Superchic v2 : a new Monte Carlo for central exclusive production

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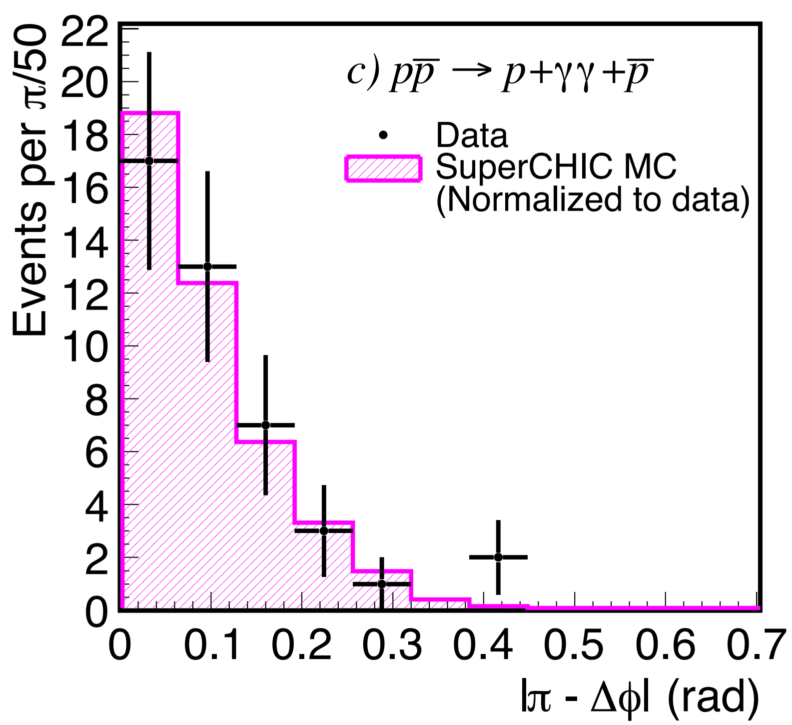
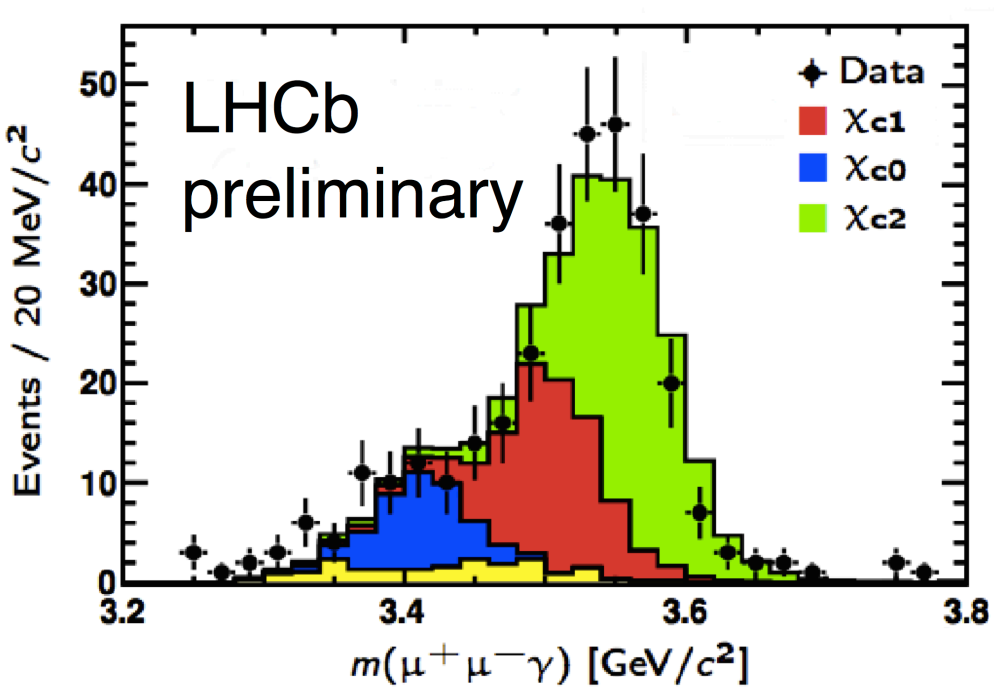
Outline

- CEP: brief introduction.
- Superchic 2: what's new.
- Present results for two specific processes:
    - J/ψ photoproduction
    - Jet production

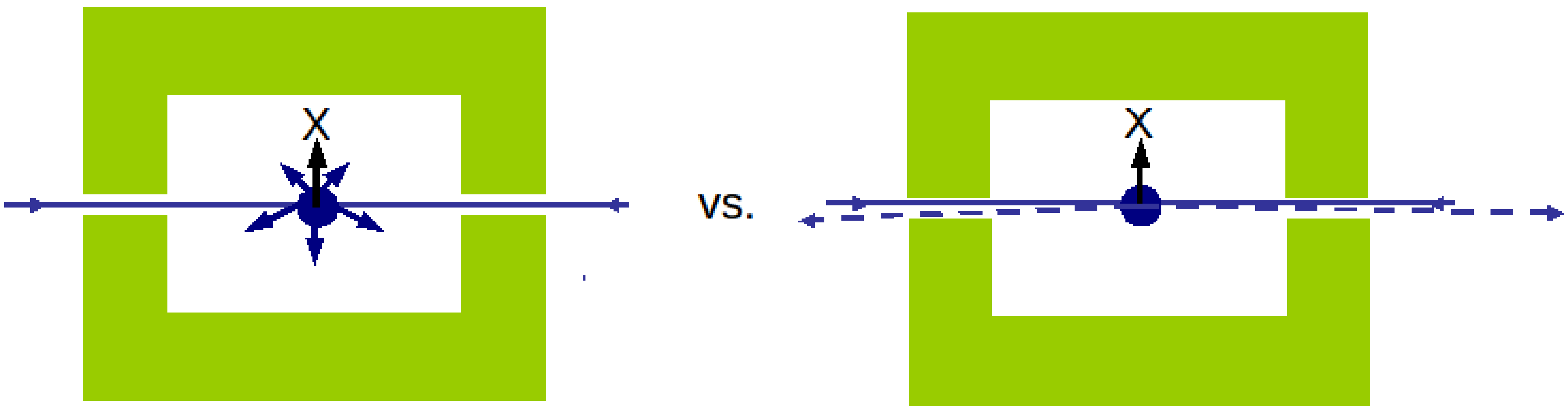




Central exclusive production (CEP) is the interaction

$$pp(\bar{p}) \to p + X + p(\bar{p})$$

- Protons remain intact after collision. Only object of interest X is produced ($X =$ jets, $J/\psi, \pi^+\pi^-, W^+W^-$...) :
  - Clean experimental environment (in absence of pile-up).
  - Can measure outgoing protons - reconstruct X 4-momentum, proton distributions...



Can (principally) occur through $I\!P I\!P$ $I\!P\gamma$ and $\gamma\gamma$ interactions

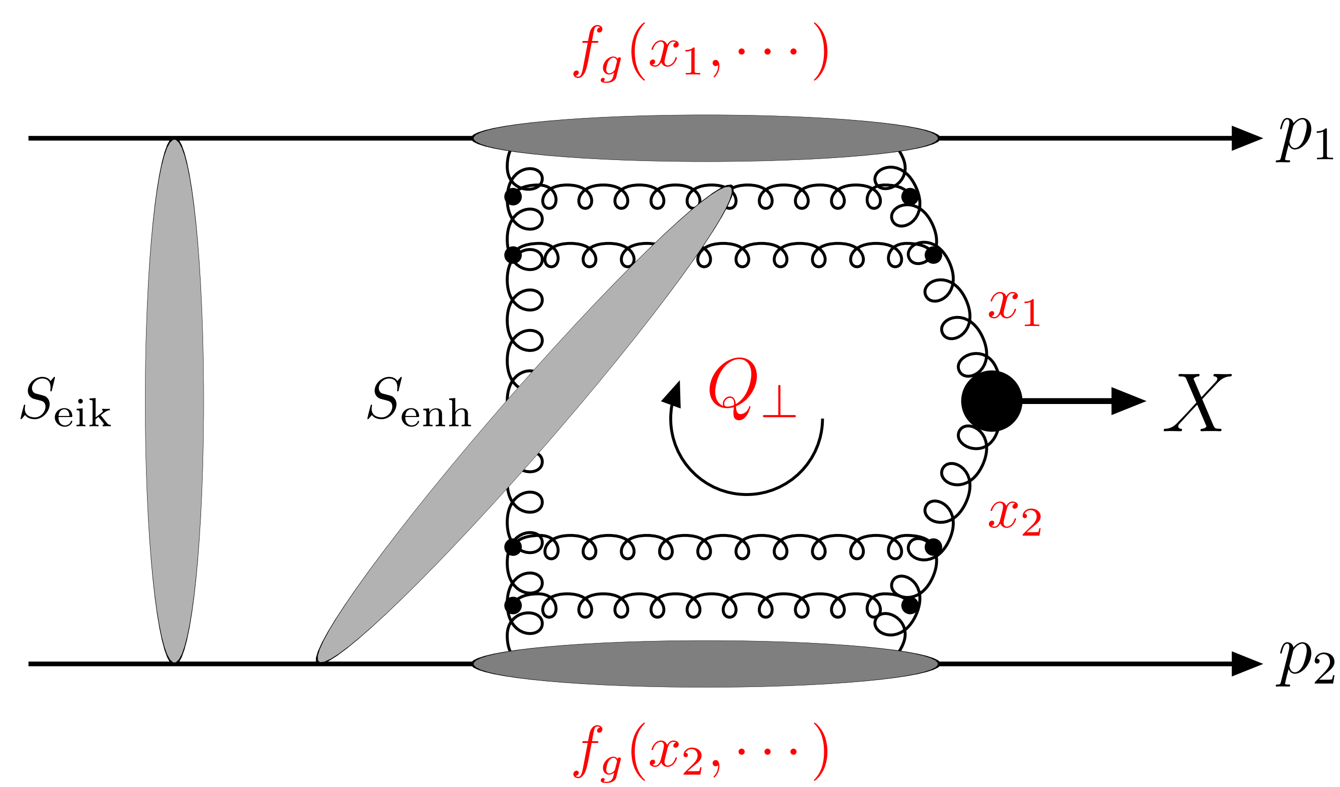
Also: Odderon

‘Durham Model’ of Central Exclusive Production

(QCD mediated)

- 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_{eik} and S^2_{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.



SuperCHIC v1

LHL talk at EDS Blois 2013

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...?).

$\longrightarrow$ Additional processes to add, but also theoretical improvements to be included.

SuperCHIC v2

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

- Theoretical developments:
  - Correct inclusion of Sudakov factor T.D. Coughlin and J.R. Forshaw, JHEP 1001 (2010) 121
  - Consistent treatment of 'skewed' gluon PDFs LHL, Phys. Rev. D88 (2013) 3, 034029
  - 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 generated:

New ▸ SM Higgs boson

New ▸ Jets: gg, heavy/massless $q\bar{q}$, ggg, massless $gq\bar{q}$

New ▸ Double quarkonia: $J/\psi J/\psi$, $J/\psi\psi(2S)$ and $\psi(2S)\psi(2S)$

▸ Light meson pairs: $\pi\pi$, KK, $\rho\rho$, $\eta(')\eta(')$, $\phi\phi$

▸ $\chi_{c,b}$: two body and J/ψ, $\Upsilon + \gamma$ channels

▸ $\eta_{c,b}$

▸ Photoproduction: J/ψ, $\psi(2S)$ and Υ HERA fit

New ▸ Two-photon interactions: W^+W^-, $\mu^+\mu^-$ and e^+e^-

Theoretical improvements

- Sudakov factor:

$$T(\boldsymbol{Q}_\perp,\mu) = \exp\left(-\int_{\boldsymbol{Q}_\perp^2}^{\hat{s}/4} \frac{\mathrm{d}k_\perp^2}{k_\perp^2}\frac{\alpha_s(k_\perp^2)}{2\pi}\int_0^{1-\Delta}\mathrm{d}z\left[zP_{gg}(z)+\sum_q P_{qg}(z)\right]\right)$$

with $\Delta = k_\perp/M_X$ T.D. Coughlin and J.R. Forshaw, JHEP 1001 (2010) 121

Different value taken in Durham results before the CF paper, but this correct prescription used after. Accounted for in MC.

- Skewed gluon PDF often related to standard unintegrated gluon by

$$f_g(x,x',Q_\perp^2,\mu^2) \approx \tilde{R}_g \frac{\partial}{\partial \ln(Q_\perp^2)}\left[xg(x,Q_\perp^2)\sqrt{T(Q_\perp,\mu^2)}\right]$$

with 'skewness factor' $\tilde{R}_g$. However more exact form can be readily implemented in MC: LHL, Phys. Rev. D88 (2013) 3, 034029

$$f_g(x,x',Q_\perp^2,\mu^2) = \frac{\partial}{\partial \ln(Q_\perp^2)}\left[H_g\left(\frac{x}{2},\frac{x}{2};Q_\perp^2\right)\sqrt{T(Q_\perp,\mu^2)}\right]$$

with $$H_g\left(\frac{x}{2},\frac{x}{2},Q^2\right) = \frac{4x}{\pi}\int_{x/4}^1 \mathrm{d}y\, y^{1/2}(1-y)^{1/2}\, g\left(\frac{x}{4y},Q^2\right)$$

Survival factor

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

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

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

- Averaged survival factor given by (in impact parameter space)

Opacity, relates to prob. of no inelastic scattering

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

One-channel for illustration

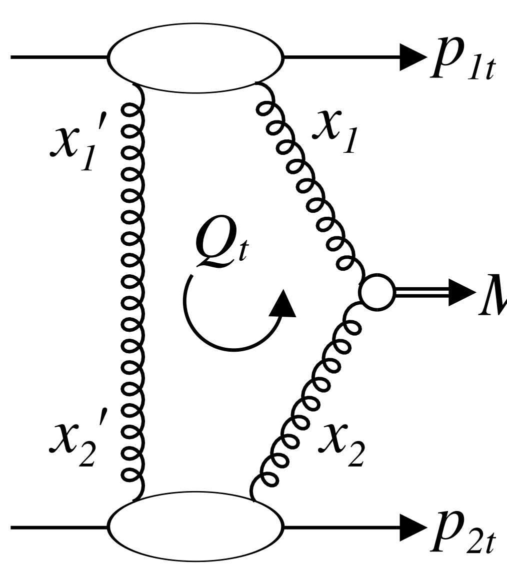
'Bare' amplitude

in $p_\perp$ space this is equivalent to

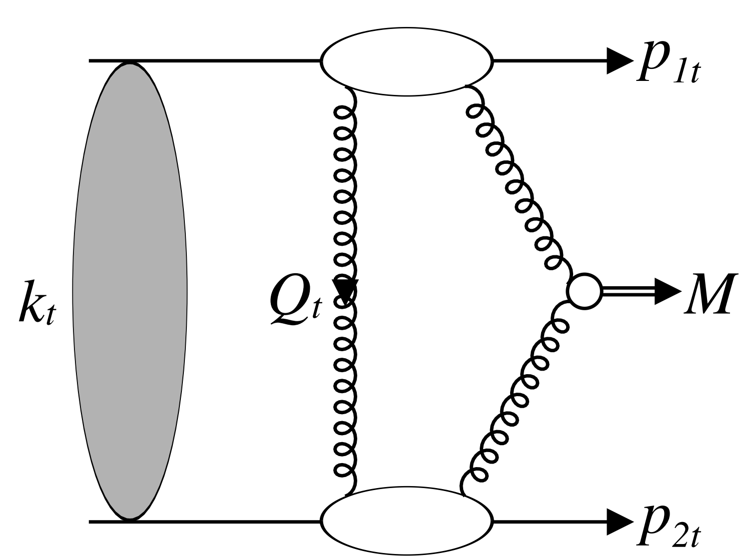
$$\langle S^2_{\rm eik}\rangle = \frac{\int d^2\mathbf{p}_{1_\perp}\, d^2\mathbf{p}_{2_\perp}\, |T(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp}) + T^{\rm res}(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp})|^2}{\int d^2\mathbf{p}_{1_\perp}\, d^2\mathbf{p}_{2_\perp}\, |T(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp})|^2}$$

where 'screened' amplitude is given by

$$T^{\rm res}(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp}) = \frac{i}{s}\int \frac{d^2\mathbf{k}_\perp}{8\pi^2}\, T_{\rm el}(s,\mathbf{k}_\perp^2)\, T(s,\mathbf{p'}_{1_\perp},\mathbf{p'}_{2_\perp})$$



'Bare' amplitude



'Screened amplitude'

- In $p_\perp$ space we can therefore write

'Bare' amplitude

$$\frac{d\sigma}{dy_X} = \int d^2\mathbf{p}_{1_\perp} d^2\mathbf{p}_{2_\perp} \frac{|T(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp}))|^2}{16^2\pi^5} S^2_{\rm eik}(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp}) \ ,$$

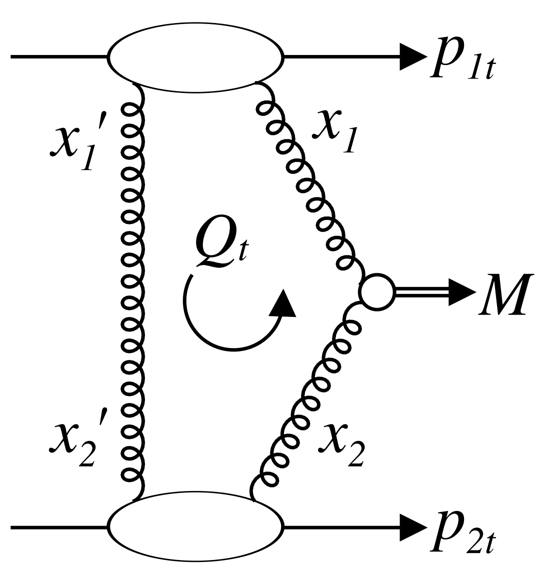
Not a constant!

with

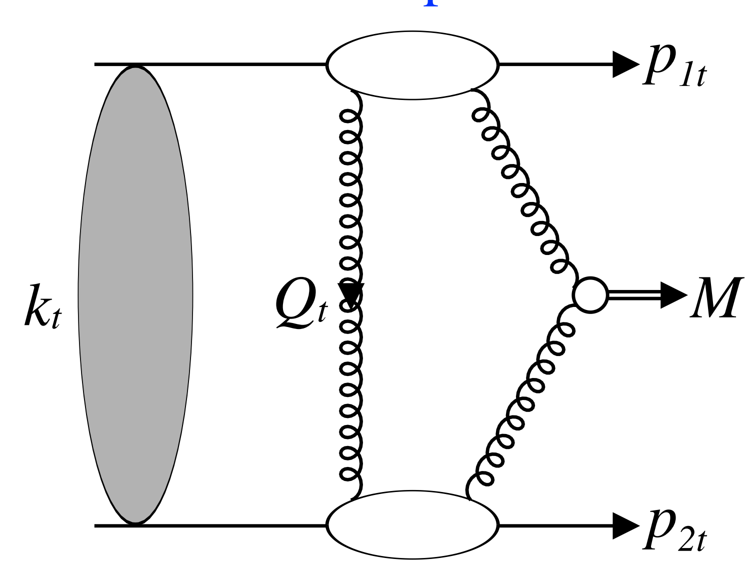
$$S^2_{\rm eik}(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp}) \equiv \frac{|T(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp}) + T^{\rm res}(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp})|^2}{|T(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp})|^2} \ ,$$

These expressions, suitably generated to multi-channel case, are used in the MC to give the correct differential treatment of $S^2_{\rm eik}$. KMR, Eur. Phys. J. C73 (2013) 2503

'Bare' amplitude

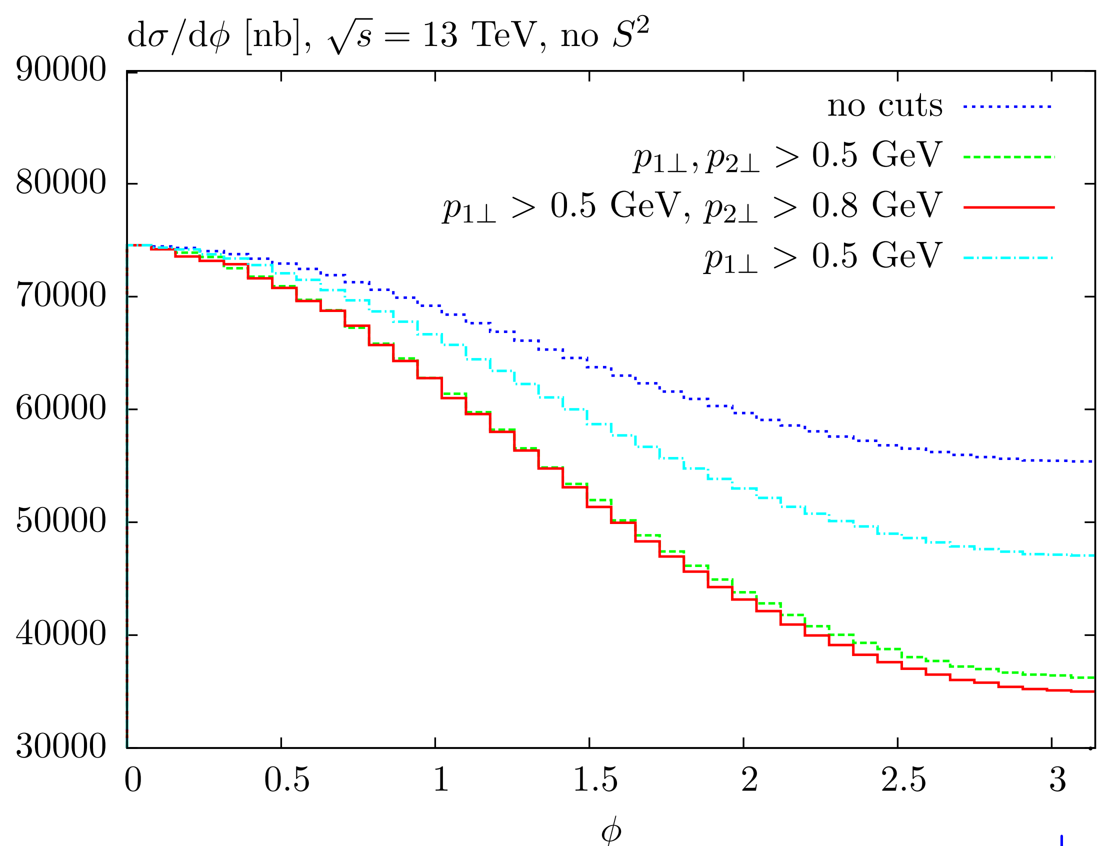


'Screened amplitude'

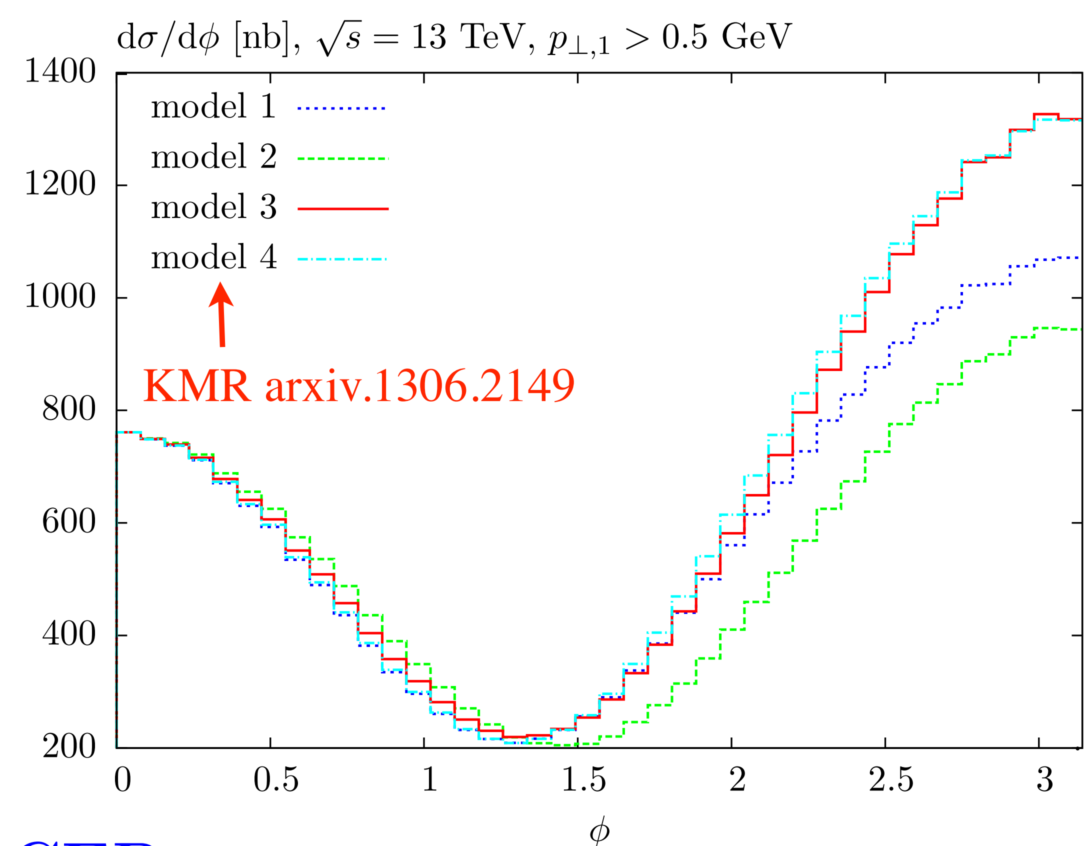


- The observation of CEP with tagged protons also provides additional information about survival factors...

S^2 off



S^2 on



$\pi^+\pi^-$ CEP

LHL, V.A. Khoze and M.G. Ryskin, arXiv:1312.4553

- Distribution in angle ϕ between outgoing protons strongly effected, in model dependent way.
- In particular true when larger values of proton $p_\perp$ are selected. Cancellation between screened and unscreened amplitudes leads to characteristic 'diffractive dip' structure

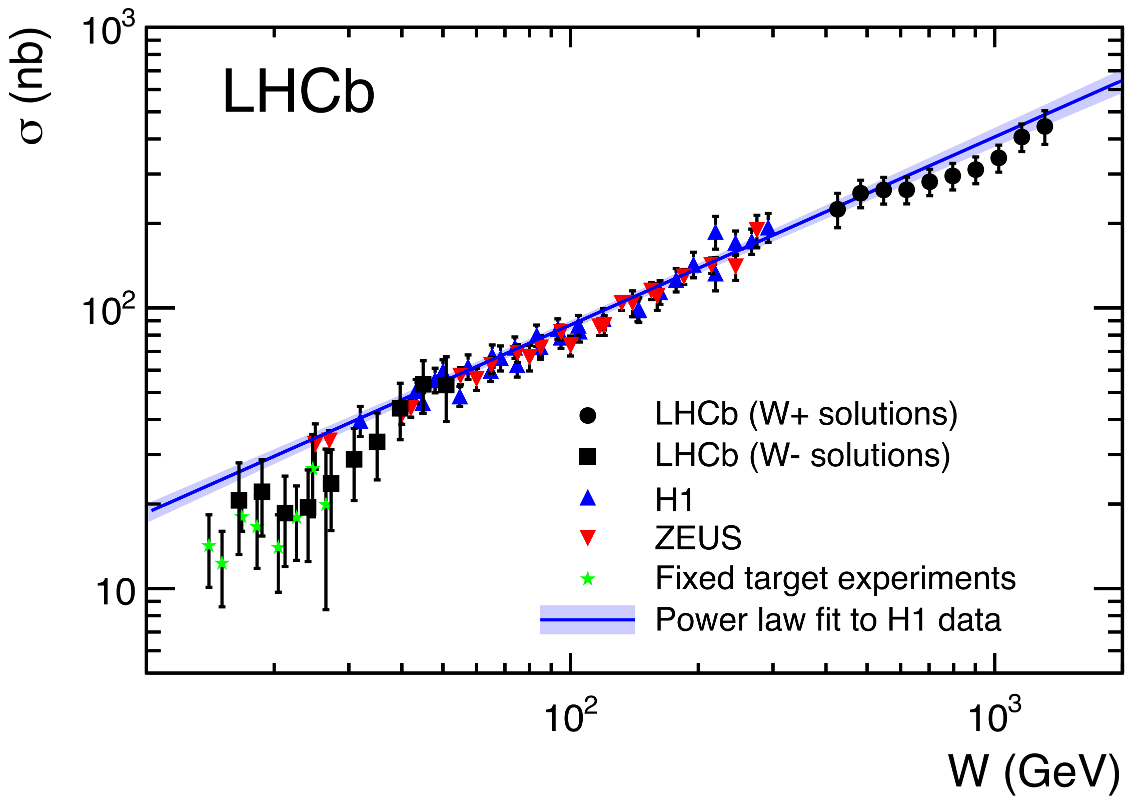
V. A. Khoze, A.D. Martin and M.G. Ryskin, hep-ph/0203122
LHL, V.A. Khoze, M.G. Ryskin and W.J. Stirling, arXiv:1011.0

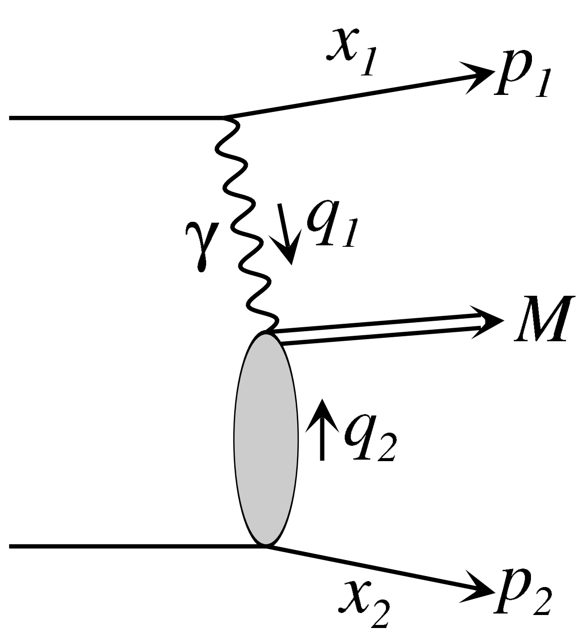
Example process: J/ψ photoproduction

- C-odd J/ψ : produced exclusively through $\gamma I\!P$ fusion.
- Observed by LHCb and ALICE at the LHC.

LHCb collab., J. Phys. G41 (2014) 055002 ALICE collab., Phys. Rev. Lett. 113 (2014) 23, 232504

- Survival effects less important compared to pure QCD CEP, but not negligible, in particular for precise comparisons.





J/ψ photoproduction: theory

- Different approaches to modeling J/ψ photoproduction available.

S.P Jones et al., J. Phys. G41 (2014) 055009

L. Motyka, G. Watt, Phys. Rev. D78 (2008) 0124023

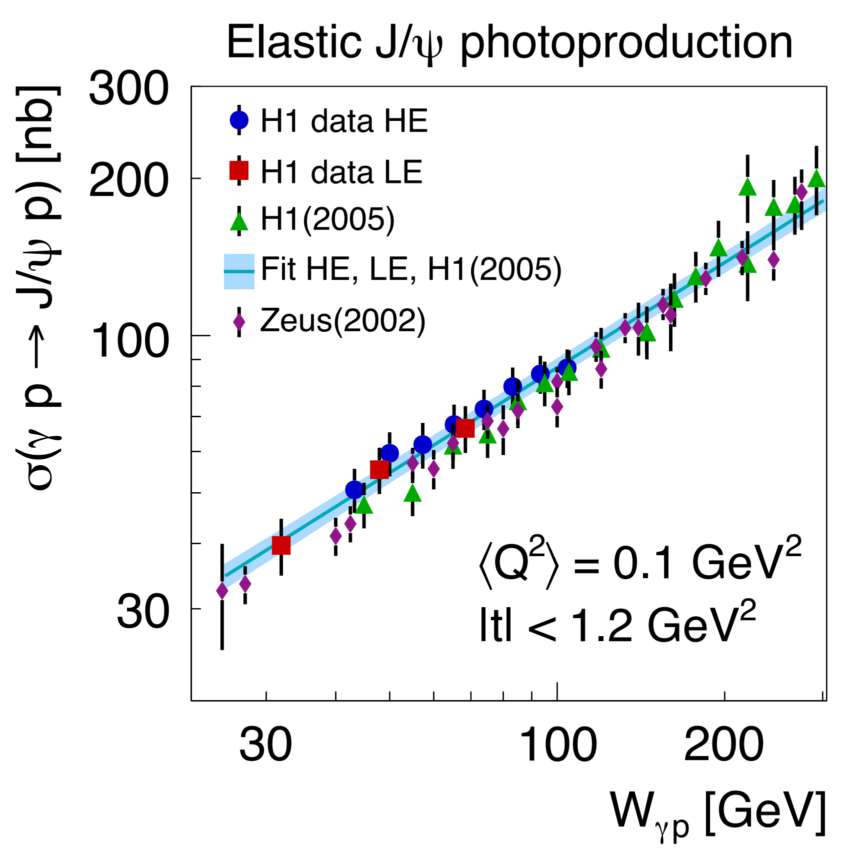
- In Superchic, take simple fit to HERA data:

$$\frac{\mathrm{d}\sigma^{\gamma p\to Vp}}{\mathrm{d}q_{2\perp}^2} = N_V \left(\frac{W_{\gamma p}}{1\,\mathrm{GeV}}\right)^{\delta_V} b_V\, e^{-b_V q_{2\perp}^2} \qquad b_V = b_0 + 4\alpha' \log\left(\frac{W_{\gamma p}}{90\,\mathrm{GeV}}\right)$$

$V = \psi$

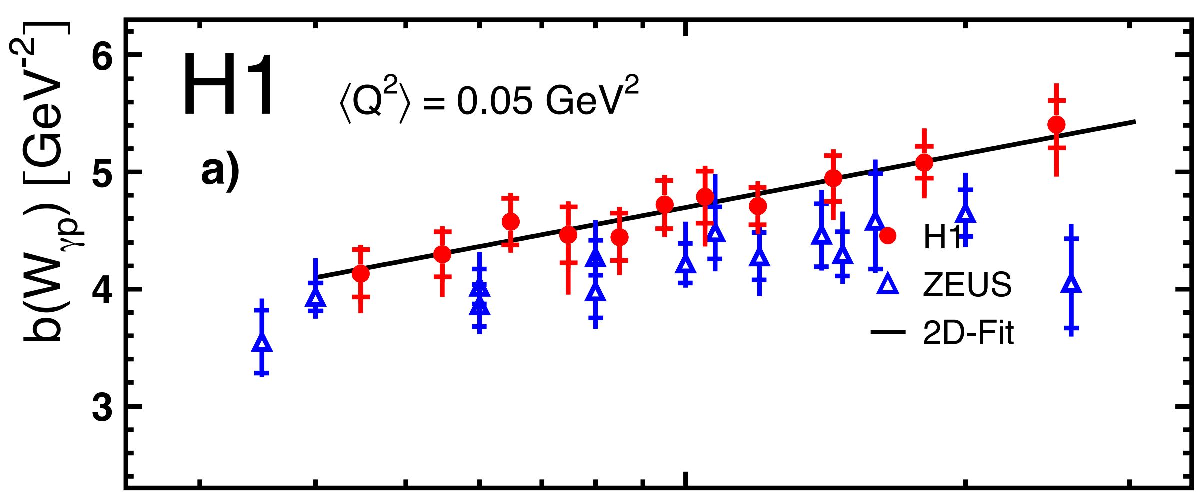
H1 find: $\delta_\psi = 0.67 \pm 0.03\,\mathrm{GeV}^2 \quad N_\psi = 81 \pm 3\,\mathrm{nb}$ Anti-correlated

In what follows we take $\delta_\psi = 0.64\,\mathrm{GeV}^2 \quad N_\psi = 81\,\mathrm{nb}$



H1 collab., Eur. Phys. J. C73 (2013) 6, 2466

$\longrightarrow$ Lower end of cross sections allowed by fit



H1 collab., Eur. Phys. J. C46 (2006) 585-603

J/ψ photoproduction: results

- We find:

LHCb acceptance, $\mu^+\mu^-$decay including spin corr.

		$2 < \eta^\mu < 4.5$	
		$\sqrt{s} = 7$ TeV	$\sqrt{s} = 13$ TeV
σ [pb]	$\sigma^\psi_{\rm bare}$	360	512
	$\sigma^\psi_{\rm sc.}$	278	405
	$\langle S^2_{\rm eik}\rangle$	0.77	0.79

- LHCb measure:

$$\sigma^{J/\psi\to\mu^+\mu^-}(2 < \eta^\mu < 4.5) = 291 \pm 7 \pm 19\,{\rm pb}$$

recall these predictions are (roughly) the lowest values in good agreement with the H1 fit (can be up to ~ 40% higher).

$\longrightarrow$ Predictions with screening effects favoured.

What about differential tests?

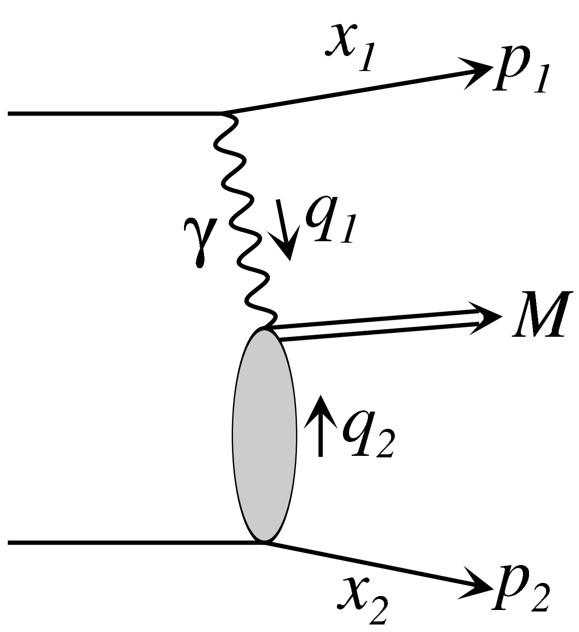
Rapidity distribution

- Photon virtuality has kinematic minimum $Q^2_{1,\mathrm{min}} = \dfrac{\xi_1^2 m_p^2}{1-\xi_1}$

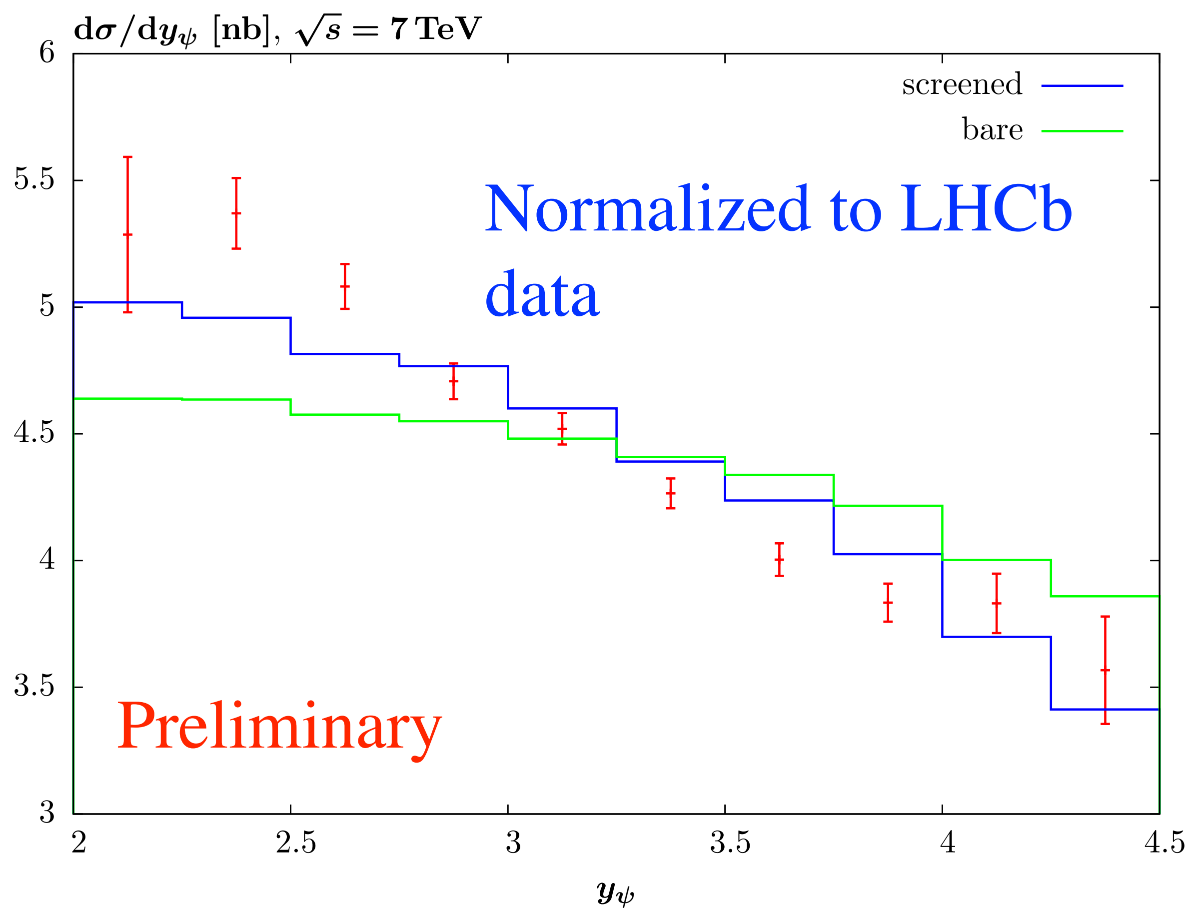
where $\xi_1 \approx \dfrac{M_\psi}{\sqrt{s}} e^{y_\psi}$ assuming photon emitted from proton 1 positive z-direction

$\longrightarrow$ Forward production $\Rightarrow$ higher photon Q^2 and less peripheral interaction

$\Rightarrow$ Smaller S^2_{eik}



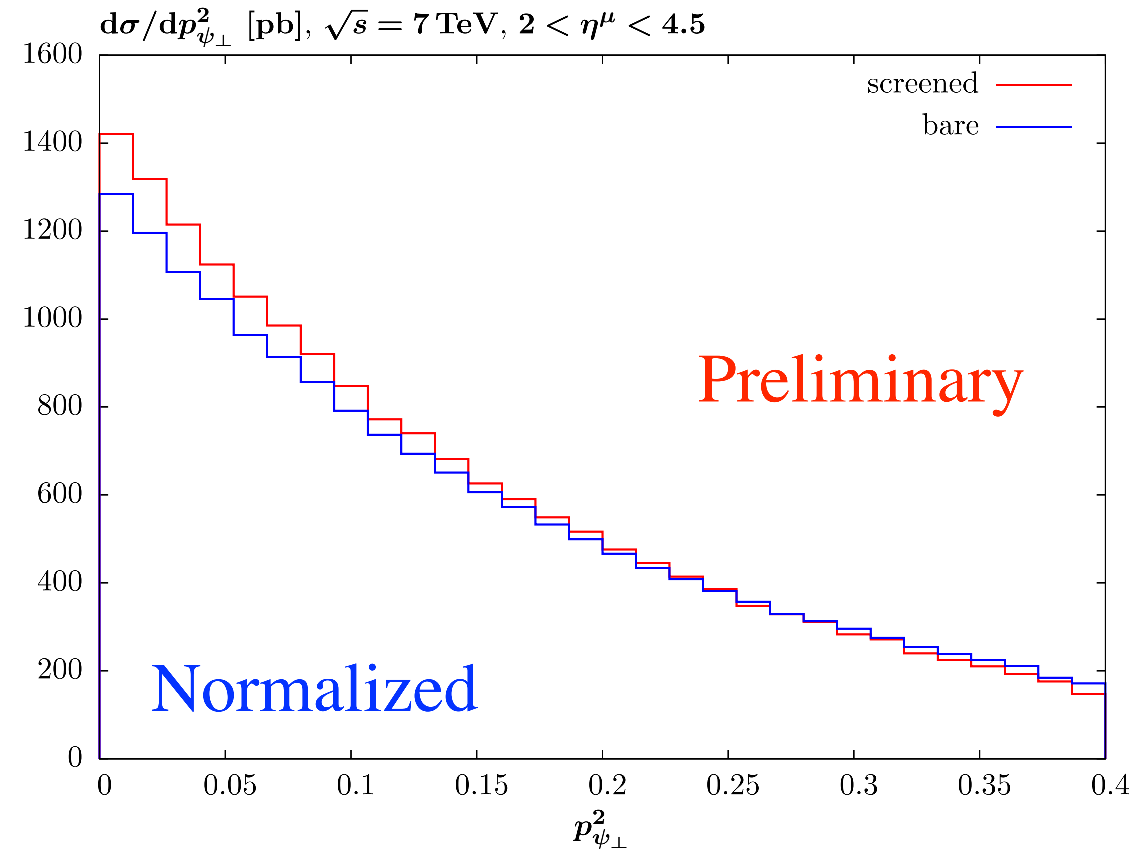
- Predicted rapidity distribution steeper due to survival effects:



- Screened prediction gives better description. Somewhat model dependent (don't have to assume HERA fit)...

$p_\perp$ distribution

- Proton $p_\perp$ transferred directly to J/ψ. Higher $p_{\psi_\perp}$ $\Rightarrow$ less peripheral, and stronger screening. $\Rightarrow$ Survival effects will steepen $p_{\psi_\perp}$ distribution.



- Fit as an exponential $\sim \exp(-bp^2_{\psi_\perp})$ with

$$b_{\rm el}^{\rm bare} = 5.0\,{\rm GeV}^{-2} \qquad b_{\rm el}^{\rm sc.} = 5.5\,{\rm GeV}^{-2}$$

with $\sim \pm 0.1\,{\rm GeV}^{-2}$ error from parameter uncertainty in HERA fit to $\gamma I\!\!P$ vertex.

$$b_V = b_0 + 4\alpha' \log\left(\frac{W_{\gamma p}}{90\,{\rm GeV}}\right)$$

- LHCb have measured this quite precisely:

$$b_{\rm el}^\psi = 5.70 \pm 0.11\,{\rm GeV}^{-2}$$

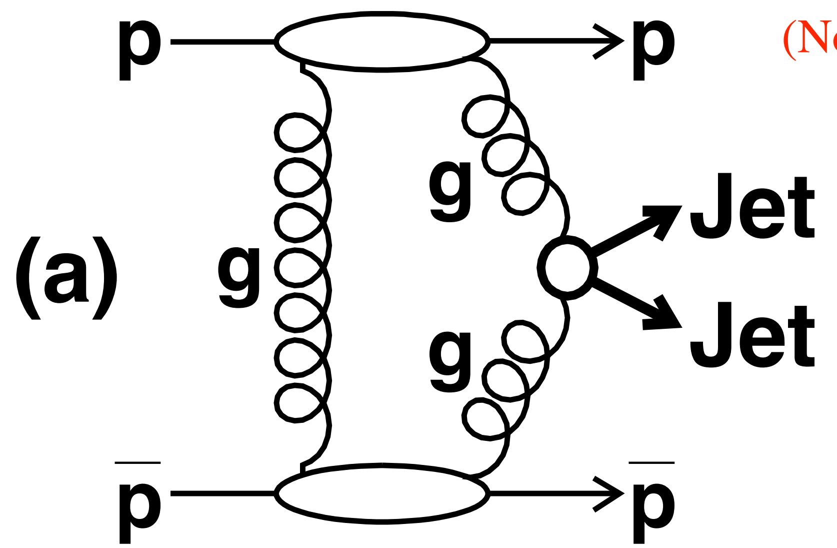
$\longrightarrow$ Survival effects again greatly improve description. Arguably less model-dependent. Crucial to include in any precise phenomenological predictions.

Example process: jet production

- 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 $X = gg, q\bar{q}, ggg, q\bar{q}g$

Dijet production

- We need the amplitudes for

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

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

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

For massless quarks this vanishes!

Helicity non-conservation along quark line

$\longrightarrow$ 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

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

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

$\longrightarrow$ 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

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

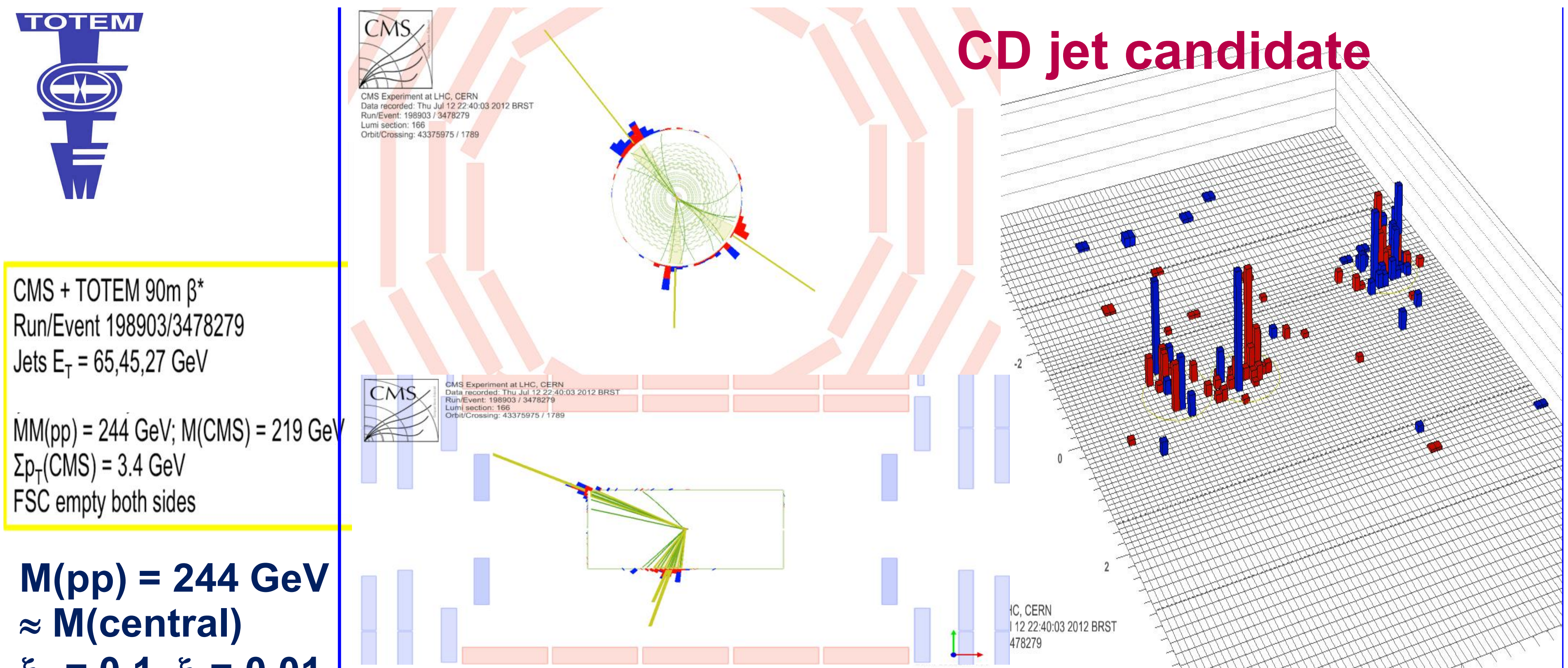
For one flavour $\Rightarrow$ multiply by $n_f = 4$

$\longrightarrow$ 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

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



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

CMS + TOTEM event displays

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 $q\bar{q}$.

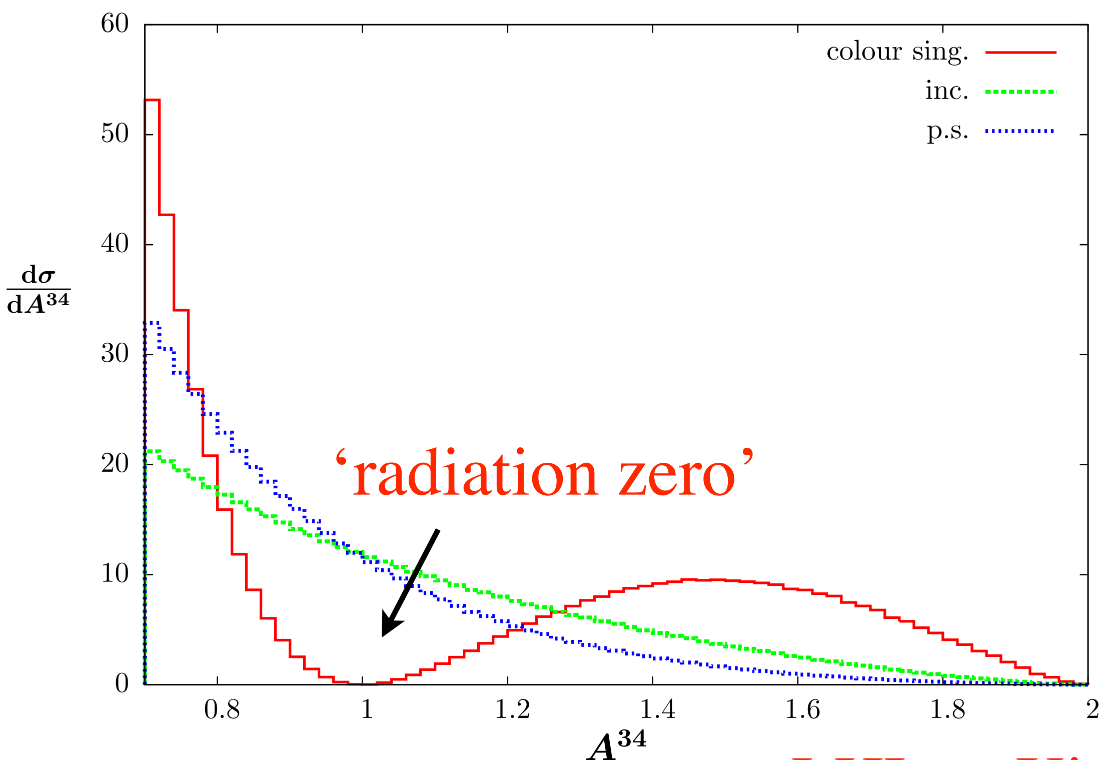
$\longrightarrow$ Clean probe of properties of gluons jets (multiplicity, particle correlations...)

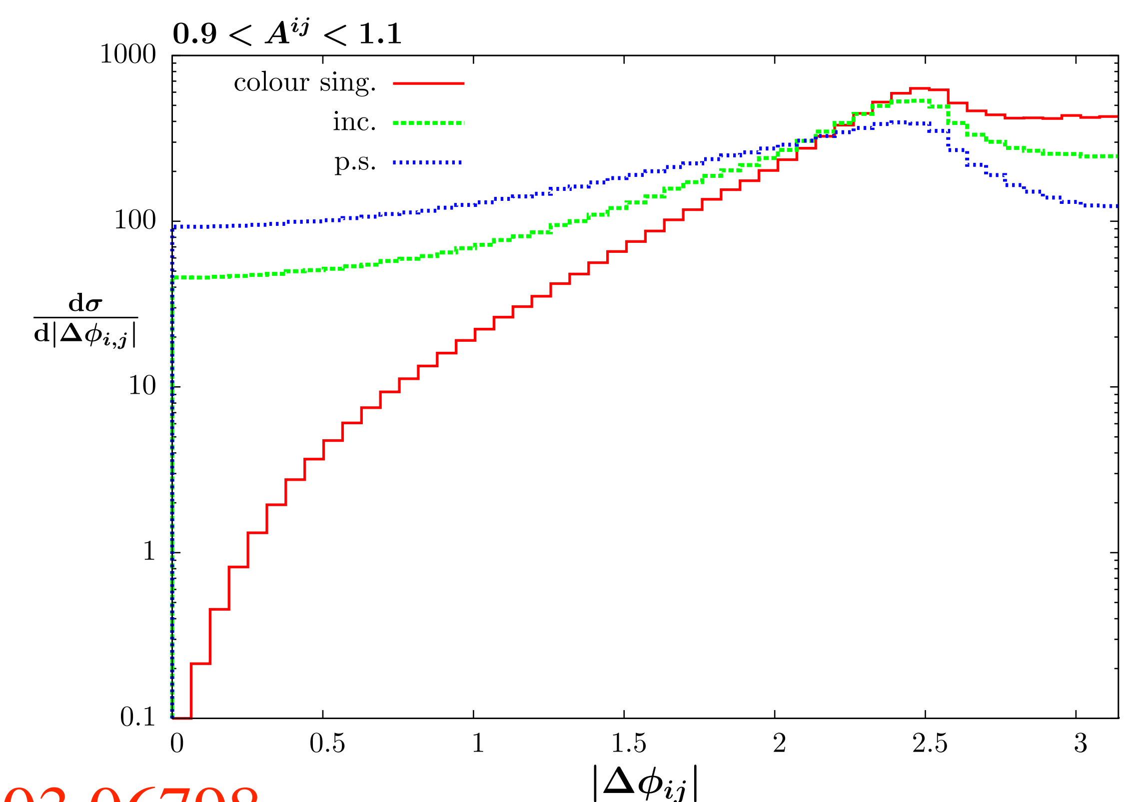
Trijet production

- 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 $m_q = 0$.

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

- In addition, new result: both ggg and $q\bar{q}g$ amplitudes for c.s. initial gluons completely vanish for certain configurations, if all particle momenta lie in a plane ($\Delta\phi_{ij} = 0, \pi$ for final--state particles). Under study.





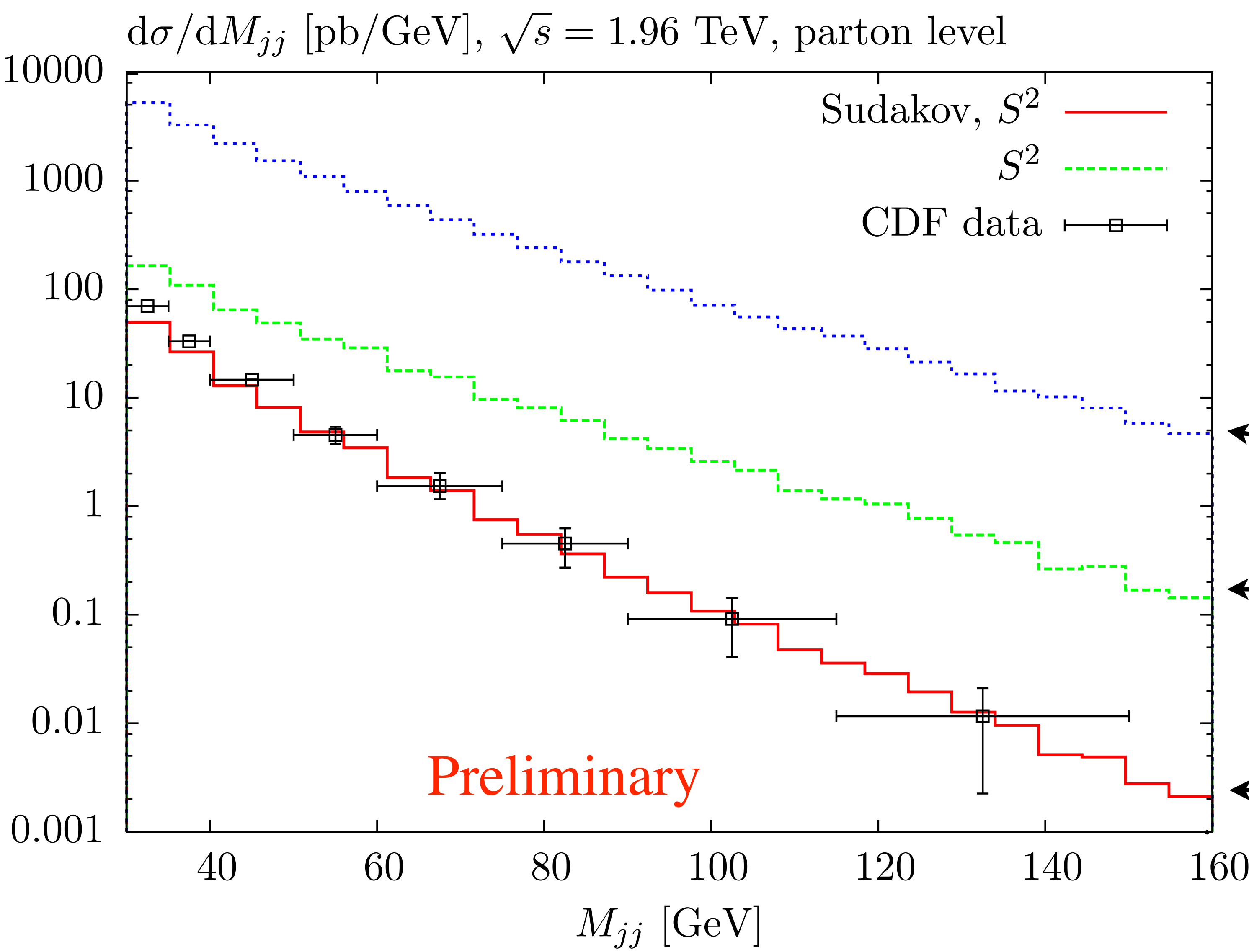
LHL, arXiv:1503.06798

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}



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

- Predictions for $\sqrt{s} = 13$ TeV :

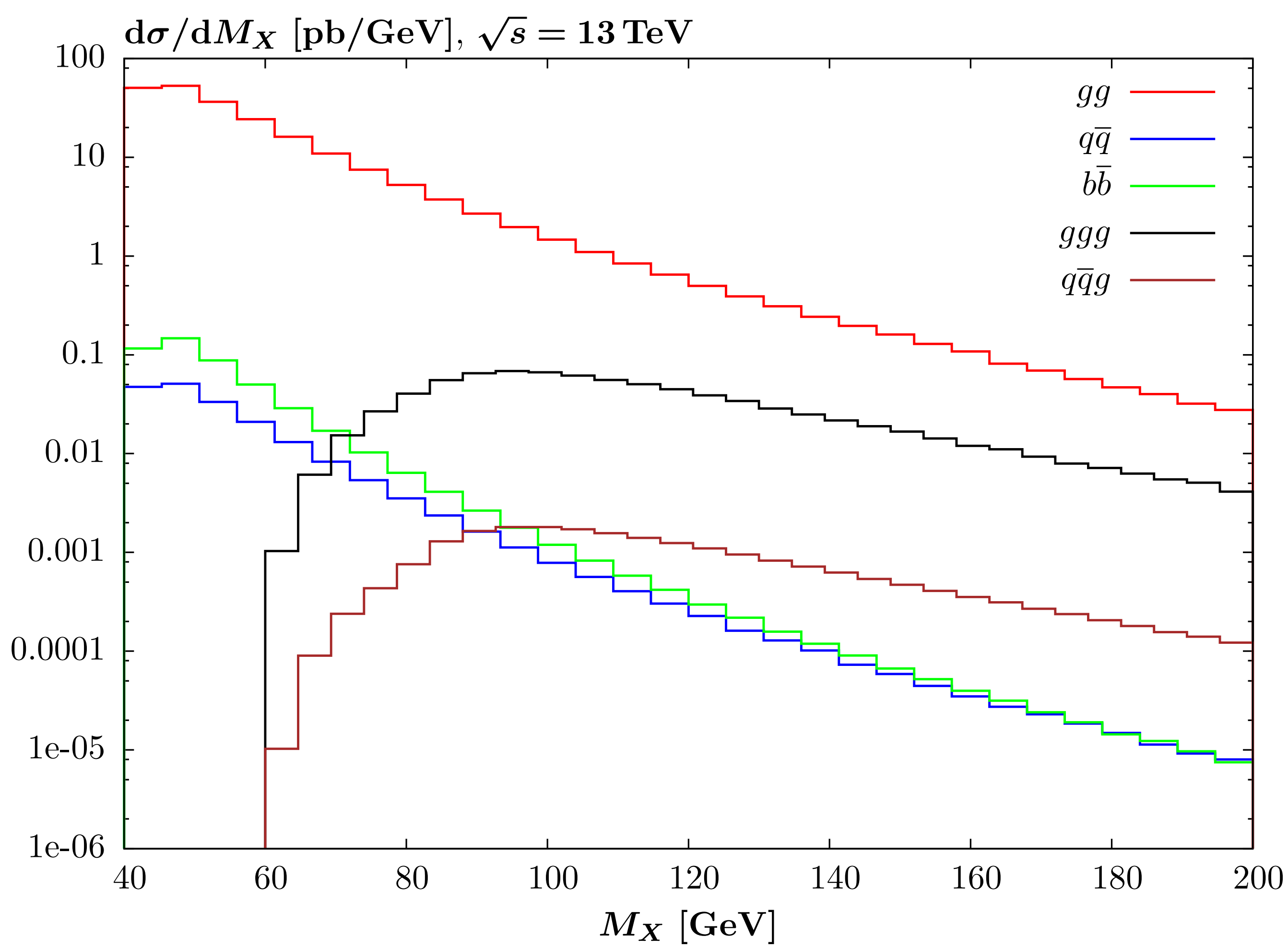
σ [pb] $\qquad |\eta_j| < 2.5$ anti–k_t, $R = 0.6$

$|p_{\perp,j}| > 20$ GeV → 75, 150

$|p_{\perp,j}| > 40$ GeV → 250

M_X(min)	gg	$q\overline{q}$	$b\overline{b}$	ggg	$gq\overline{q}$
75	120	0.073	0.12	6.0	0.14
150	4.0	1.4×10^{-3}	1.7×10^{-3}	0.78	0.02
250	0.13	5.2×10^{-5}	5.2×10^{-5}	0.018	5.0×10^{-4}

one flavour (under the $b\overline{b}$ column) MMHT14 LO PDFs



Summary and outlook

- Have discussed new 'Superchic 2' MC. Builds on previous MC, but with significant changes/extensions:
    - Theoretical improvements, most important a fully differential treatment of survival effects. Crucial to have this in many cases.
    - Completely re-structured: LHAPDF interface, and complete calculation performed 'on-line', structured so that additional processes can be easily added.
    - New processes added: jets, Higgs, two-photon interactions, double quarkonia...
    - In the immediate future: $D\overline{D}$ production will be included. Other processes?
- Will be released on $O(\mathrm{Month})$ timescale, with accompanying paper.