Central Exclusive Production and the Durham Diffractive Program

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ISMD 2013, 15-20 September, IIT Chicago, IL

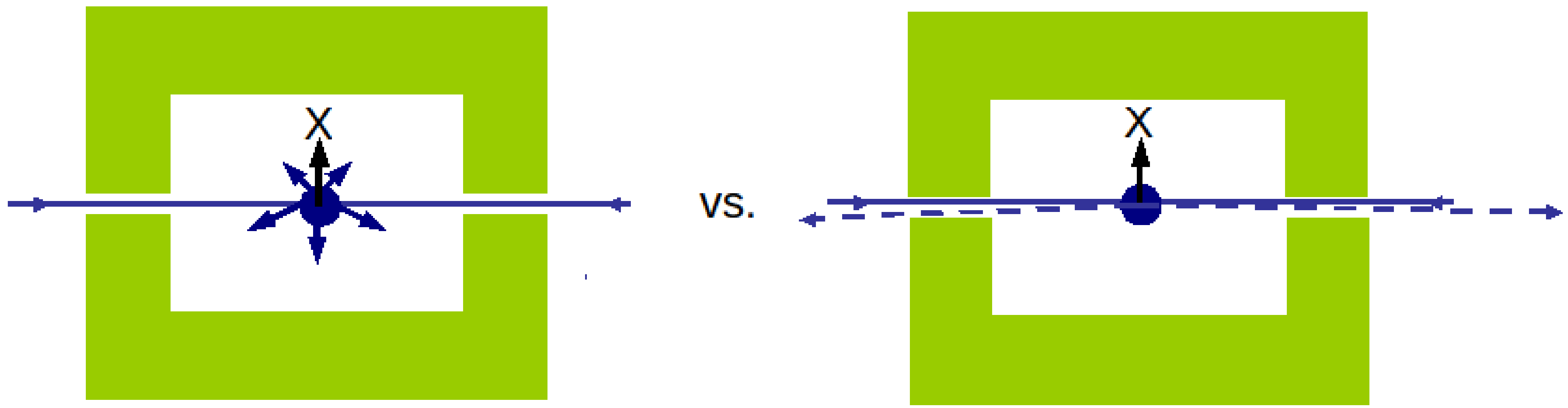
Based on work by V.A. Khoze, M.G. Ryskin, W.J. Stirling and L.A. Harland-Lang. (KHRYSTHAL collaboration)
Now KHARYS collaboration

Central Exclusive Diffraction

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

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

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

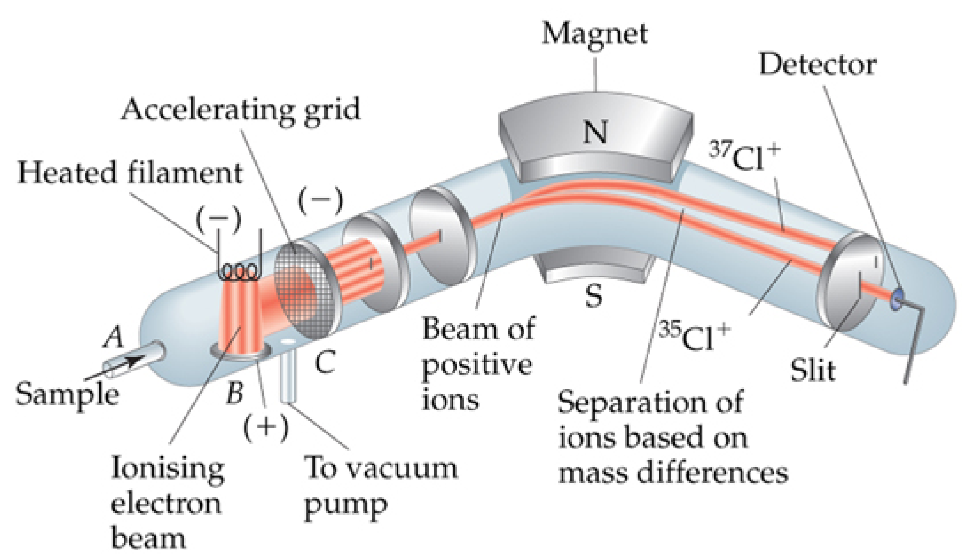


Why is it interesting?

• '$J_z^{PC} = 0^{++}$selection rule' : demanding exclusivity strongly selects particular quantum numbers. $\Longrightarrow$ Allows clean determination of central object properties and can suppress background in some cases (e.g. $H \to b\bar{b}$).

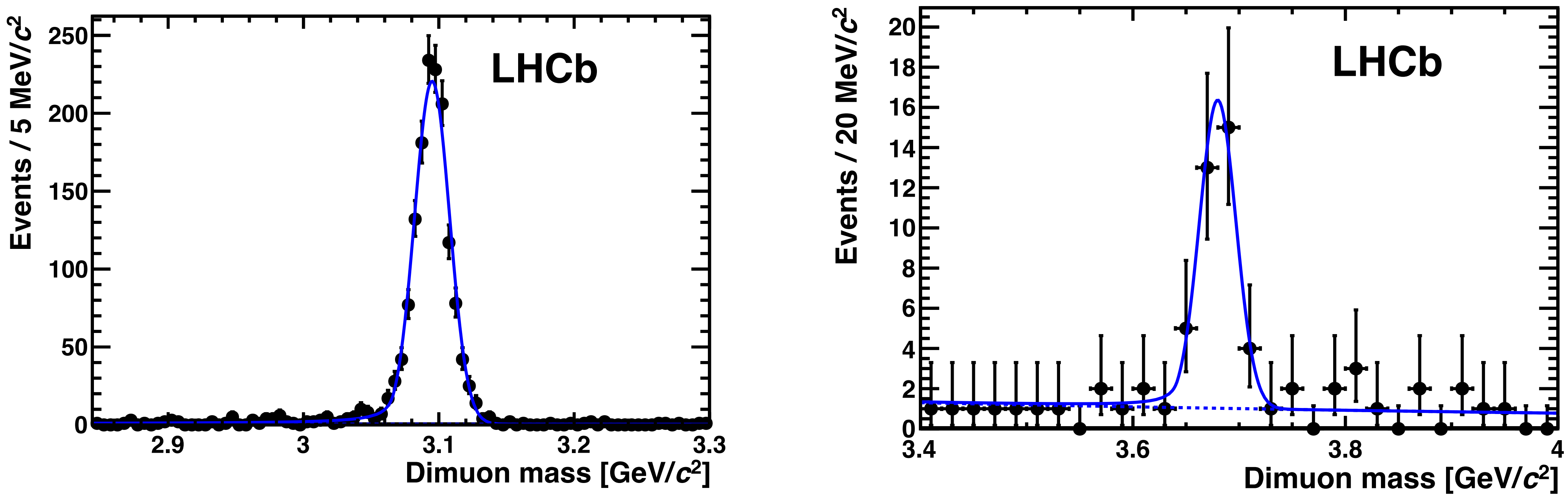
• Outgoing intact protons can be tagged and 4-momenta measured by detectors placed far from the beamline:

- Experimental handle for selecting events.
- 'Missing mass' measurement of central system.
- Correlations between proton momenta sensitive to models of soft physics and object quantum numbers.

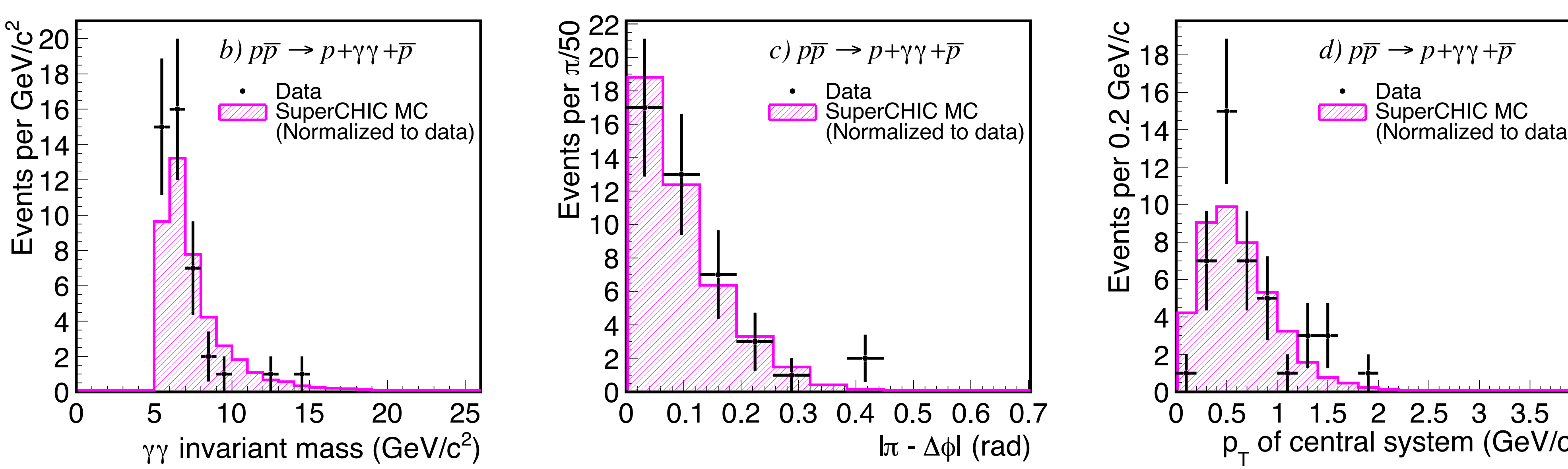


▲ **Figure 1.23 A mass spectrometer.** Cl atoms are introduced on the left side of the spectrometer and are ionised to form Cl^+ ions, which are then directed through a magnetic field. The paths of the ions of the two isotopes of Cl diverge as they pass through the magnetic field. As drawn, the spectrometer is tuned to detect $^{35}Cl^+$ ions. The heavier $^{37}Cl^+$ ions are not deflected enough for them to reach the detector.

- Theoretically: a complementary and novel application of QCD.
- Experimentally: very clean signal. Data already taken at the Tevatron (jj, $\gamma\gamma$, l^+l^-, χ_c, J/ψ, $\pi^+\pi^-$...) and taken/looked for at the LHC. Many plans for future measurements, lot of potential channels....



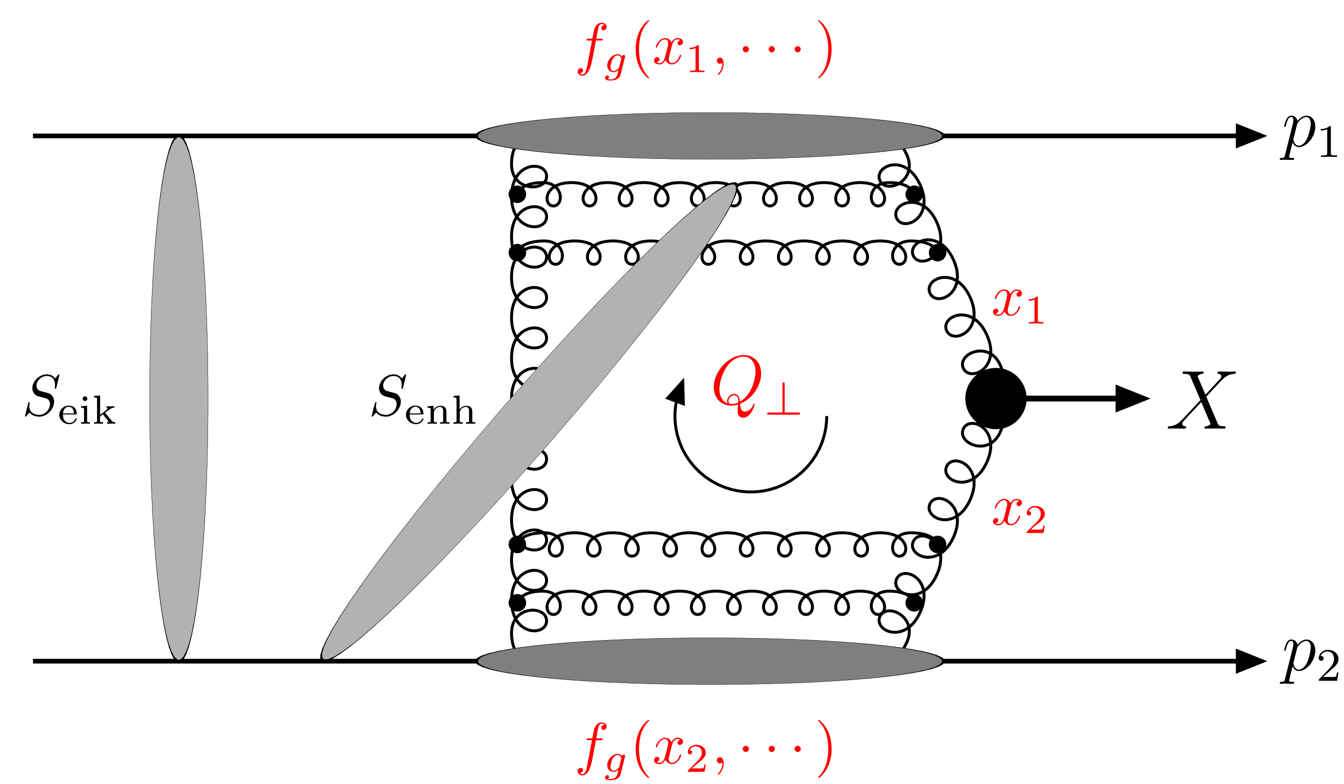
arXiv:1301.7084



CDF collaboration, PRL 108, 081801 (2012)

‘Durham Model’ of Central Exclusive Production

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



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

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

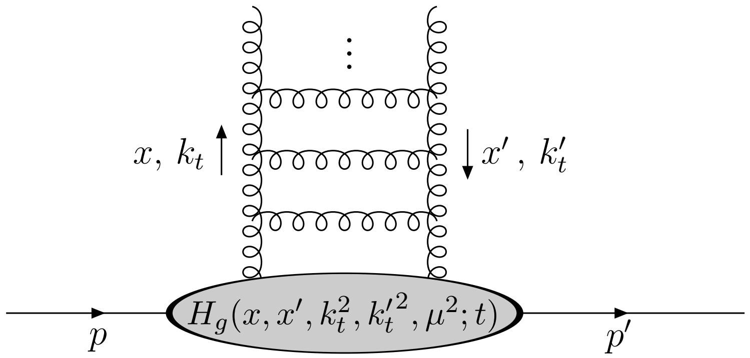
Calculating CEP : ingredients

- 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

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!

Detailed and clear treatment for Higgs CEP given in T.D. Coughlin and J.R. Forshaw, JHEP 1001:121, 2010. arXiv: 0912.3280

• CEP via Durham mechanism can in principle produce any particle which couples directly/indirectly to gluons:

Meson pairs ($\pi^+\pi^-, \eta(')\eta('), \pi^0\pi^0, KK$...), Heavy quarkonia, conventional ($\chi_c, \chi_b \cdots$) and exotic ($X(3872)$), Dijets, Diphotons, BSM objects, the Higgs Boson, Glueballs...

• CEP of lower mass states, for which there is/will be data serve as 'Standard Candles', and give support for model predictions ($\longrightarrow$ Higgs, New physics...).
• But these are also of interest in their own right. The unique dynamics of the CEP process provides additional information/insight that is not always possible via more conventional inclusive channels.

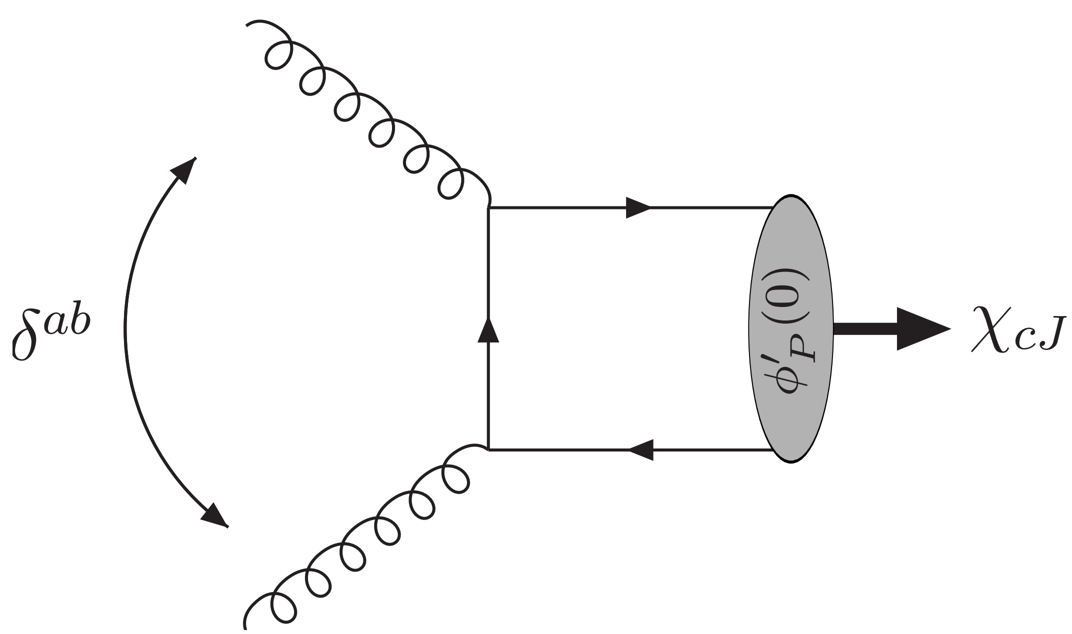
'**Durham diffractive program**' : developing the theory for these processes and implementing this in a MC (SuperChic, see Hepforge), to compare with Tevatron, RHIC and LHC data.
Will discuss some, but not all, such processes in the rest of this talk...

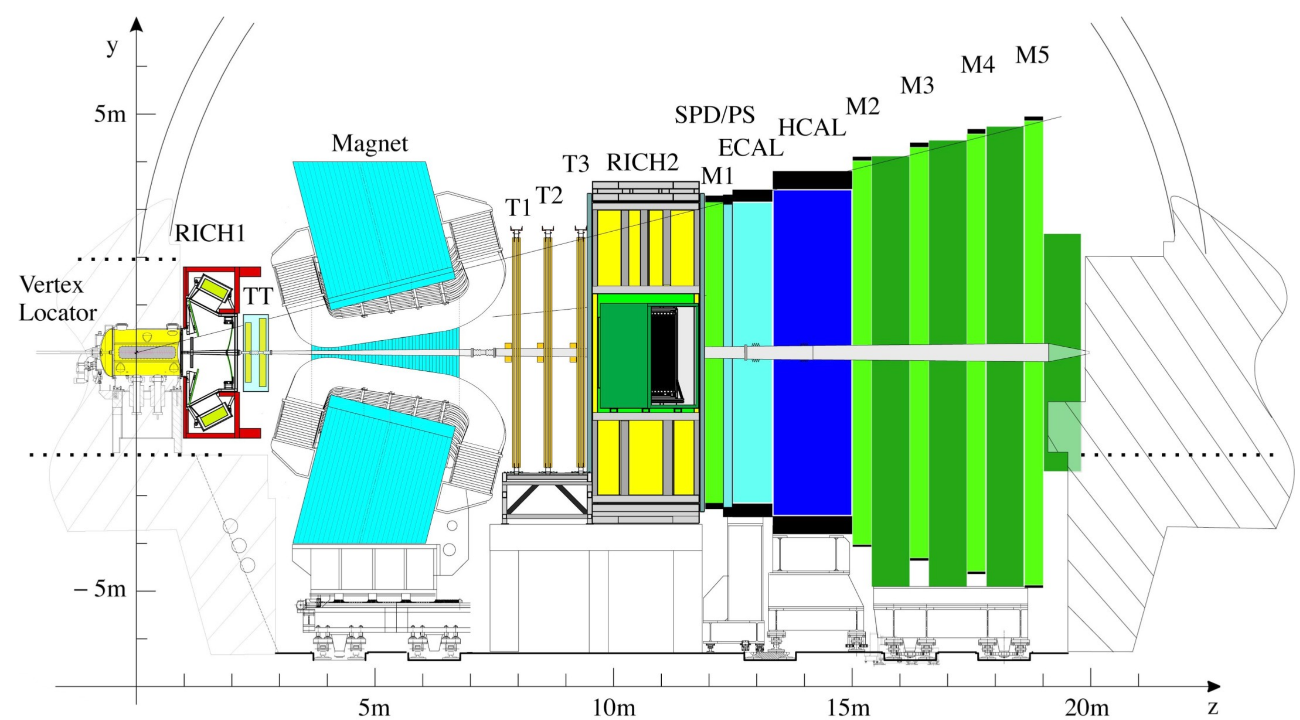
HKRS: arXiv:0909.4748, 1005.0695

Heavy quarkonia

$$\chi_{cJ}\,:\,L=1,S=1,J^{PC}=(0,1,2)^{++}\ c\bar{c}\ \text{meson states},\ M_{\chi_c}\approx 3.5\ \text{GeV}.$$

- Production cross sections determined by unique CEP kinematics:
  - χ_{c2} : in the non-relativistic quarkonium approximation coupling to gg in a $J_z=0$ state vanishes (dominant configuration for CEP).
  - χ_{c1} : Landau-Yang theorem forbids coupling of a $J=1$ particle to on-shell gluons (true to good approximation in CEP). Additionally suppressed by specific form of vertex.
- No suppression in χ_{c0} $\Rightarrow$ expect strong hierarchy in rates. Completely different to inclusive case.





- Measurements made by CDF and LHCb, by vetoing on additional activity in given η range in the $\chi_c \to J/\psi\gamma$ channel (favours $\chi_{c(1,2)}$).
  - CDF show good agreement with Durham predictions, while LHCb see:

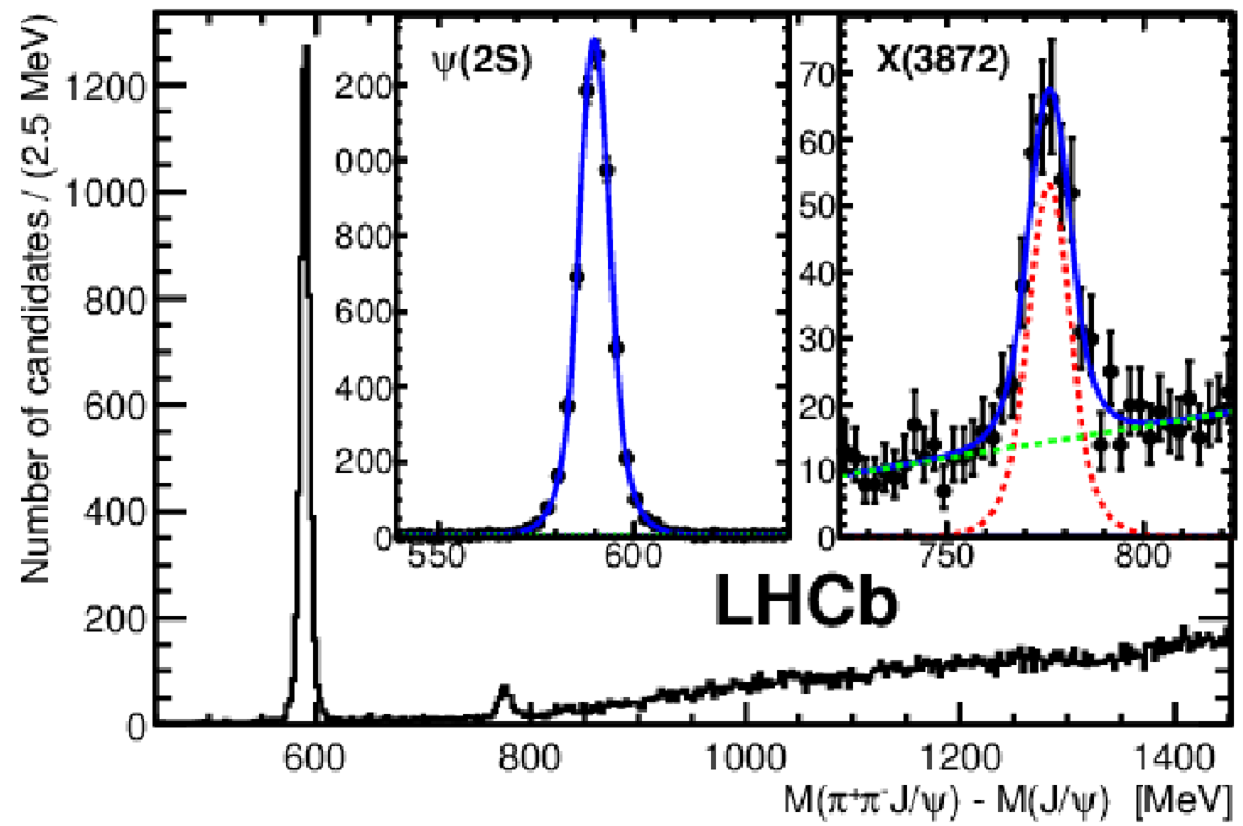
CERN-LHCb-CONF-2011-022

	$\frac{\sigma(pp\to pp(\mu^+\mu^-+\gamma))}{\mathrm{Br}(J/\psi\to\mu^+\mu^-)\mathrm{Br}(\chi_{cJ}\to J/\psi\gamma)}$ 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 $\chi_{c(0,1)}$ states. Do not expect to see (and do not see) in inclusive production. LHCb, arXiv:1307.4285 : **first** inclusive χ_{c0}
- Good data/theory agreement for $\chi_{c(0,1)}$ states (within quite large theory uncertainty), but significant χ_{c2} excess. Could be due to proton dissociation (forward shower counters...?), or further theory input could be needed (relativistic/non-perturbative corrections...).

Exotic quarkonia: the 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.

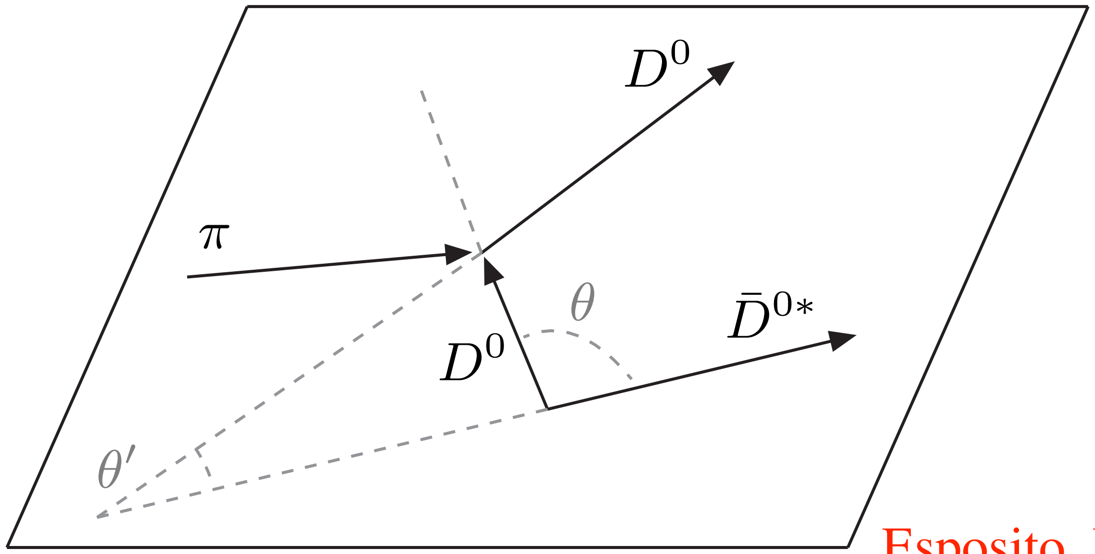


- Possible J^{PC} assignments were 1^{++} or 2^{-+}.
- New LHCb data (arXiv:1302.6269) rejects 2^{-+} at 8 sigma level $\rightarrow \eta_{c2}(1^1D_2)$ ruled out.
- Exotic interpretations still possible or conventional $\chi_{c1}(2^3P_1)$ charmonium?

Insight from CEP

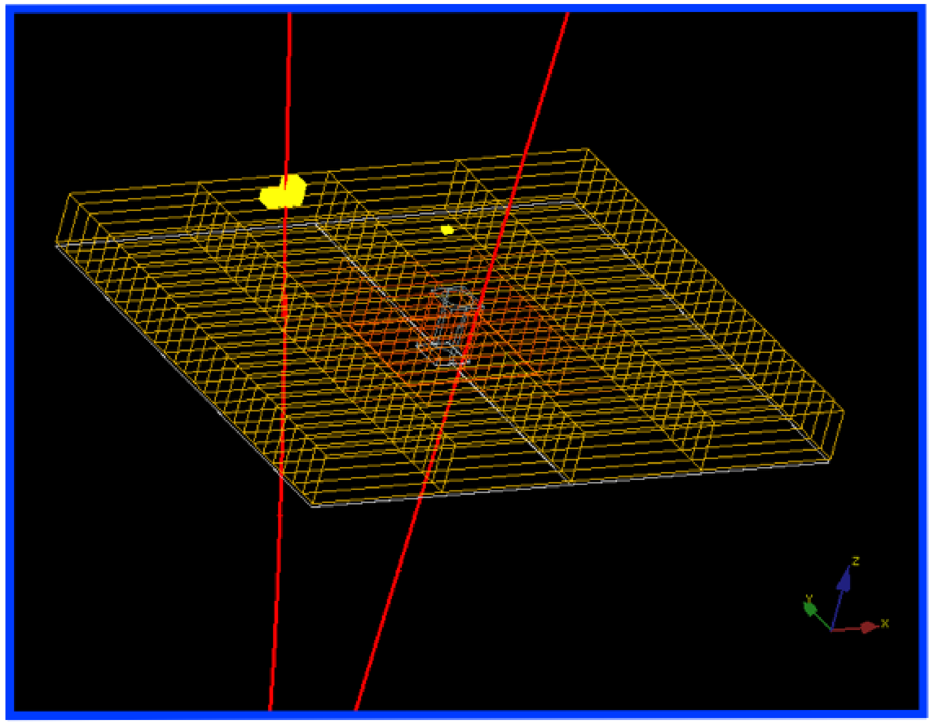
- In CEP the state X is produced directly, i.e. at short distances: $gg \to X(3872)$ and nothing else. $\to$ would be clear evidence of a direction production mode.
- In an inclusive environment, for which additional soft quarks, D-mesons etc can be present/emitted it should be easier to form molecular state (arXiv:1305.0527, 1008.2868, 0911.2016...). 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 $|\phi_P'(0)|^2$.



$k_0 < 50$ MeV	0π	1π	3π
Herwig	10	19	802
Pythia	3	21	814

Esposito, Piccinini, Pilloni, Polosa: arXiv:1305.0527



See Mike Albrow's talk

CEP of meson pairs

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.

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

HKRS: arXiv:1304.4262, 1302.2004, 1204.4803, 1105.1626

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

HKRS arXiv: 1204.4803, Lebiedowicz, Pasechnik, Szczurek, PLB 701:434-444, 2011

Perturbative regime

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

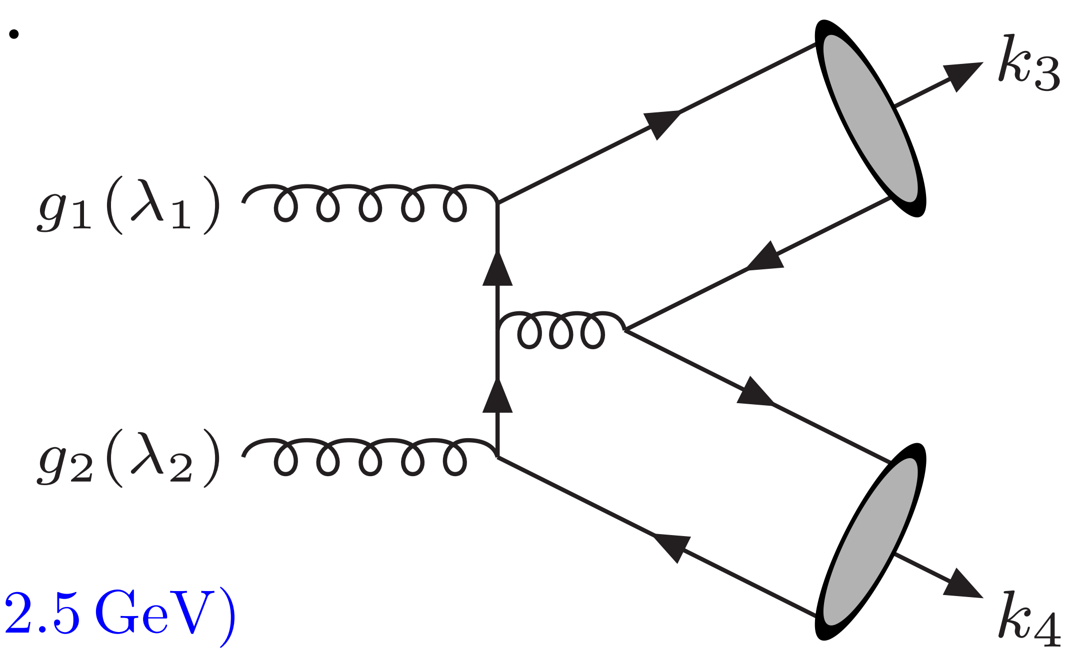
Brodsky, Lepage: Phys.Rev. D24 (1981) 1808....

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

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

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

- For flavour non-singlet mesons ($\pi\pi, KK\ldots$) diagrams of type shown contribute. Vanish for $J_z = 0$ gluons. $\Longrightarrow$ Strong suppression in CEP cross sections expected.



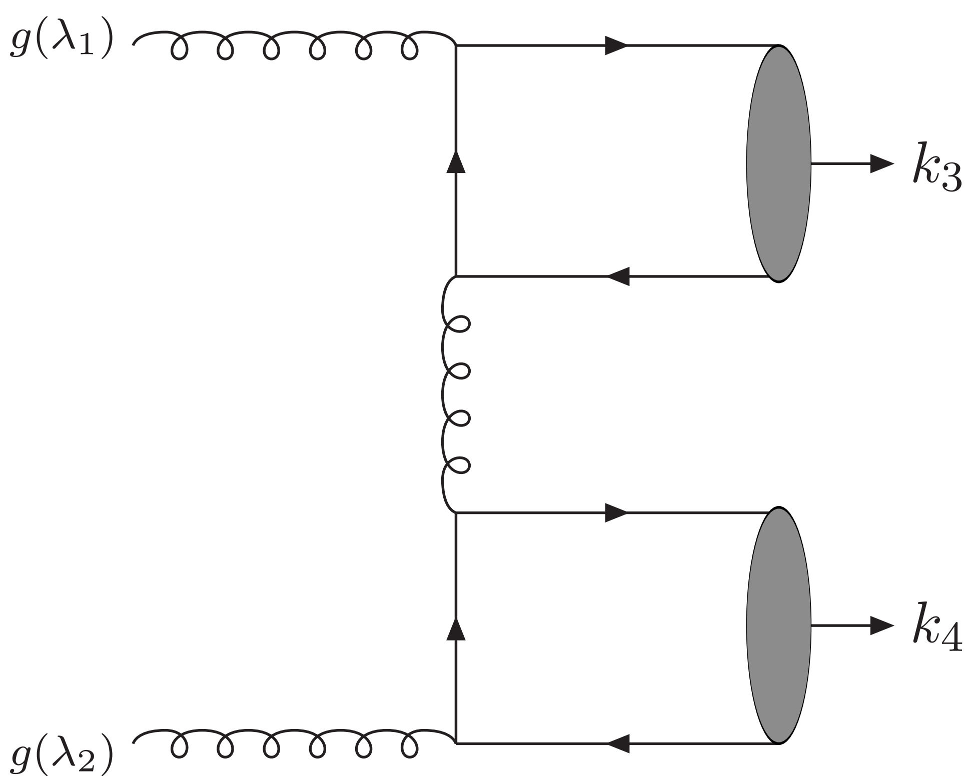
$(E_\perp(\gamma) > 2.5\,\mathrm{GeV})$

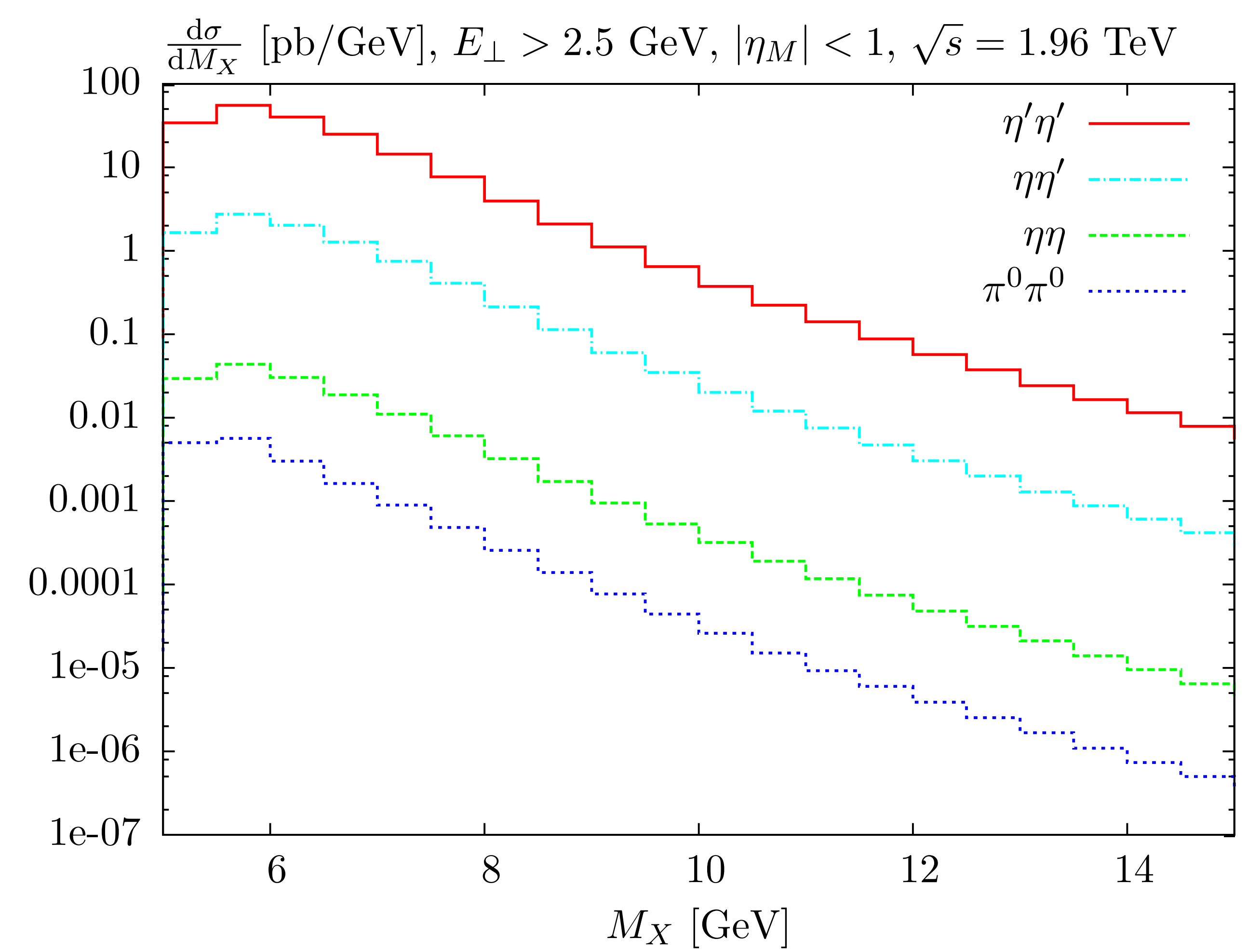
Seen in CDF $\gamma\gamma$ data (arXiv:1112.0858): $N(\pi^0\pi^0) < 0.35$ @ 95 % confidence

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

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. $\eta'\eta'$ rate is predicted to be large!



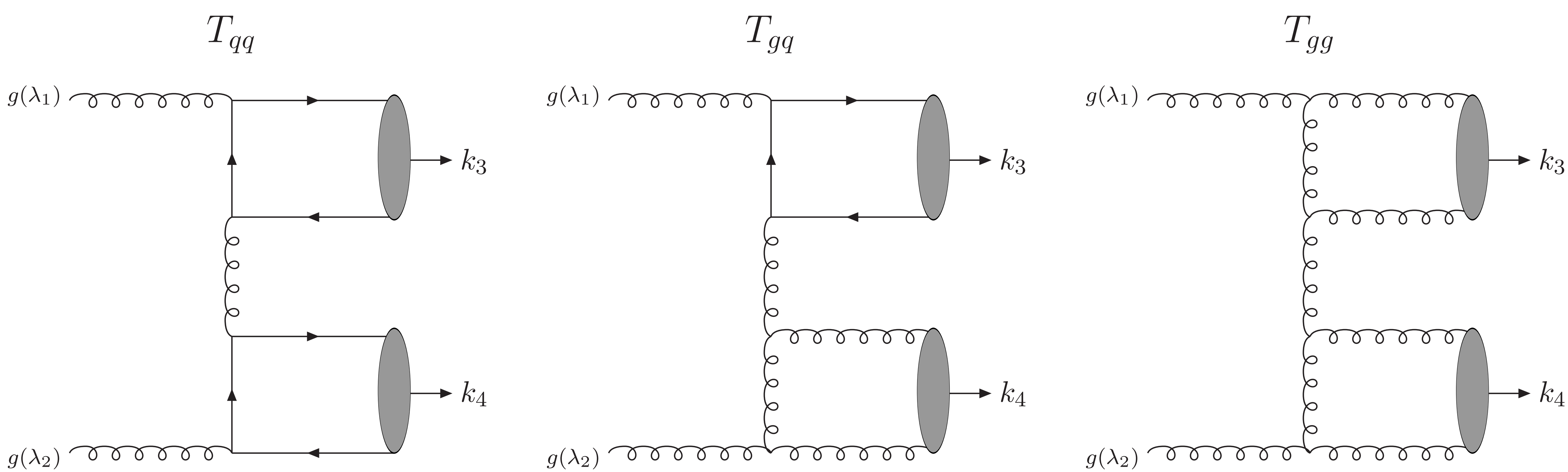


The gluonic component of the $\eta'(\eta)$

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

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



HKRS: arXiv:1302.2004

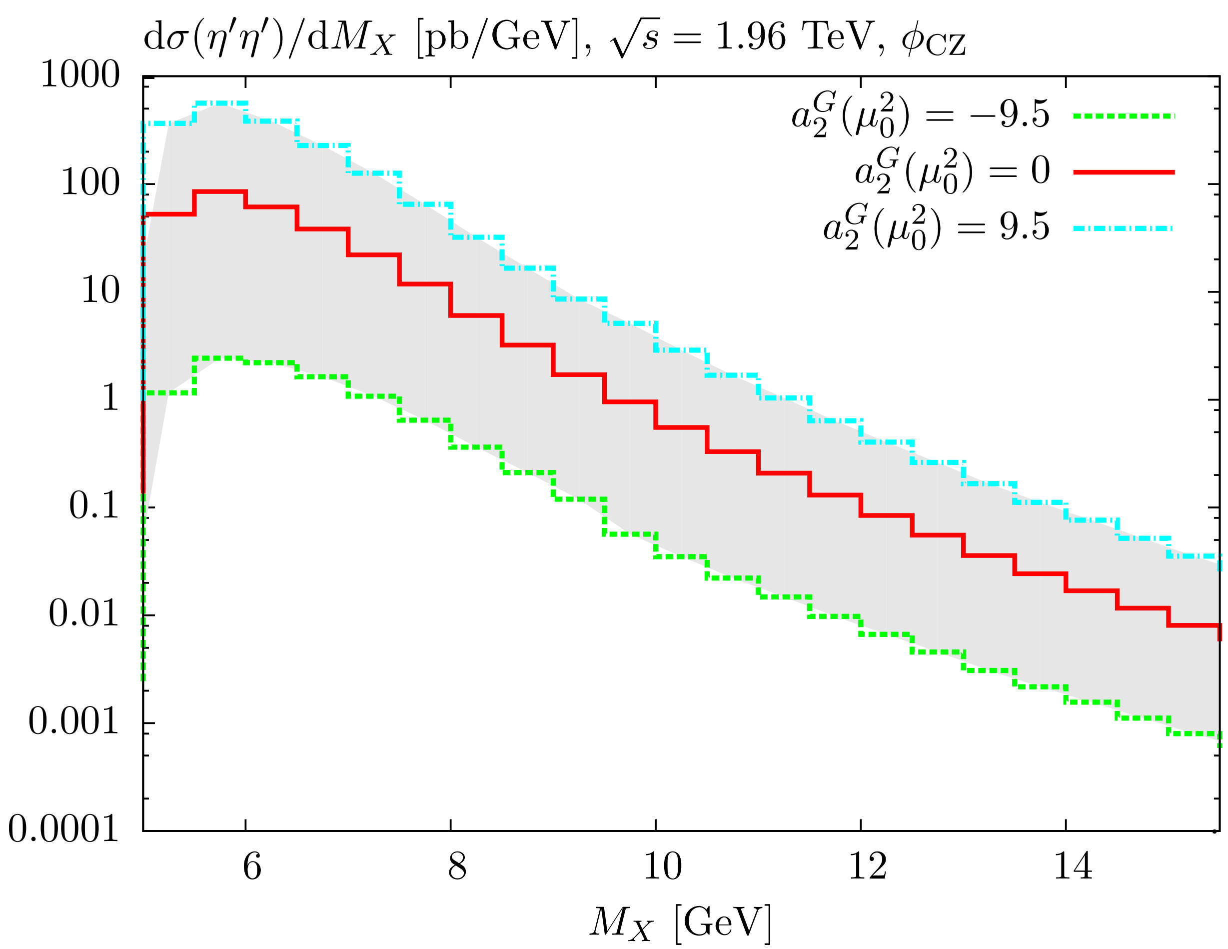
• Find that the relevant $gg \to gg q\bar{q}(gg)$ amplitudes do not vanish for $J_z = 0$ incoming gluons $\Longrightarrow$ no suppression present. Enter at same (leading) order to $q\bar{q}$ component.

Kroll, Passek-Kumericki

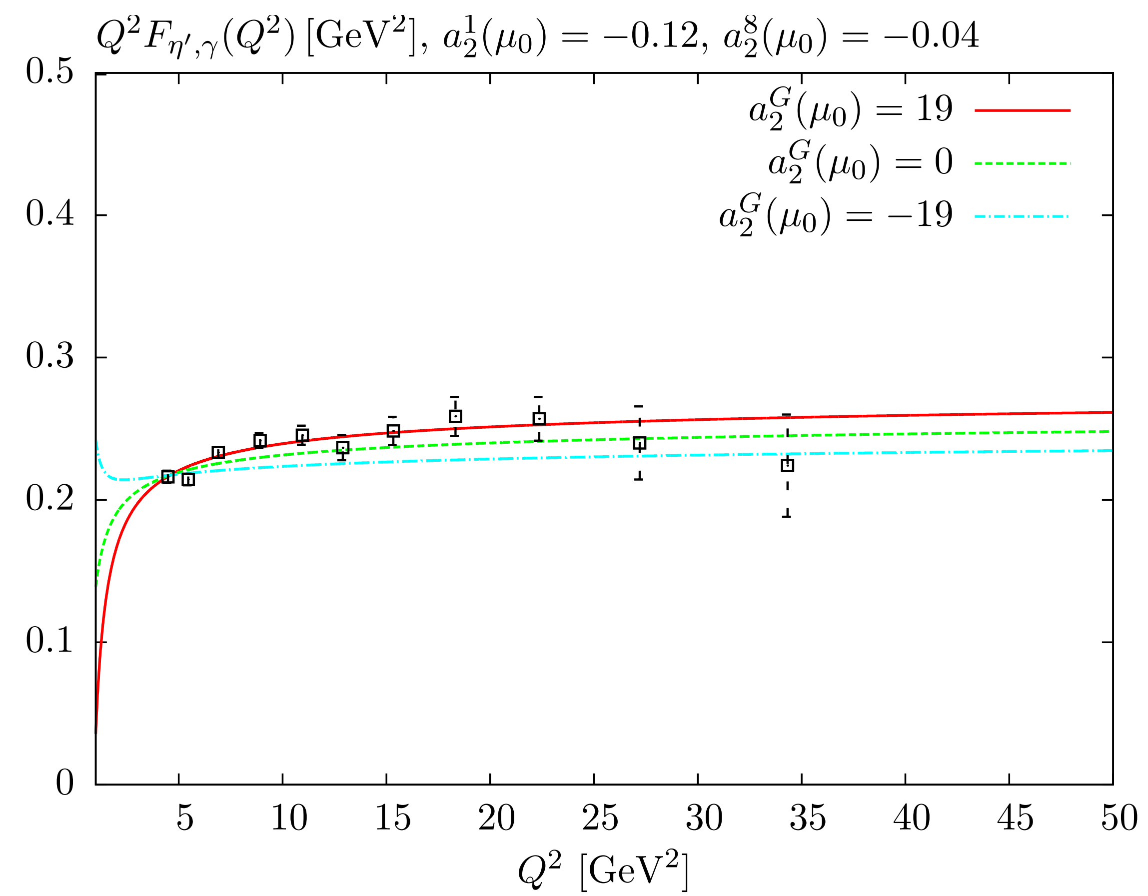
• Taking the central fit of arXiv:1206.4870, we would expect a ~ order of magnitude increase in the $\eta(')\eta(')$ cross section!

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

HKRS: arXiv:1302.2004



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



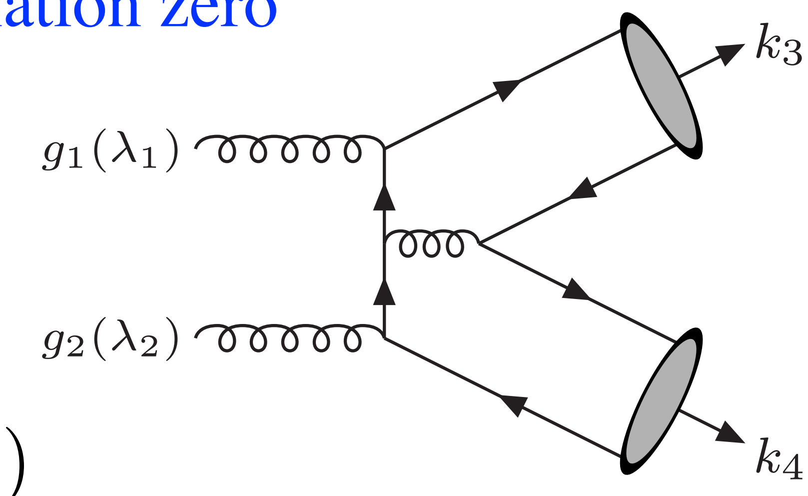
An evaluation of these exclusive amplitudes has lead to many interesting theoretical features :

Flavour non-singlets :

$$T_{++} = T_{--} = 0 \longleftarrow$$ Complete cancellation

QCD Radiation zero

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



Flavour singlets :

(8 diagrams)

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

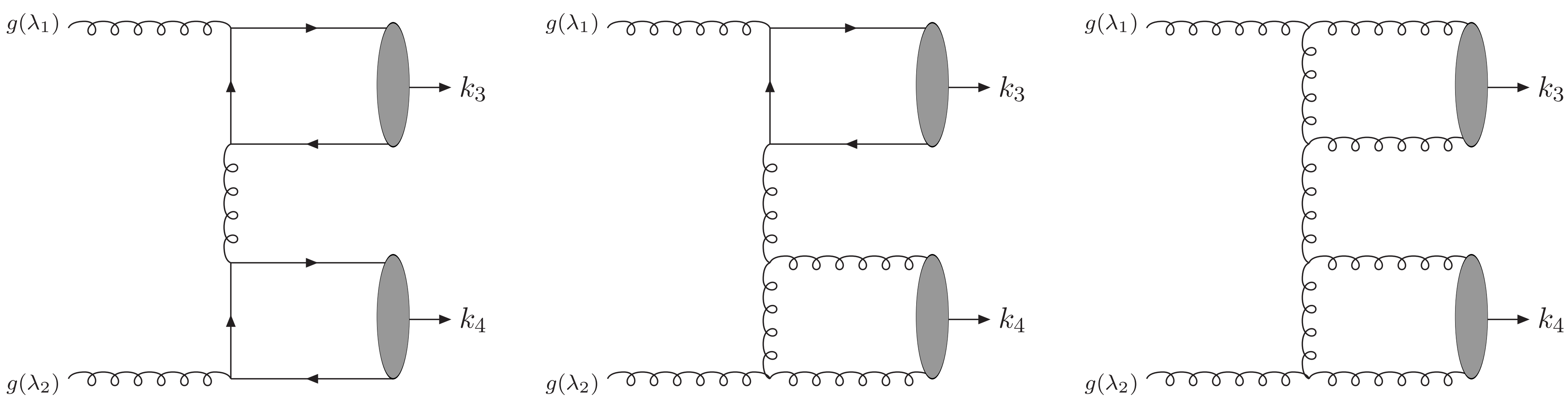
(76 diagrams)

$$T_{++}^{gq.} = T_{--}^{gq.} = 2\,T_{++}^{qq.}\frac{N_c^2}{\sqrt{N_c(N_c^2-1)}}(2x-1)$$

(130 diagrams)

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

Identical in form up to overall normalization!



Can understand in MHV framework, for more info see HKRS 1302.2004, 1304.4262.

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

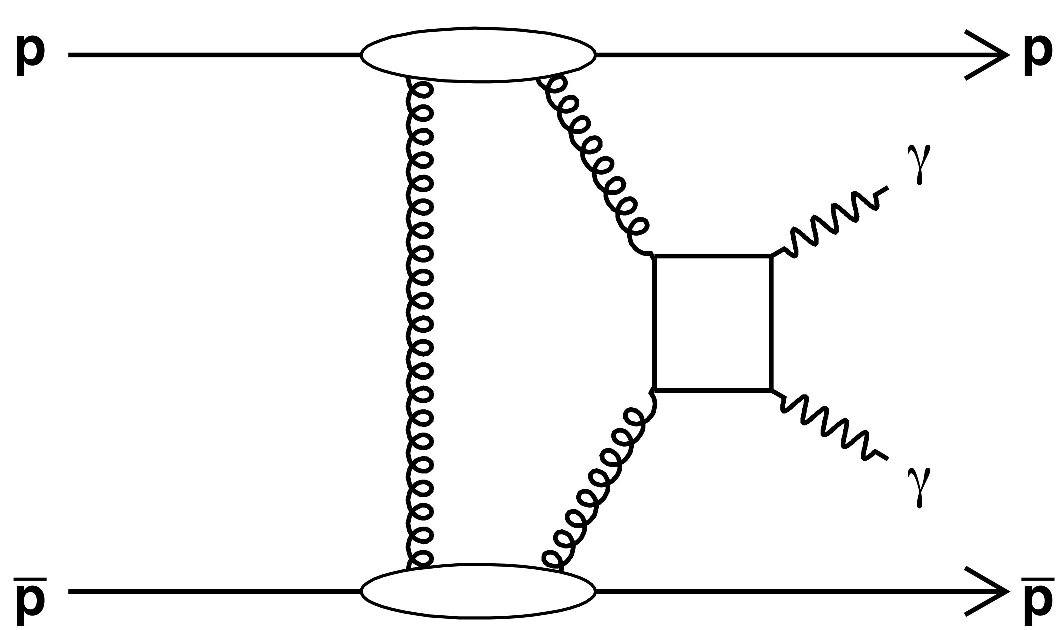
for $E_\perp$ >2.5 GeV, $|\eta_\gamma| < 1$ HKRS: EPJC 72 (2012) 2110

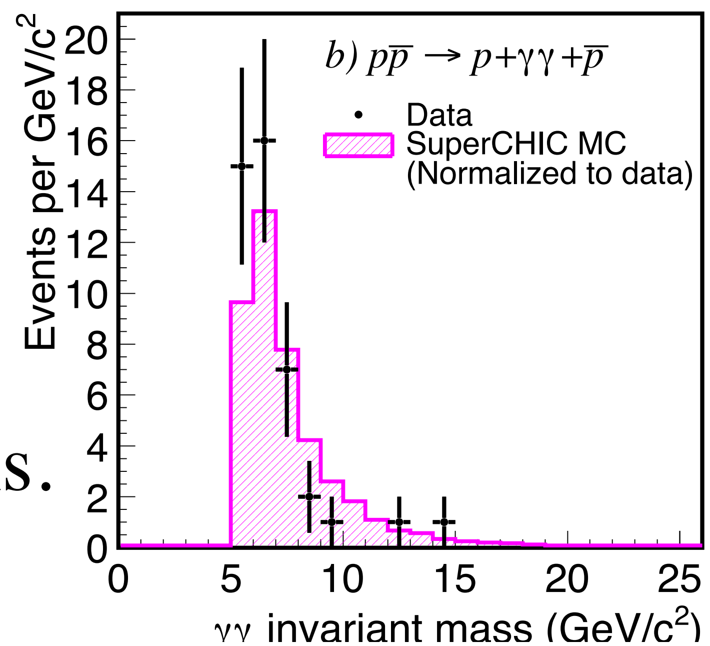
- In good agreement with Durham **predictions**:

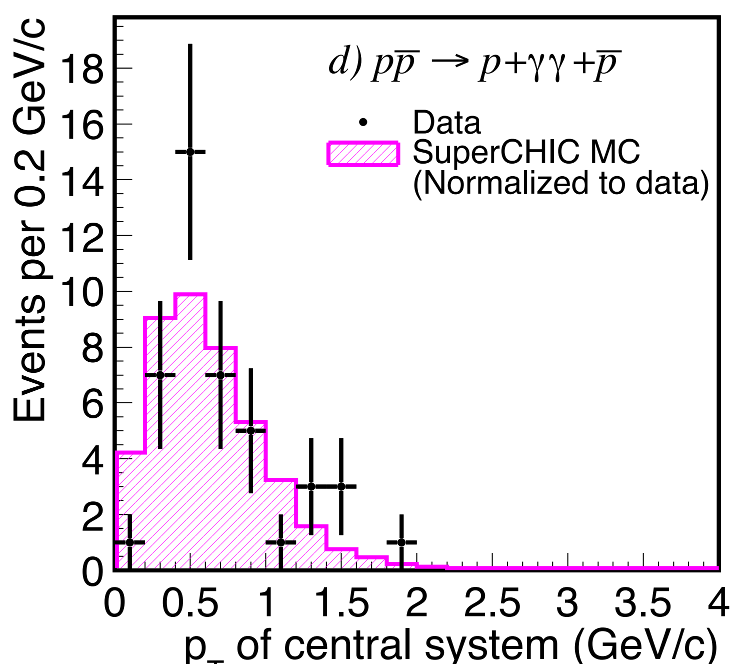
	MSTW08LO	CTEQ6L	GJR08LO
$\sqrt{s} = 1.96$ TeV ($\lvert\eta\rvert < 1$)	1.4	2.2	3.6

- CMS have set limits close to Durham LHC predictions. CMS-PAS-FWD-11-004.

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



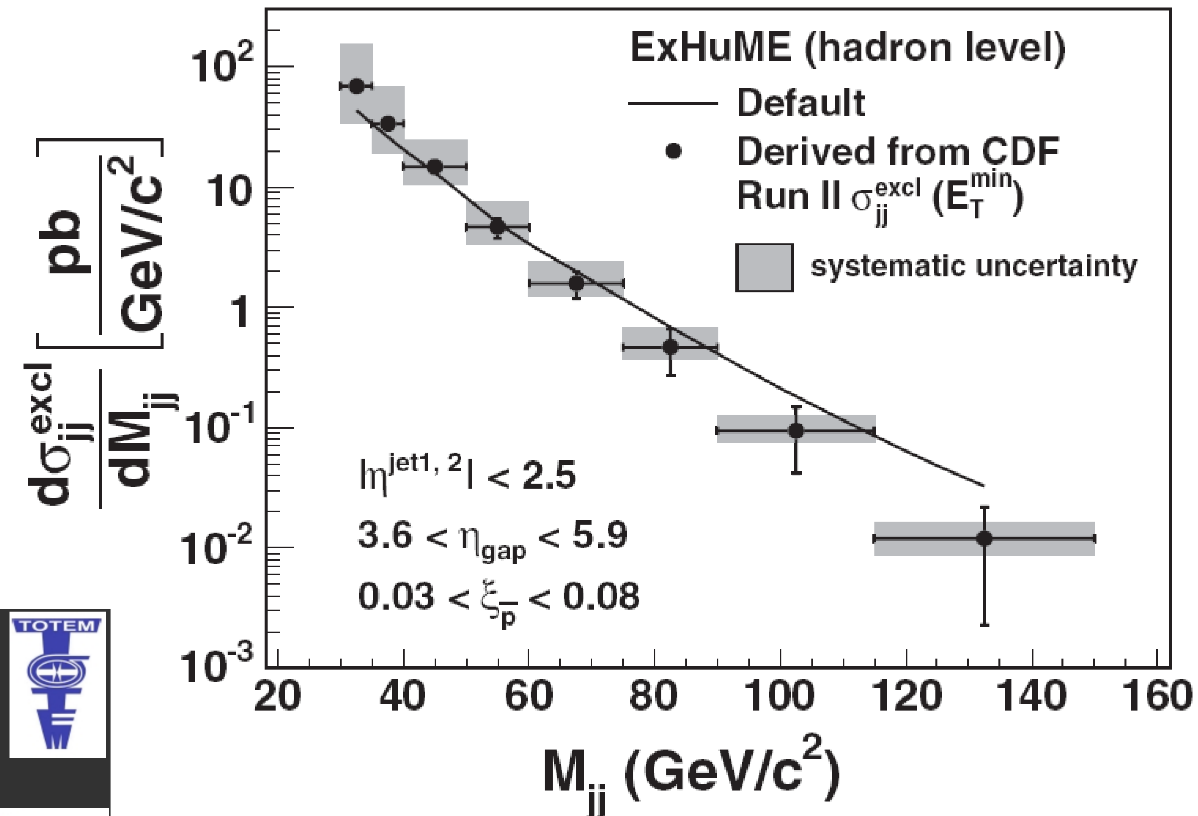


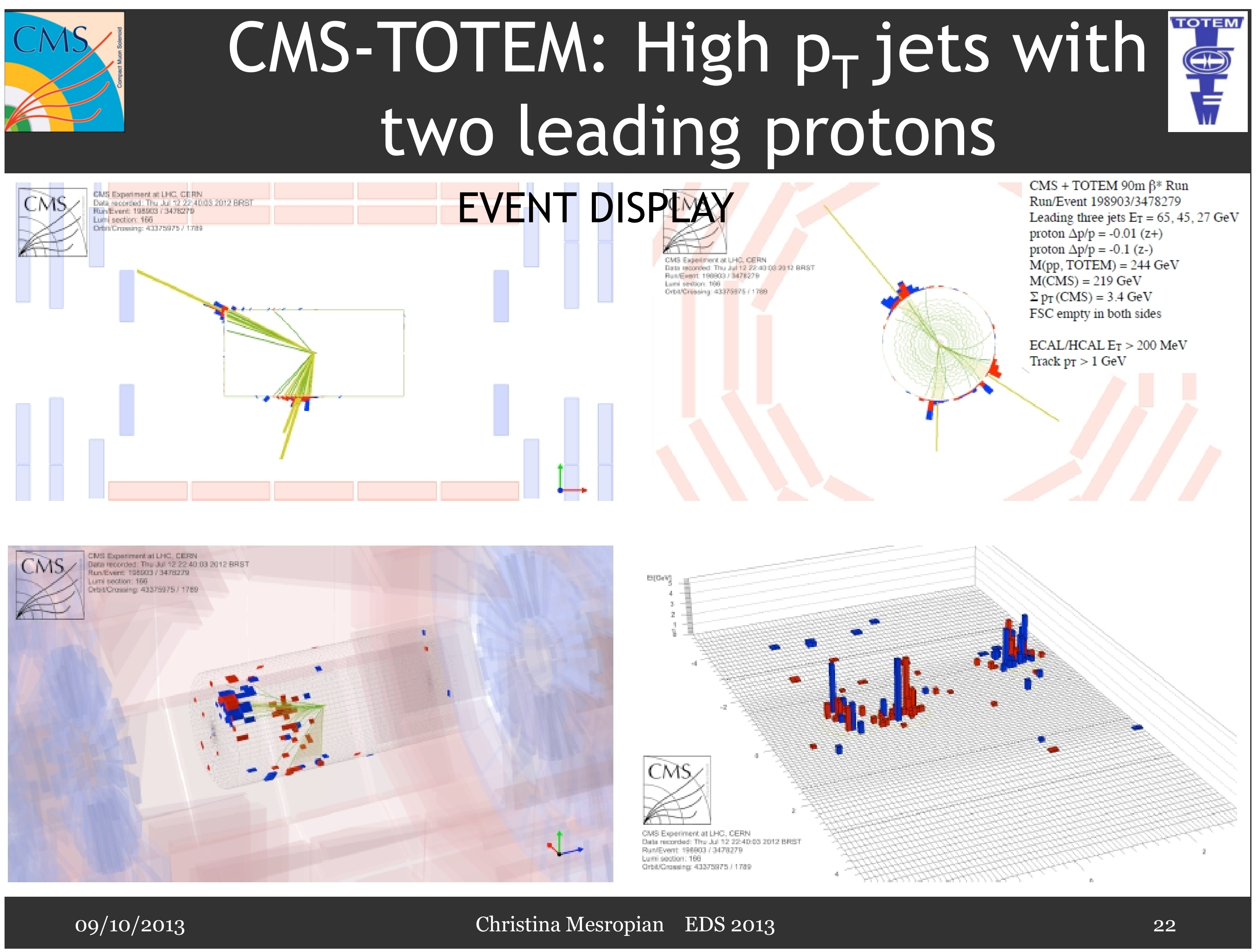


The future (I) : exclusive jets at the LHC

Measured by CDF already....

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

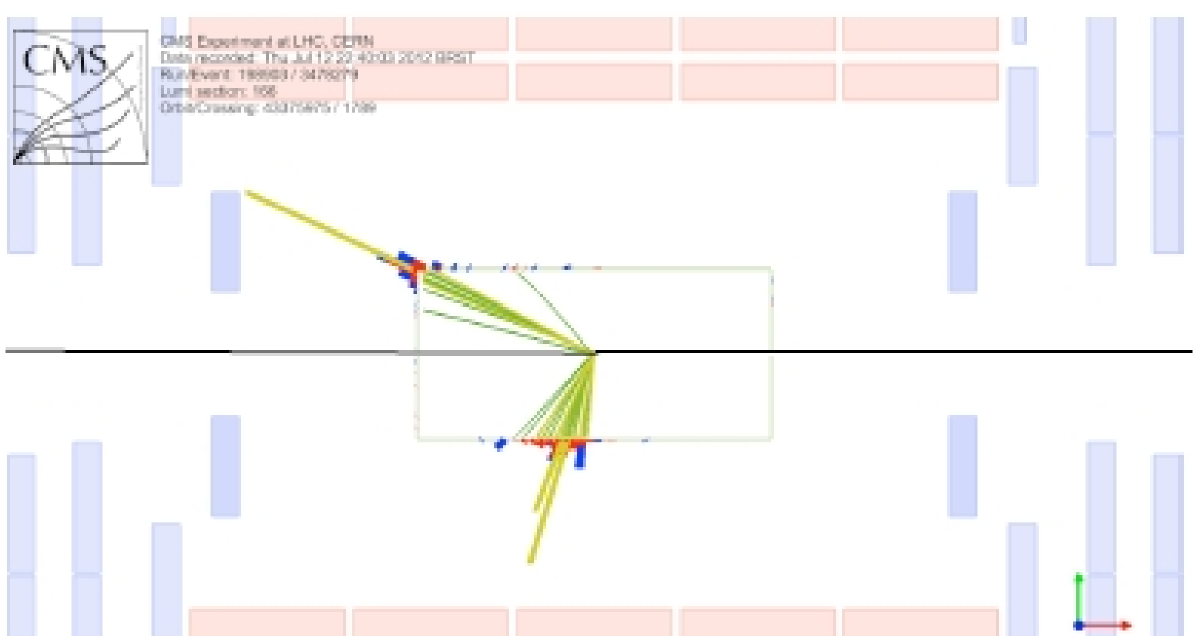


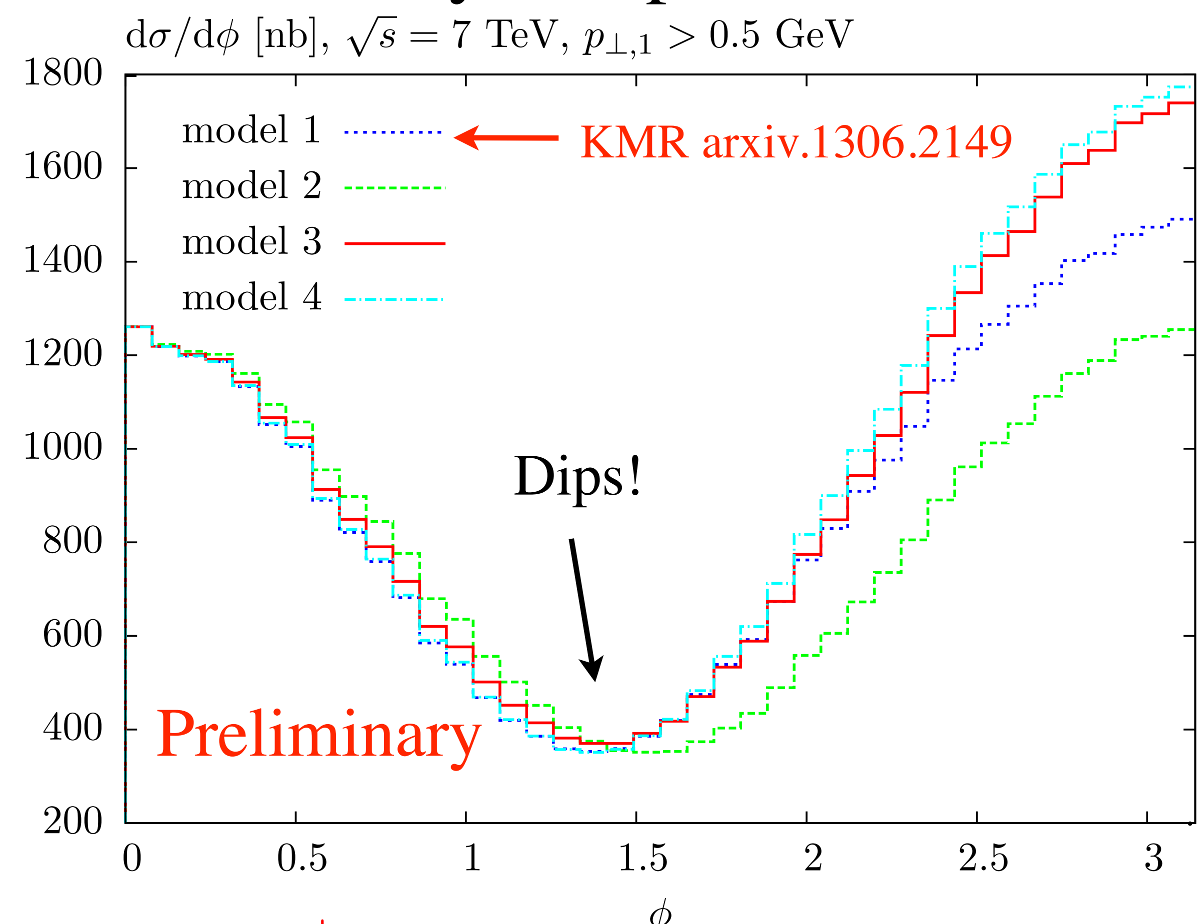


Events now taken by CMS + TOTEM

Christina Mesropian, EDS Blois 2013

- Expect quite different behaviour to inclusive case:
  - Suppression in quark dijets (LO $gg \to q\bar{q}$ vanishes for massless quarks and $J_z = 0$ gluons).
  - 'Mercedes' configuration for 3-jets favoured.
  - Sharper fall off with M_{jj} driven by 'Sudakov factor', QCD resummation effect.
- Correlations between outgoing proton momenta sensitive to model of soft proton-proton interactions.
- Ongoing work to develop up to date and theoretically complete MC for this.





For $\pi^+\pi^-$ but similar for jet production

The future (2) : the exclusive Higgs

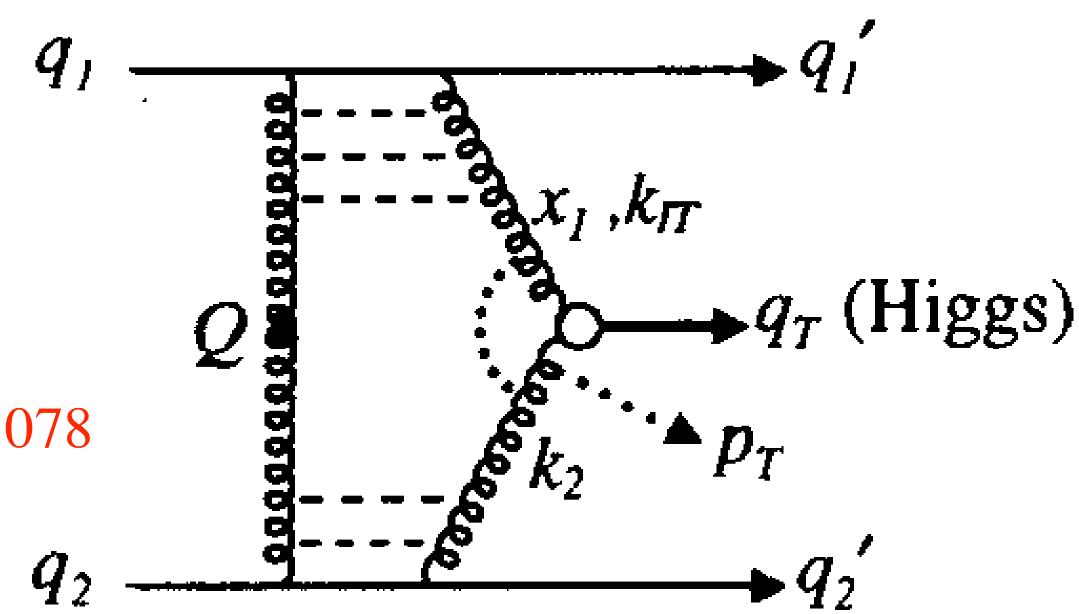
- Can consider the exclusive production of the Higgs:

$$pp \to p \; + \; H \; + \; p$$

- As above, the LO $gg \to q\bar{q}$ amplitude vanishes for $J_z = 0$ gluons and massless quarks. $\Longrightarrow$ strong suppression in $b\bar{b}$ direct BG, and $S/B \sim 1$ with $H \to b\bar{b}$ attainable in exclusive channel.

B. Cox et al. JHEP 0710 (2007) 090, M. G. Albrow et al. JINST 4 (2009) T10001, arXiv:0806.0302

- Selection rule: produced system dominantly 0^{++}
- Other BSM Higgs scenarios (SUSY...) can be more favourable.
- Assymmetry in proton azimuthal distribution could probe CP-violating effects. KMR, hep-ph/0401078
- Needs proton detectors at 420m from IP : proposed for ATLAS/CMS, not installed yet.



V.A. Khoze et al. / Physics Letters B 401 (1997) 330–336

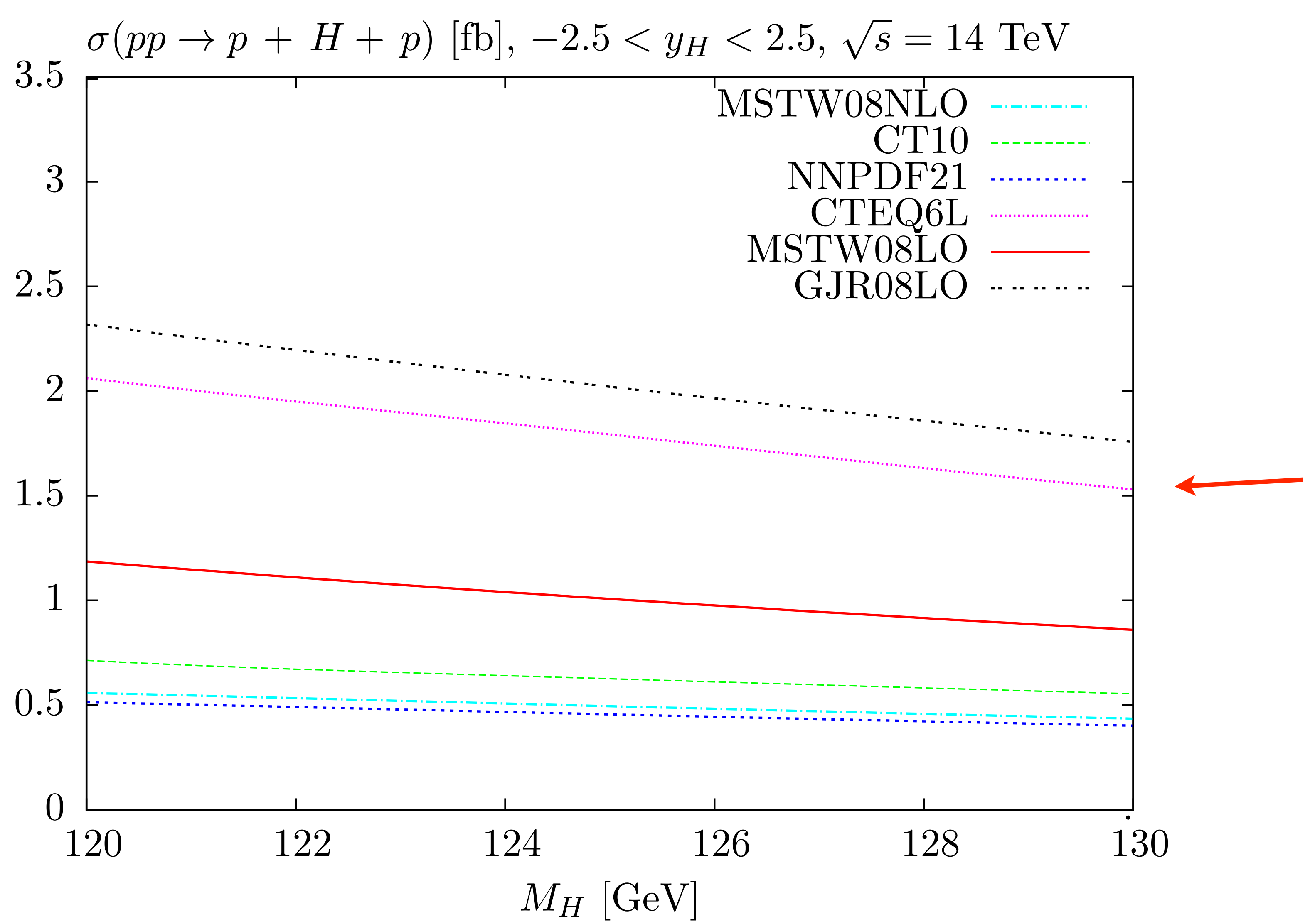
- Higgs cross section predictions guided in particular by CDF $\gamma\gamma$ data

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

Theory

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

- Expect quite small $\sim$ fb cross sections - price paid for exclusivity.



The SuperCHIC MC

A MC event generator including[8]:

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

$\longrightarrow$ Via close collaboration with experimental collaborations, in both proposals for new measurements and applications of SuperCHIC, it is becoming an important tool for current and future CEP studies.
Suggestions for additional modes etc to include/study are welcome!

Conclusions

- CEP in hadron collisions offers a promising and complementary framework within which to study Standard Model and new physics signals.
- Exclusive processes observed at the Tevatron, RHIC and low pile-up/luminosity LHC can serve as 'standard candles' for the exclusive Higgs, and other new physics, but are of interest in their own right.
- In this talk I have presented an overview of some such processes.
- Our work also forms part of a broader program: new LHC forward physics WG (http://lpcc.web.cern.ch/lpcc/index.php?page=fwd_wg).
- Many other channels not discussed today are possible, and hopefully many more CEP results to come in the future!