Exclusive Jet Production at the LHC

Lucian Harland-Lang, IPPP Durham

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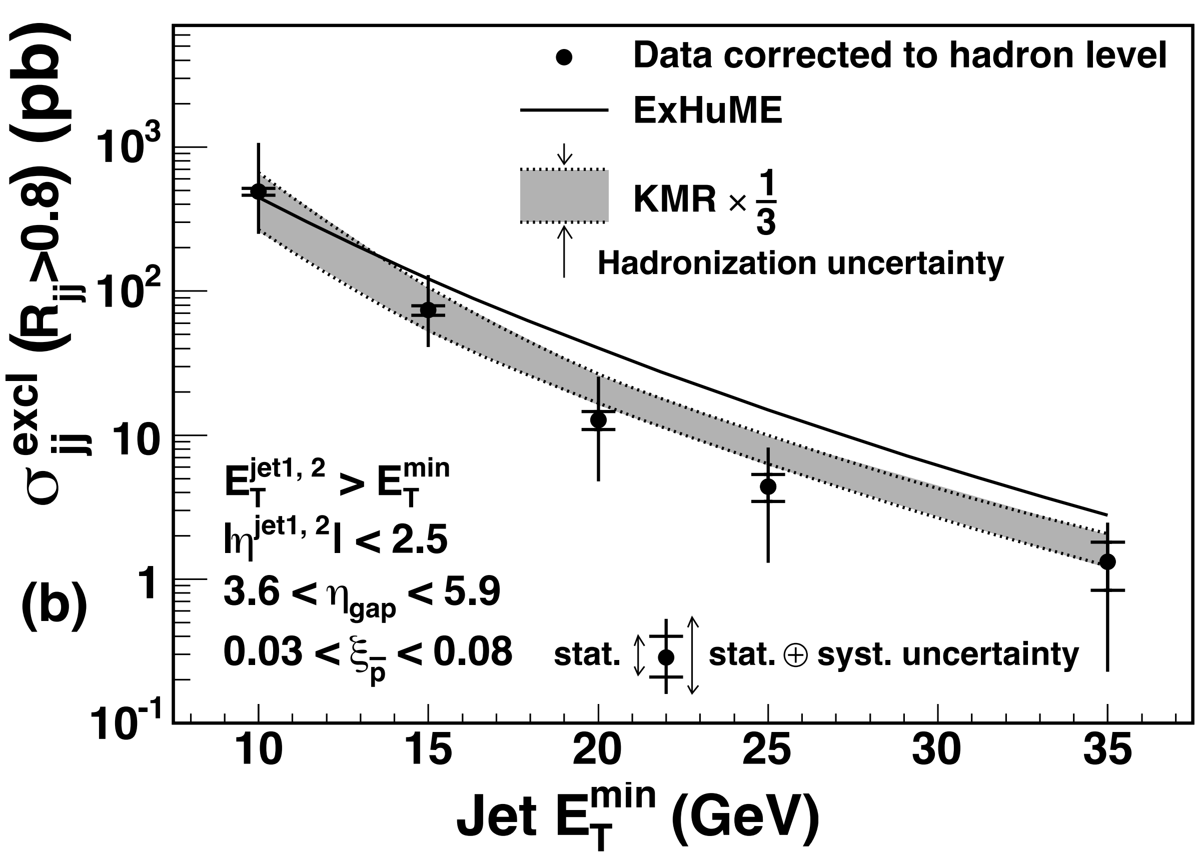
Based on work by V.A. Khoze, L.A. Harland-Lang and M.G. Ryskin
(KHARYS collaboration)

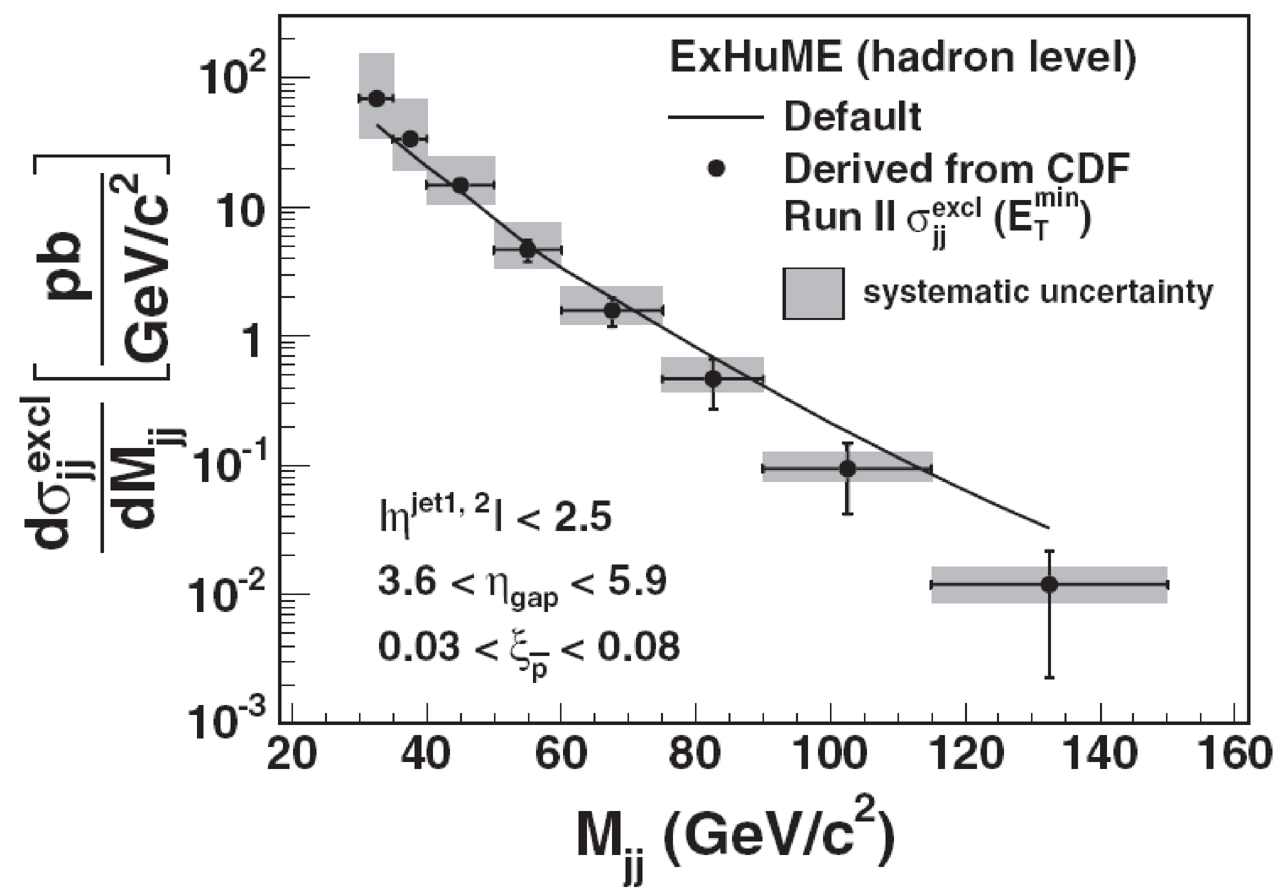
Exclusive Jet production at the Tevatron

- Exclusive dijet production measured by CDF in 2008, by D0 in 2011.

CDF Collab., Phys.Rev.D77:052004,2008   D0 collab. Phys.Lett. B705 (2011) 193

- Data compared quite well with Exhume MC implementation of the Durham model, giving support to this (perturbative) approach.
- However the MC (and theory) used is not up to date or complete (in particular with tagged protons).
- In this talk I will discuss some new theory work on this process, and a new MC for this (and other CEP), currently under development.



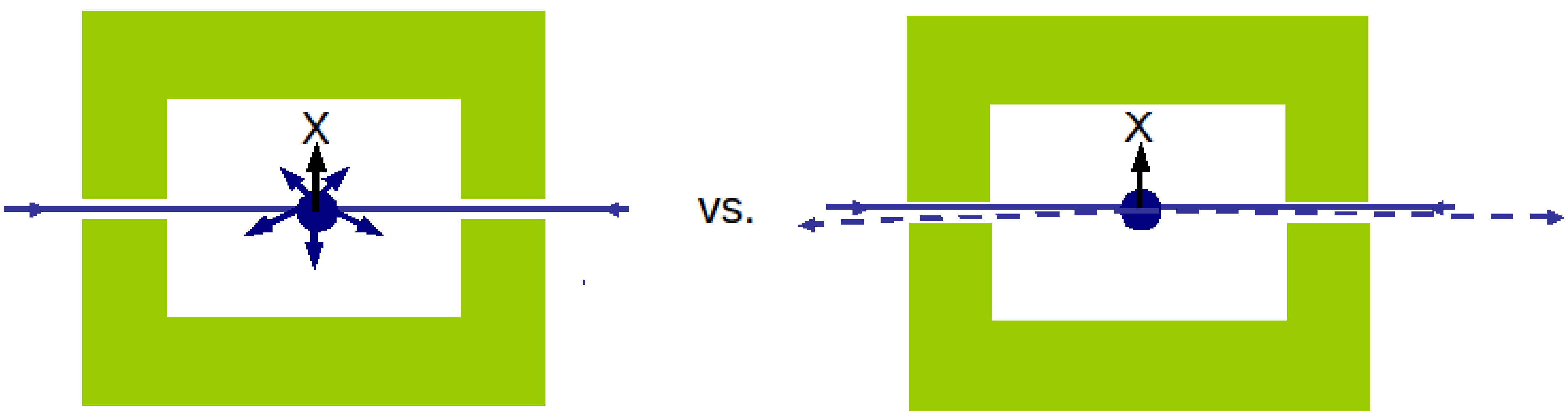


Central Exclusive Diffraction

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

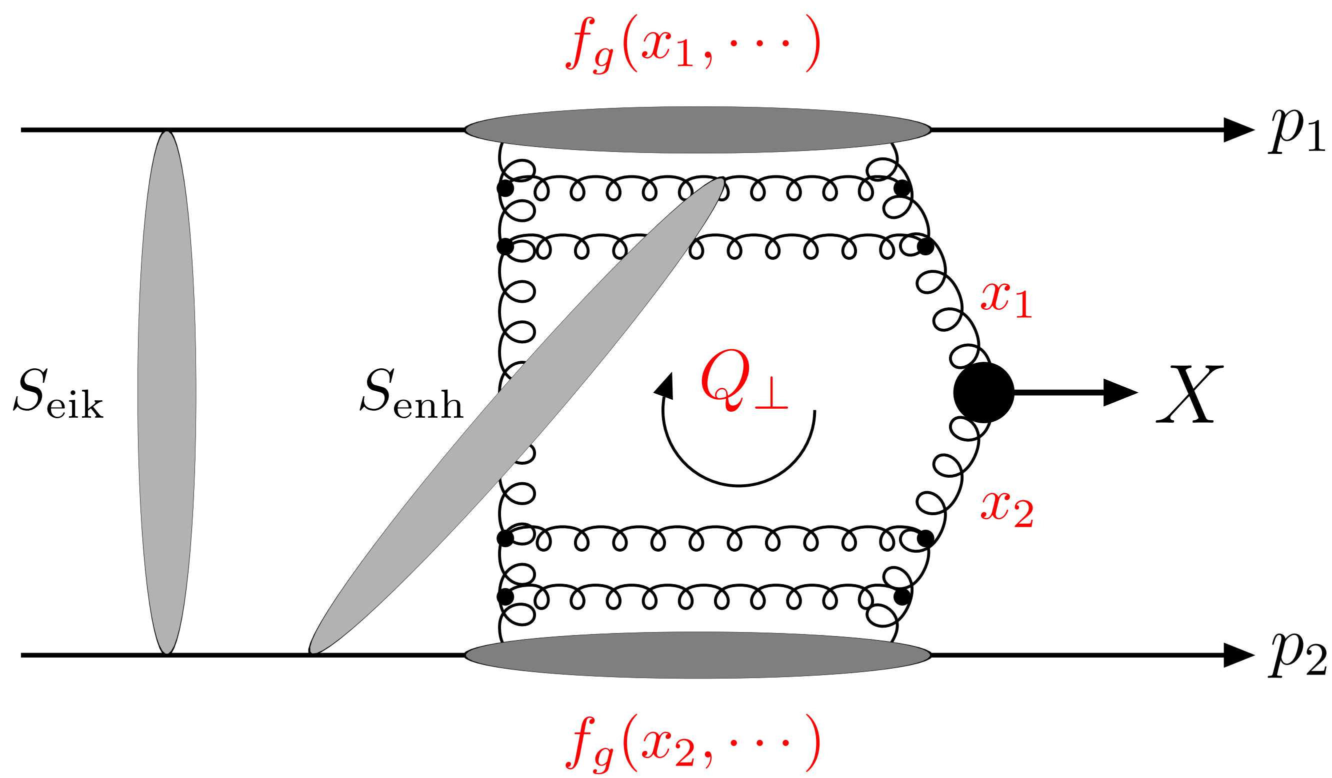
$$h(p_1)h(p_2) \to h(p_1') \; + \; X \; + \; h(p_2')$$

- 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.



'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.

Exclusive jet production

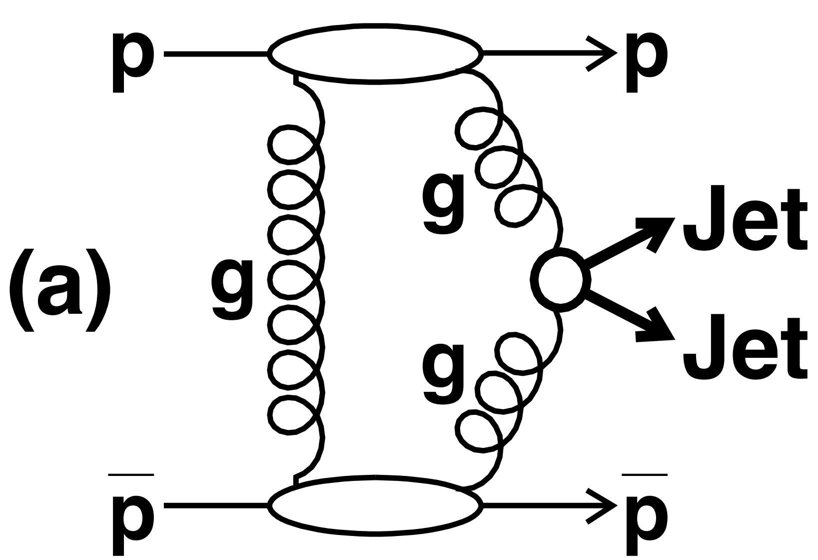
- Can consider case that central object is a number of jets, e.g. dijet CEP

$$pp \to p + jj + p$$

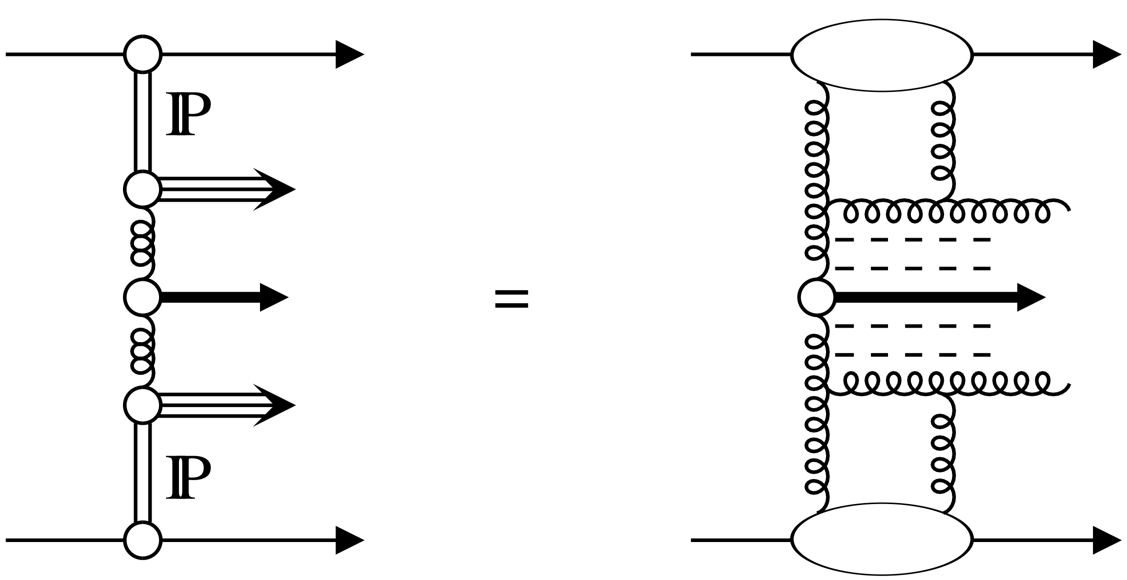
- More complicated than case where a simple object (χ_c, $\gamma\gamma\cdots$) is produced, as a jet consists of many particles, with no unique assignment of all final state particles to a given jet.

$\longrightarrow$ Experimentally: not as simple as demanding some number of jets and no additional particles.

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



'Exclusive'



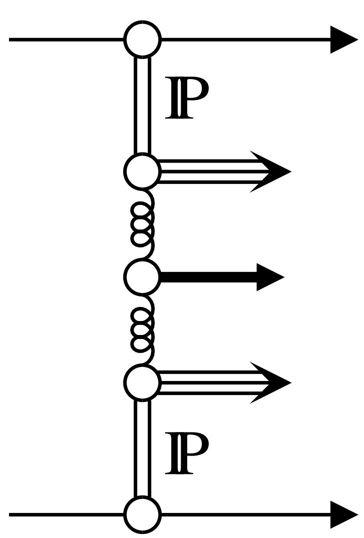
'Inelastic DPE'

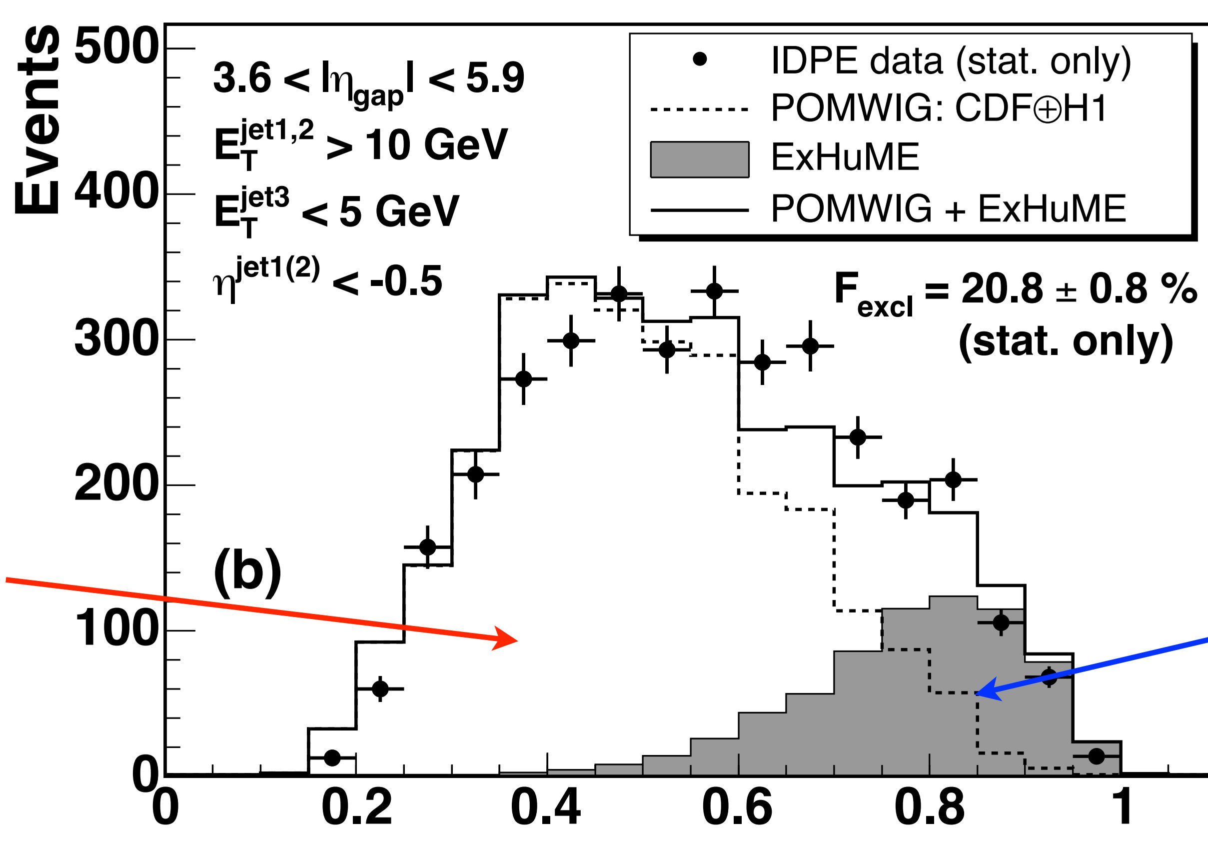
- However can consider e.g. $$R_{jj} \equiv M_{jj}/M_X$$

- For a idealized exclusive signal $R_{jj} = 1$. However smearing effects and radiation outside of the jets will broaden this, and signal will be a peak towards $R_{jj} \sim 1$

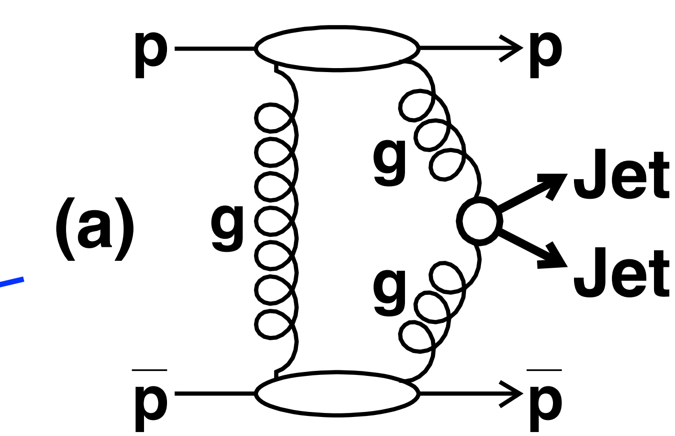
See also R_j variable - V.A. Khoze, A.D. Martin, M.G. Ryskin , Eur.Phys.J. C48 (2006) 467-475, hep-ph/0605113

- For inelastic DPE, will get a distribution over all R_{jj}





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

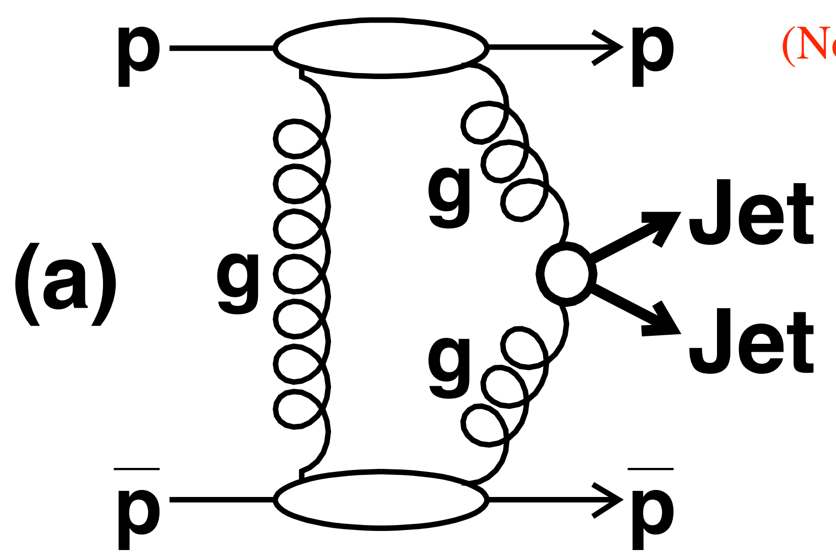


Exclusive jet production: theory

- 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

- We need the amplitudes for

$$gg \to gg \quad \text{and} \quad gg \to q\bar{q}$$

For colour singlet gluons. $J_z = 0$ selection rule $\Rightarrow$ dominant contribution will come from amplitude for incoming gluons with $(++,--)$ helicities. These are given by

$$\mathcal{M}\left(g(\pm)g(\pm) \to g(\pm)g(\pm)\right) = \delta^{CD} \frac{N_c}{N_c^2 - 1} \frac{32\pi\alpha_s}{(1-\cos^2\theta)}$$

Other final state helicities give vanishing amplitudes

$$\mathcal{M}\left(g(\pm)g(\pm) \to q_h \bar{q}_{\bar{h}}\right) = \frac{\delta^{cd}}{2N_c} \frac{16\pi\alpha_s}{(1-\beta^2\cos^2\theta)} \frac{m_q}{M_X} (\beta h \pm 1)\, \delta_{h,\bar{h}}$$

Helicity non-conservation along quark line

For massless quarks this vanishes!

$\longrightarrow$ Quark jets dynamically suppressed by selection rule

Production subprocess

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

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

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

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

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

What about light quark jets?

Light quark jets

- For light quark jets ($m_q \to 0$) the leading order $J_z = 0$ production amplitude (dominant for CEP) will vanish. $\Rightarrow$ Must consider sub-leading $|J_z| = 2$ contribution. Find that:

$$\mathcal{M}(g(\pm)g(\mp) \to q_h \overline{q}_{\bar{h}}) = \frac{\delta^{cd}}{2N_c} 8\pi\alpha_s \left(\frac{1 \pm h\cos\theta}{1 \mp h\cos\theta}\right)^{1/2} \delta_{h,-\bar{h}}$$

- In general such a $|J_z| = 2$ contribution is suppressed in CEP by

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

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

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

- Combining these we have

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

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

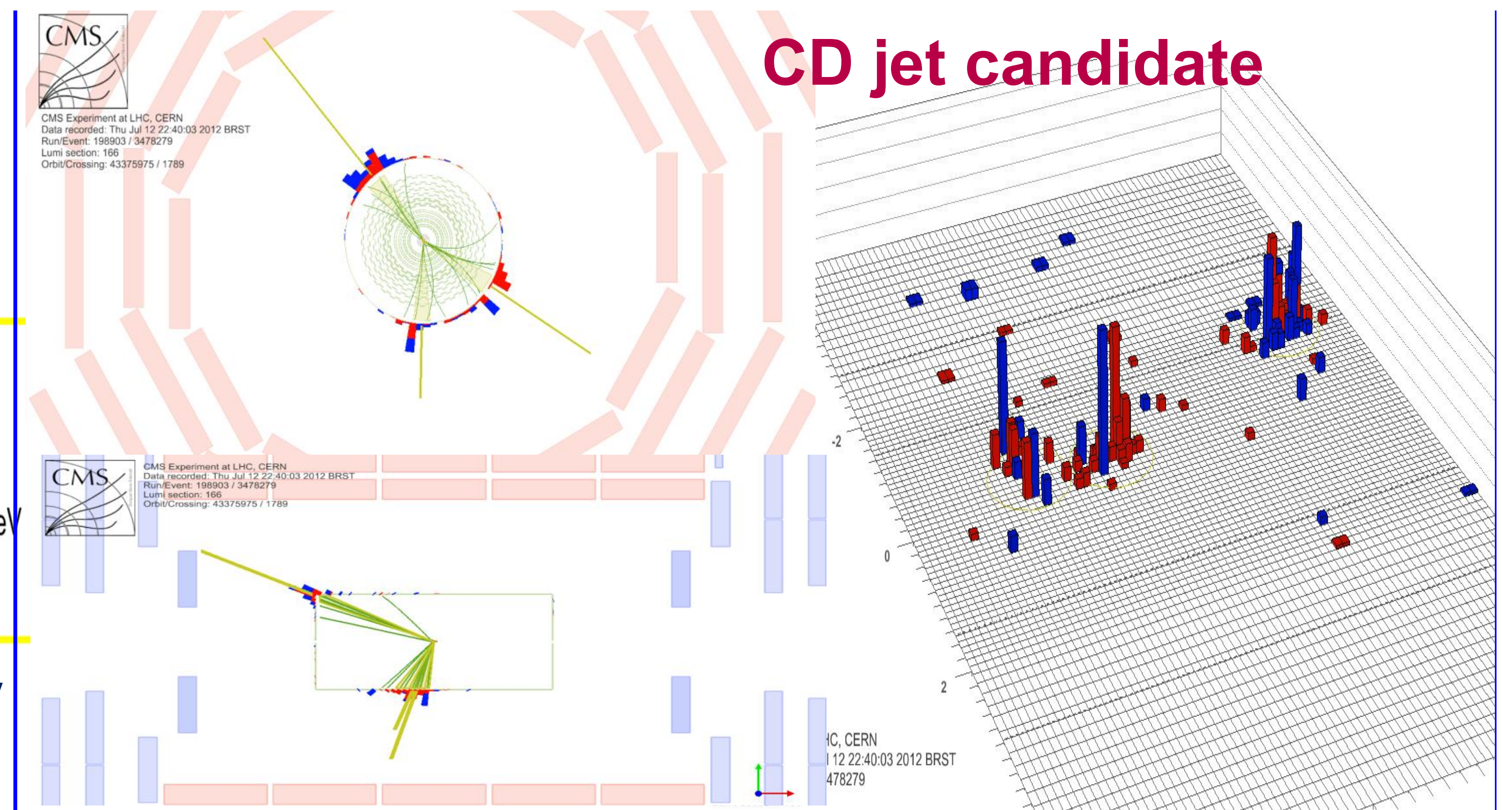
Verified in CDF data sample of $b\bar{b}$ jets

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

CMS + TOTEM 90m β*
Run/Event 198903/3478279
Jets E_T = 65,45,27 GeV

MM(pp) = 244 GeV; M(CMS) = 219 GeV
Σp_T(CMS) = 3.4 GeV
FSC empty both sides

M(pp) = 244 GeV
≈ M(central)
ξ_1 = 0.1 ξ_2= 0.01



CMS + TOTEM event displays (Kenneth's talk)

Mike Albrow's EDS 2013 summary talk, arXiv:1310.7047 :

> 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...)

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

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

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

$\Rightarrow$ 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 (→ $\frac{1}{E_g}$)

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

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)...

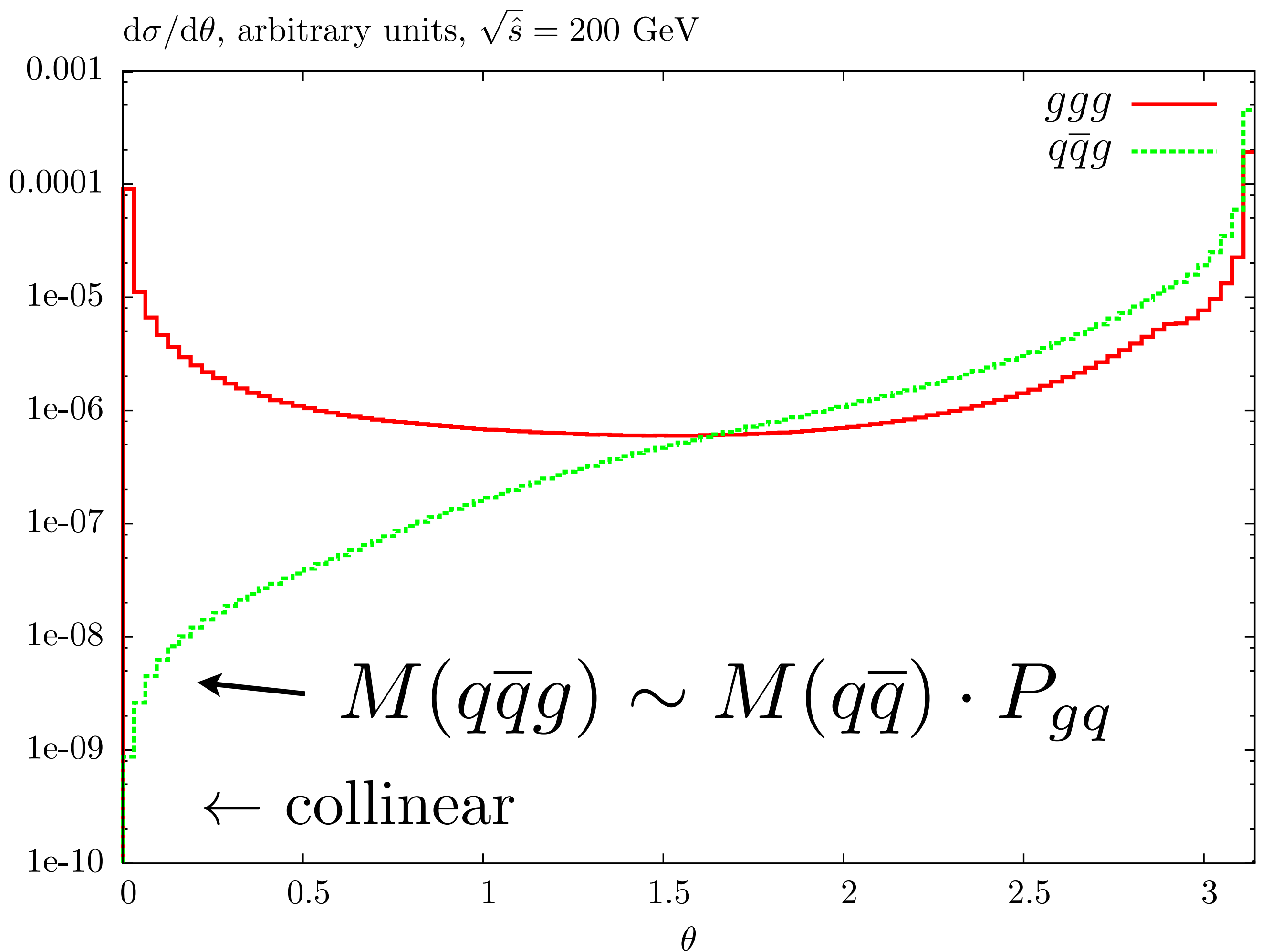
$|y_i| < 5$ $\sqrt{\hat{s}} = 200$ GeV

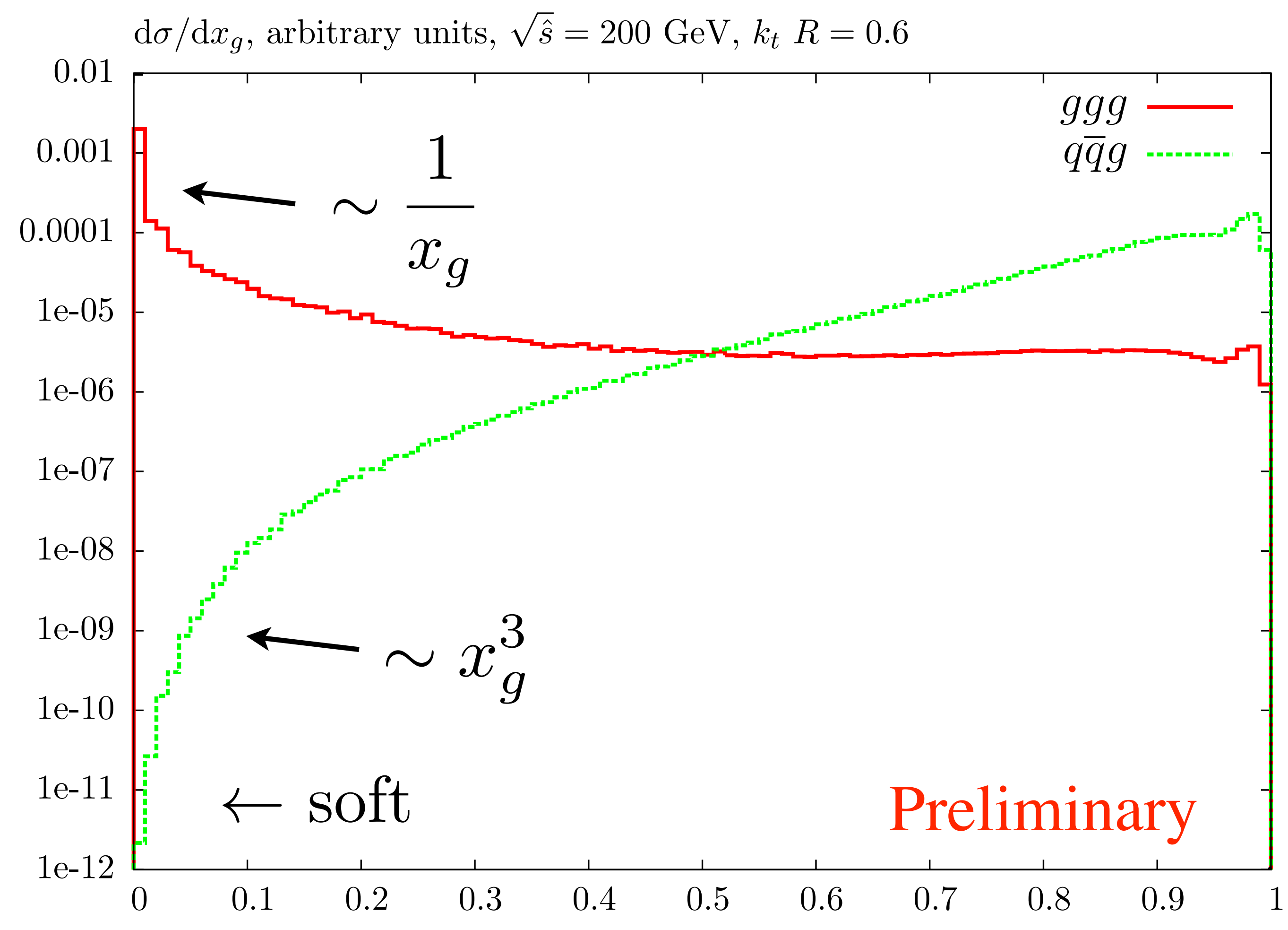
$q\bar{q}g$, ggg normalised to each other

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

θ: g–b quark angle
(for ggg between arbitrary gluons)

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





$\longrightarrow$ Expect relative enhancement of 'Mercedes-like' configuration for $q\bar{q}g$ events.

Can perform detailed comparison of $q\bar{q}g$ vs. ggg topologies. Consider, e.g. standard event shape variables, thrust and C-parameter

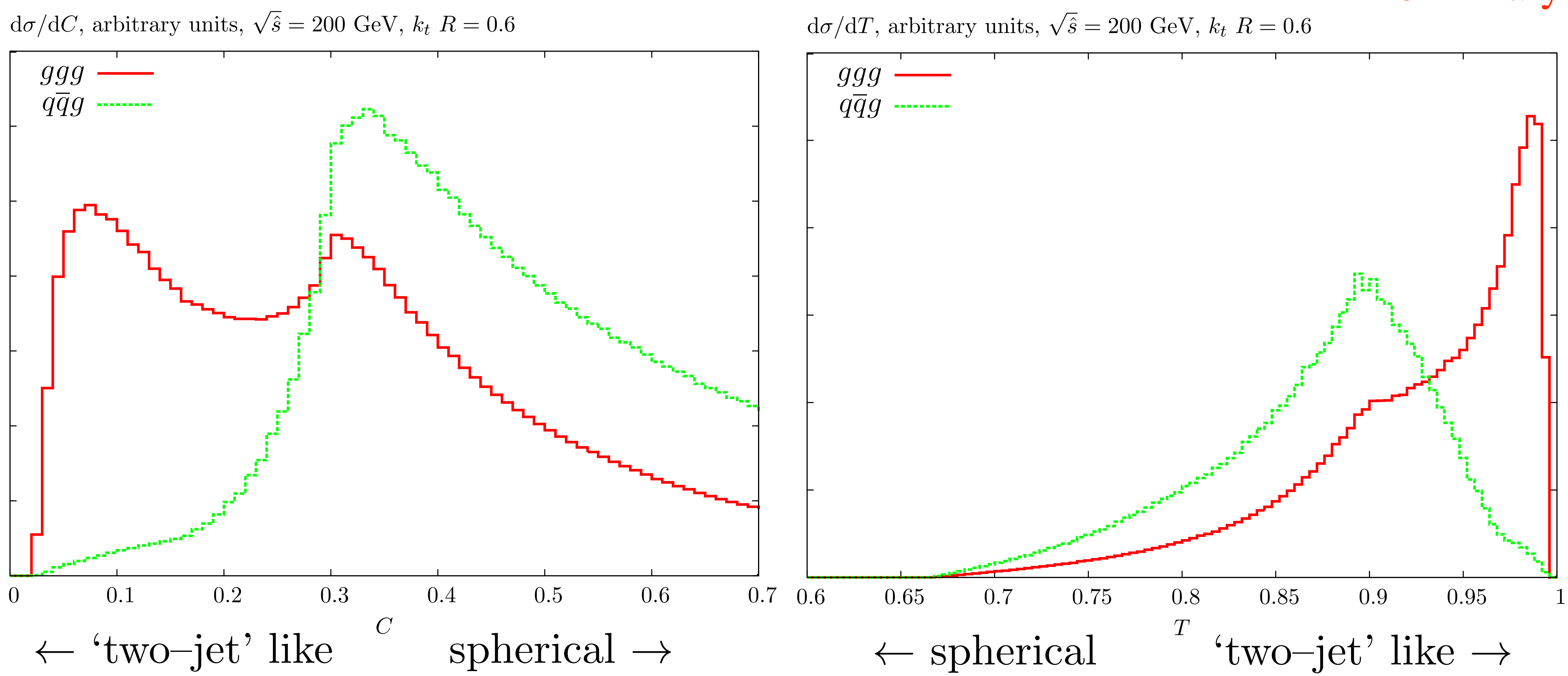
$i, j = 1, 2, 3$

$$T = \max_{\mathbf{n}} \frac{\sum_i |\mathbf{p}_i \cdot \mathbf{n}|}{\sum_i |\mathbf{p}_i|} \qquad C = \frac{3}{2} \frac{\sum_{i,j} [|\mathbf{p}_i||\mathbf{p}_j| - (\mathbf{p}_i \cdot \mathbf{p}_j)^2 / |\mathbf{p}_i||\mathbf{p}_j|]}{(\sum_i |\mathbf{p}_i|)^2}$$

See Stirling, Ellis, Webber, *QCD and collider physics*

Plots at subprocess level only $\Rightarrow$ full CEP study underway

Preliminary

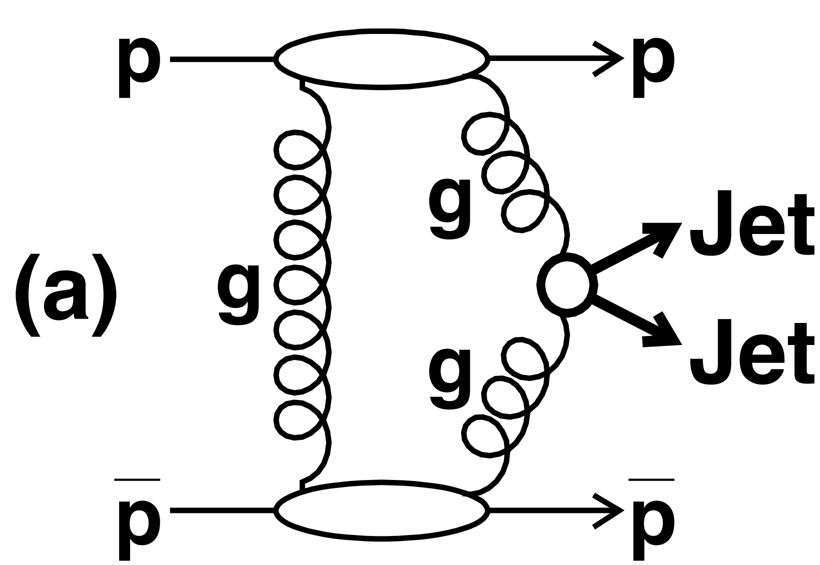


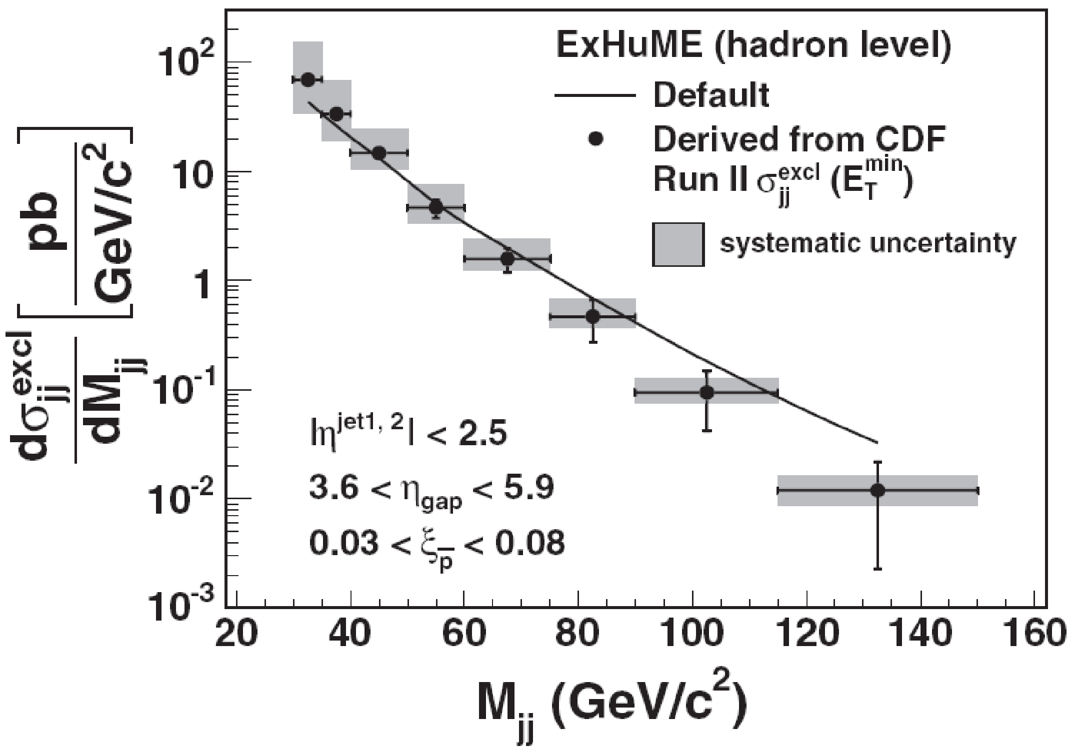
New Monte Carlo implementation

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 LHL, V.A. Khoze, M.G. Ryskin, W.J. Stirling, Eur.Phys.J. C69 (2010)
  - 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





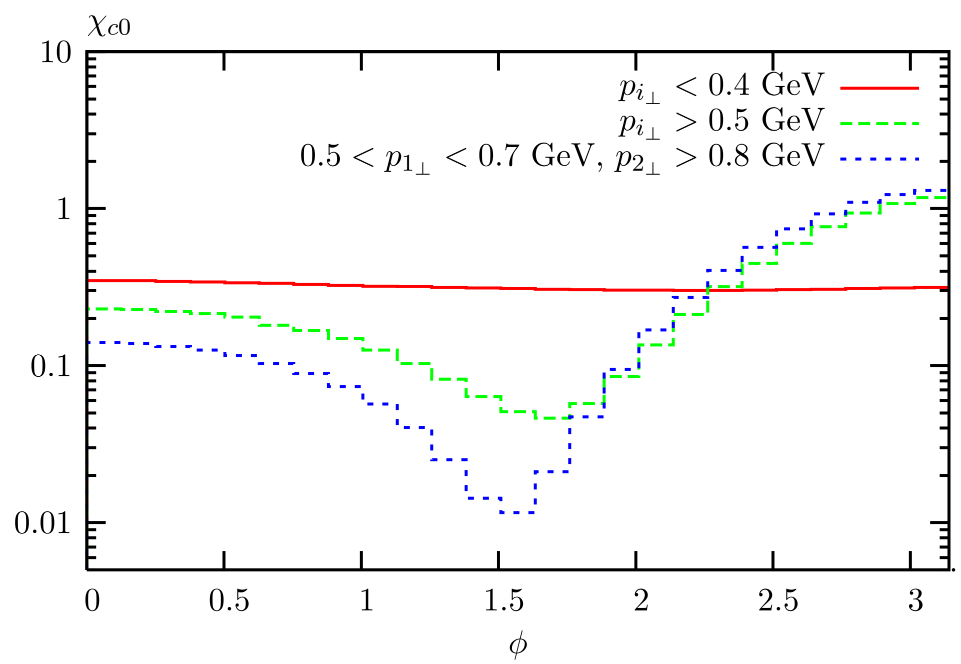
• Most importantly, neither of these include survival effects in a complete way:

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

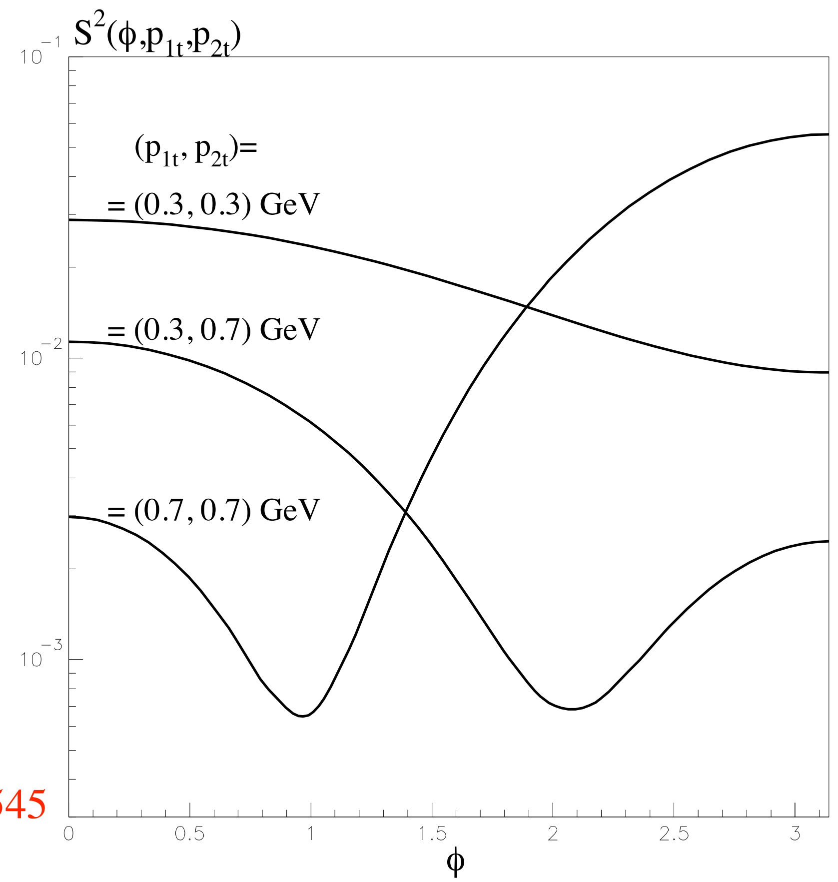
• Survival factor is not constant, but depends on (and effects) the distribution of the outgoing proton $p_\perp$ vectors.

$\rightarrow$ Expected suppression will depend on specific process, and soft survival factors can have a dramatic effect on the predicted distributions ($\Rightarrow$ tagged protons)

V.A. Khoze, M.G. Ryskin, A.D. Martin, Eur.Phys.J C24 (2002) 58



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

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

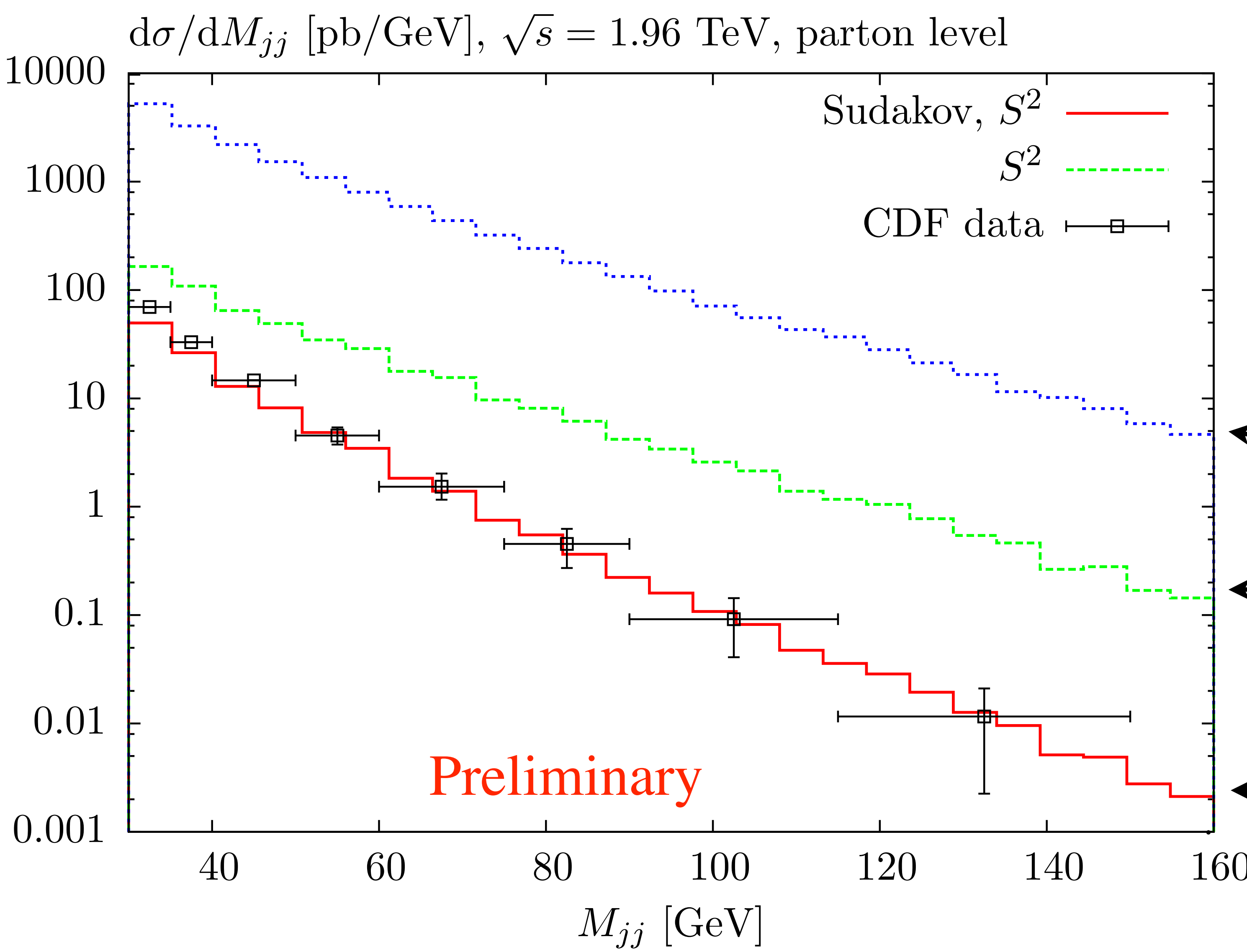
- To be made public in the mid-distant future

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+ATLAS, TOTEM/PPS+CMS), no need for special runs, but M_X must be larger (ξ acceptance of proton taggers)

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

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

σ [pb]

$q\bar{q}$ Preliminary

See Kenneth's talk(s)

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

- Low luminosity CMS + TOTEM, event selection:

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

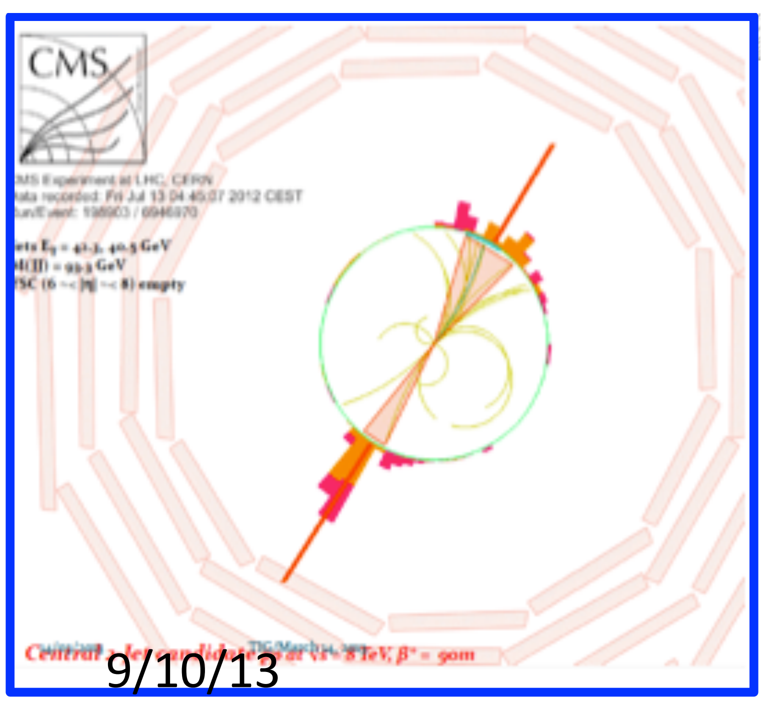
$$\Rightarrow \sigma(gg) \approx 100\ \mathrm{pb}$$

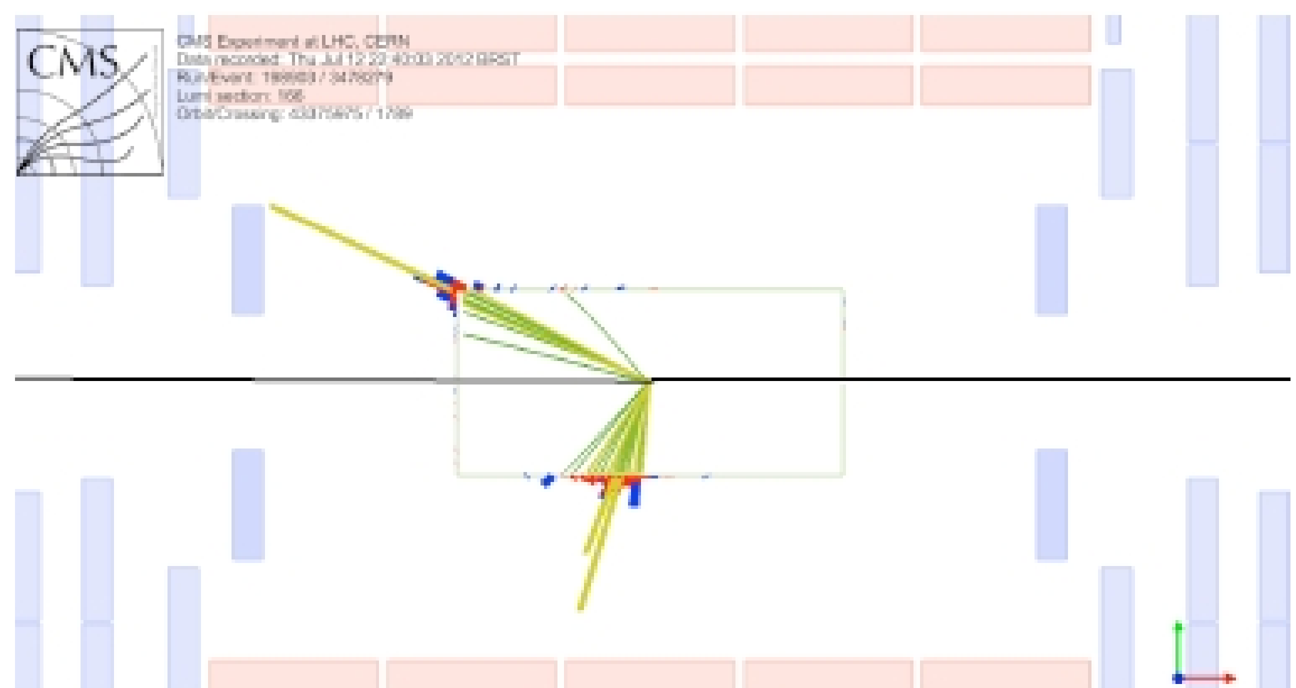
- High luminosity CMS + TOTEM ('CT PPS') event selection:

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

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

$M_X > 390\ \mathrm{GeV}$





CMS + TOTEM event displays

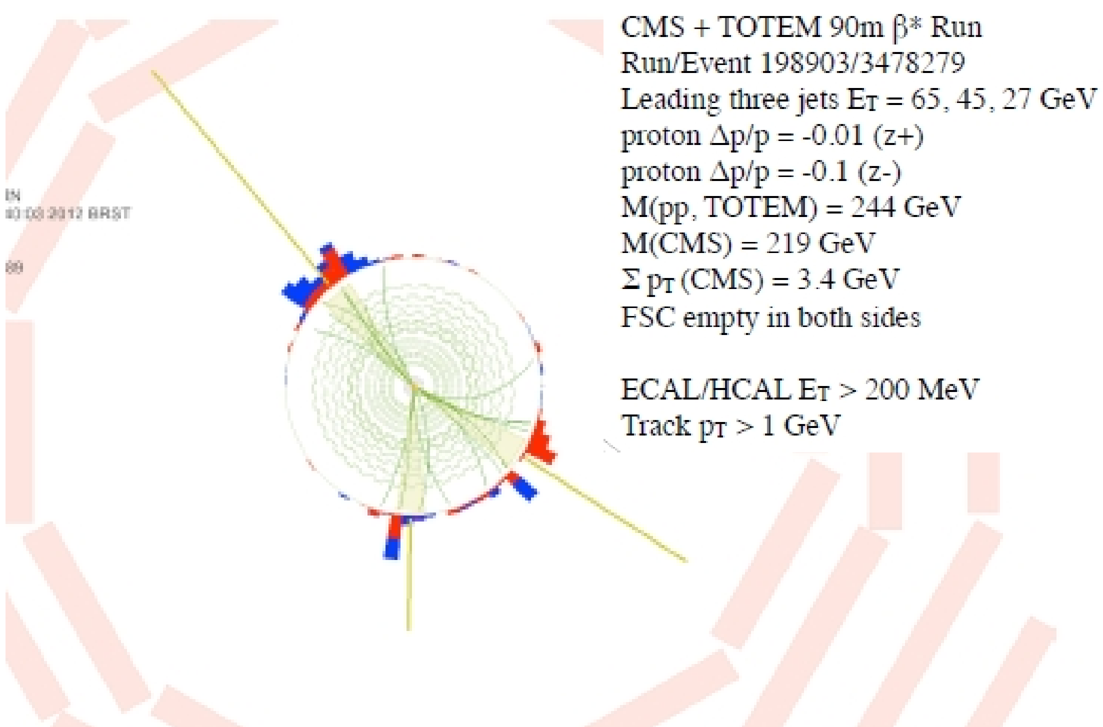
Trijet cross sections: $|\eta_j| < 2.5$ anti–k_t, $R = 0.6$

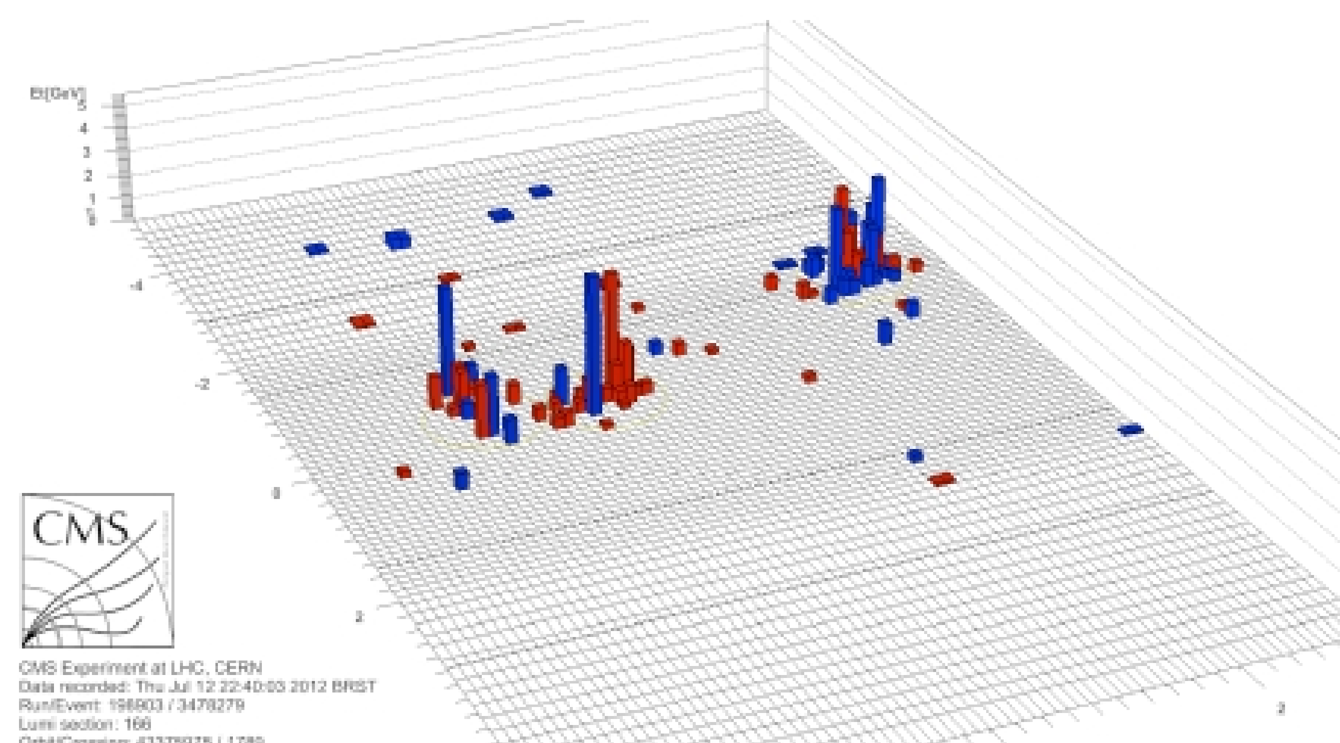
$b\bar{b}g$ ~ factor of 4 $(= n_f)$ smaller

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

σ [pb] $\sum q = c, s, u, d$

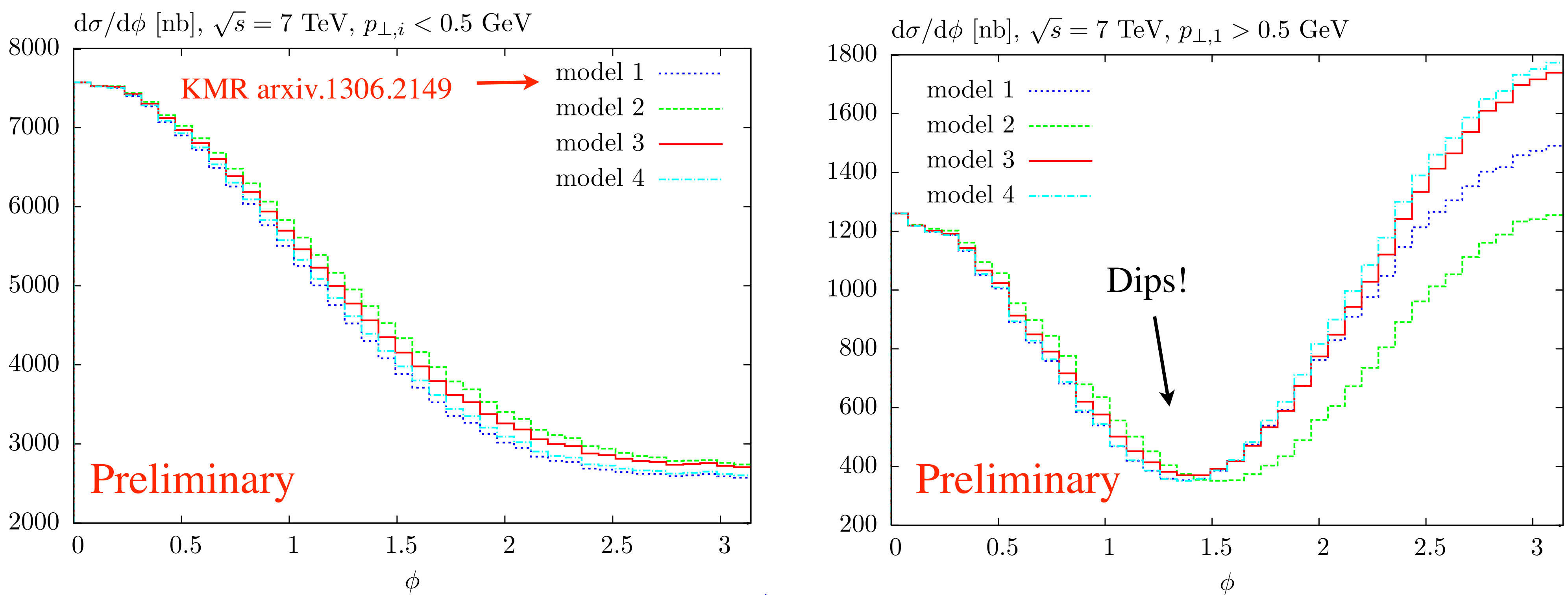
Preliminary





• 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 (in progress)

Conclusions and Outlook

- Exclusive jets at the LHC present an interesting and potentially unique probe of QCD. (Although many other interesting CEP topics!)
- The Durham perturbative approach makes very clear predictions, which are quite different from 'standard' inclusive case:
  - Isolated gg dominance (LO $gg \to q\bar{q}$ vanishes for massless quarks and $J_z = 0$ gluons). See also: $H \to b\bar{b}$
  - Three-jet production. Different topologies: ggg vs. $gq\bar{q}$, still lots to look at here: theory work underway.
- Correlations between outgoing proton momenta sensitive to S^2

$\longrightarrow$ Strong motivation for very interesting program of CEP measurements, with tagged protons at the LHC, both at low/medium (TOTEM+CMS, ALFA+ATLAS) and high (AFP, PPS/TOTEM+CMS...) luminosity.

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