SuperChic v2 : a new Monte Carlo for central exclusive production

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LHC Forward Physics and Diffraction WG
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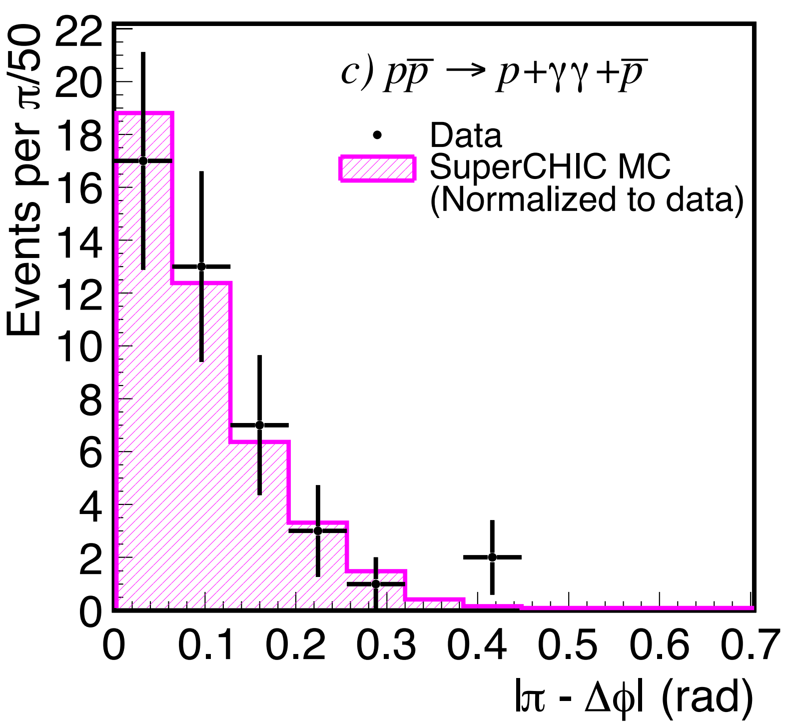
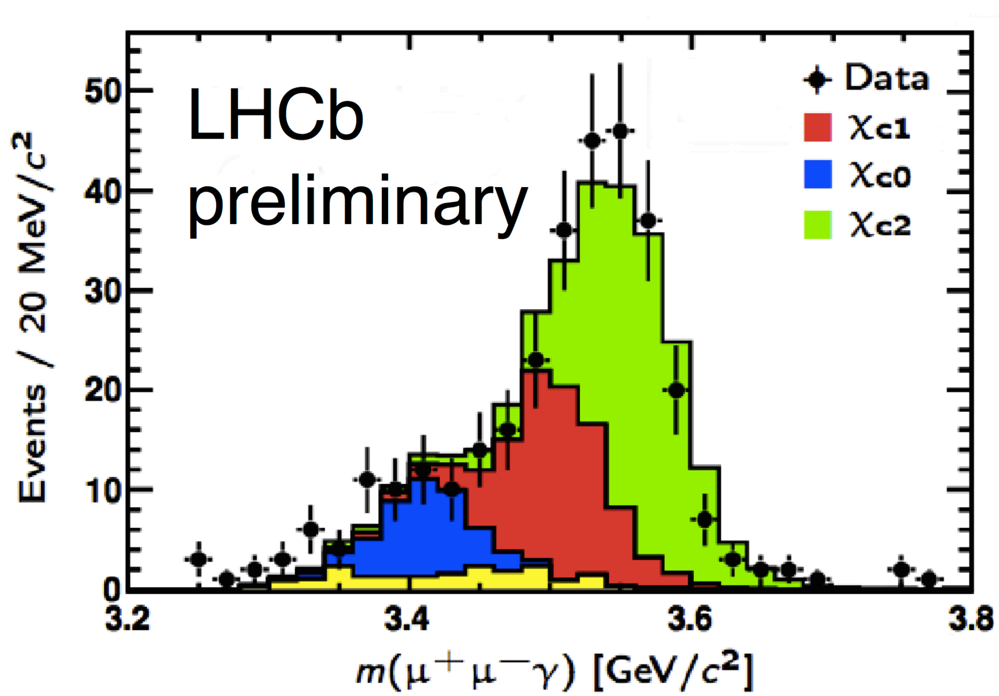
In collaboration with Valery Khoze and Misha Ryskin

Outline

- CEP: brief introduction.
- SuperChic 2: what's new.
- Present results for some example processes.
- Ongoing work: the photon PDF with rapidity gaps.

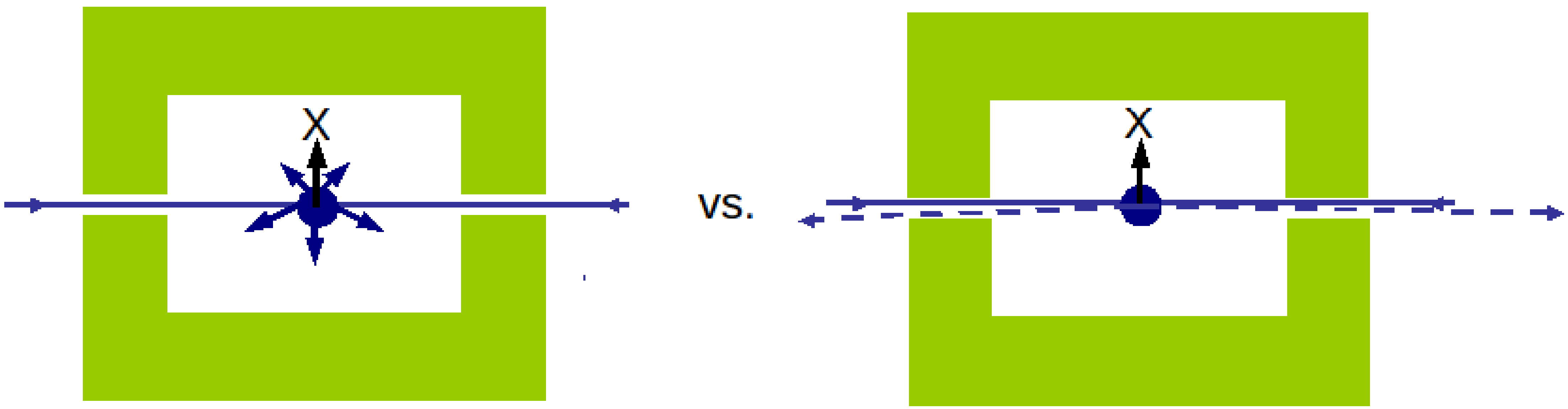




Central exclusive production (CEP) is the interaction

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

- 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...



Also: Odderon

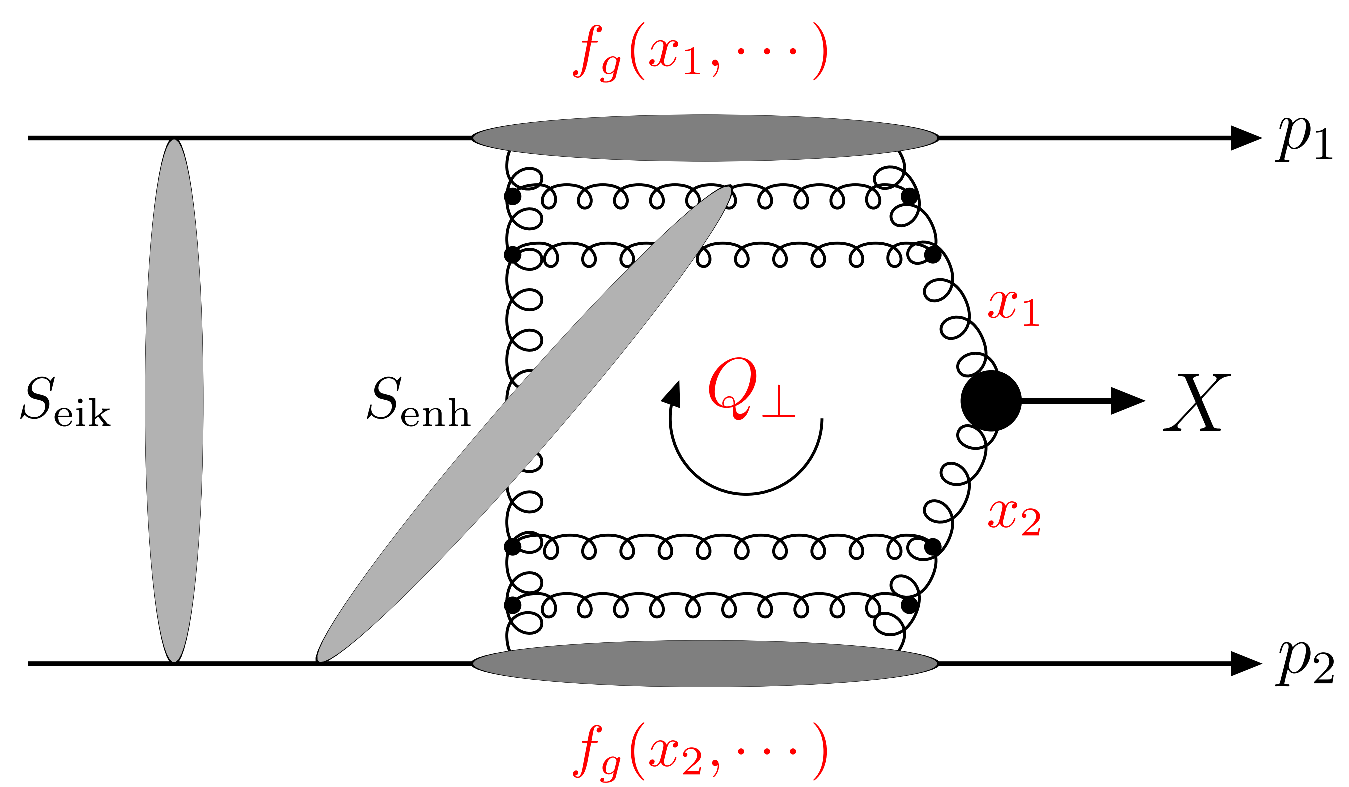
Can (principally) occur through $I\!P I\!P$, $I\!P\gamma$ and $\gamma\gamma$ interactions

'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, $S^2_{\rm eik}$ 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.



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 released in August. 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.

IPPP/15/34
DCPT/15/68

Exclusive physics at the LHC with SuperChic 2

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Abstract

We present a range of physics results for central exclusive production processes at the LHC, using the new `SuperChic 2` Monte Carlo event generator. This includes significant theoretical improvements and updates, most importantly a fully differential treatment of the soft survival factor, as well as a greater number of generated processes. We provide an overview of the latest theoretical framework, and consider in detail a selection of final states, namely exclusive 2 and 3 jets, photoproduced vector mesons, two–photon initiated muon and W boson pairs and heavy $\chi_{c,b}$ quarkonia.

- MC + user manual available on Hepforge:

SuperChic 2 - A Monte Carlo for Central Exclusive Production

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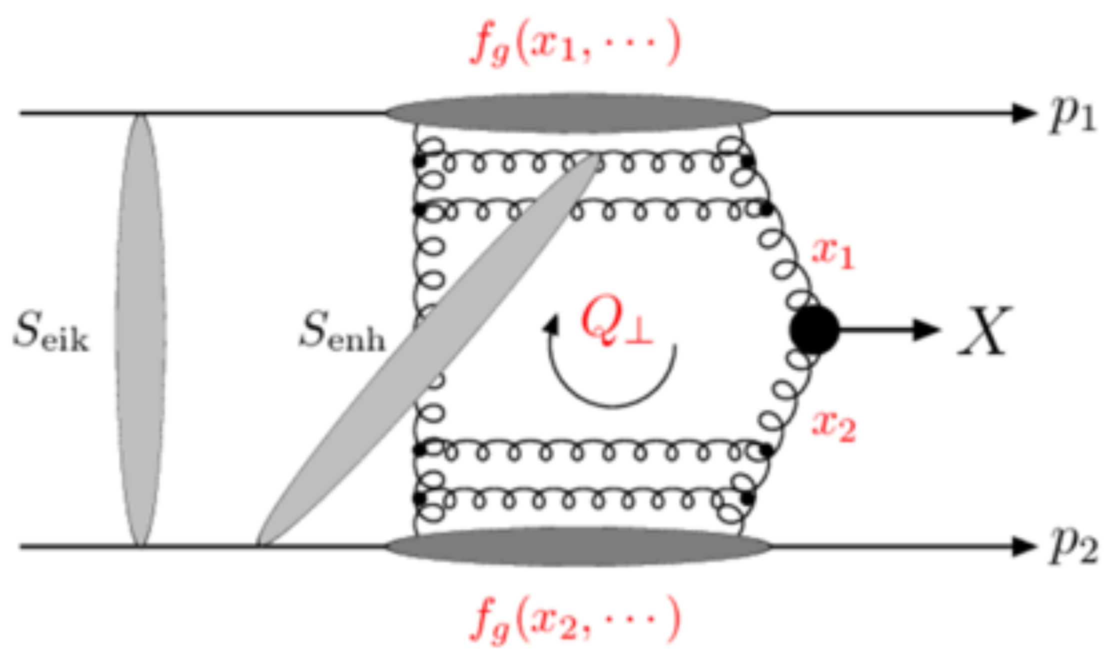
SuperChic is a Fortran based Monte Carlo event generator for central exclusive production. A range of Standard Model final states are implemented, in most cases with spin correlations where relevant, and a fully differential treatment of the soft survival factor is given. Arbitrary user-defined histograms and cuts may be made, as well as unweighted events in the HEPEVT and LHE formats. For further information see the user manual.



A list of references can be round here and the code is available here.

Comments to Lucian Harland-Lang < l.harland-lang (at) ucl.ac.uk >.

- 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^-, l^+l^- and Higgs
  - New ▸ Photoproduction: ρ and ϕ
  - New ▸ Two-photon interactions in electron/positron collisions

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

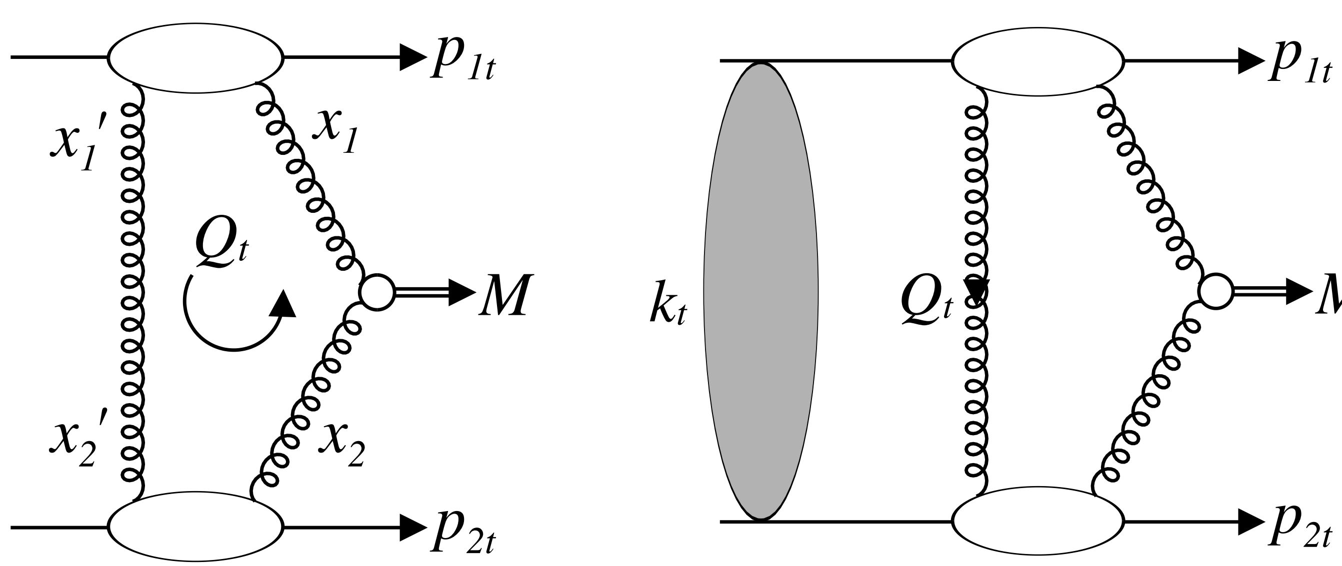
'Bare' amplitude

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

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

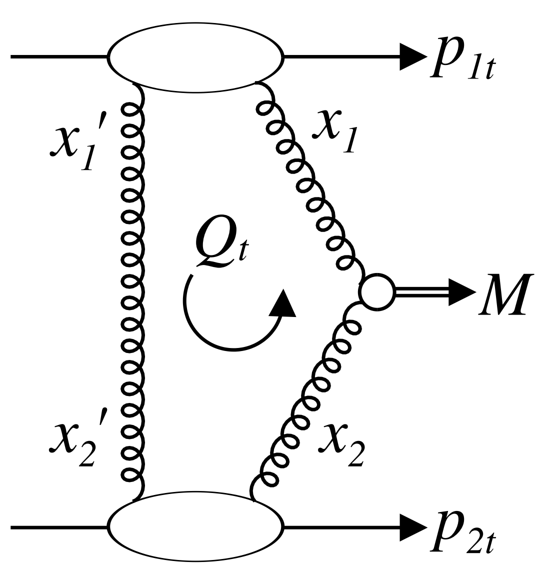
Not a constant!

with

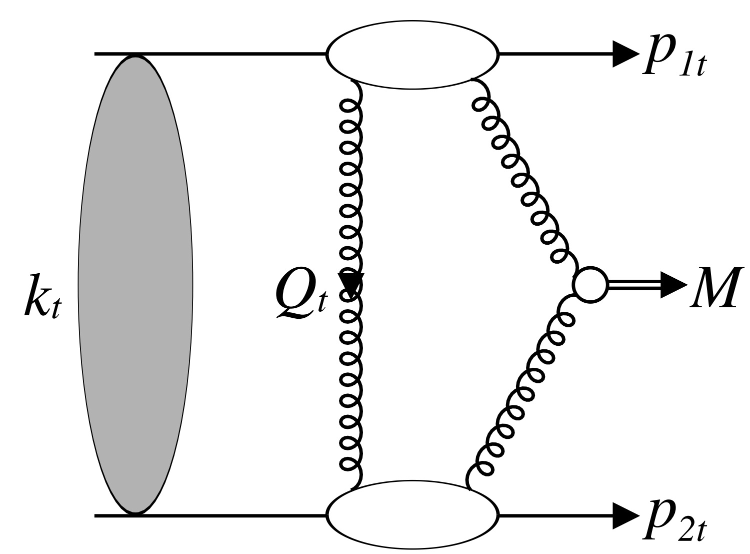
$$S^2_{\mathrm{eik}}(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp}) \equiv \frac{|T(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp}) + T^{\mathrm{res}}(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp})|^2}{|T(s,\mathbf{p}_{1_\perp},\mathbf{p}_{2_\perp})|^2} \; ,$$

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

'Bare' amplitude

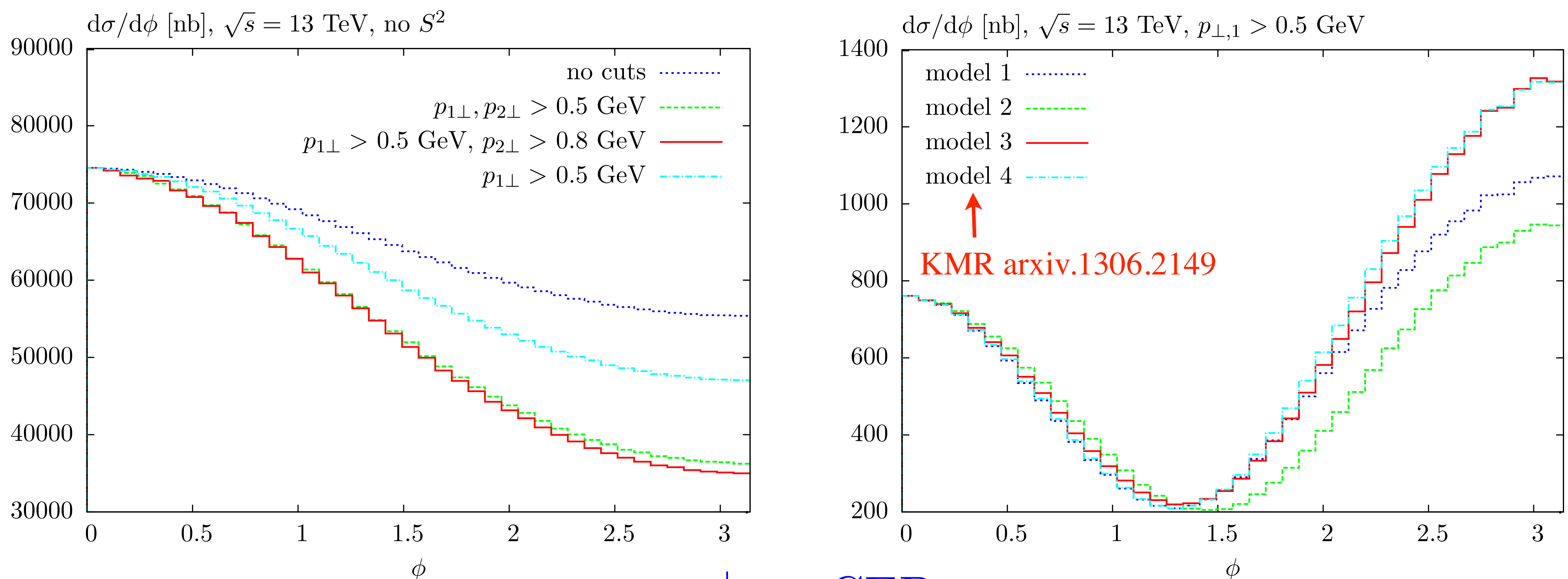


'Screened amplitude'



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

S^2 off $\qquad$ 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

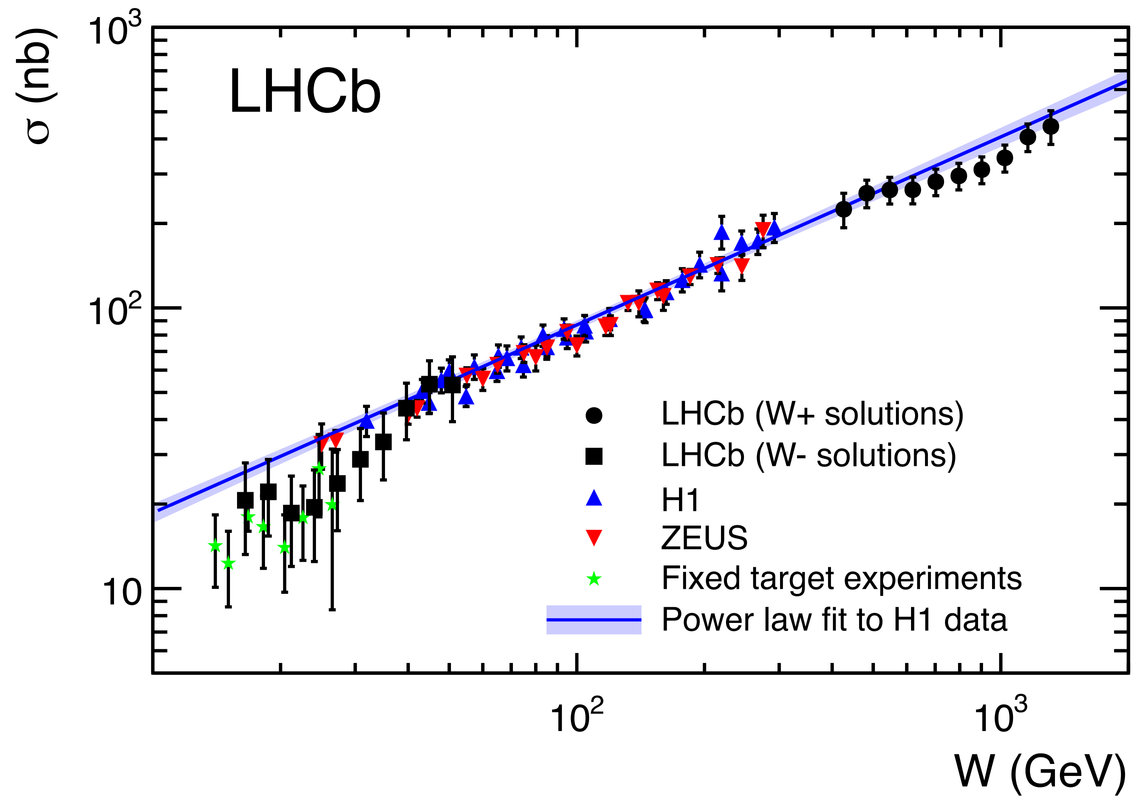
V. A. Khoze, A.D. Martin and M.G. Ryskin, hep-ph/0203122
LHL, V.A. Khoze, M.G. Ryskin and W.J. Stirling, arXiv:1011.0680

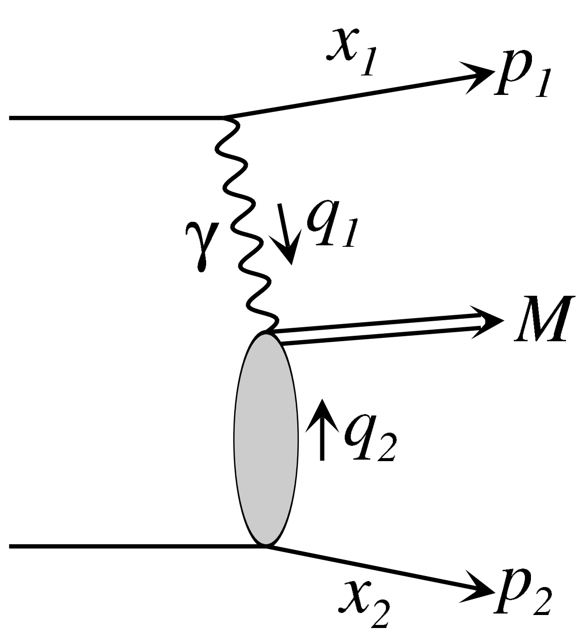
Example process: J/ψ photoproduction

- 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

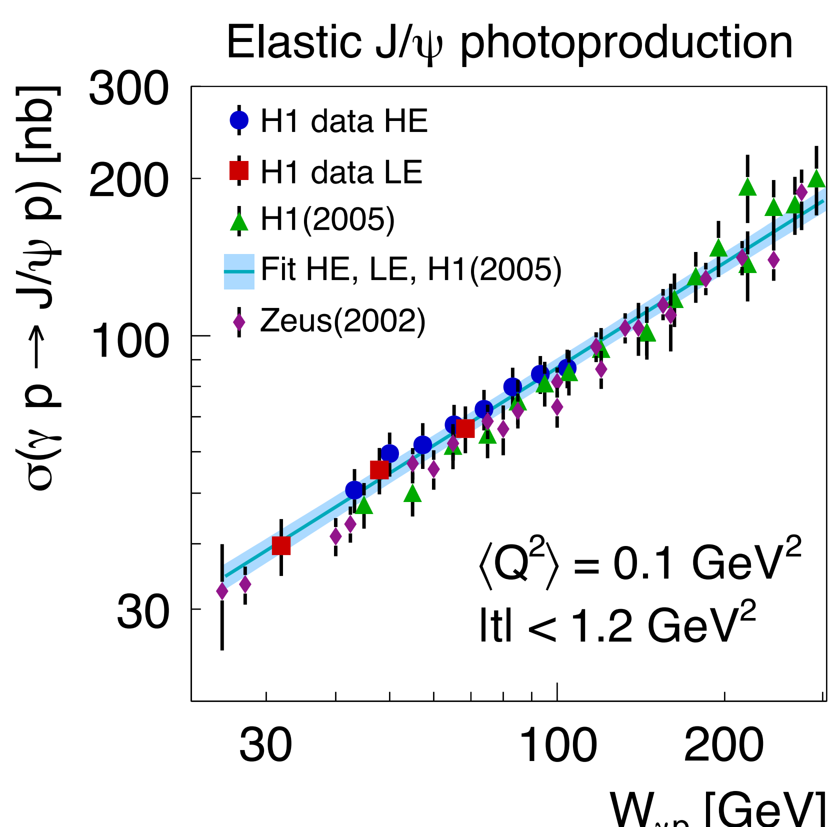
- In Superchic, take simple fit to HERA data:

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

$V = \psi$

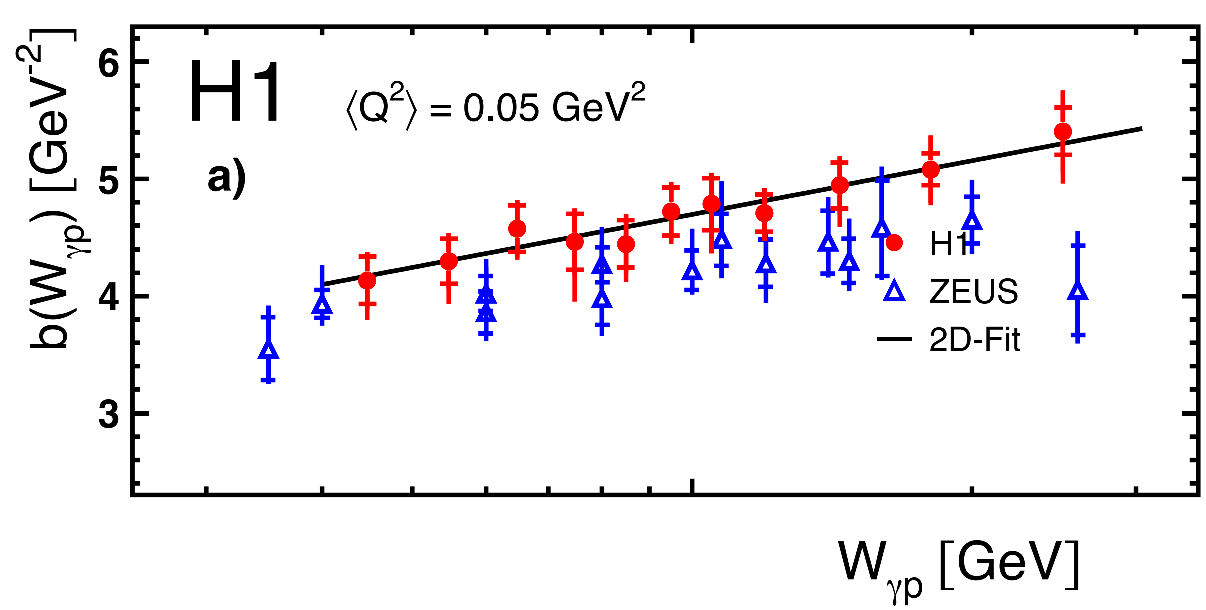
H1 find: $\delta_\psi = 0.67 \pm 0.03$ $\quad N_\psi = 81 \pm 3\,\text{nb}$ Anti-correlated

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



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]	$\sigma^{\psi}_{\rm bare}$	359	511
	$\sigma^{\psi}_{\rm sc.}$	278	406
	$\langle S^2_{\rm eik} \rangle$	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?

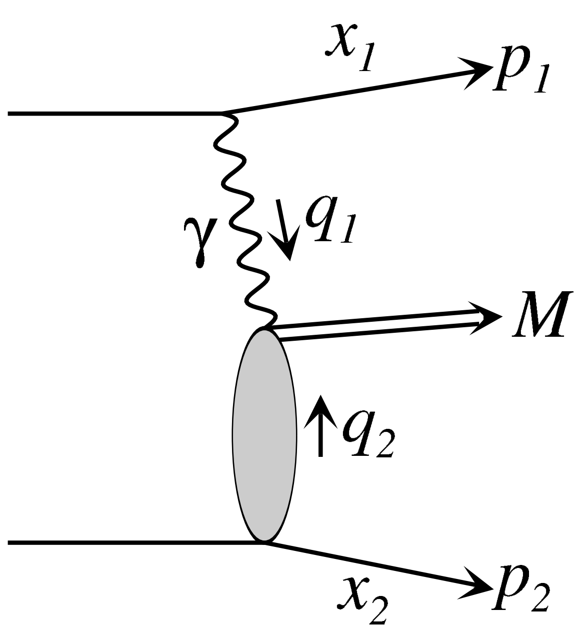
Rapidity distribution

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

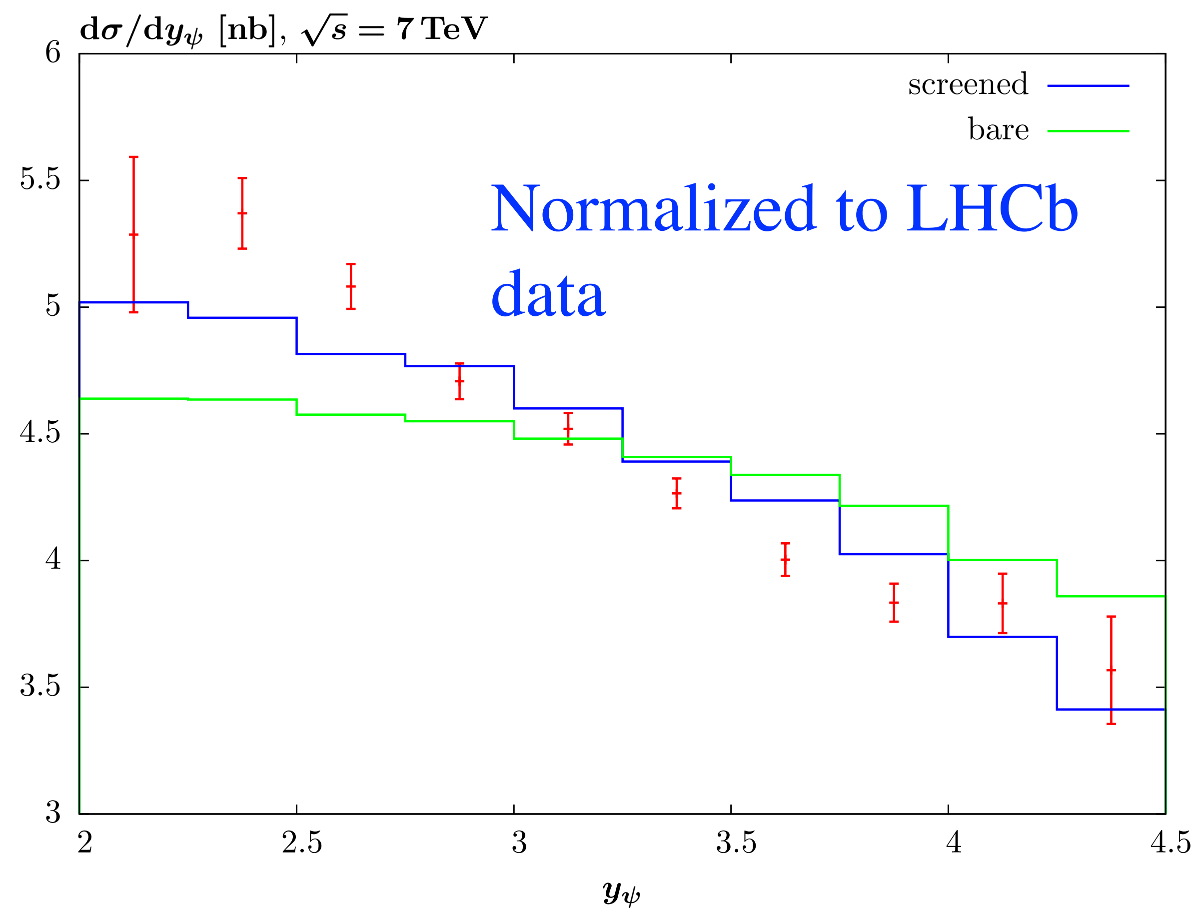
where $\xi_1 \approx \frac{M_\psi}{\sqrt{s}} e^{y_\psi}$ assuming photon emitted from proton 1 positive z-direction

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

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



- 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

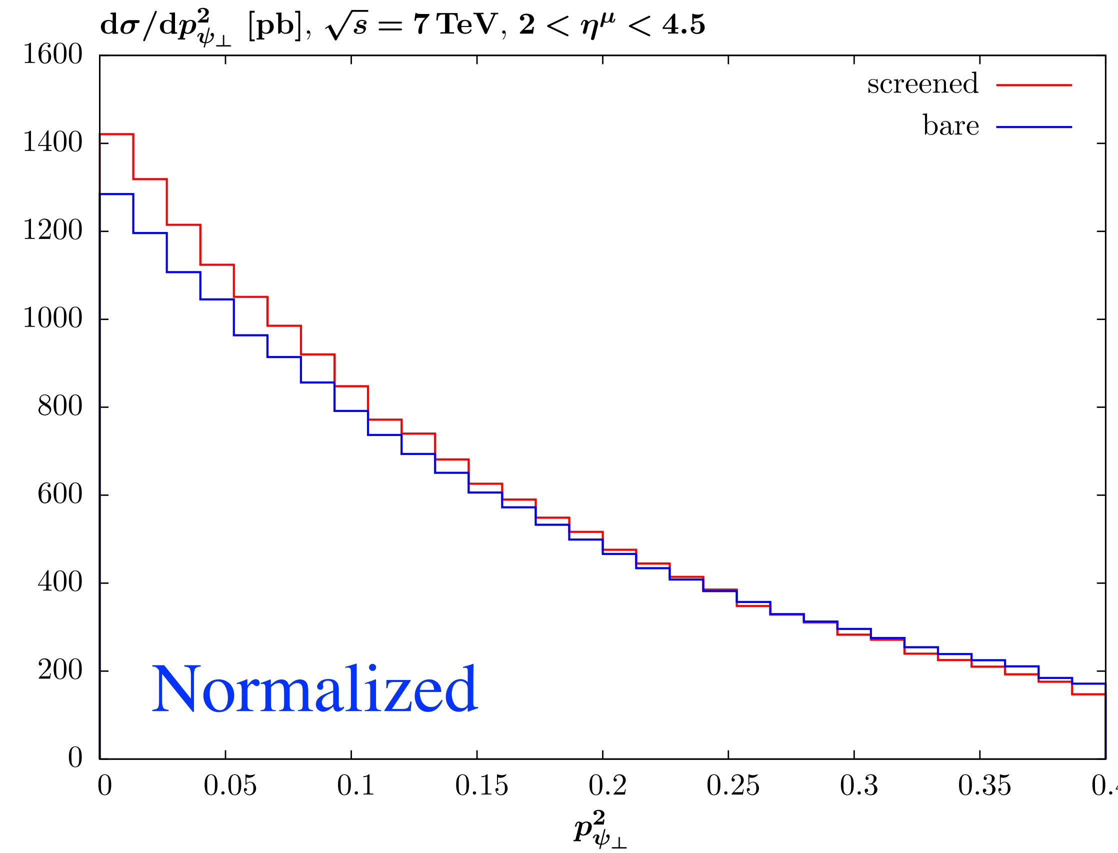
- Proton $p_\perp$ transferred directly to J/ψ. Higher $p_{\psi_\perp}$ $\Rightarrow$ less peripheral, and stronger screening. $\Rightarrow$ Survival effects will steepen $p_{\psi_\perp}$ distribution.

- 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.

Two-photon initiated processes

• Two-photon initiated exclusive processes are in principle very well understood (standard equiv. photon approx.). Proposed as luminosity test and probe of anomalous gauge couplings.

EPA luminosity

$$\frac{\mathrm{d}\sigma_{pp\to pXp}}{\mathrm{d}\Omega} = \int \frac{\mathrm{d}\sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})}{\mathrm{d}\Omega}\frac{\mathrm{d}L^{\gamma\gamma}}{\mathrm{d}W_{\gamma\gamma}}\mathrm{dW}_{\gamma\gamma}\ ,$$

• However: in proton-proton collisions a correct inclusion of S^2 essential.

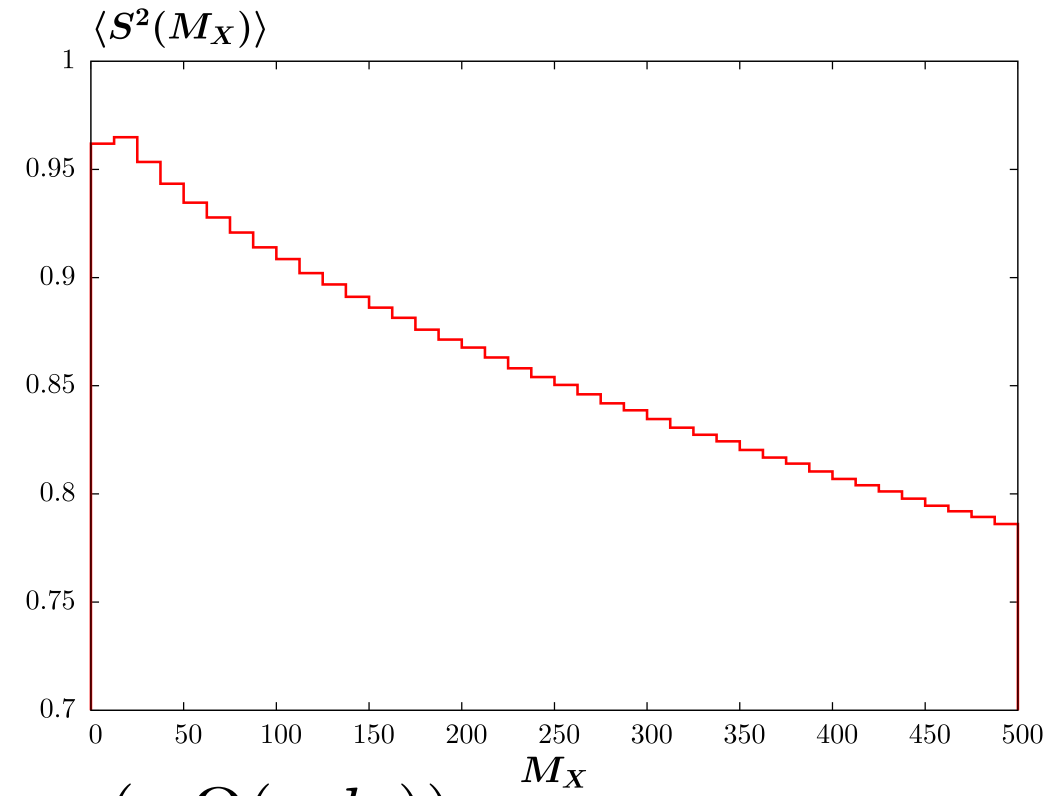
• General considerations: the EPA flux prefers small photon virtualities

$$Q^2_{i,\min} = \xi_i^2 m_p^2/(1-\xi_i) \qquad \xi \sim \frac{W_{\gamma\gamma}}{\sqrt{s}}e^{\pm y_X}$$

and therefore interaction highly peripheral $\longrightarrow \langle S^2\rangle \sim 1$

• But still important for precise treatment, and as before if $W_{\gamma\gamma}$ large or for forward production, then $\langle S^2\rangle$ is smaller.

$M_X = W_{\gamma\gamma}$



- Consider $\langle S^2(M_X)\rangle$ for $\mu^+\mu^-$ production: clear drop with M_X seen.
- Recall expression for survival factor:

$\gamma\gamma \to X$

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

$\longrightarrow$ Important to correctly include b_t dependence of subprocess amplitude

(massless leptons)

- l^+l^- production: the $\gamma\gamma \to l^+l^-$ amplitudes vanish for $J_z = 0$ initial state photons. It turns out this leads to less absorption than naive expectations.
- In particular, this leads to dependence on event selection: by demanding small $p_\perp(l^+l^-)$, get $\langle S^2\rangle$ very close to 1.

V.A. Khoze, A.D. Martin, R.Orava, M.G. Ryskin, Eur. Phys. J. C19 (2001) 313-322

	$\mu^+\mu^-$	$\mu^+\mu^-$, $M_{\mu\mu} > 2M_W$	$\mu^+\mu^-$, $p_\perp^{\rm prot.} < 0.1$ GeV	W^+W^-
$\sigma_{\rm bare}$	6240	11.2	3170	87.5
$\sigma_{\rm sc.}$	5990	9.58	3150	71.9
$\langle S^2_{\rm eik}\rangle$	0.96	0.86	0.994	0.82

- ATLAS data on exclusive $\mu^+\mu^-$ and e^+e^- production: arXiv:1506.07098.

- Important of including survival effects is discussed, and measurements compared to predictions of Dyndal & Schoeffel- form of one-channel calculation, with specific assumptions about the form of the opacity:

M. Dyndal and L. Schoeffel, Phys. Lett. B741 (2015) 66-70

EPA flux ↘

$$S^2_{\gamma\gamma} = \frac{\int_{b_1>r_p}\int_{b_2>r_p} n(\vec{b}_1,\omega_1)n(\vec{b}_2,\omega_2)P_{non-inel}(|\vec{b}_1-\vec{b}_2|)d^2\vec{b}_1 d^2\vec{b}_2}{\int_{b_1>0}\int_{b_2>0} n(\vec{b}_1,\omega_1)n(\vec{b}_2,\omega_2)d^2\vec{b}_1 d^2\vec{b}_2} \qquad P_{non-inel}(b) = |1-\exp(-b^2/(2B))|^2,$$

does not include b_t dependence of $\gamma\gamma \to l^+l^-$ amplitude.

$\longrightarrow$ Misses important physics, may overestimate suppression due to S^2 .

- ATLAS measure:

$$\sigma^{\text{excl.}}_{\gamma\gamma\to\mu^+\mu^-} = 0.628 \pm 0.032\,(\text{stat.}) \pm 0.021\,(\text{syst.})\ \text{pb}\,,$$

$$\sigma^{\text{excl.}}_{\gamma\gamma\to e^+e^-} = 0.428 \pm 0.035\,(\text{stat.}) \pm 0.018\,(\text{syst.})\ \text{pb}\,.$$

- Superchic 2 predictions: $\sigma(\mu^+\mu^-) = 0.74\,\text{pb}$ $\quad\sigma(e^+e^-) = 0.46\,\text{pb}$ $\quad\langle S^2_{\text{eik}}\rangle \sim 0.94$

$\longrightarrow$ Good agreement for e^+e^-, some tension with $\mu^+\mu^-$. Higher precision and more differential (in e.g. $p_\perp(\mu^+\mu^-)$) data will shed more light on this. Tagged protons: eliminate dissociative BG.

Ongoing project: the photon PDF with rapidity gaps

- As well as exclusive processes considered in previous slides, can also consider inclusive, or semi-inclusive photon--initiated processes.

- For inclusive production have usual factorization:

$$\sigma = \int \mathrm{d}x_1 \, \mathrm{d}x_2 \, \gamma(x_1, \mu^2) \, \gamma(x_2, \mu^2) \hat{\sigma}(\gamma_1 \gamma_2 \to X)$$

- $\gamma(x, \mu^2)$: photon PDF, distribution of photons within proton, determined from (QED) DGLAP evolution of starting distribution $\gamma(x, \mu_0^2)$.

- But what about diffractive/semi-inclusive processes?

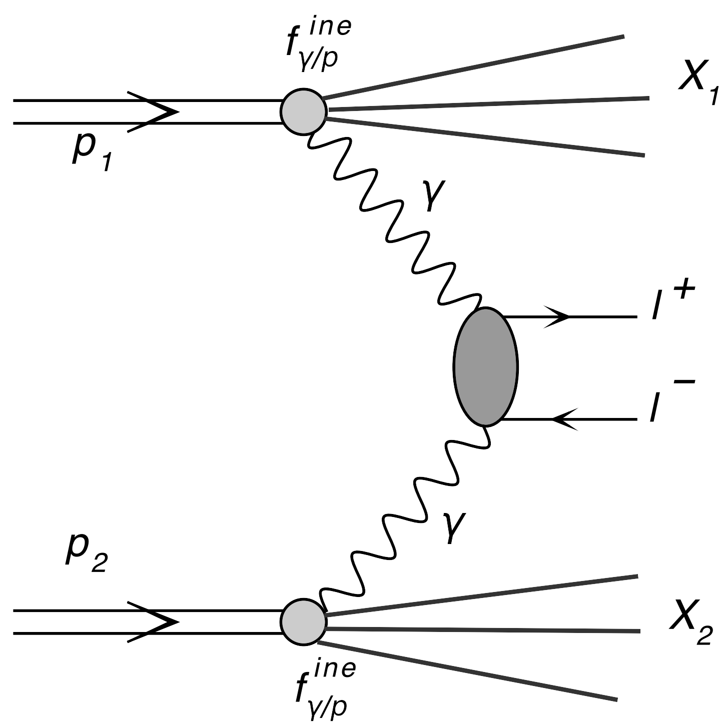


Fig: M. Luszczak et al., 1510.00294

The photon PDF with rapidity gaps

- Want to calculate distribution of photons in semi-exclusive case, i.e. with large rapidity gap veto between central system and dissociation system. Corresponds to experimental situation in absence of proton tagging.

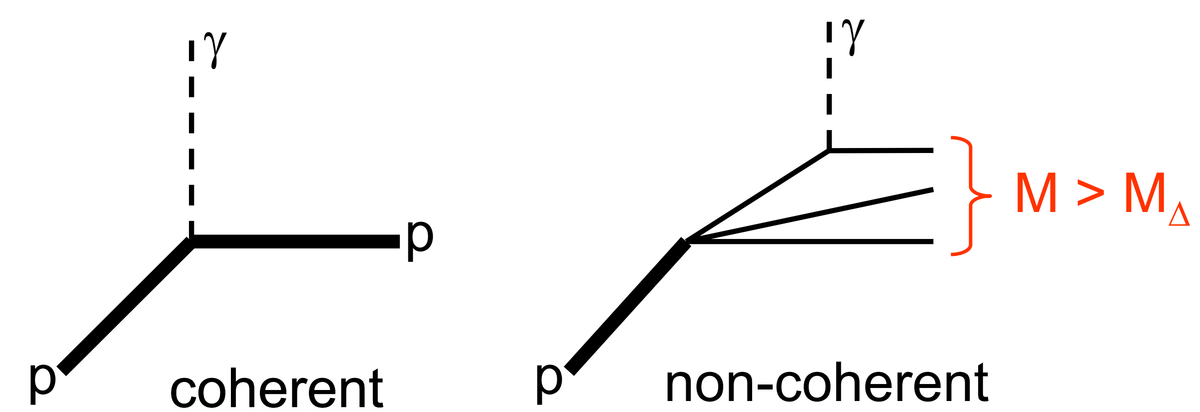
- Consider photon PDF at scale Q^2 ($\sim M_X^2$) :

$$\gamma(x,Q^2) = \gamma(x,Q_0^2) + \frac{\alpha}{2\pi}\int_{Q_0^2}^{Q^2} \frac{dQ'^2}{Q'^2}\int_x^1 \frac{\mathrm{d}z}{z}\left(P_{\gamma\gamma}(z)\,\gamma(\frac{x}{z},Q'^2) + \sum_q P_{\gamma q}(z)\,q(\frac{x}{z},Q'^2)\right) .$$

  - $\gamma(x,Q_0^2)$: input PDF, given in terms of :

    - 'Coherent' component: elastic $p \to p + \gamma$ and low mass excitations, leads naturally to rapidity gap.

    - 'Incoherent' component: emission from individual quark lines. As we have kinematic constraint on quark $k_\perp < Q_0 \sim 1\,\mathrm{GeV}$, the rapidity of produced secondaries is large.



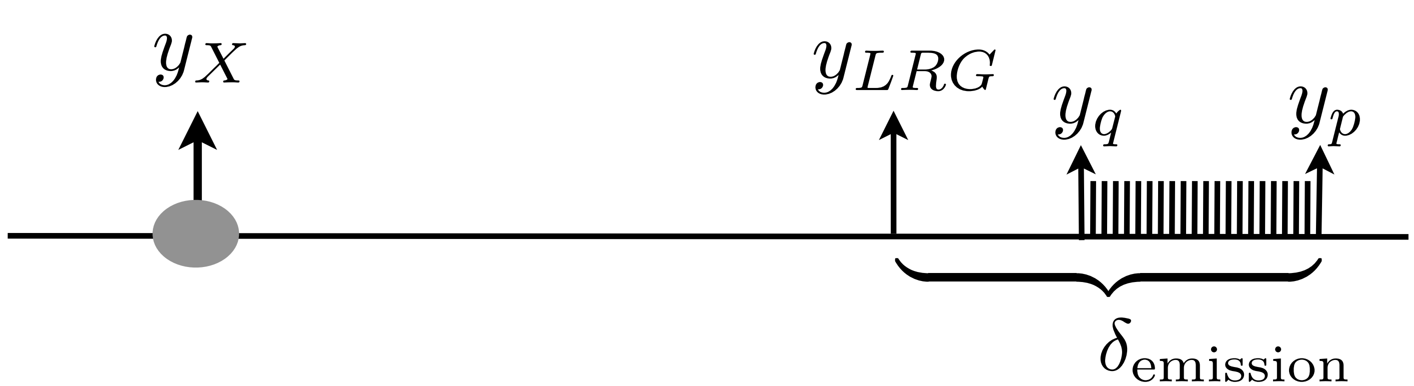
The photon PDF with rapidity gaps

- Thus PDF from input term (emission up to scale $Q_0 \sim 1\,\mathrm{GeV}$) naturally generates rapidity gaps. What about DGLAP evolution to hard scale $Q \sim M_X$?

Purely virtual

$$\gamma(x,Q^2) = \gamma(x,Q_0^2) + \frac{\alpha}{2\pi}\int_{Q_0^2}^{Q^2}\frac{dQ'^2}{Q'^2}\int_x^1\frac{\mathrm{d}z}{z}\left(P_{\gamma\gamma}(z)\,\gamma(\frac{x}{z},Q'^2) + \sum_q P_{\gamma q}(z)\,q(\frac{x}{z},Q'^2)\right).$$

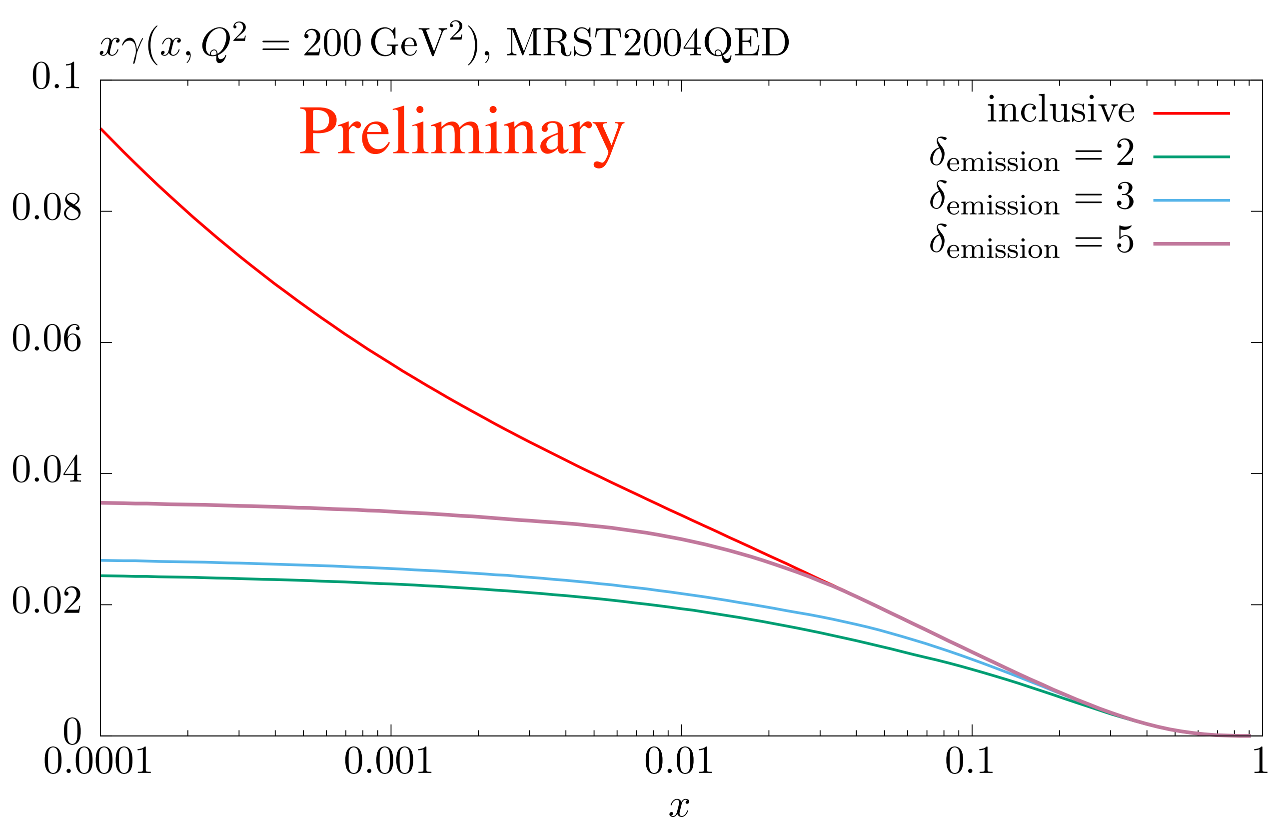
  - At LO in α the photon PDF is generated by the $q \to q\gamma$ transition, governed by splitting function $P_{\gamma q}(z)$.
  - Require that emitted quark lies in rapidity interval $\delta_{\rm emission}$, beyond LRG region $\longrightarrow$ kinematic considerations show this can be included in DGLAP evolution via a simple Θ function constraint on z, Q^2 integration region.

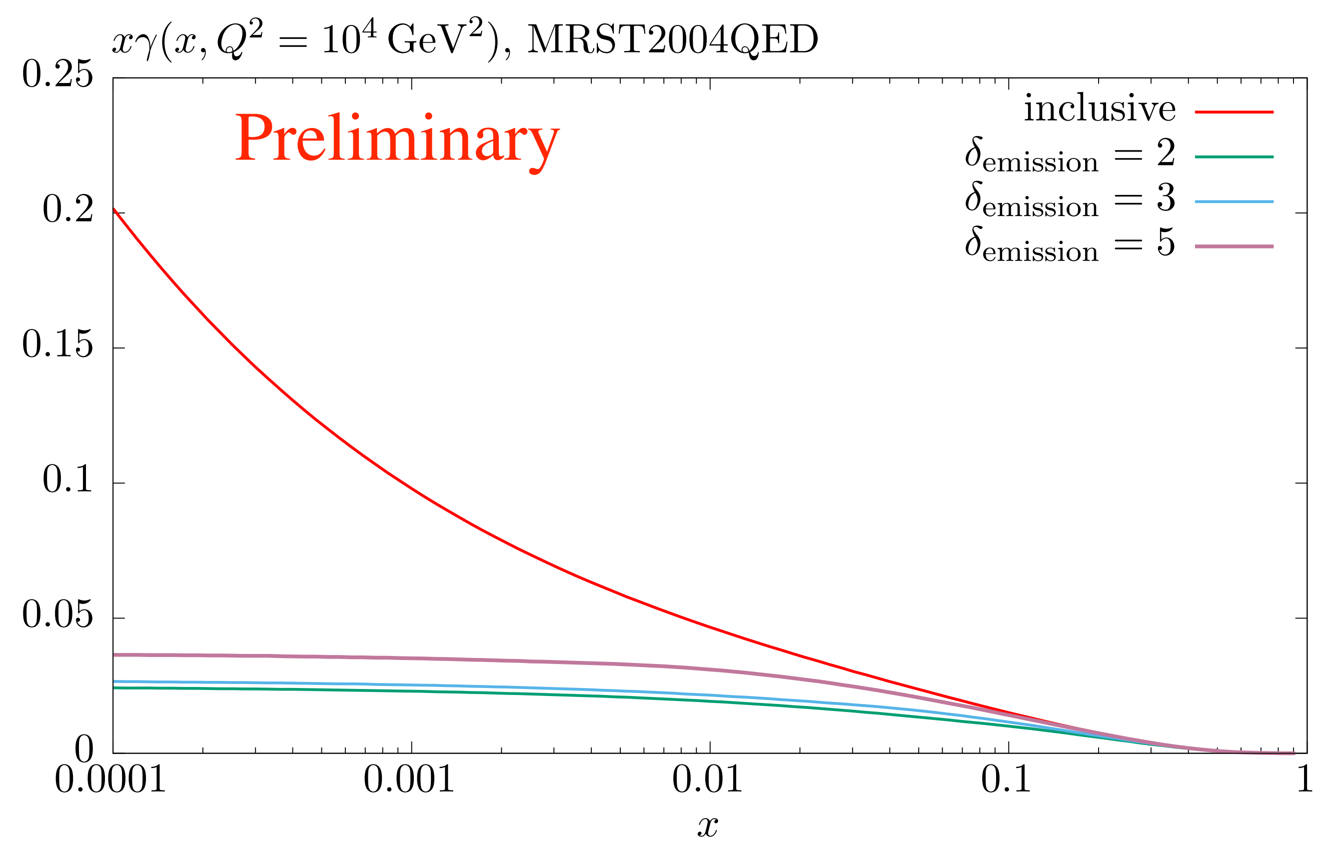


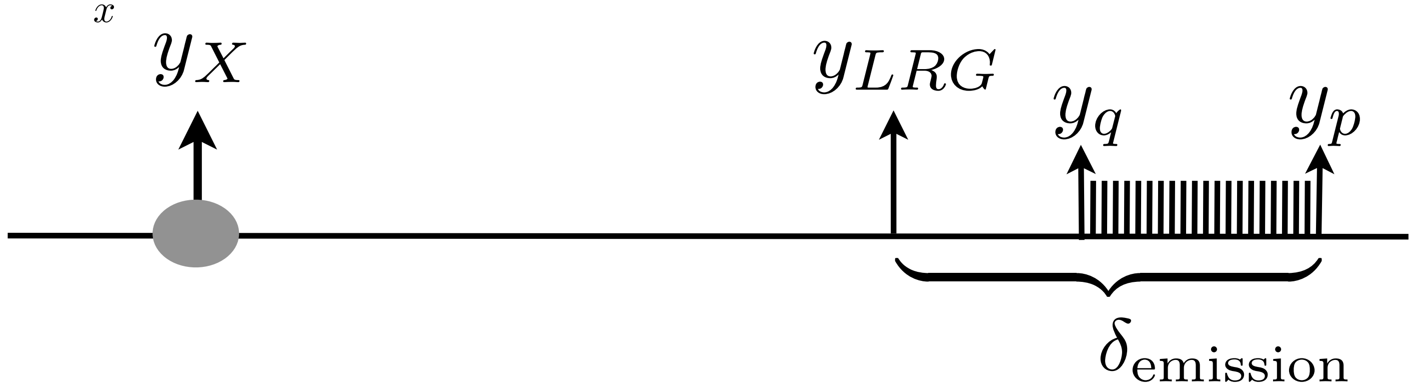
The photon PDF with rapidity gaps

- First look: consider MRST2004QED PDFs: particular model for $\gamma(x, Q_0^2)$ and then DGLAP evolution.
- Consider different values of $\delta_{\rm emission}$ where secondary emission is allowed.

$\longrightarrow$ Clear suppression vs. inclusive case, in particular at lower x .







The photon PDF with rapidity gaps

- In addition to secondary particle production due to DGLAP $q \to q\gamma$ splitting, rapidity gaps may be spoilt by additional soft proton-proton interaction $\longrightarrow$ need to include survival factor, S^2.
- However, the size of S^2 depends on amount of 'perturbative' emission, and this explicitly breaks simple factorization picture:

$$\sigma = \int \mathrm{d}x_1\,\mathrm{d}x_2\,\underbrace{\gamma(x_1,\mu^2)\,\gamma(x_2,\mu^2)}\hat{\sigma}(\gamma_1\gamma_2 \to X)$$

$$\downarrow$$

$$\sim \left(\gamma(x_1,Q_0^2) + \int \frac{\mathrm{d}Q'^2}{Q'^2}\int_{x_1}^1 \frac{\mathrm{d}z}{z} P_{\gamma q}(z)\cdots\right)\left(\gamma(x_2,Q_0^2) + \int \frac{\mathrm{d}Q'^2}{Q'^2}\int_{x_2}^1 \frac{\mathrm{d}z}{z} P_{\gamma q}(z)\cdots\right)$$

- Multiplying out gives four terms, each with its own S^2. The size of the 'effective' photon PDF for rapidity gap events depends on what other proton is doing. Work is ongoing on this.

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?

- Paper on the arxiv: arXiv:1508.02718.

- Briefly outlined ongoing work on the photon PDF in events with rapidity gaps: paper out soon.