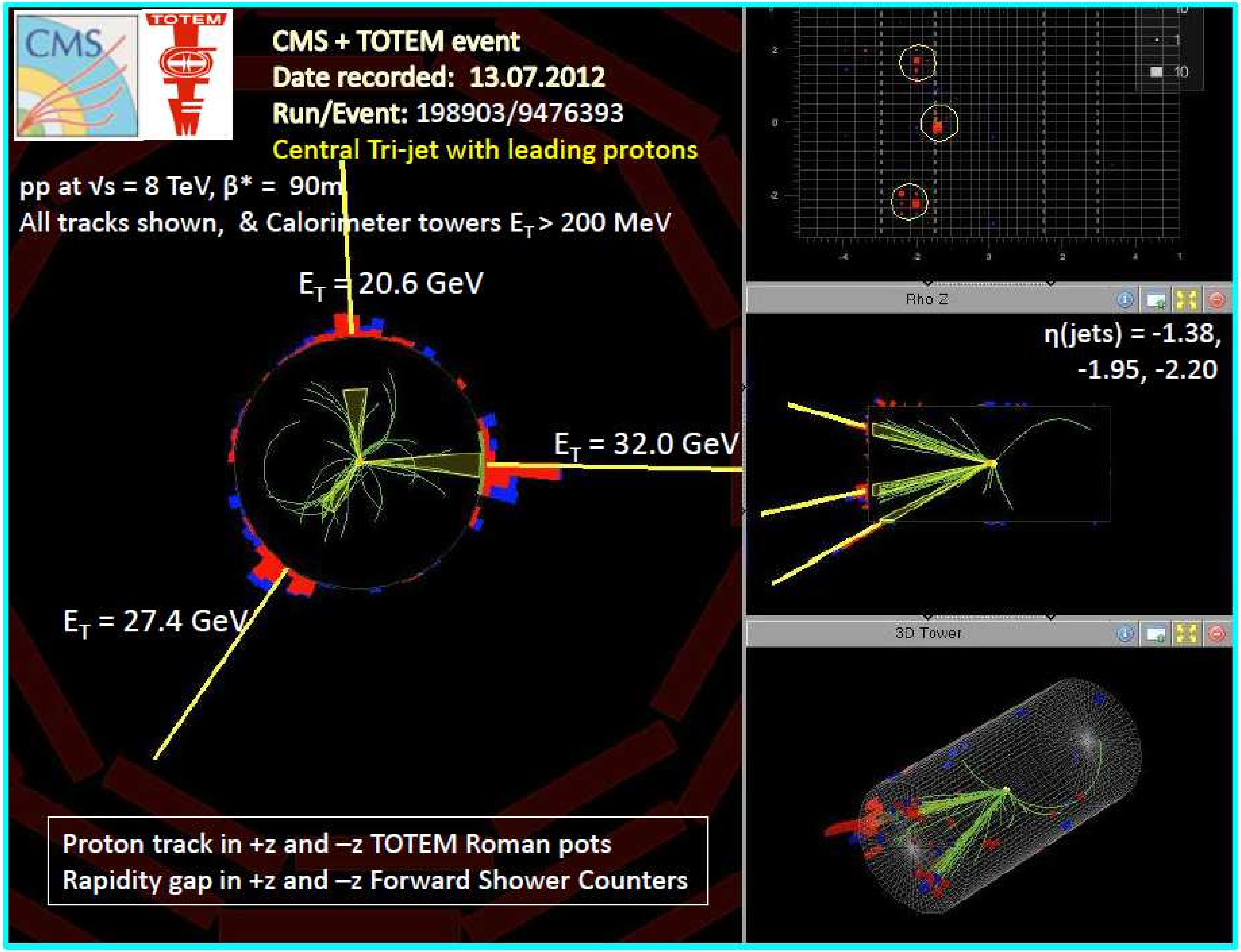
$M_X\,(\mathrm{min})$ [GeV]	For comparison gg	ggg	$q\bar{q}g$	
75	120	3.1	0.30	$\lvert p_{\perp,j}\rvert > 20$ GeV
100	30	2.1	0.22	
150	4.1	0.56	0.054	
150	1.9	0.046	2.5×10^{-3}	$\lvert p_{\perp,j}\rvert > 40$ GeV
250	0.14	0.013	8.8×10^{-4}	
250	0.082	2.0×10^{-3}	1.7×10^{-4}	$\lvert p_{\perp,j}\rvert > 60$ GeV

σ [pb] $\sum q = c, s, u, d$ Preliminary






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


CMS
TOTEM
CMS + TOTEM event
Date recorded: 13.07.2012
Run/Event: 198903/9476393
Central Tri-jet with leading protons
pp at √s = 8 TeV, β* = 90m
All tracks shown, & Calorimeter towers E_T > 200 MeV
E_T = 20.6 GeV
E_T = 32.0 GeV
E_T = 27.4 GeV
Rho Z
η(jets) = -1.38, -1.95, -2.20
3D Tower
Proton track in +z and –z TOTEM Roman pots
Rapidity gap in +z and –z Forward Shower Counters