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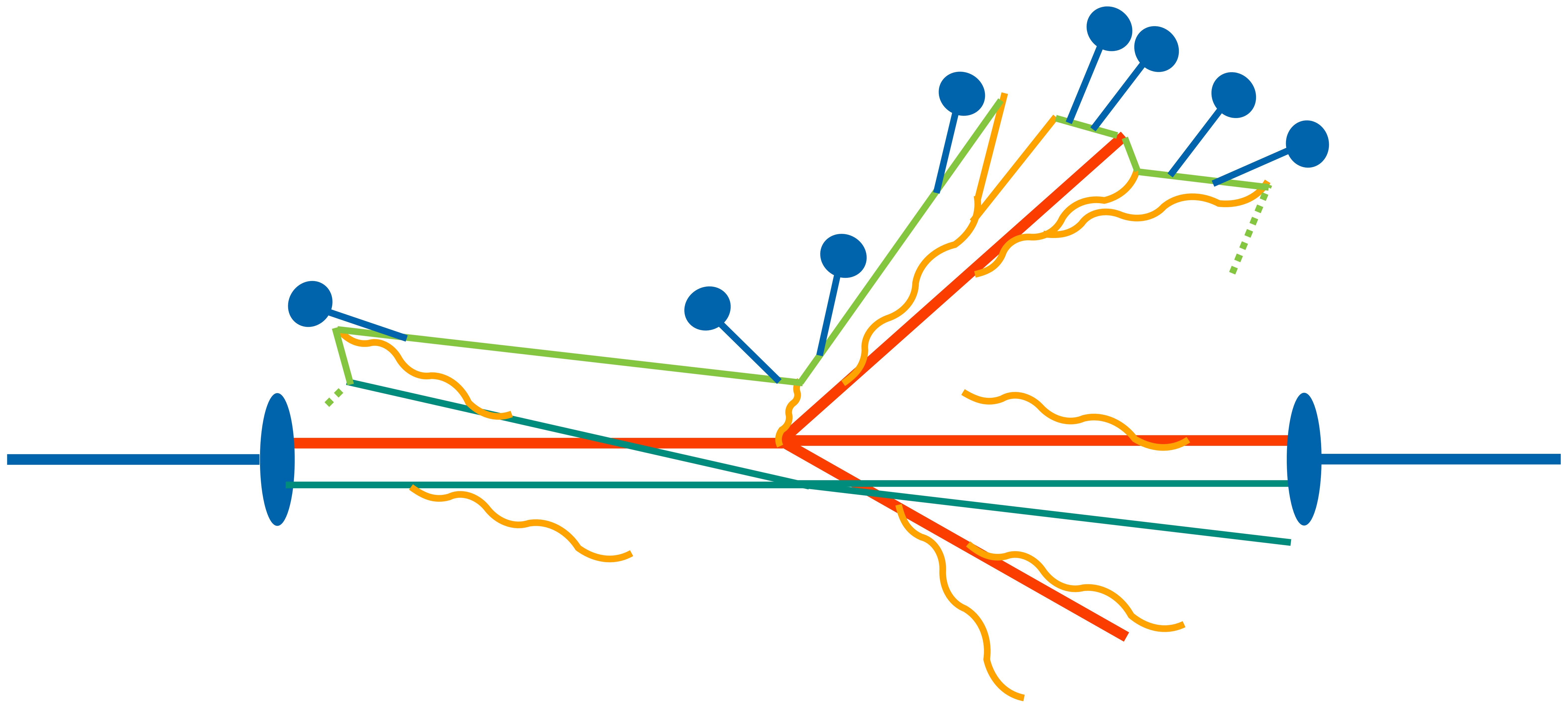
Soft QCD & Phenomenology with Herwig 7

Simon Plätzer
Particle Physics — University of Graz / University of Vienna

At the
MPI@LHC Workshop
Lisbon/Online | 11 October 2021

QCD cross sections



$$d\sigma \sim \mathrm{L} \times d\sigma_H(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{MPI} \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

Herwig 7 Overview

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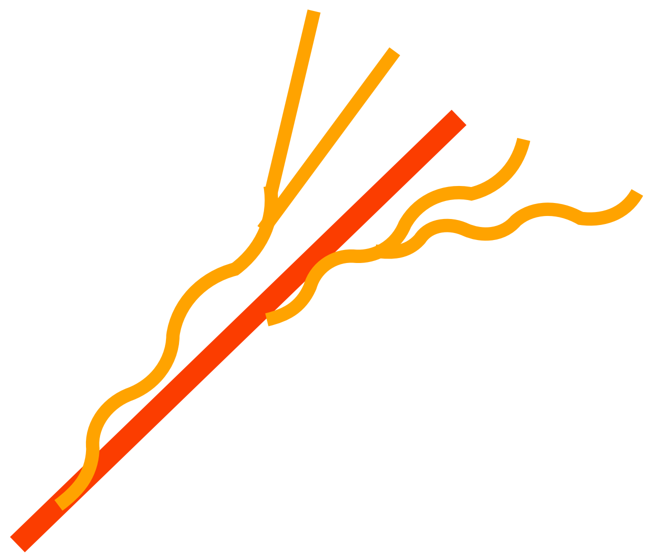
[Herwig collaboration – Eur.Phys.J. C76 (2016) 665]

Hard partonic scattering:
NLO QCD routinely

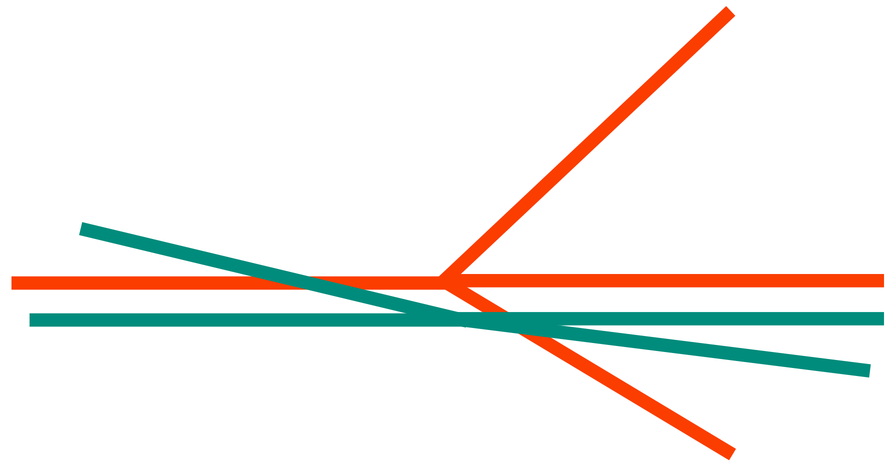


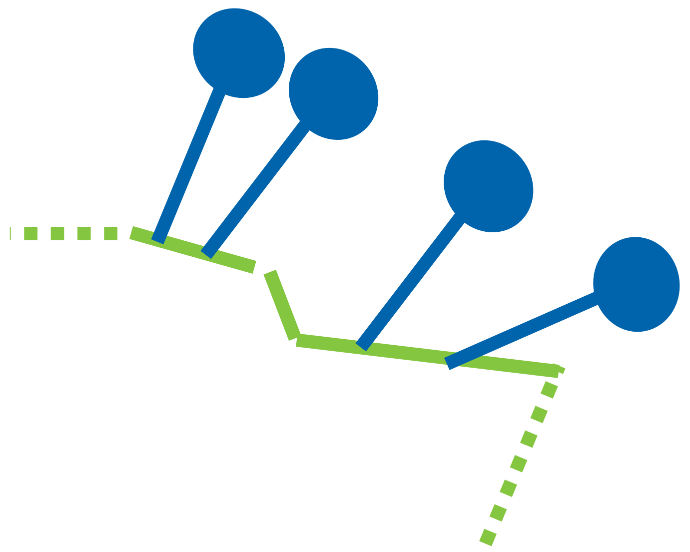
[Plätzer, Gieseke – EPJ C72 (2012) 2187]
[Plätzer — JHEP 1308 (2013) 114]
[Bellm, Gieseke, Plätzer — EPJ C78 (2018) 244]

Jet evolution — parton branching:
NLL sometimes, mostly unclear

[Gieseke, Stephens, Webber – JHEP 0312 (2003) 045]
[Plätzer, Gieseke – JHEP 1101 (2011) 024]
[Bellm, Nail, Plätzer, Schichtel, Siodmok – EPJ C76 (2016) 665]

Multi-parton interactions
Hadronization





Eikonal MPI

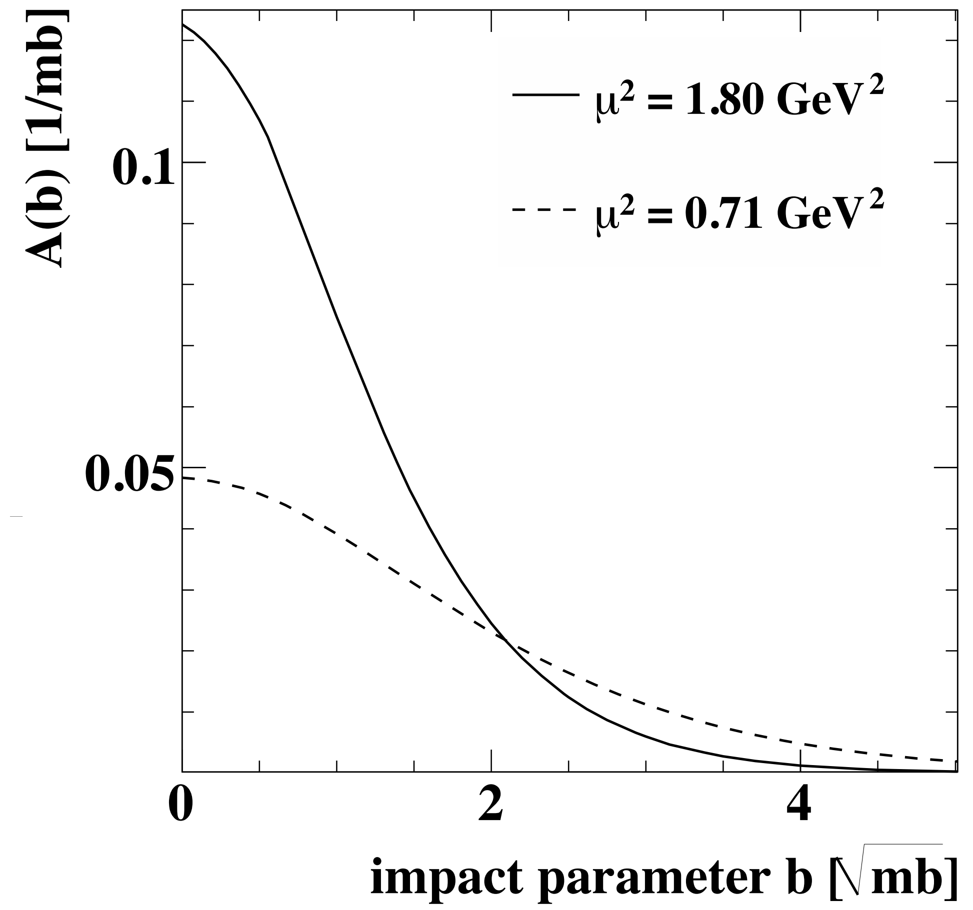
Cluster Hadronization

$$\mathrm{d}\sigma \sim \mathrm{L} \times \mathrm{d}\sigma_H(Q) \times \mathrm{PS}(Q \to \mu) \times \mathrm{MPI} \times \mathrm{Had}(\mu \to \Lambda) \times \ldots$$

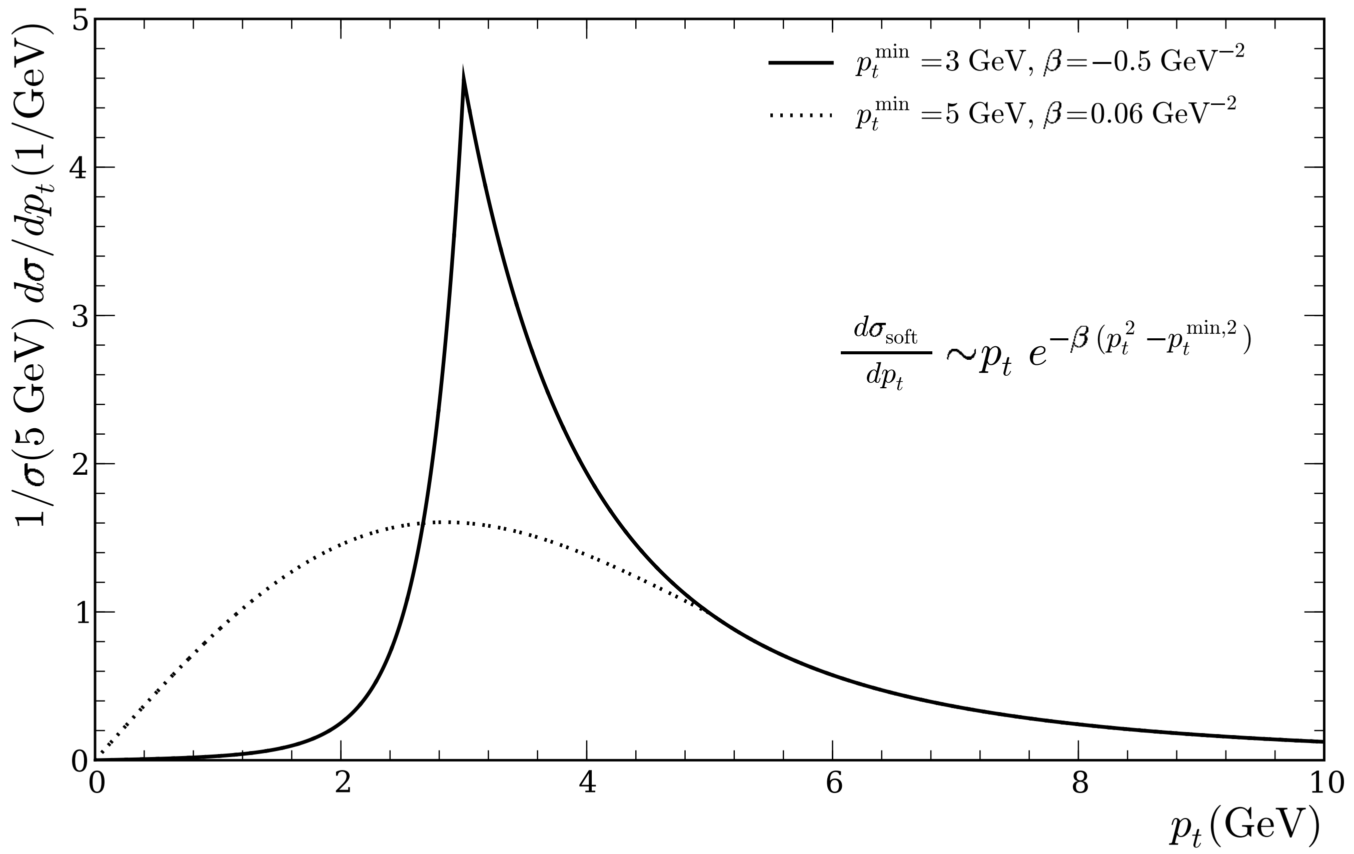
See Jo's talk on Thursday on double parton scattering.

Eikonal MPI Model

Key ingredients for MPI modelling in Herwig 7

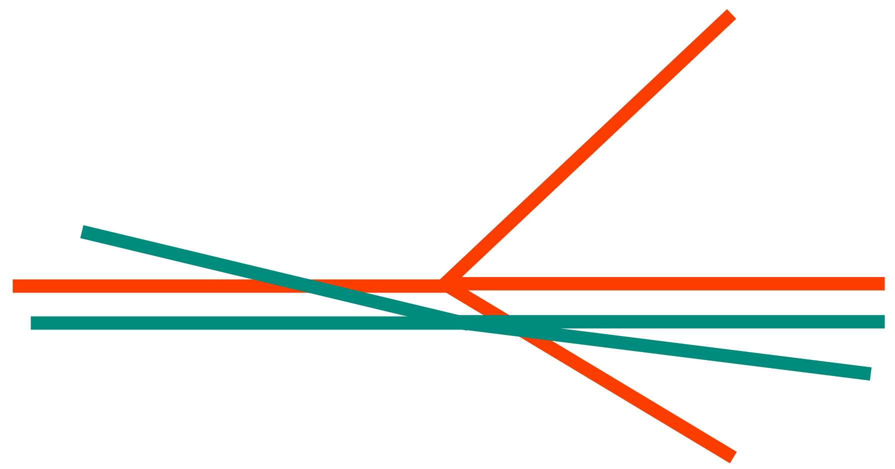


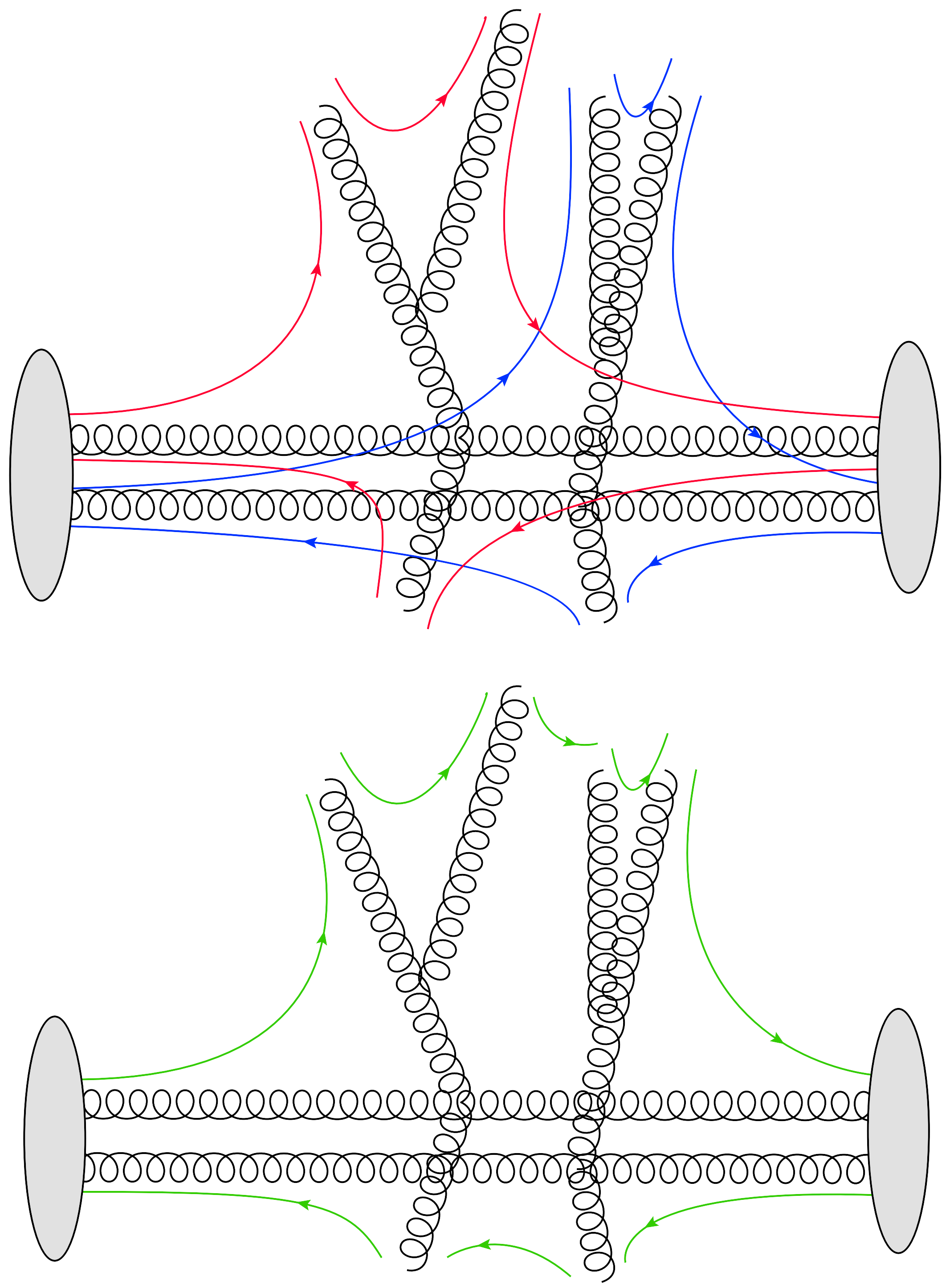
matter distribution



soft & hard scatters

$$p_{\perp}^{\min}(s) = p_{\perp,0}^{\min}\left(\frac{b+\sqrt{s}}{E_0}\right)^{c}$$





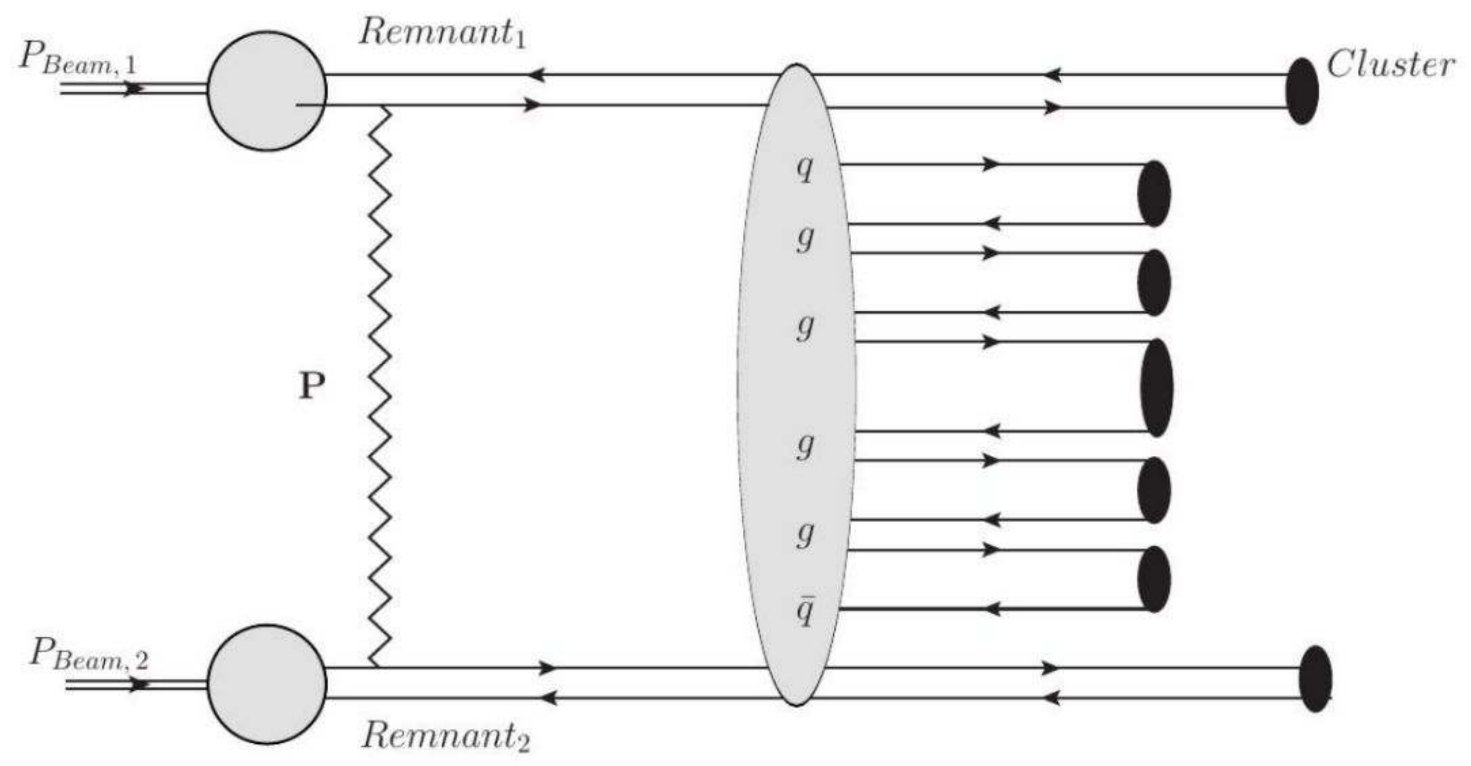
colour reconnection

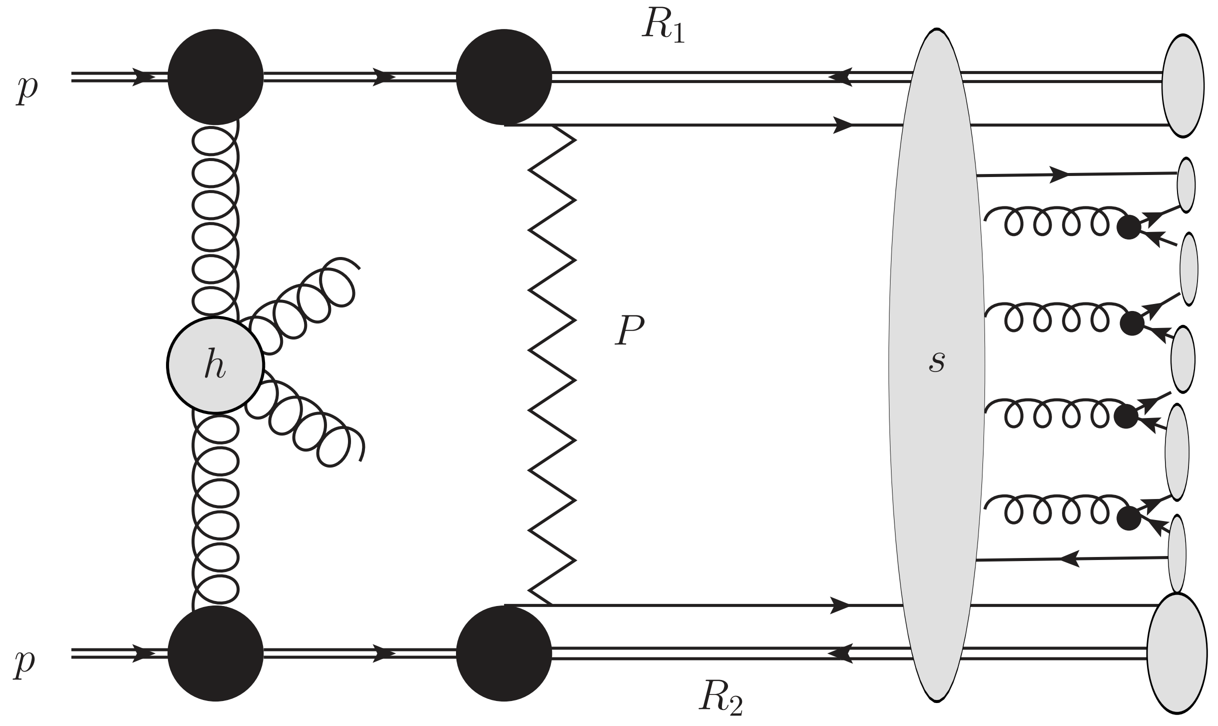
[Figure by Stefan Gieseke]

[Gieseke, Loshaj, Kirchgasser — EPJ C77 (2017) 156]
[Bellm, Gieseke, Kirchgasser — EPJC 80 (2020) 469]
[Gieseke, Kirchgaesser, Plätzer – EPJ C 78 (2018) 99]

Soft MPI

Additional soft ladders and diffractive topologies

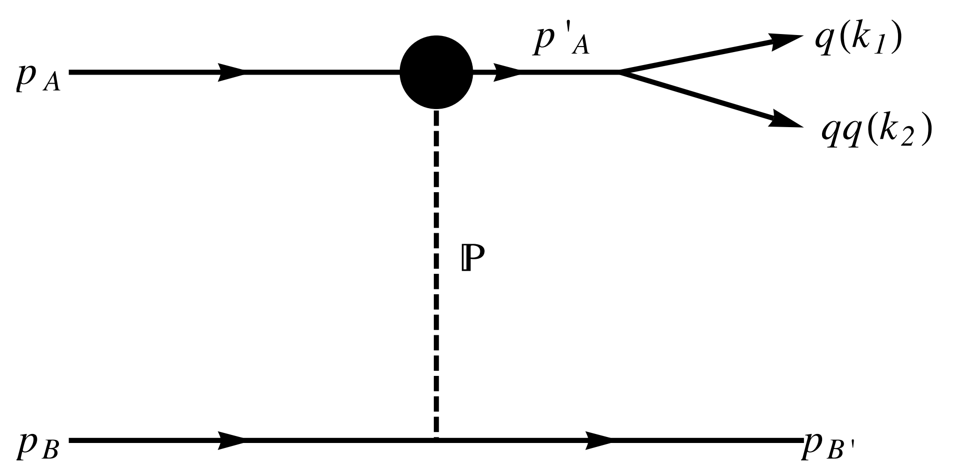


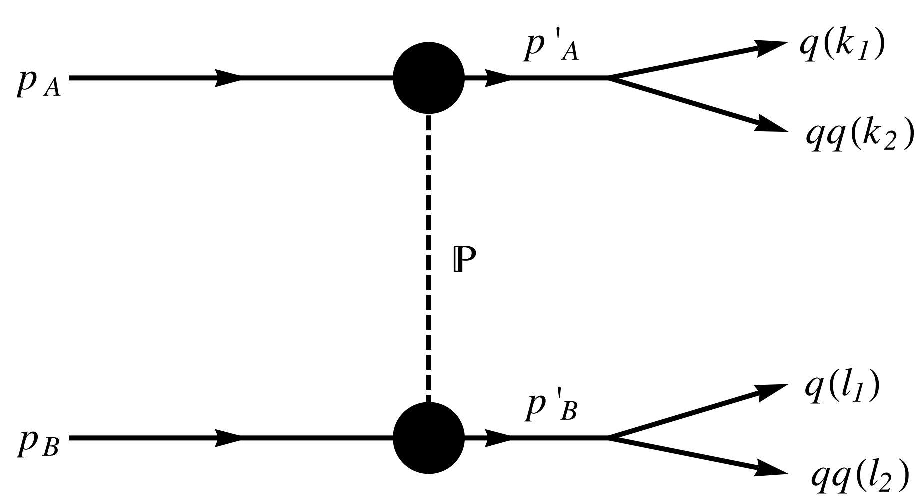


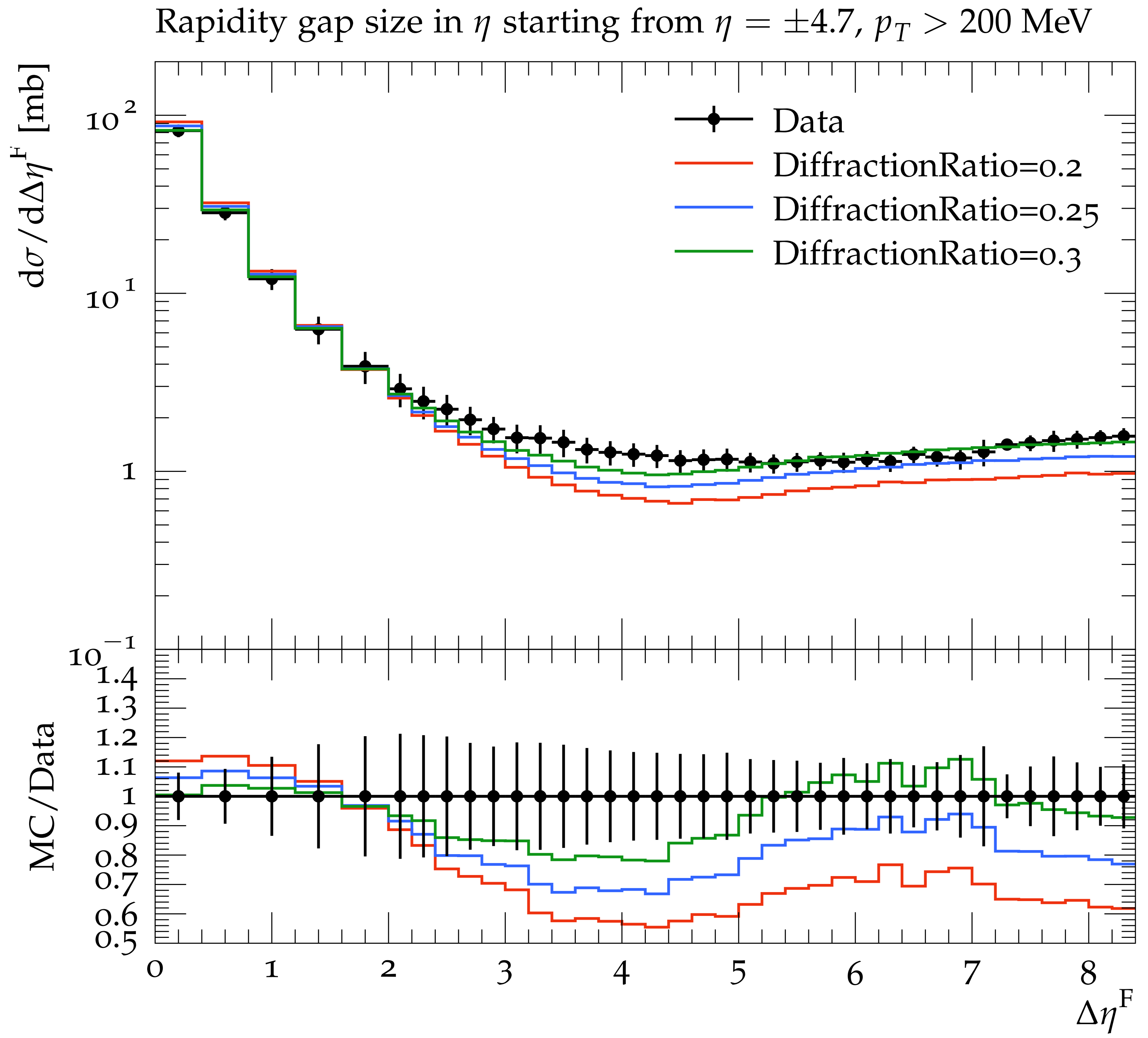
Single and double diffraction only included through tuning:
lack of energy extrapolation.

$$\sigma_{\text{inel}}(s) \equiv \sigma_{\text{inel}}^{\text{non-diff}}(s) = \sigma_{\text{tot}}(s) - \sigma_{\text{el}}(s) - \sigma_{\text{diff}}(s)$$

$$\sigma_{\text{diff}}(s) = R_{\text{diff}}\sigma_{\text{tot}}(s)$$

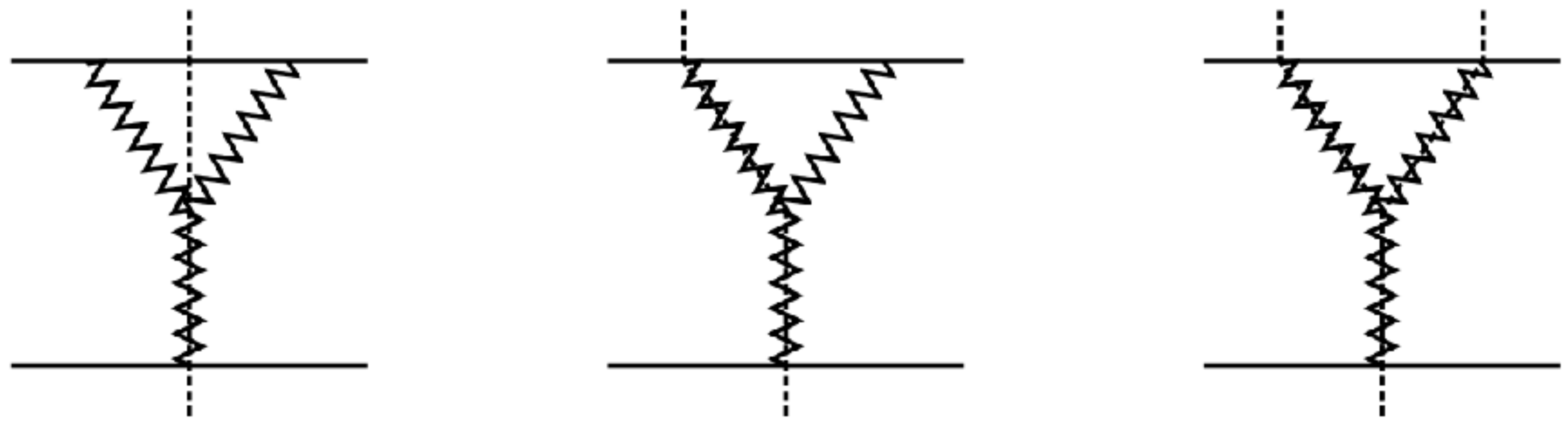






[Bellm, Gieseke, Kirchgasser — EPJC 80 (2020) 469]
[Gieseke, Loshaj, Kirchgasser — EPJ C77 (2017) 156]

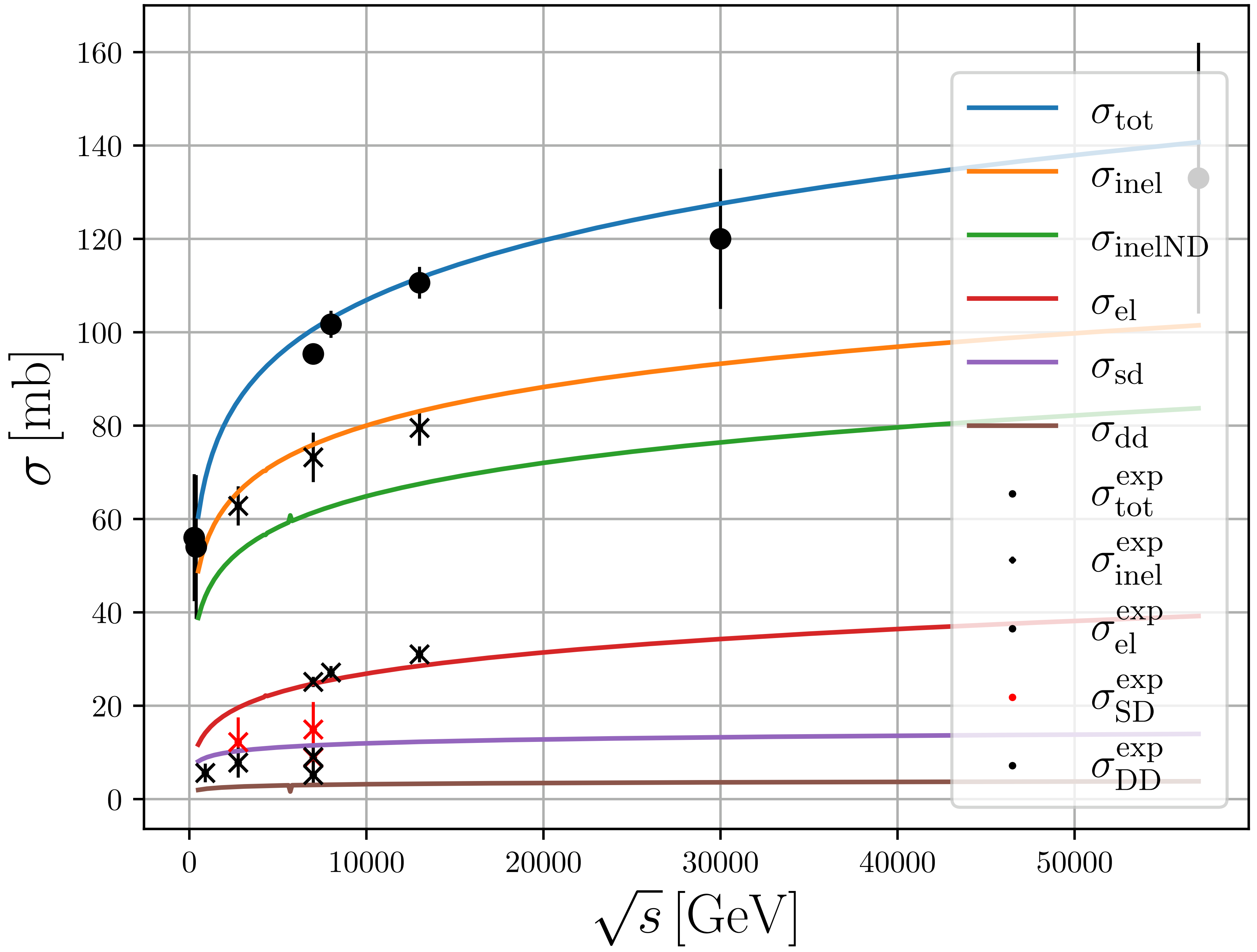
Diffraction



High-mass diffraction

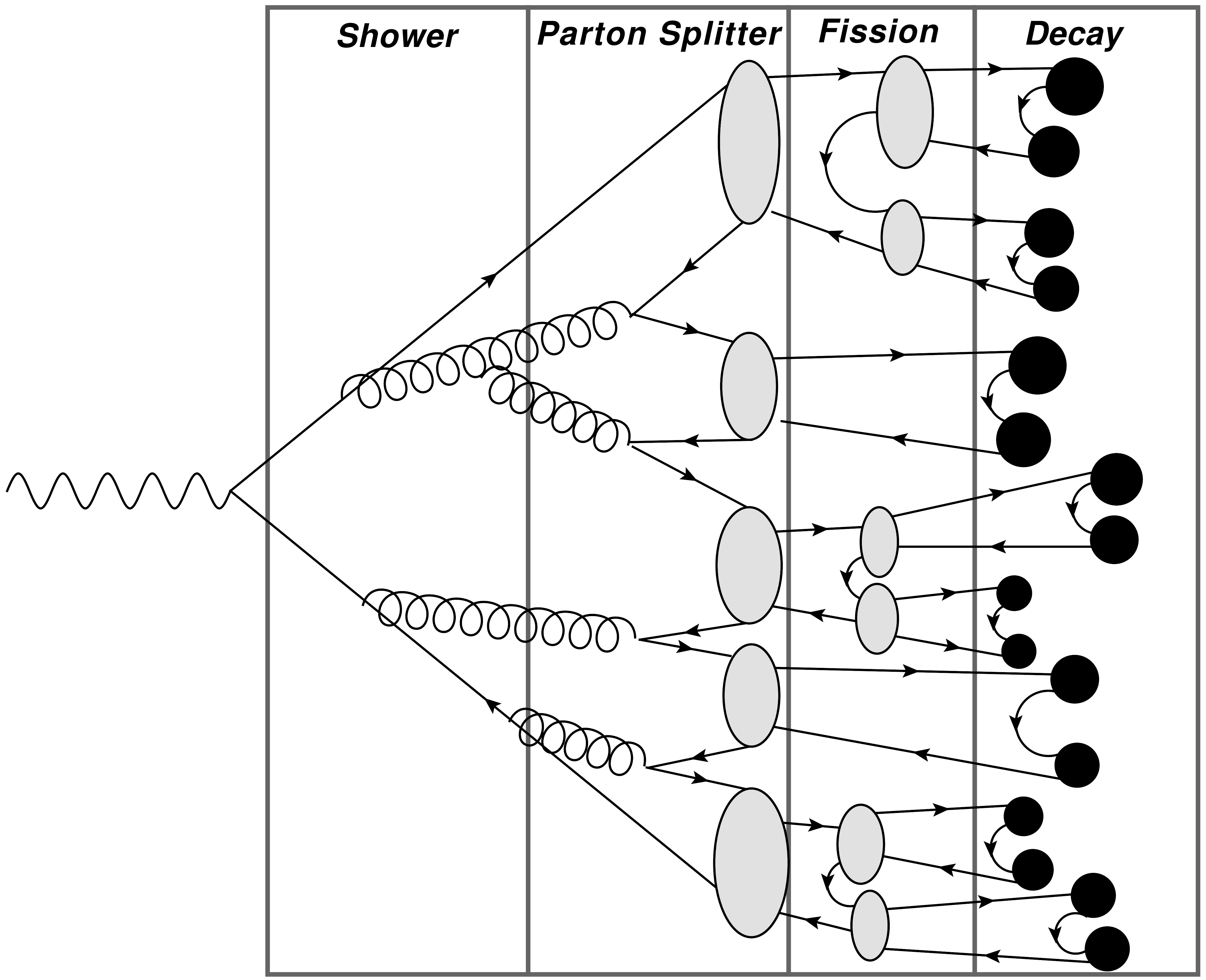
Multiperipheral particle production

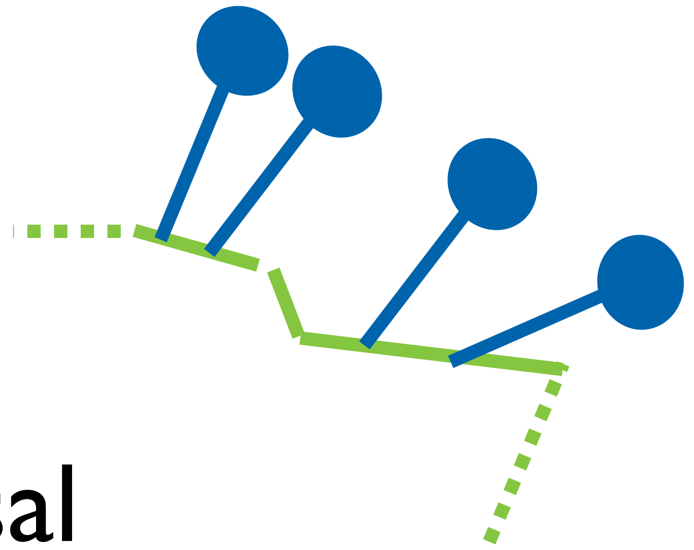
- So far best description of cross sections for g3p=0
- Cross sections as predictions of the model (no DL parametrisation)
- Good extrapolation of energy dependence



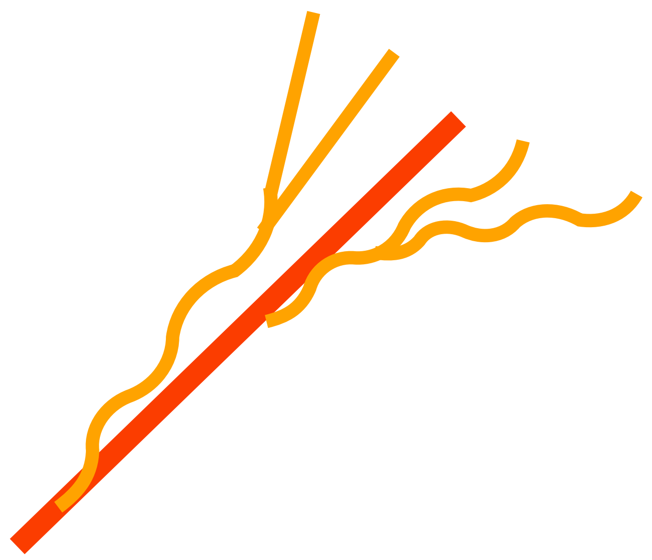
[Seymour, Kirchgaesser, Gieseke — in progress]

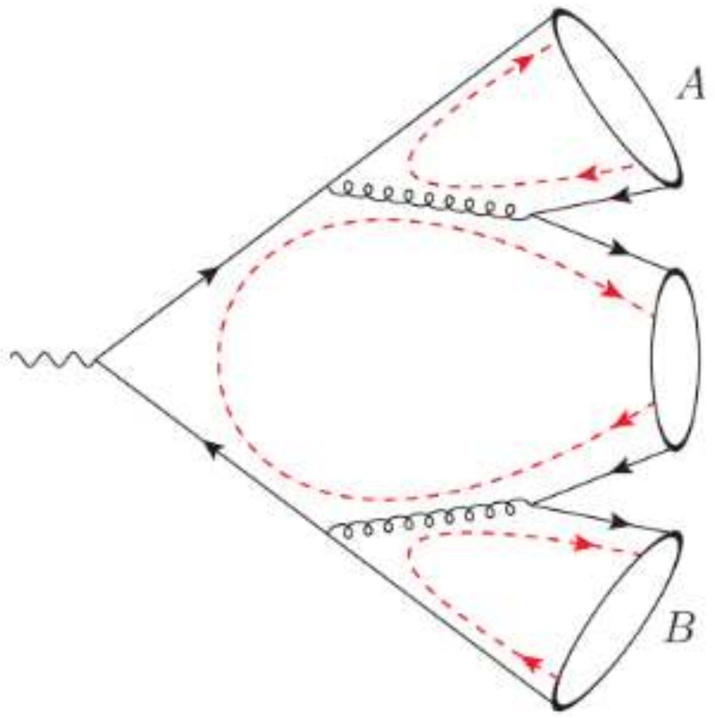
Cluster Hadronization

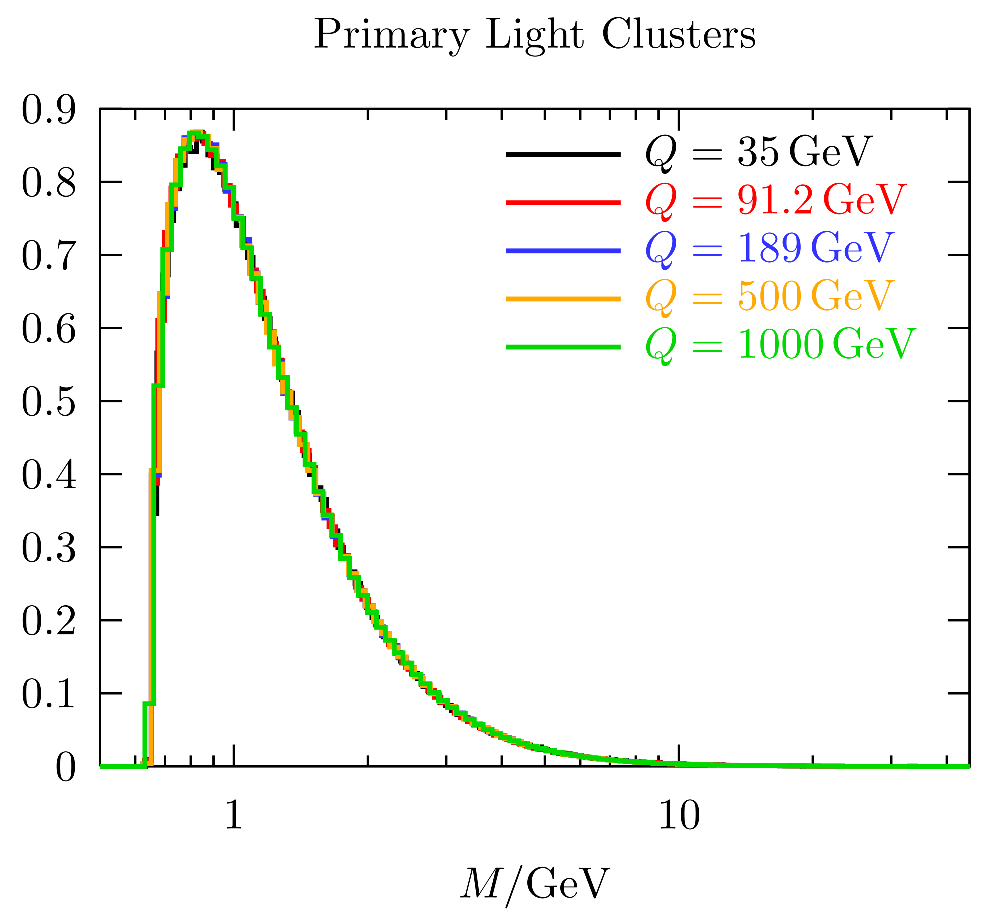




Coherent shower evolution triggers universal cluster spectrum: pre-confinement.



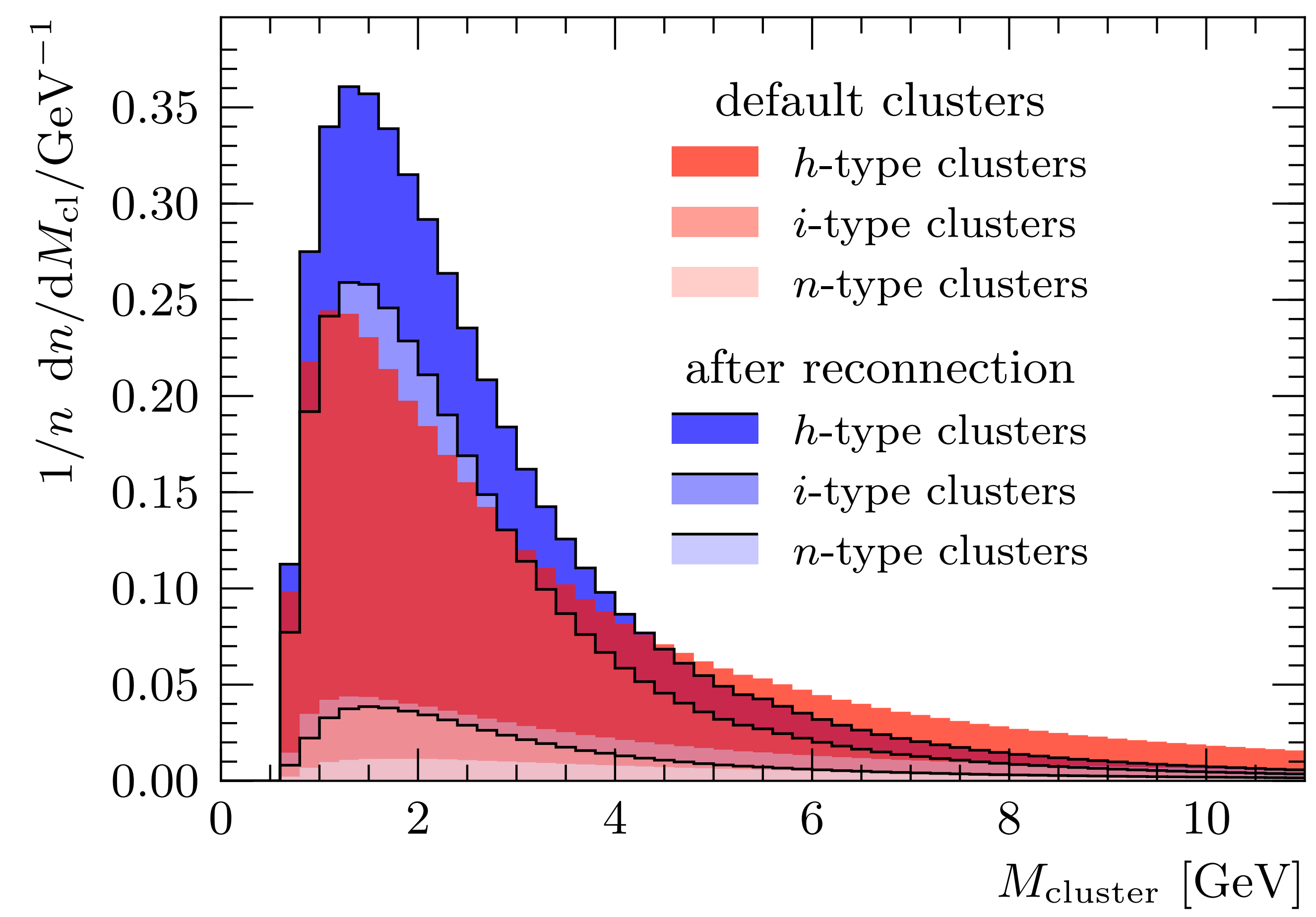




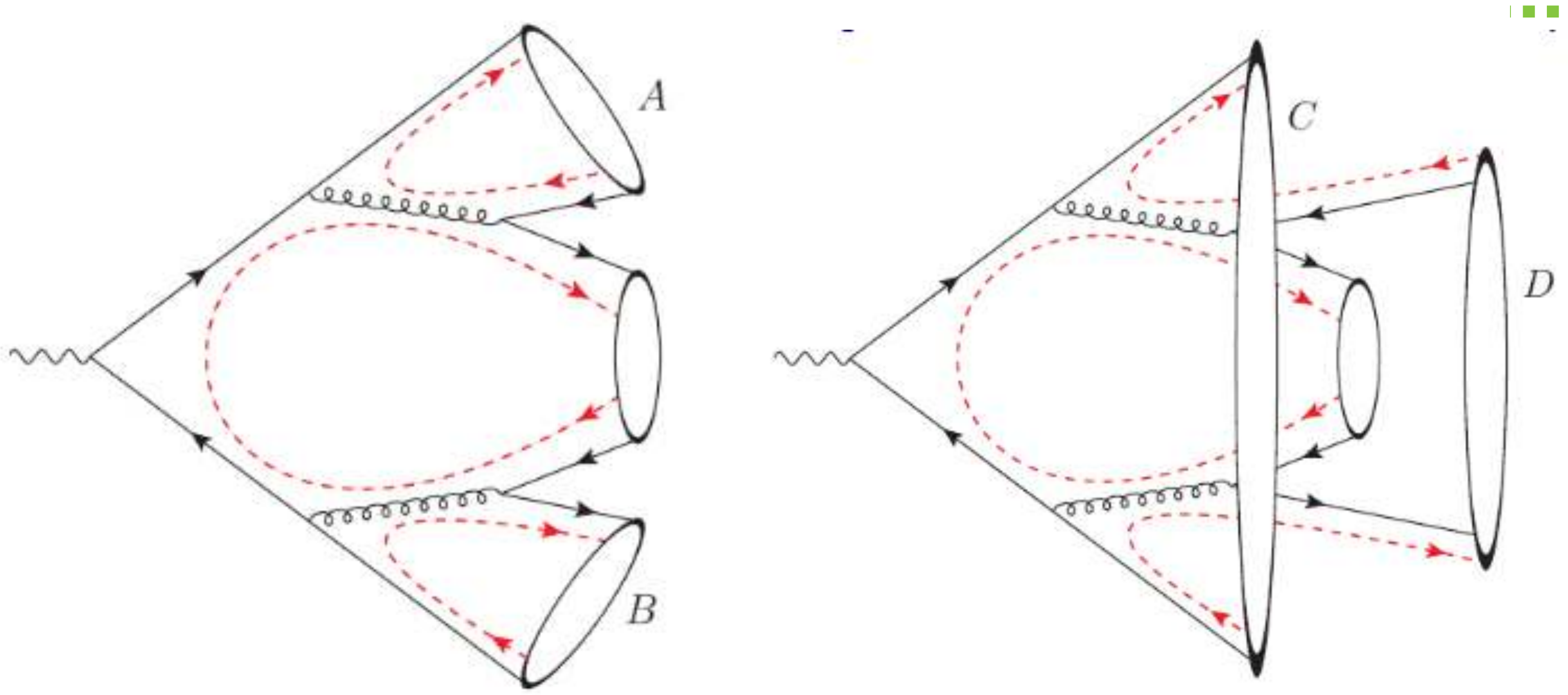
[Figure by Patrick Kirchgaesser]

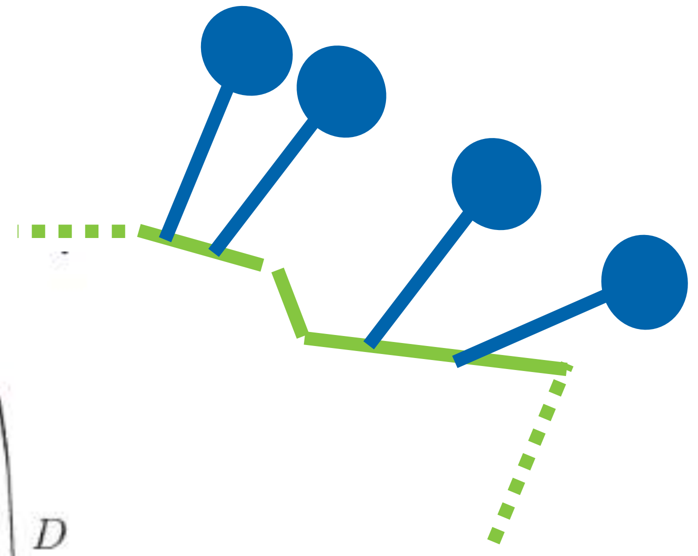
[Herwig++ 1.0 release — Gieseke et al. JHEP 02 (2004) 005]

Colour Reconnection



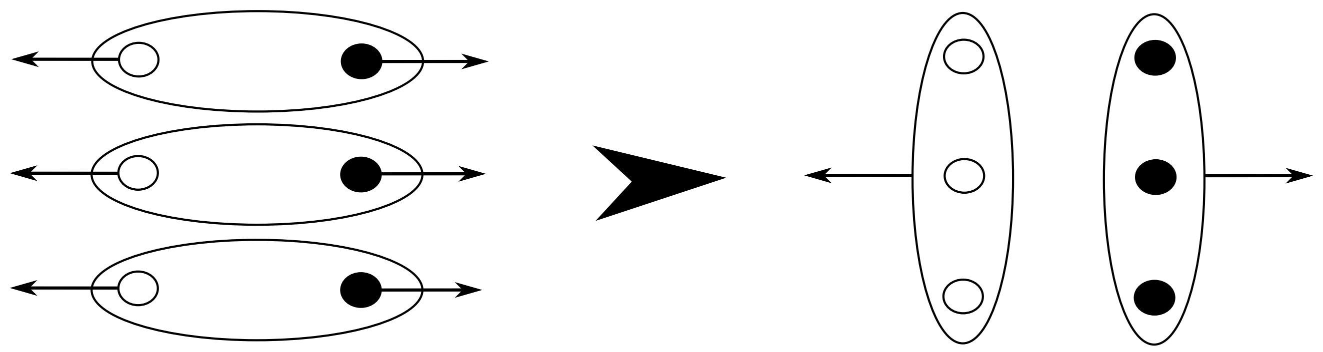
Plain colour reconnection uses fixed reconnection probability and lambda measure.



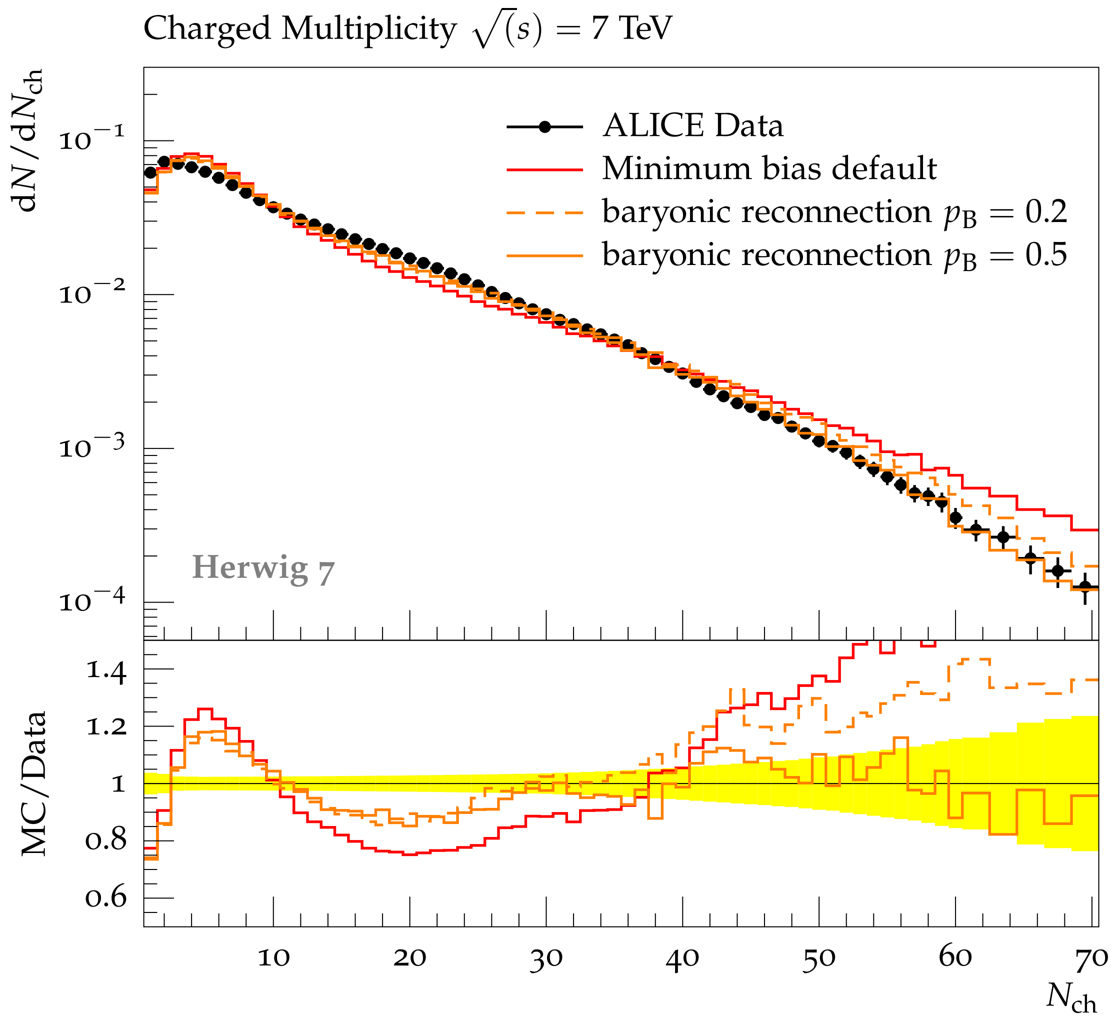


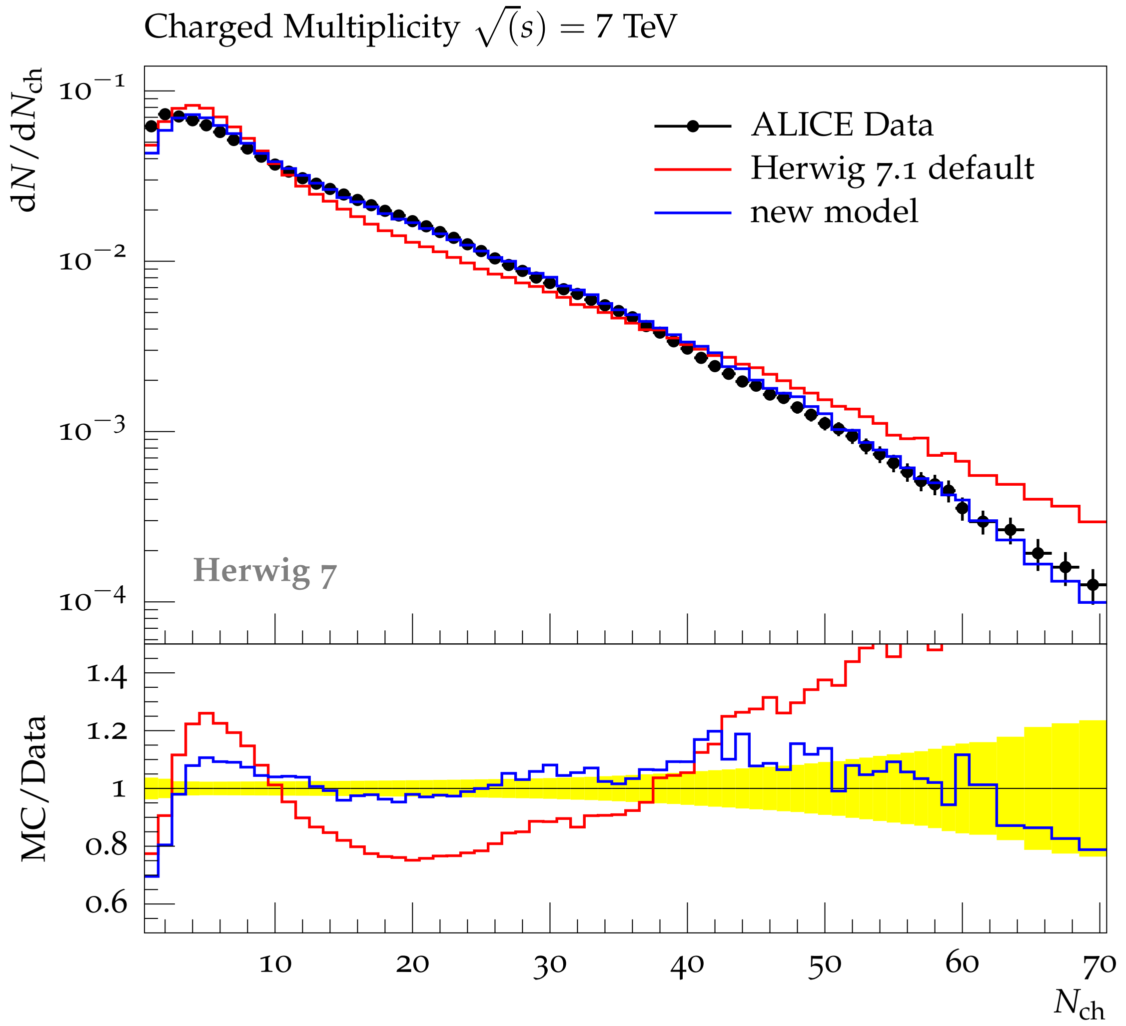
[Gieseke, Röhr, Siodmok — EPJ C72 (2012) 2225]

Generalize to geometric measure and baryonic systems



$$R_{q,qq} + R_{\bar{q},\bar{q}\bar{q}} < R_{q,\bar{q}} + R_{qq,\bar{q}\bar{q}}$$

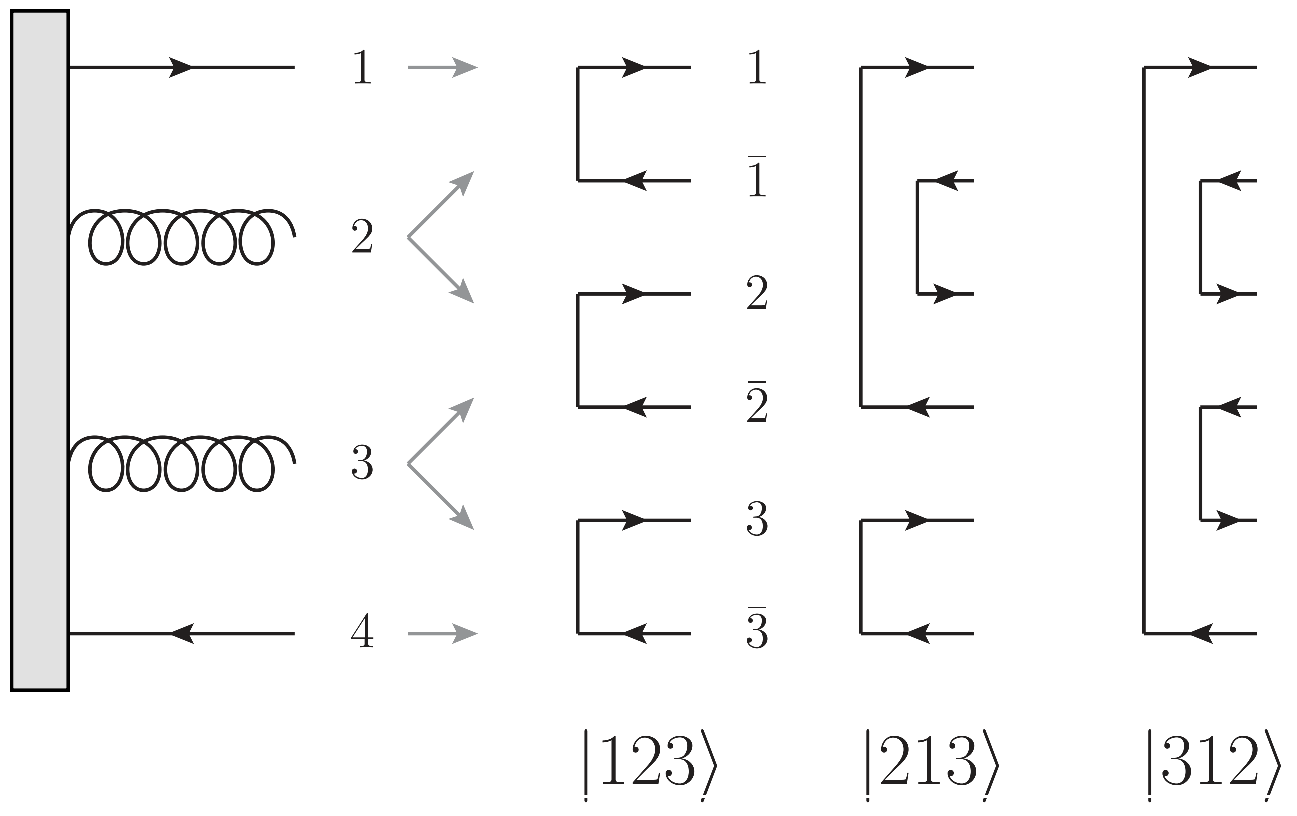


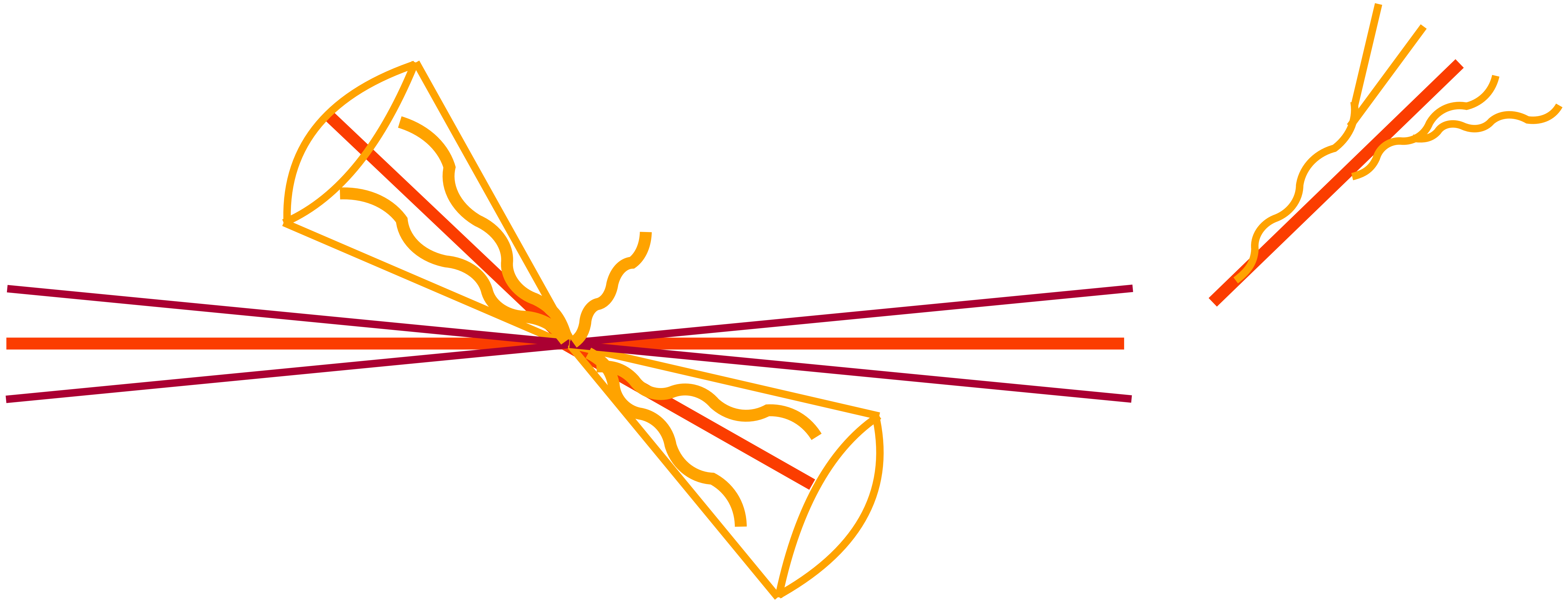


[Gieseke, Kirchgaesser, Plätzer – EPJ C 78 (2018) 99]

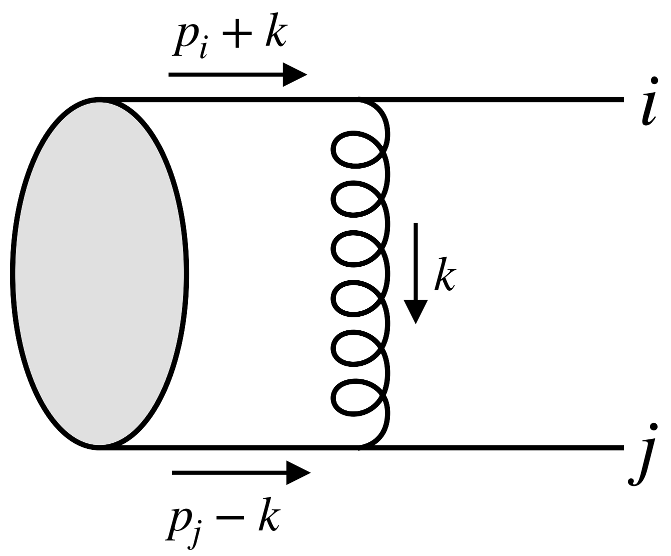
Interlude: Showers

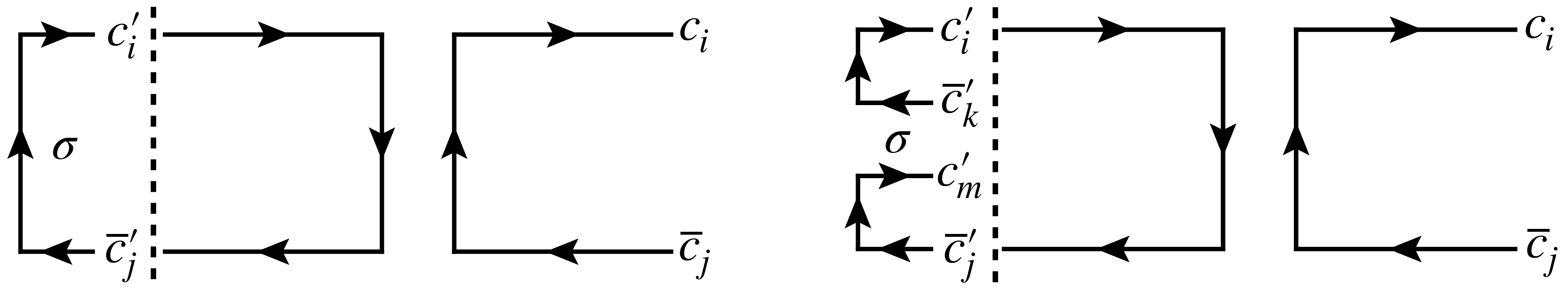
Resummation of general, in particular, non-global observables requires colour evolution





Virtual exchanges mediate (at least) dipole flips





$$[\tau|\mathbf{\Gamma}^{(1)}|\sigma\rangle = \left(\Gamma_\sigma^{(1)} + \frac{1}{N^2}\rho^{(1)}\right)\delta_{\sigma\tau} + \frac{1}{N}\Sigma_{\sigma\tau}^{(1)}$$

dipole flips

[Forshaw, Holguin, Plätzer – JHEP 1908 (2019) 145]
[De Angelis, Forshaw, Plätzer — PRL 126 (2021) 11]
[Plätzer, Ruffa — JHEP 06 (2021) 007]

[Plätzer – EPJ C 74 (2014) 2907]

Colour Reconnection: Perturbative Analysis

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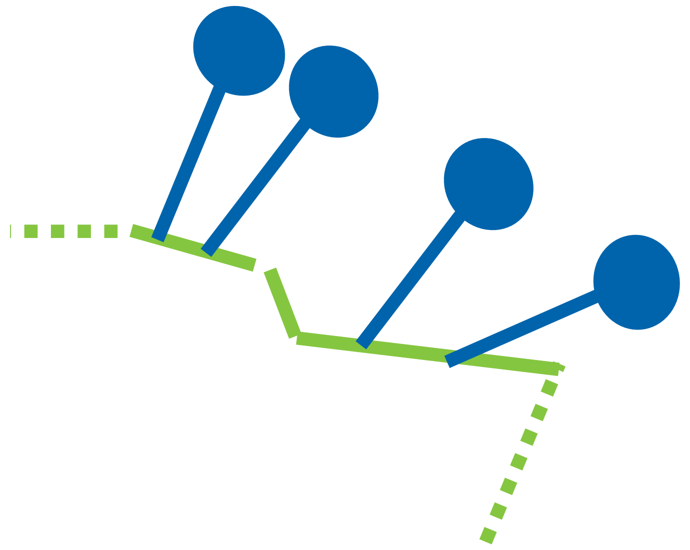
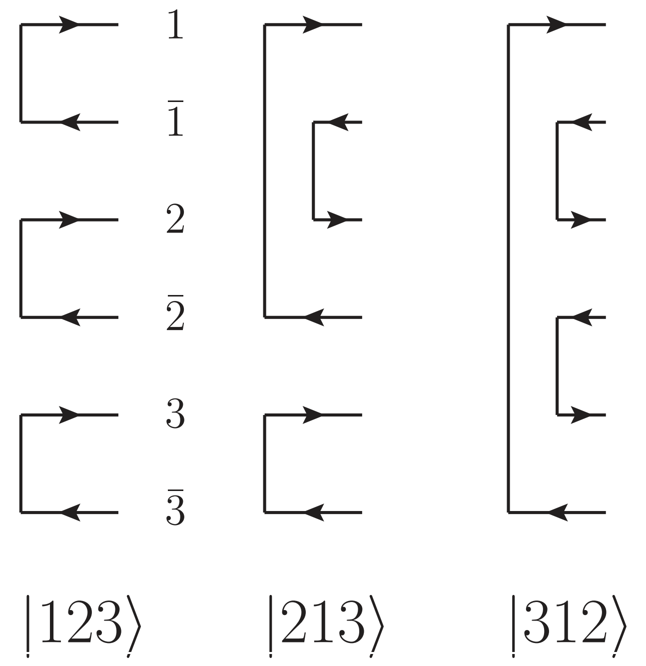
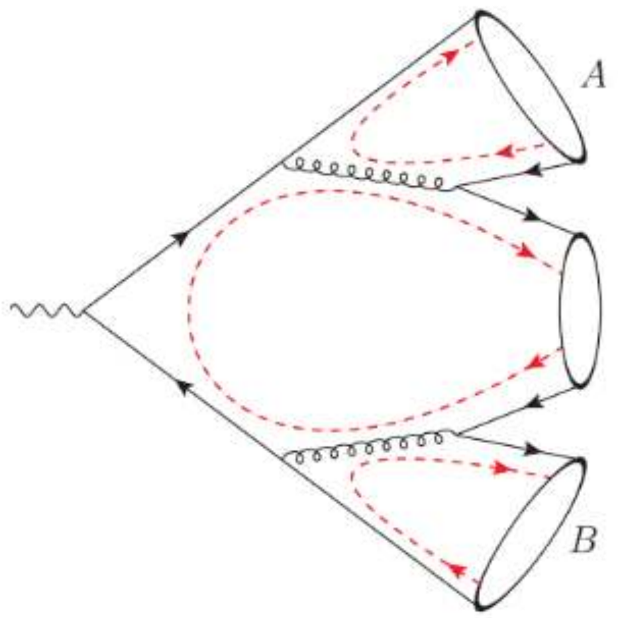
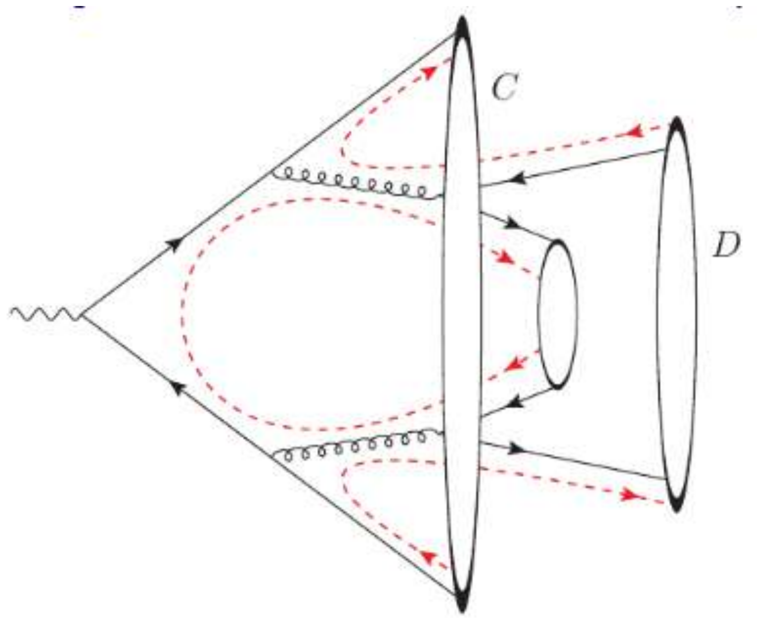
To what extend has this got to do with colour reconnection?

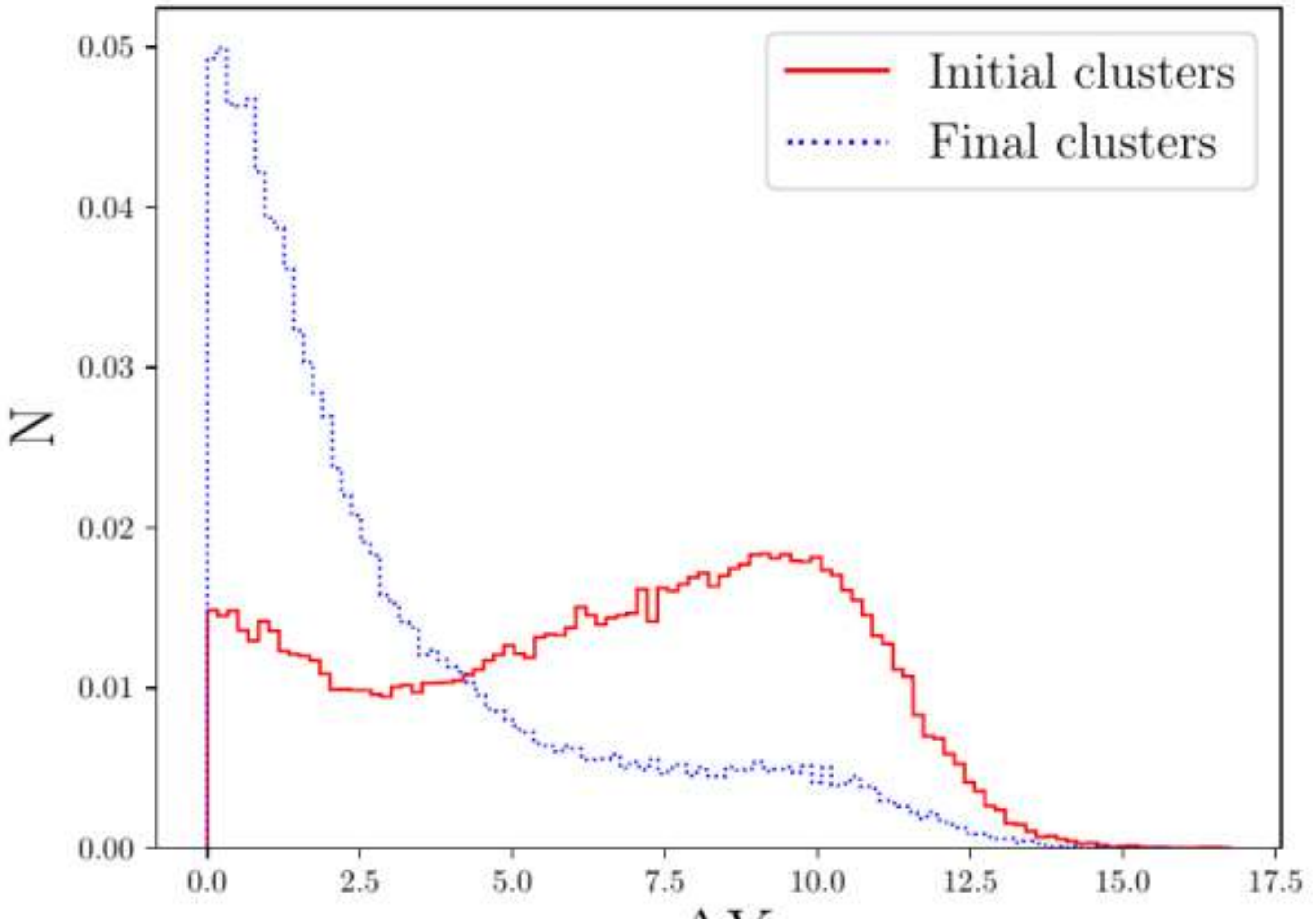








Soft gluon evolution supports geometric models.



$$\mathcal{A}_{\tau\to\sigma} = \langle\sigma|\mathbf{U}\left(\{p\},\mu^2,\{M_{ij}^2\}\right)|\tau\rangle$$

$$\mathcal{A}_{\tau\to B_{ijk}\otimes\tilde{\sigma}_{ijk}} = \langle B_{ijk}|\otimes\langle\tilde{\sigma}_{ijk}|\mathbf{U}\left(\{p\},\mu^2,\{M_{ij}^2\}\right)|\tau\rangle$$

$$|B_{ijk}\rangle = \frac{1}{N_B}\epsilon^{ijk}\epsilon_{\bar{i}\bar{j}\bar{k}} = \frac{1}{N_B}\left(\left|\begin{matrix} i & j & k \\ \bar{i} & \bar{j} & \bar{k}\end{matrix}\right\rangle + \left|\begin{matrix} j & k & i \\ \bar{i} & \bar{j} & \bar{k}\end{matrix}\right\rangle + \left|\begin{matrix} k & i & j \\ \bar{i} & \bar{j} & \bar{k}\end{matrix}\right\rangle - \left|\begin{matrix} j & i & k \\ \bar{i} & \bar{j} & \bar{k}\end{matrix}\right\rangle - \left|\begin{matrix} i & k & j \\ \bar{i} & \bar{j} & \bar{k}\end{matrix}\right\rangle - \left|\begin{matrix} k & j & i \\ \bar{i} & \bar{j} & \bar{k}\end{matrix}\right\rangle\right)$$

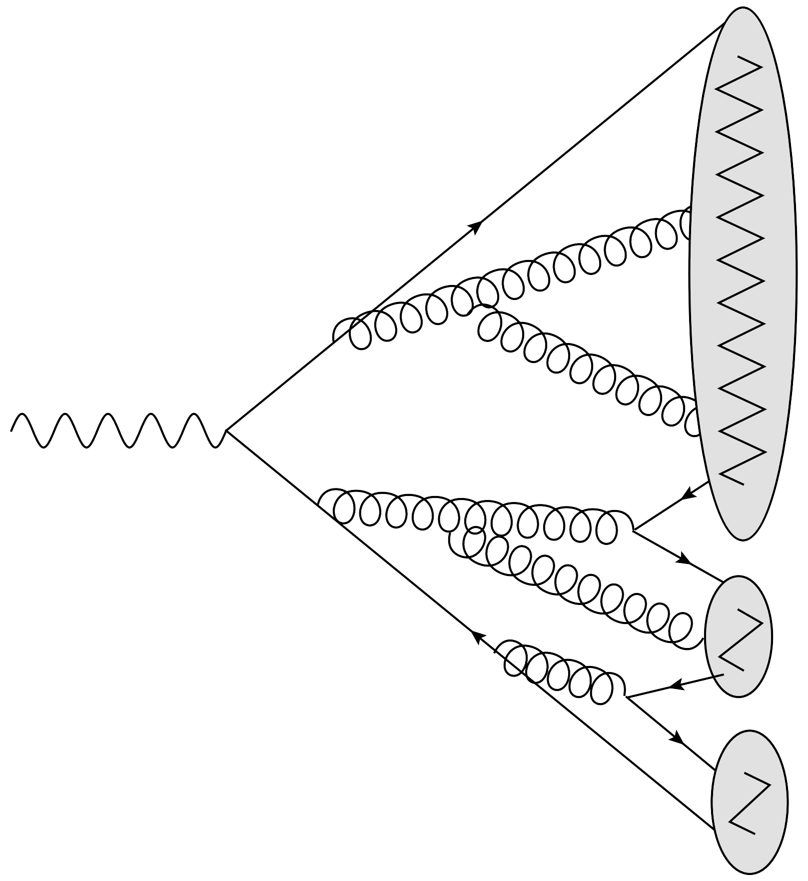
Colour evolution operator

$$\mathbf{U}\left(\{p\},\mu^2,\{M_{ij}^2\}\right) = \exp\left(-\sum_{i\neq j}\int_{\mu^2}^{M_{ij}^2}\frac{\mathrm{d}q^2}{q^2}(-\mathbf{T}_i\cdot\mathbf{T}_j)\Gamma_{\mathrm{cusp}}\left(\ln\frac{2p_i\cdot p_j}{q^2} - i\pi\right)\right)$$

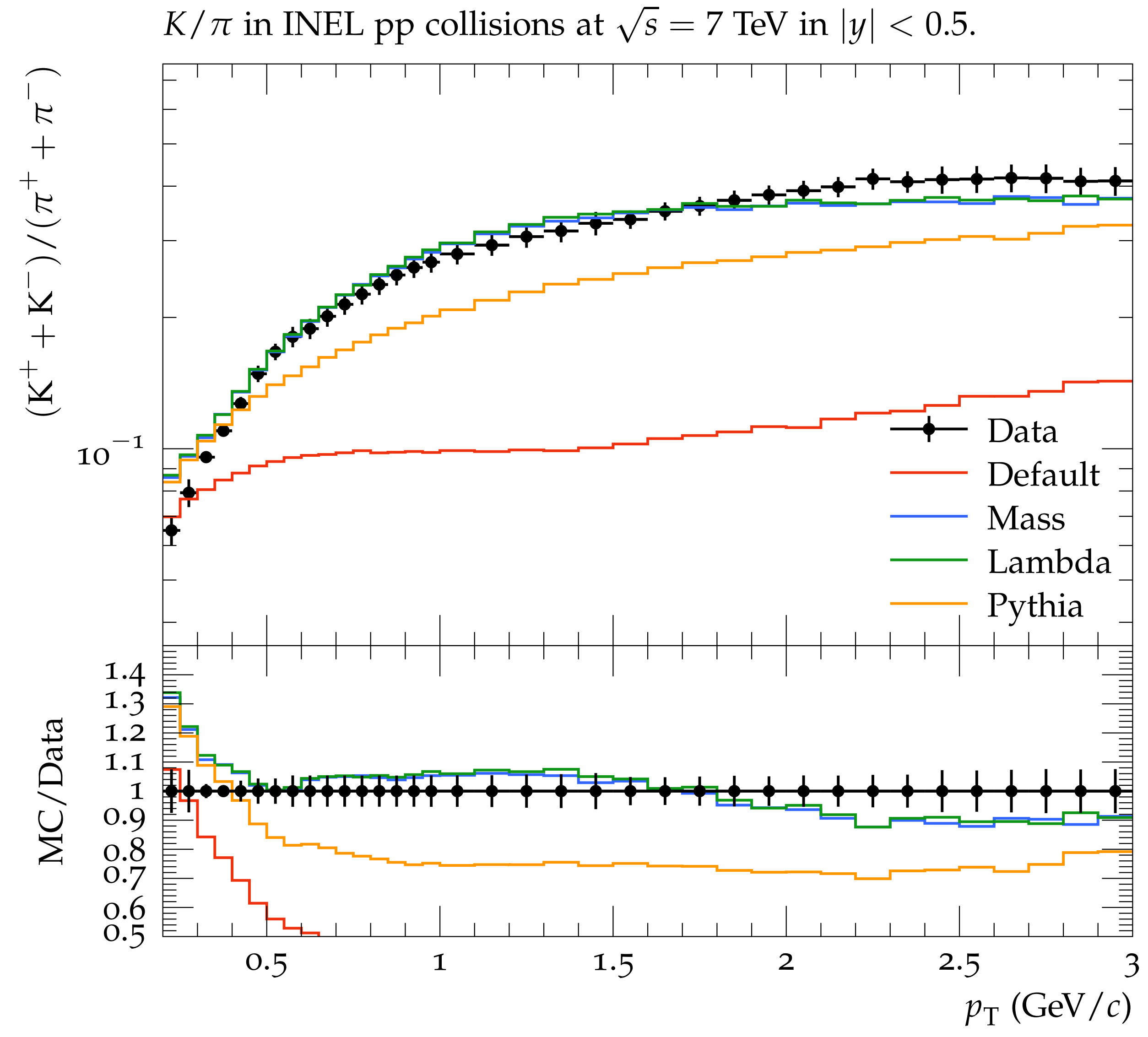
[Gieseke, Kirchgaesser, Plätzer, Siodmok – JHEP 11 (2018) 149]

Colour Reconnection: More Development

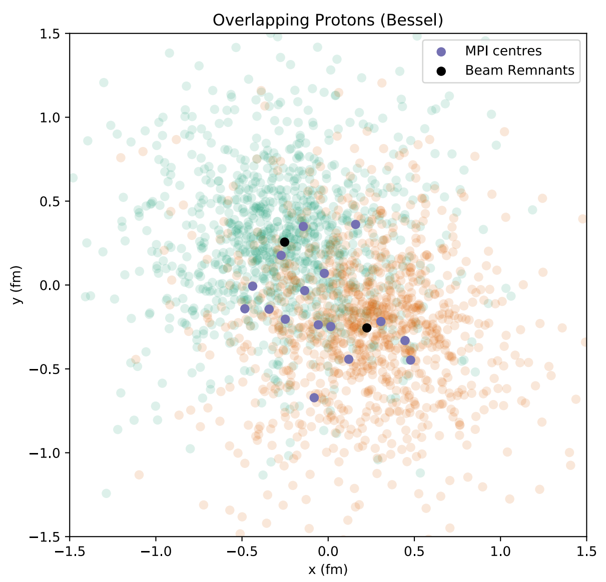
Energy dependence in strange production

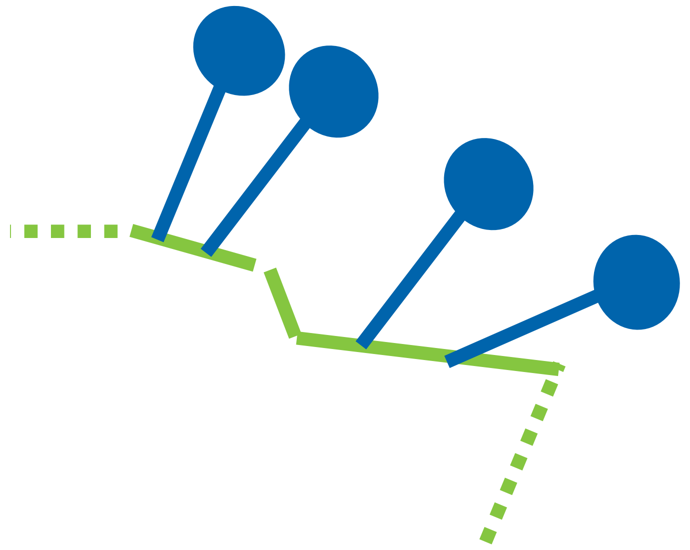


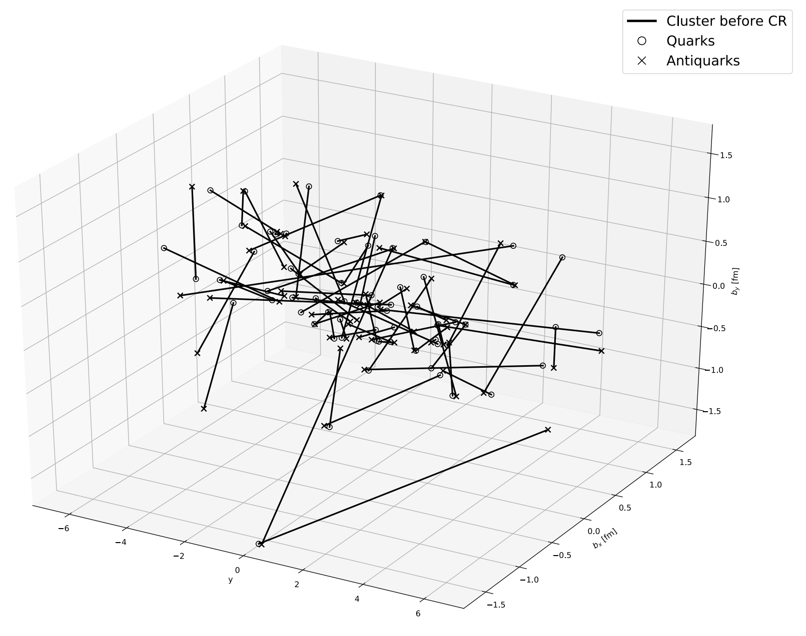
$$w_s(m)^2 = \exp\left(\frac{-m_0^2}{m^2}\right)$$

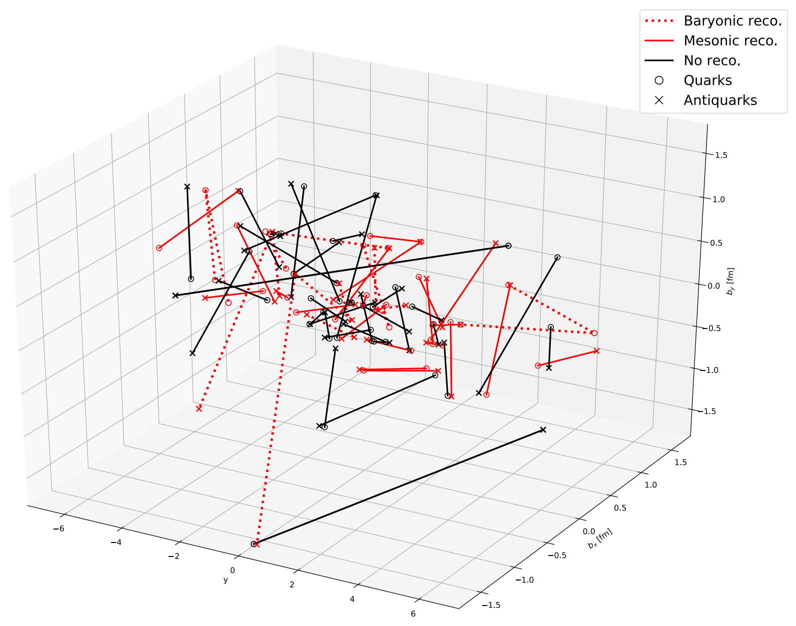


[Duncan, Kirchgaesser – EPJ C79 (2019) 61]









Spacetime information in MPI and showers:
Vital input to geometric colour reconnection.

[Bellm, Duncan, Gieseke, Myska, Siodmok – EPJ C79 (2019) 1003]

Heavy Ion Collisions

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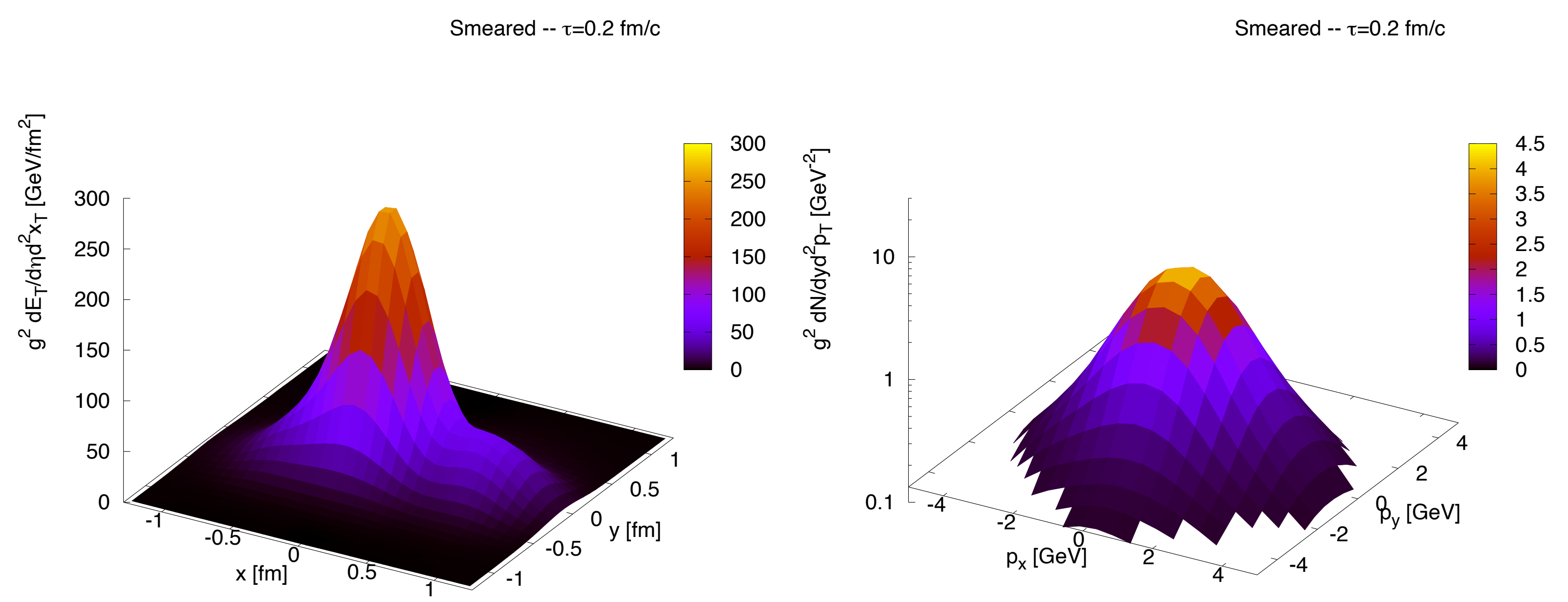
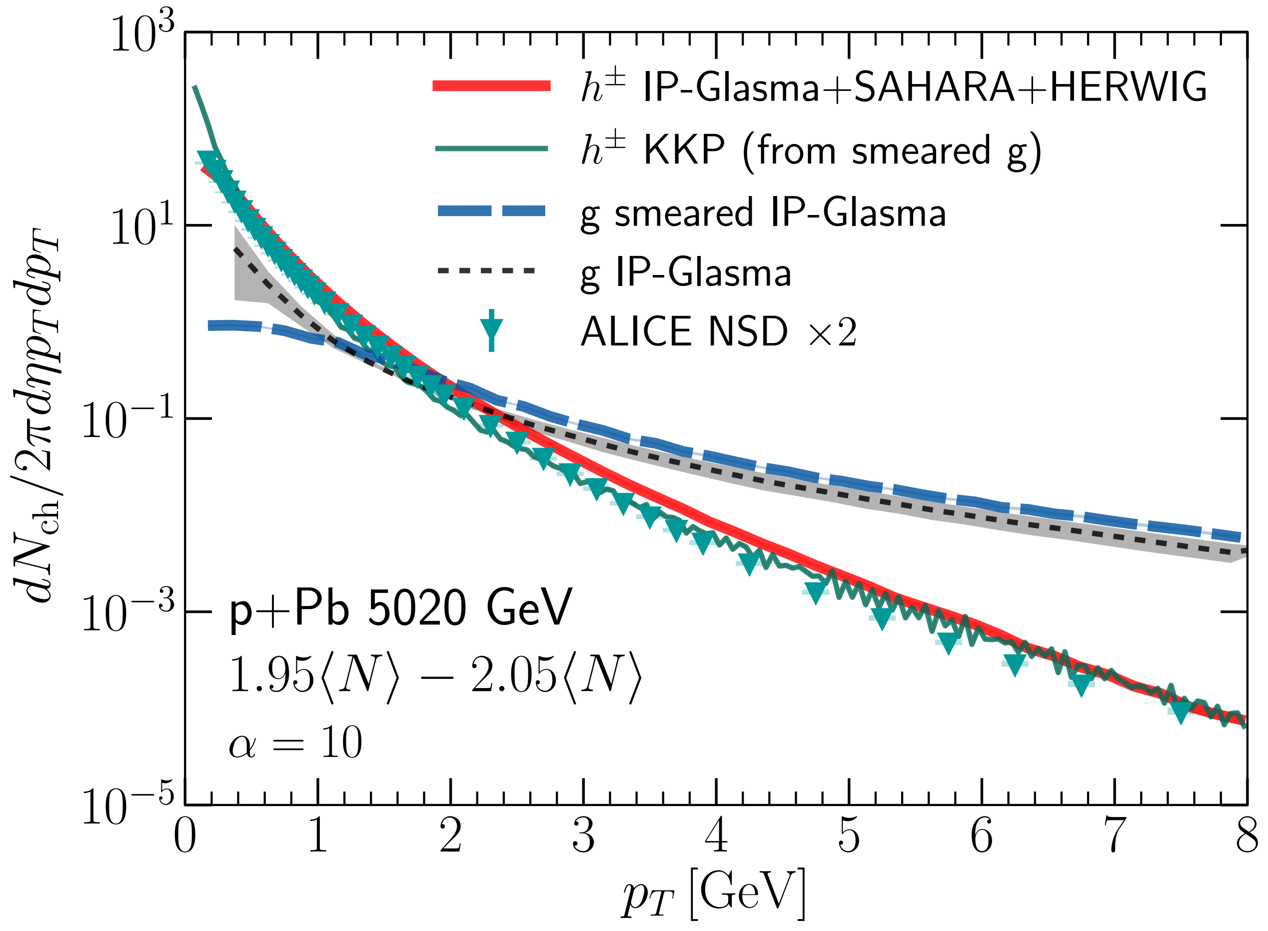


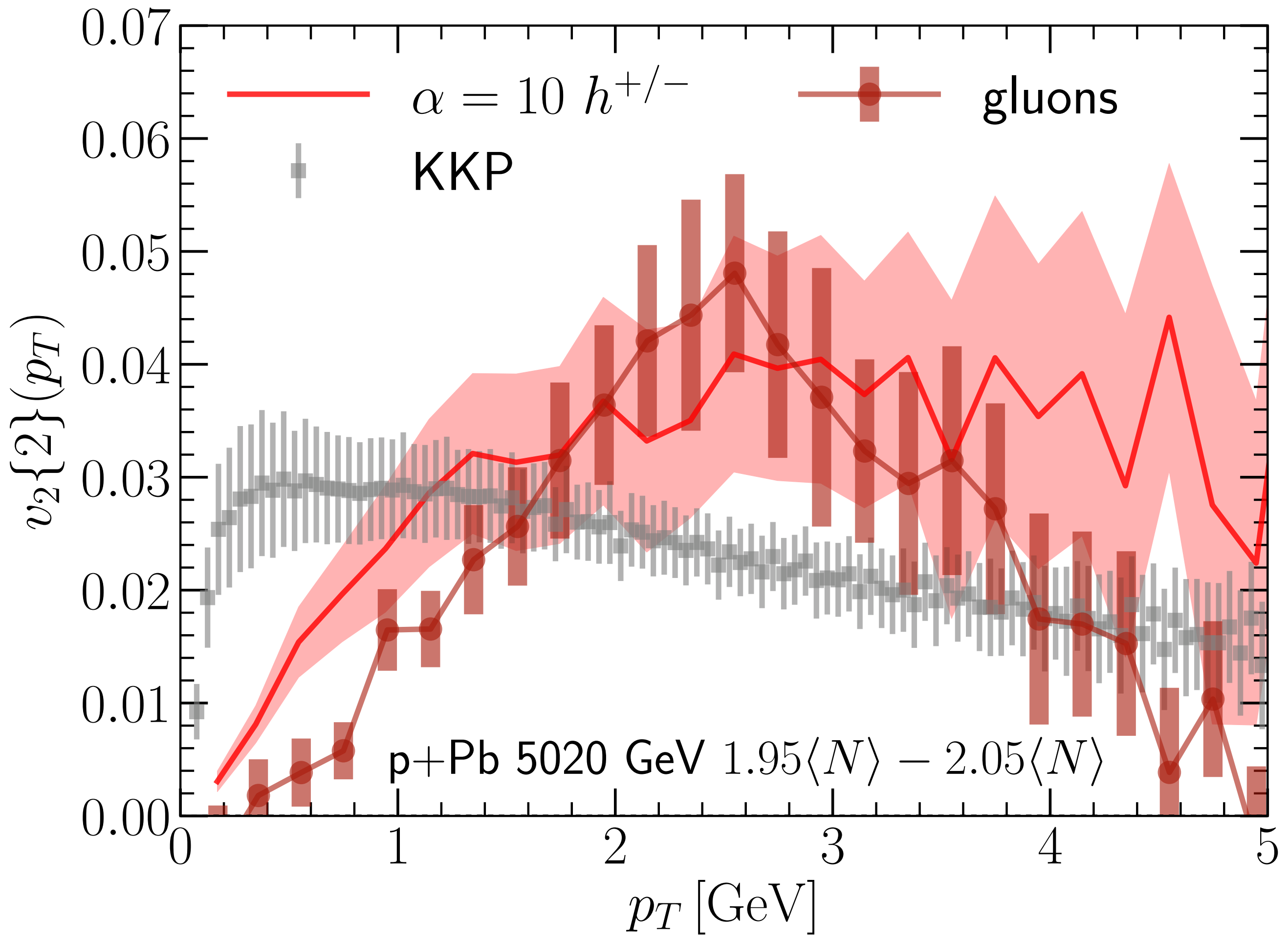
Clustering and hadronization of gluon ensembles from IP-Glasma simulations.

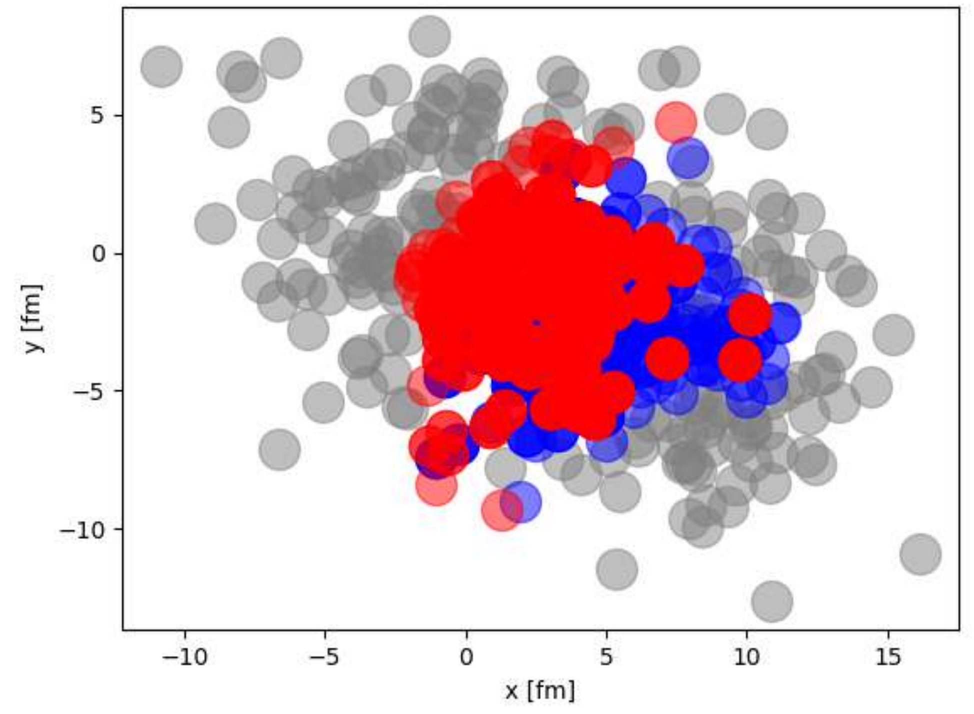
Transverse Husimi distribution

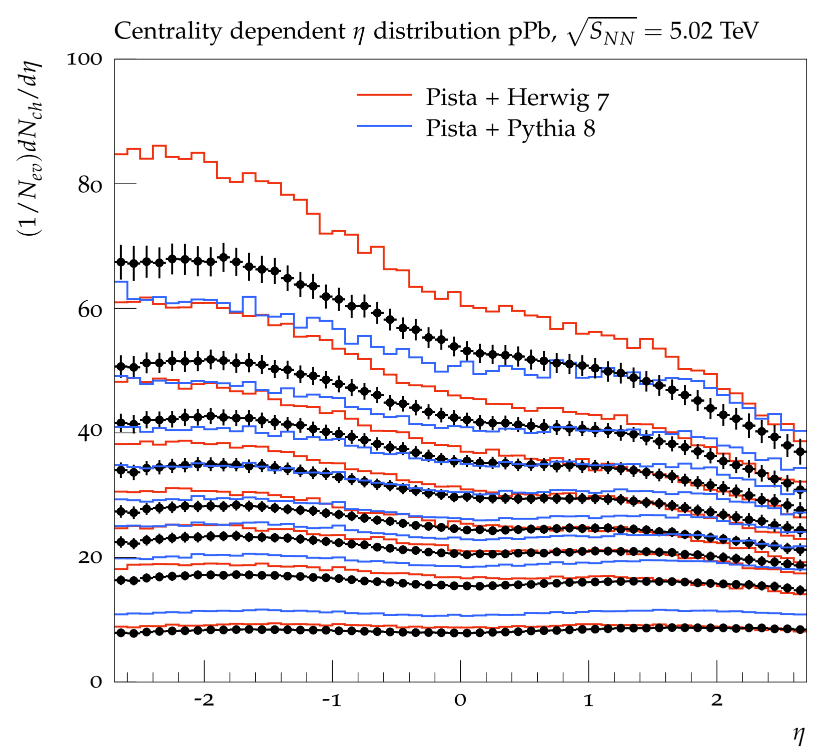
Transverse energy density

Glauber model "pre-burner": PISTA









[Greif, Greiner, Plätzer, Schenke, Schlichting - Phys. Rev. D. 103 (2021) 5]

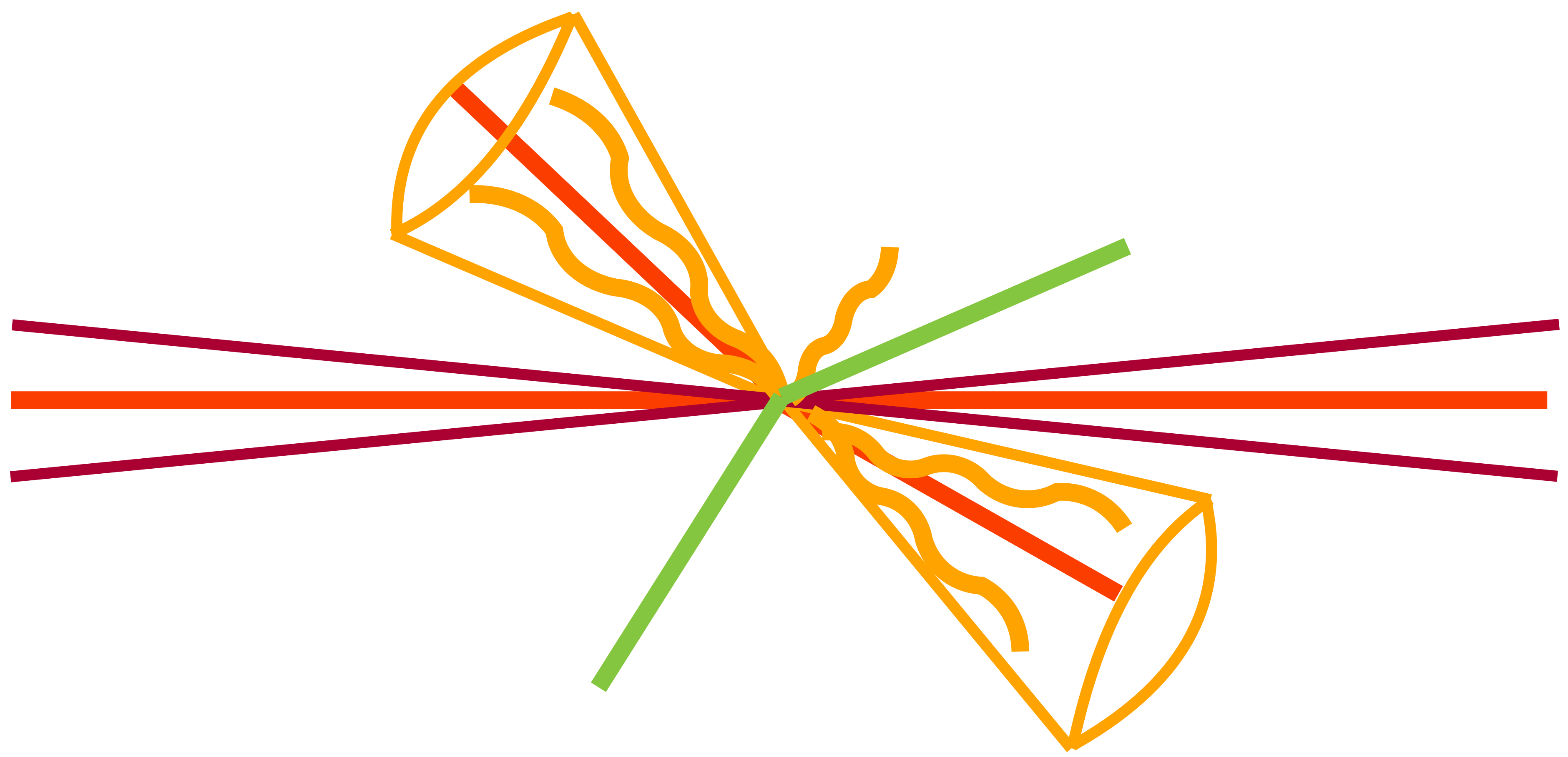
[Bellm, Bierlich — arXiv:1807.01291]

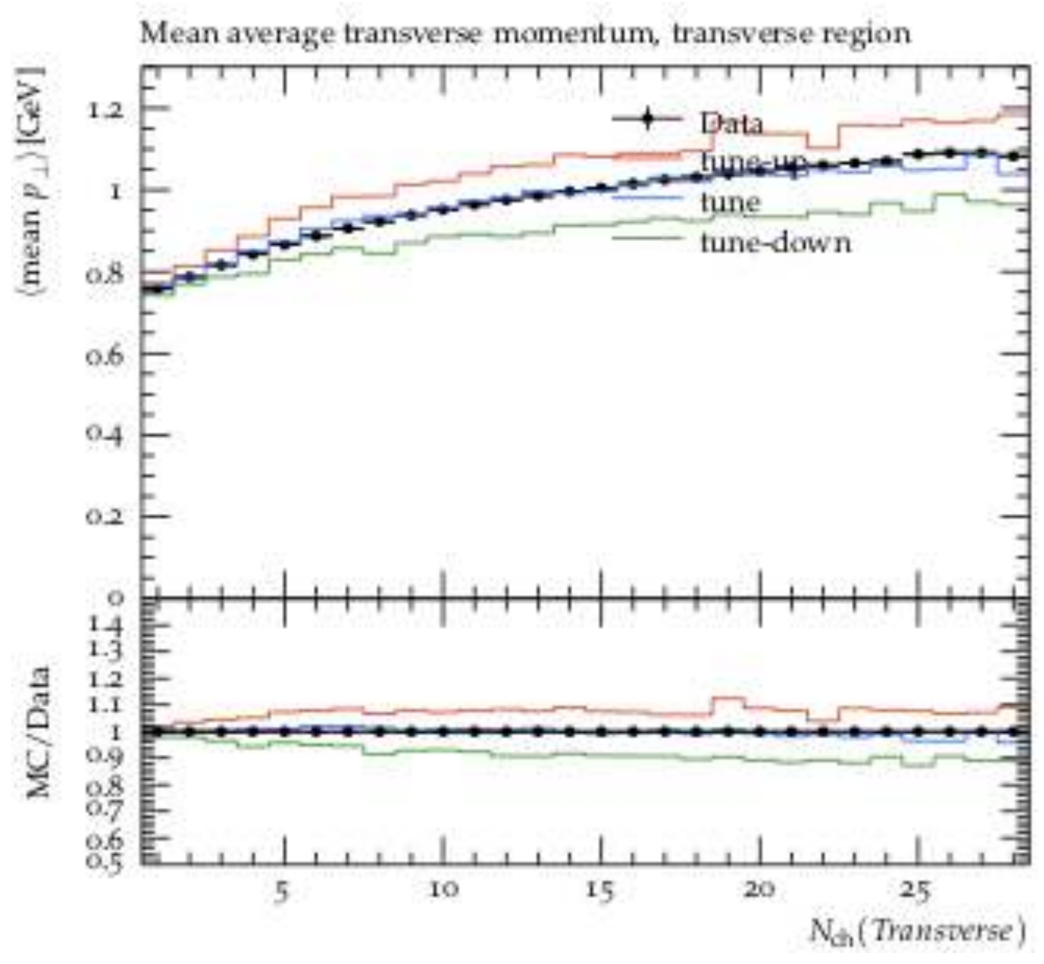
Impact on Phenomenology

We know about the impact of multi-parton interactions, but what is the uncertainty?

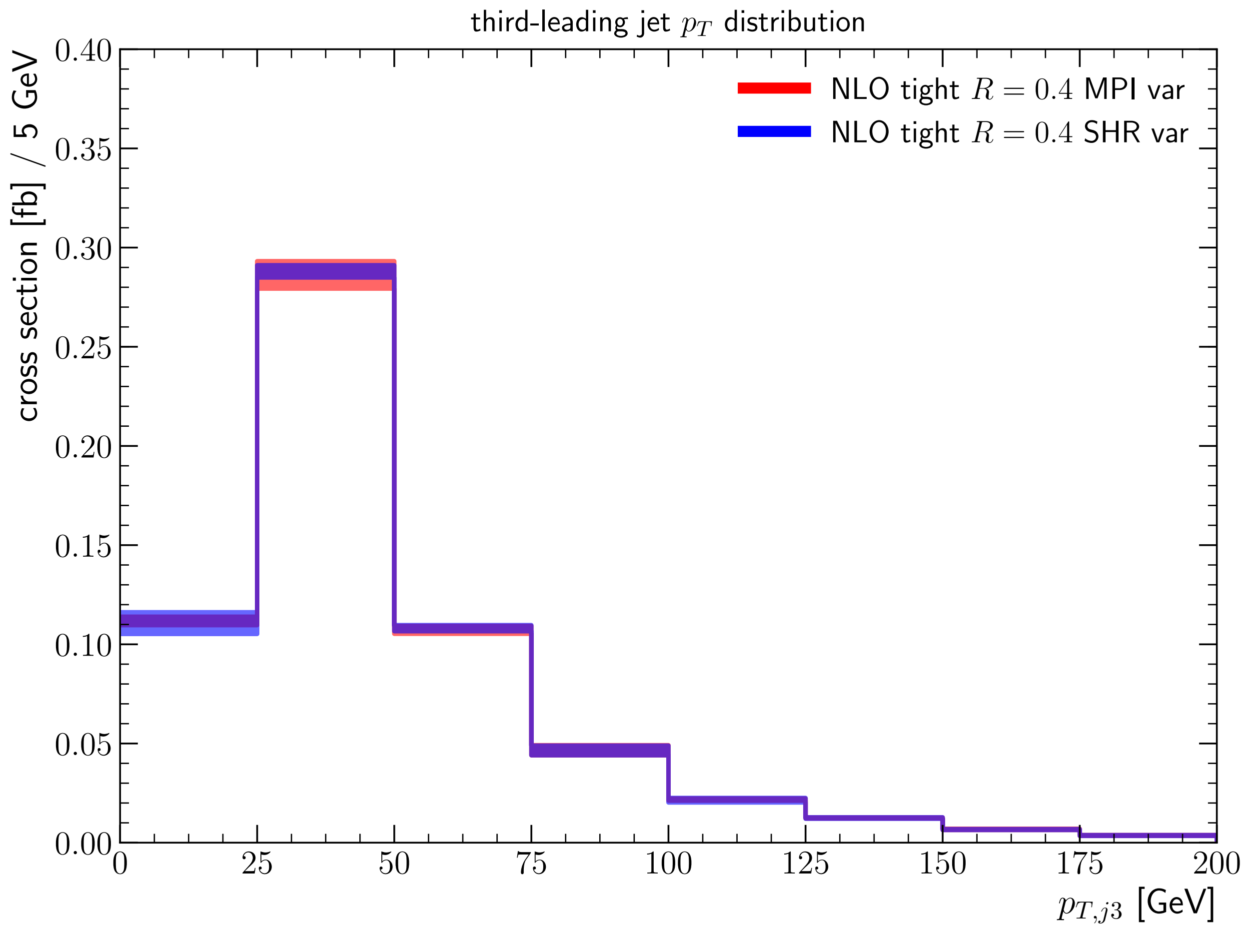
Benchmark in VBF Z production at NLO+PS.

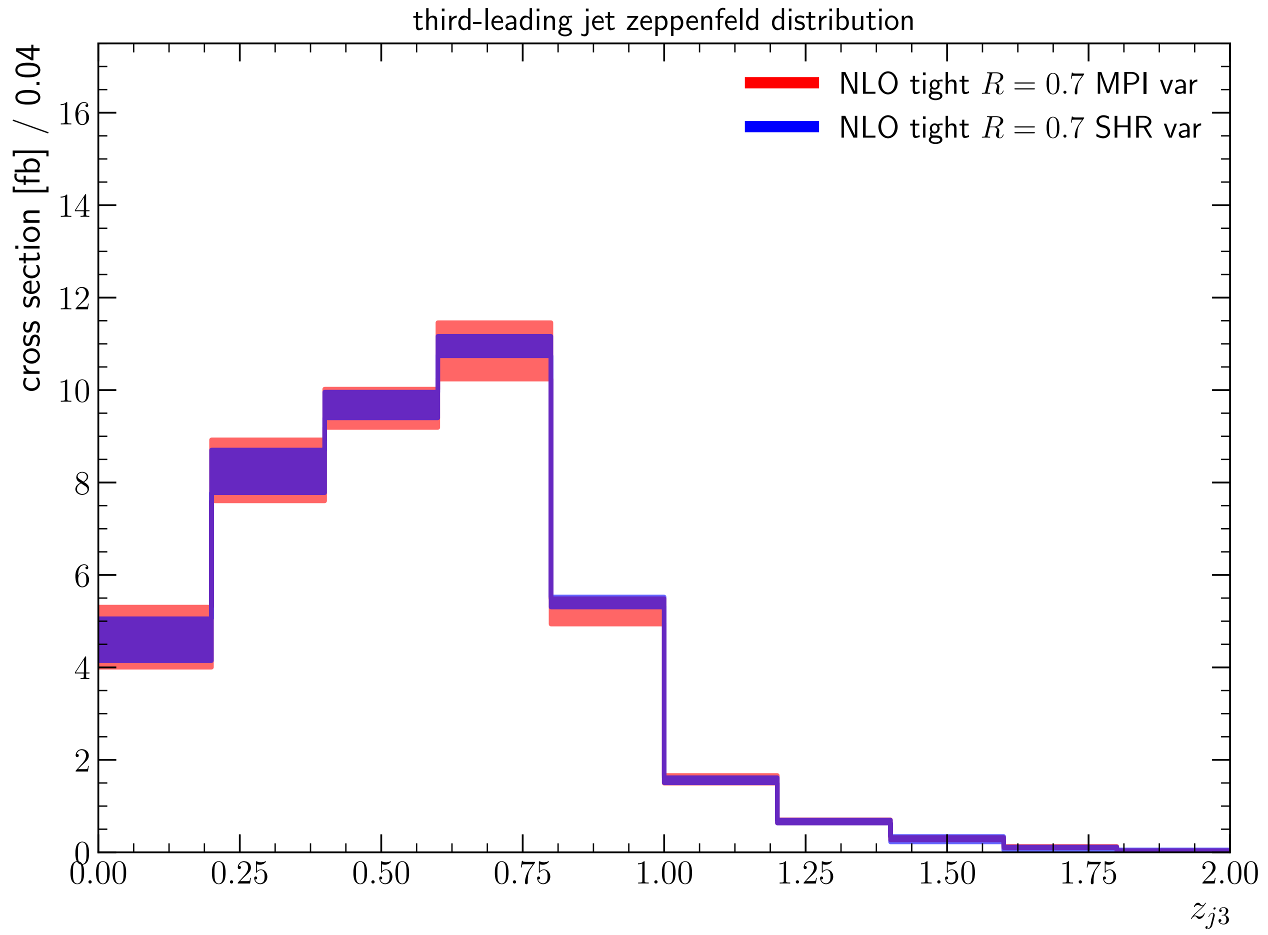
Extrapolate model parameter variations into central jet veto observables.





Variations similar or even outrange the perturbative ones.





[Bittrich, Kirchgaesser, Papaefstathiou, Plätzer, Todt — arXiv:2110.01623]

Instanton induced processes

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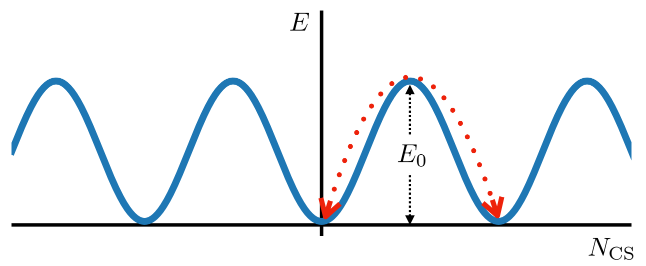
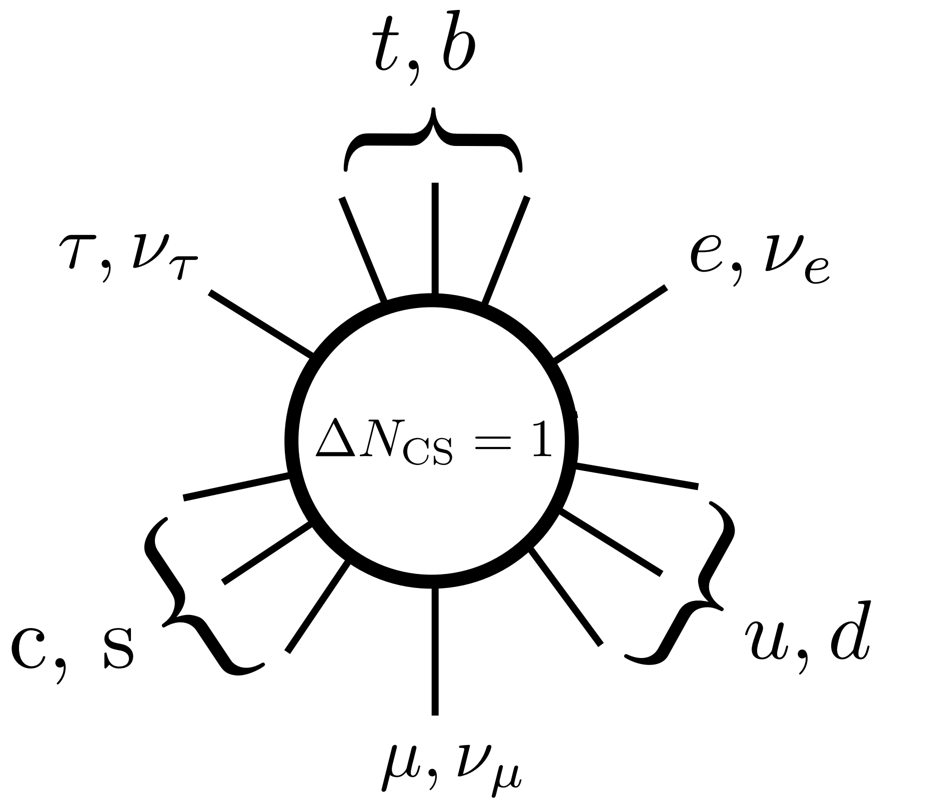
Framework for "blob" type processes and non-trivial vacua.
E.g. electroweak sphalerons

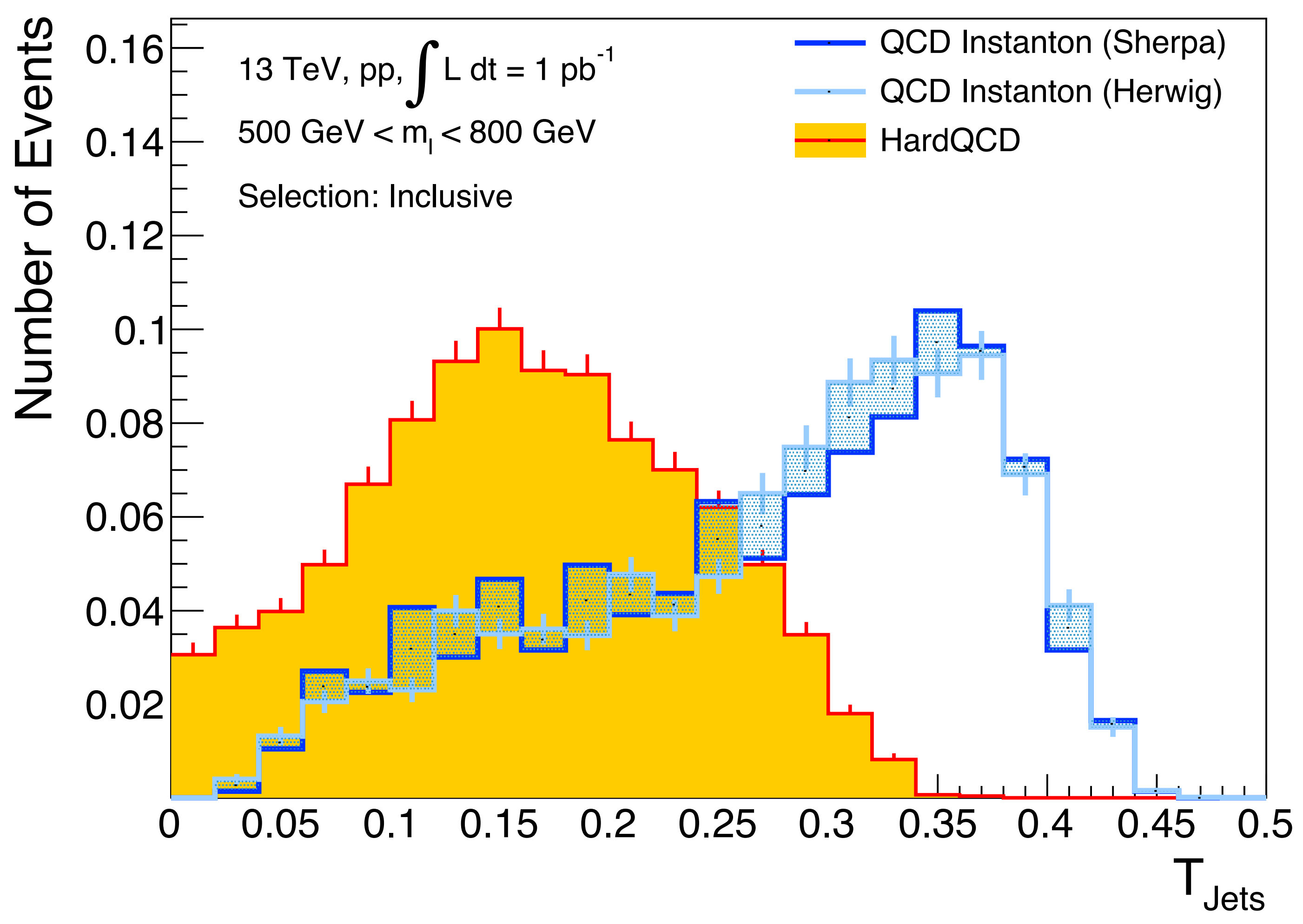


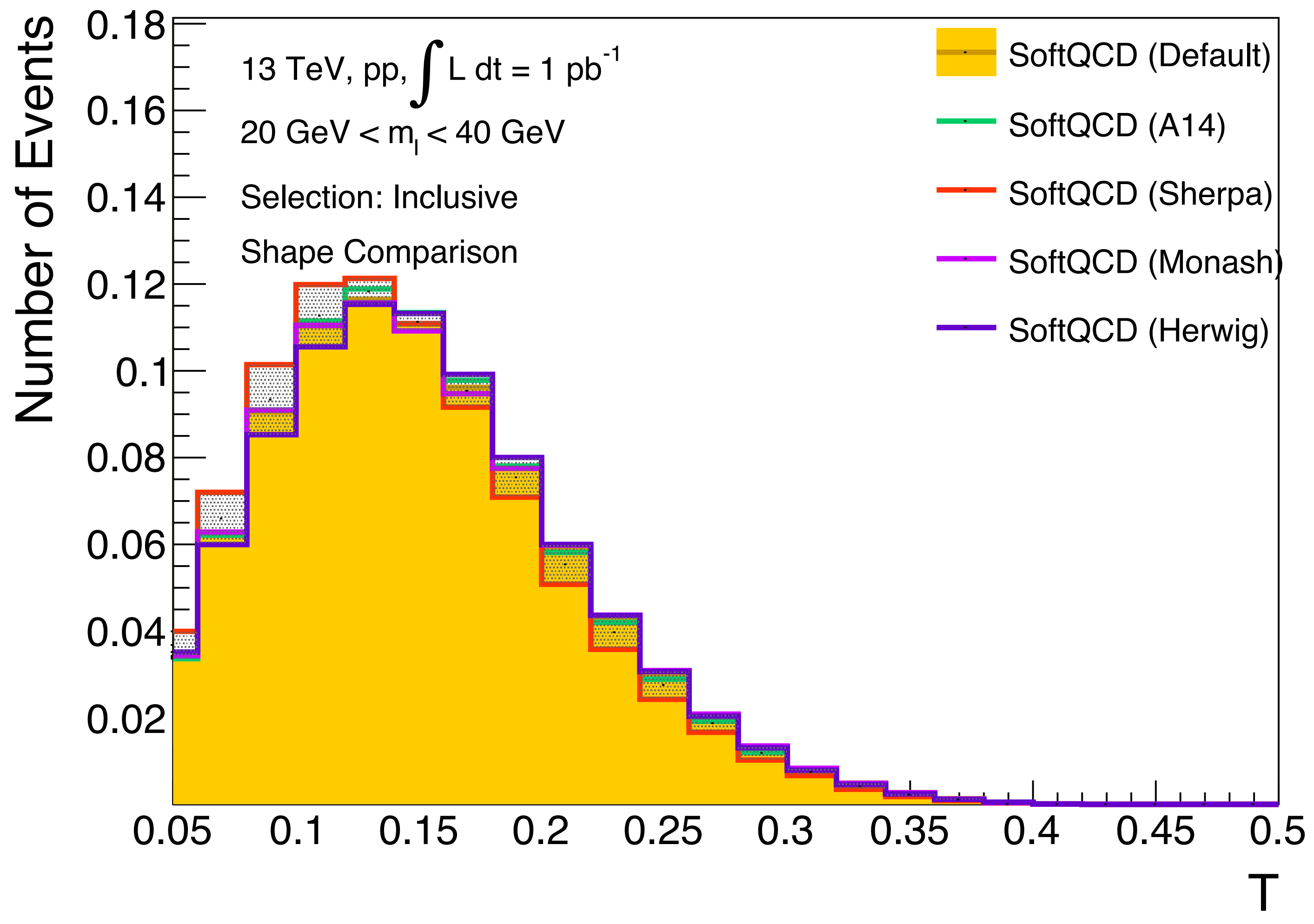
[Papaefstathiou, Plätzer, Sakurai — JHEP 1912 (2019) 017]

$$q + q \to 7\bar{q} + 3\bar{\ell} + n_B W/Z/\gamma/H.$$



Generalize to QCD instantons:
"Soft bombs" — possibly hidden/drowned in MPI?





$$g + g \to n_g g + \sum_{f=1}^{N_f} (q_{Rf} + \bar{q}_{Lf}).$$

Need to understand colour structure and further details of showering and hadronization.

[Amoroso — based on Instanton simulation in Herwig 7]
[Papaefstathiou, Plätzer — unpublished]

[Cormier, Jin, Kirchgaesser, Papaefstathiou, Plätzer — in progress]

Summary

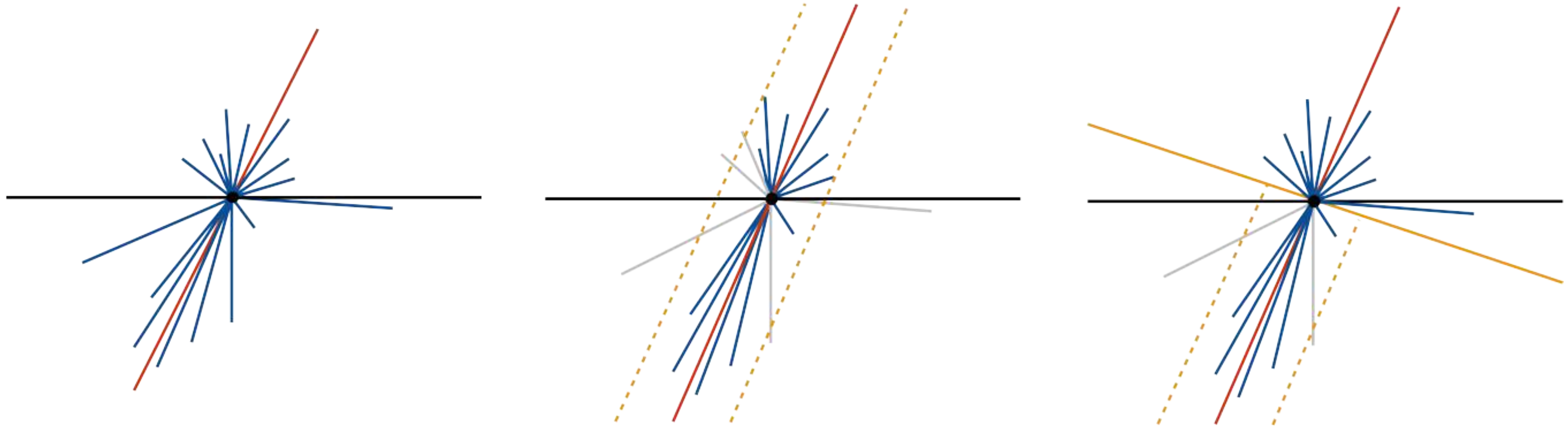
Herwig 7 has a large range of opportunities for soft QCD effects and MPI.

Better understanding of showers, colour reconnection and hadronization connects to MPI modelling:
Extend abilities and use towards:

- Heavy ion collisions
- Model uncertainties
- Non-trivial Standard Model effects

Thank you!

Pressing issues in parton showers



NLO with matching

NLL with coherent branching
Issues in dipole showers

Issues in coherent branching
LL with dipole showers

Understand and decide on accuracy of (existing) parton shower algorithms, take as a starting point for incremental improvements.

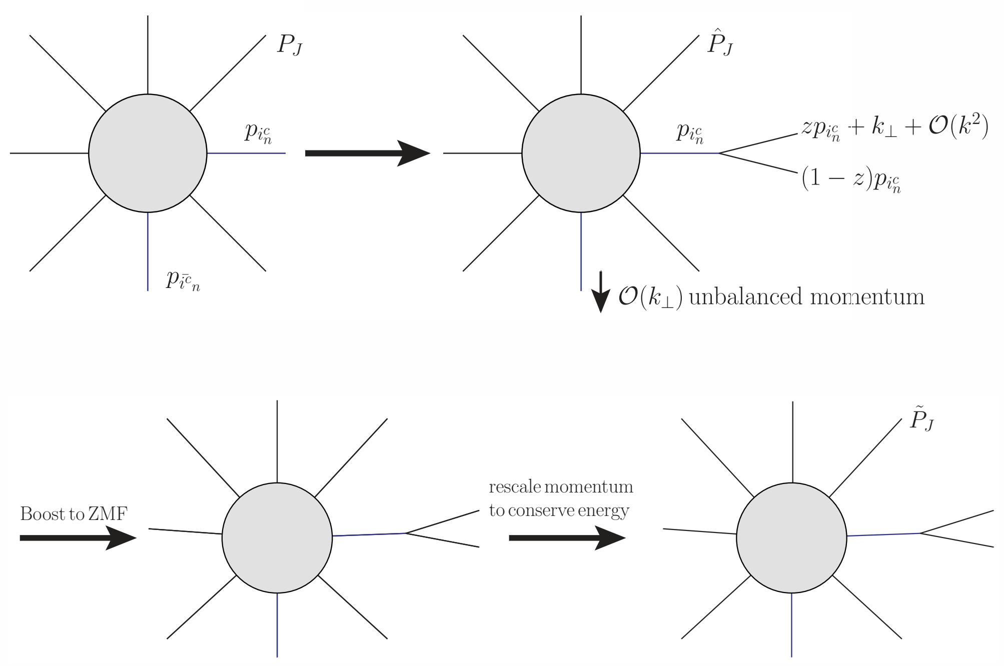
[Dasgupta, Dreyer, Hamilton, Monni, Salam et al. — JHEP 09 (2018) 033, …]
[Hoang, Plätzer, Samitz — JHEP 1810 (2018) 200]
[Bewick, Ferrario, Richardson, Seymour — JHEP 04 (2020) 019]

$$\sigma(n \text{ jets}, \tau) \sim \sum_k \sum_{l \leq 2k} c_{nkl}\ \alpha_s^k(Q)\ \ln^l \frac{1}{\tau}$$

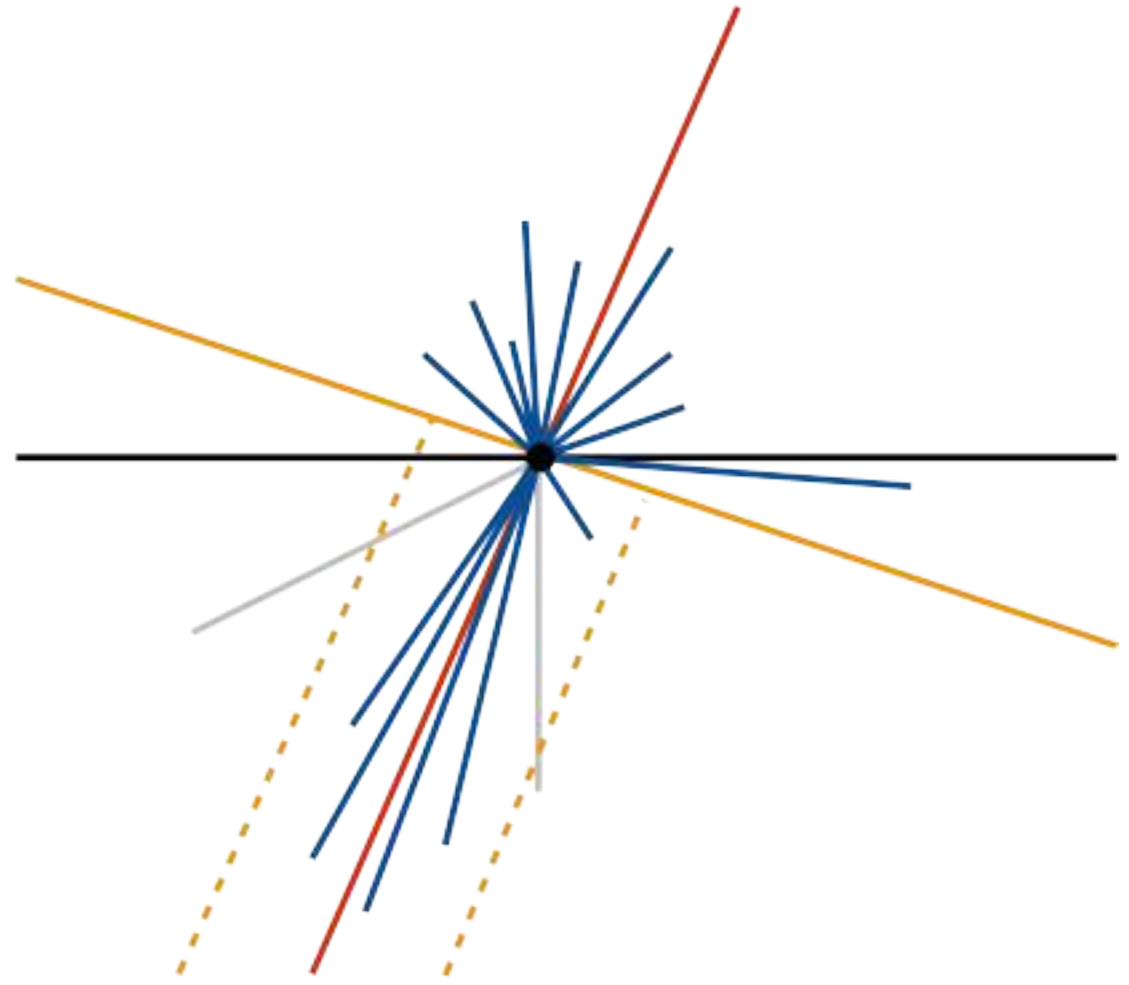
Pressing issues in parton showers

$$\frac{p_{i_n}\cdot p_{j_n}}{p_{i_n}\cdot q_n\; p_{j_n}\cdot q_n} \longrightarrow$$

$$\frac{p_{i_n}\cdot p_{j_n}}{p_{i_n}\cdot q_n\; p_{j_n}\cdot q_n} - \frac{T\cdot p_{j_n}}{T\cdot q_n}\,\frac{1}{p_{j_n}\cdot q_n} + \frac{T\cdot p_{i_n}}{T\cdot q_n}\,\frac{1}{p_{i_n}\cdot q_n}$$



[Dasgupta, Dreyer, Hamilton, Monni, Salam —PRL 125 (2020) 5]
[Forshaw, Holguin, Plätzer – JHEP 09 (2020) 014]



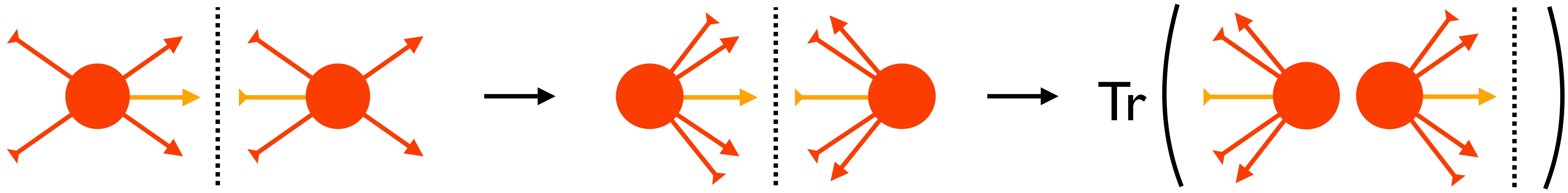
Dipole showers reproducing coherent branching:
NLL & NLC global, LL & LC non-global

Understand and decide on accuracy of (existing) parton shower algorithms, take as a starting point for incremental improvements.

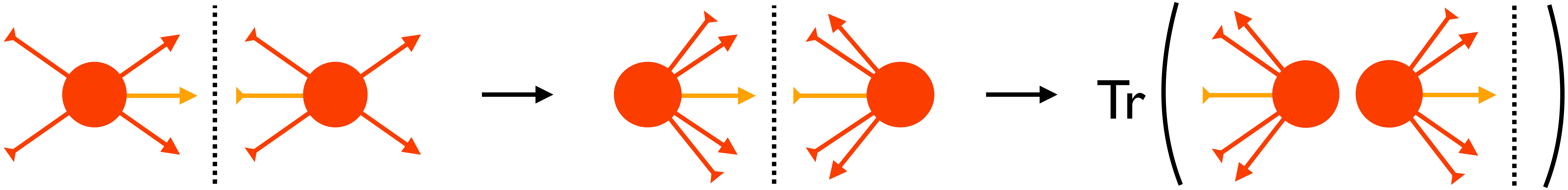
[Dasgupta, Dreyer, Hamilton, Monni, Salam et al. — JHEP 09 (2018) 033, …]
[Hoang, Plätzer, Samitz — JHEP 1810 (2018) 200]
[Bewick, Ferrario, Richardson, Seymour — JHEP 04 (2020) 019]

$$\sigma(n\ \text{jets}, \tau) \sim \sum_k \sum_{l\leq 2k} c_{nkl}\ \alpha_s^k(Q)\ \ln^l \frac{1}{\tau}$$

Cross Sections and Amplitudes



Cross Sections and Amplitudes



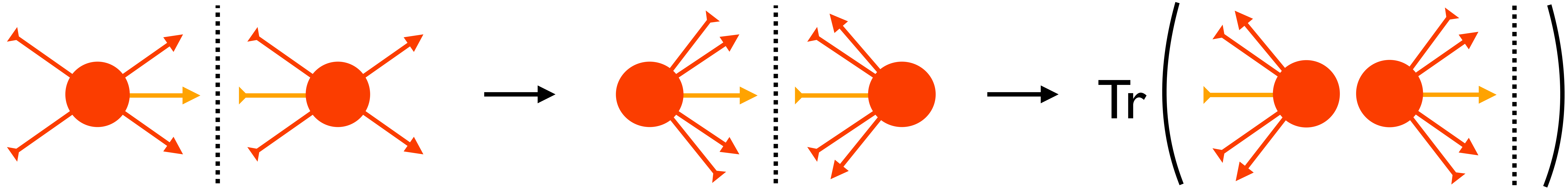
$$\sigma[u] = \sum_n \int \mathrm{Tr}\left[\mathbf{A}_n\right] u(q_1, \ldots, q_n) \mathrm{d}\phi(q_1, \ldots, q_n)$$

sum over emissions

'density operator' ~ amplitude amplitude⁺

observable and phase space

Cross Sections and Amplitudes

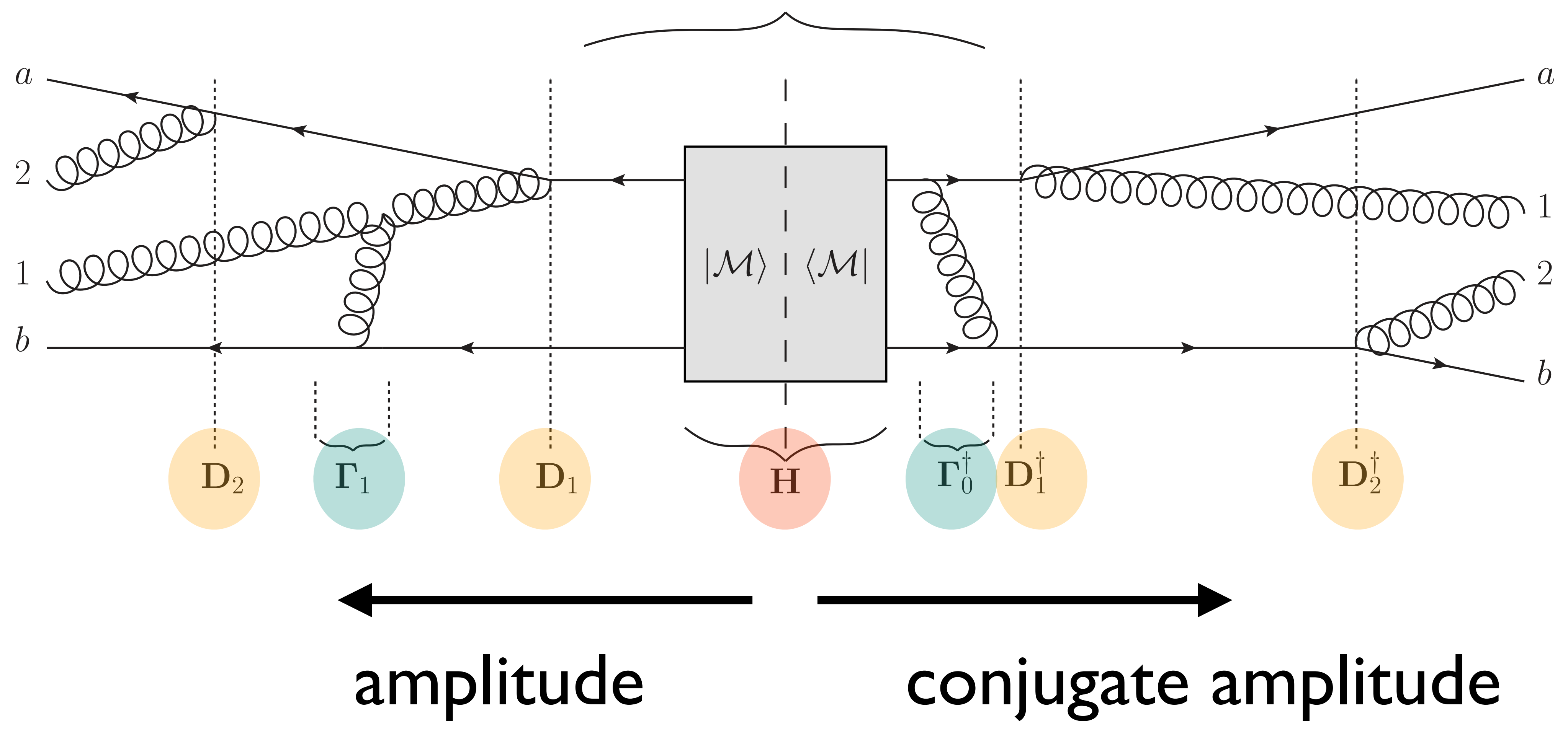


$$\mathbf{A}_n(q) = \int_q^Q \frac{\mathrm{d}k}{k}\, \mathrm{P}e^{-\int_q^k \frac{\mathrm{d}k'}{k'}\boldsymbol{\Gamma}(k')}\, \mathbf{D}_n(k)\, \mathbf{A}_{n-1}(k)\, \mathbf{D}_n^\dagger(k)\, \overline{\mathrm{P}}e^{-\int_q^k \frac{\mathrm{d}k'}{k'}\boldsymbol{\Gamma}^\dagger(k')}$$

Markovian algorithm at the amplitude level:
Iterate gluon exchanges and emission.

Different histories in amplitude and conjugate amplitude needed to include interference.

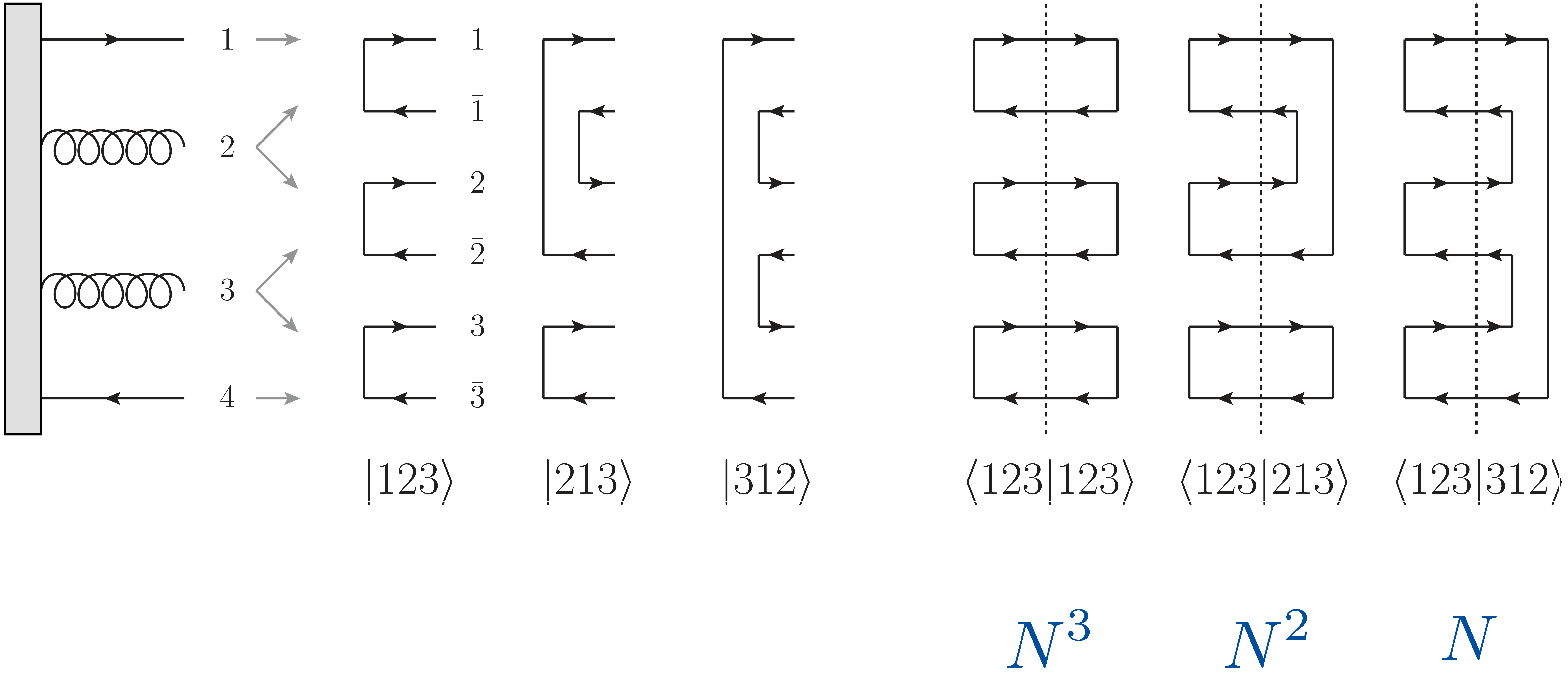
[Angeles, De Angelis, Forshaw, Plätzer, Seymour – JHEP 05 (2018) 044]
[Forshaw, Holguin, Plätzer – JHEP 1908 (2019) 145]



Tracking colour

Decompose amplitudes in flow of colour charge.

$$\mathrm{Tr}\left[\mathbf{A}_n\right] = \sum_{\sigma,\tau} A_{\tau\sigma} \langle\sigma|\tau\rangle$$

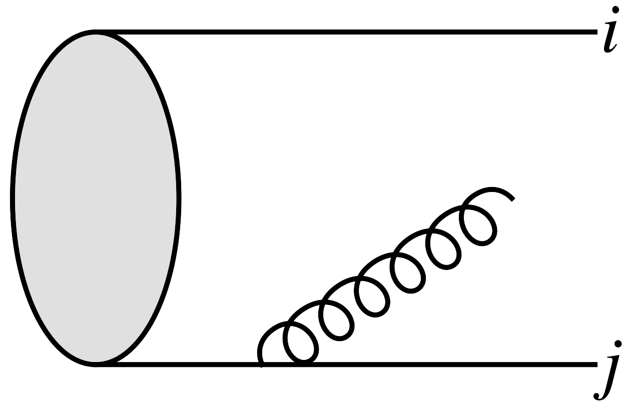


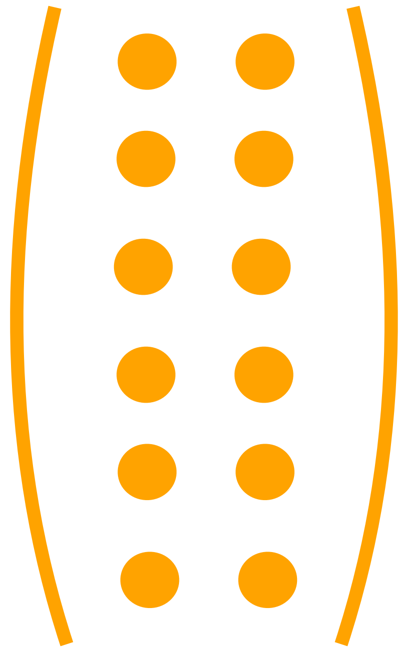
[Plätzer – EPJ C 74 (2014) 2907]
[Angeles, De Angelis, Forshaw, Plätzer, Seymour – JHEP 05 (2018) 044]

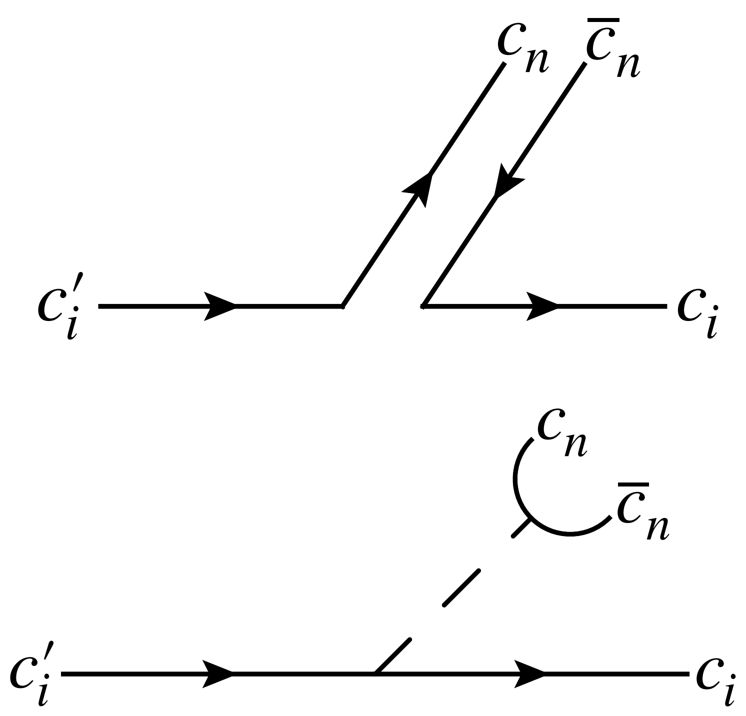
Tracking colour

Gluon emission

$$\mathbf{D}_n(k)$$



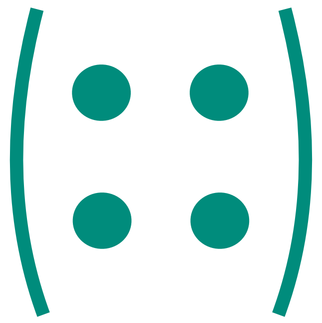


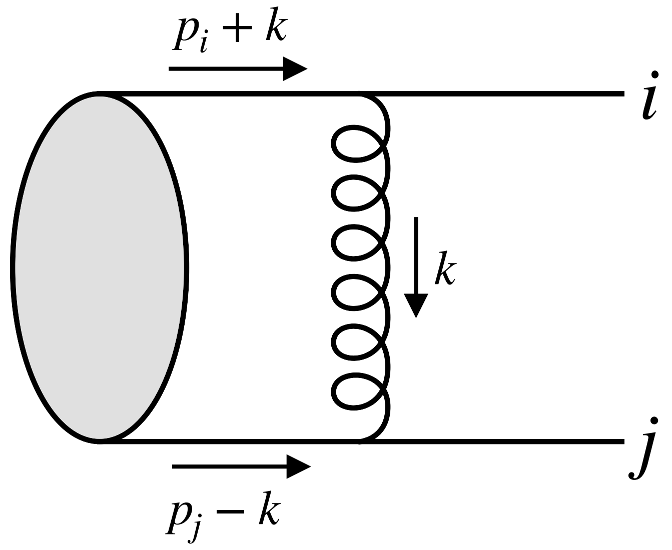


Explicit suppression in 1/N

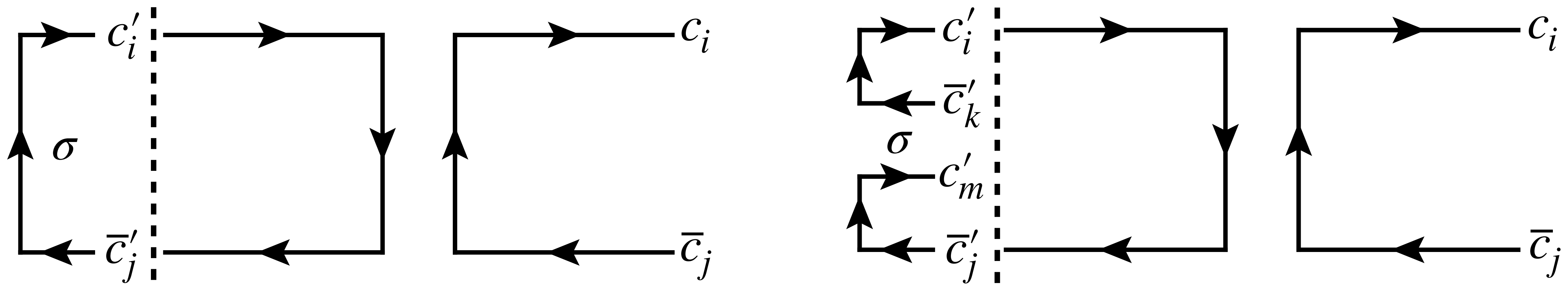
Gluon exchange

$$\mathrm{P}e^{-\int_q^k \frac{\mathrm{d}k'}{k'}\mathbf{\Gamma}(k')}$$





$$[\tau|\mathbf{\Gamma}|\sigma\rangle = (\alpha_s N)[\tau|\mathbf{\Gamma}^{(1)}|\sigma\rangle + (\alpha_s N)^2[\tau|\mathbf{\Gamma}^{(2)}|\sigma\rangle + \ldots$$



$$[\tau|\mathbf{\Gamma}^{(1)}|\sigma\rangle = \left(\Gamma_\sigma^{(1)} + \frac{1}{N^2}\rho^{(1)}\right)\delta_{\sigma\tau} + \frac{1}{N}\Sigma_{\sigma\tau}^{(1)}$$

dipole flips — implicit suppression in 1/N

Systematically expand around large-N limit summing towers of terms enhanced by $\alpha_S N$

[Plätzer – EPJ C 74 (2014) 2907] — diagrams from [Ruffa, MSc thesis 2020]

Diffraction in Herwig

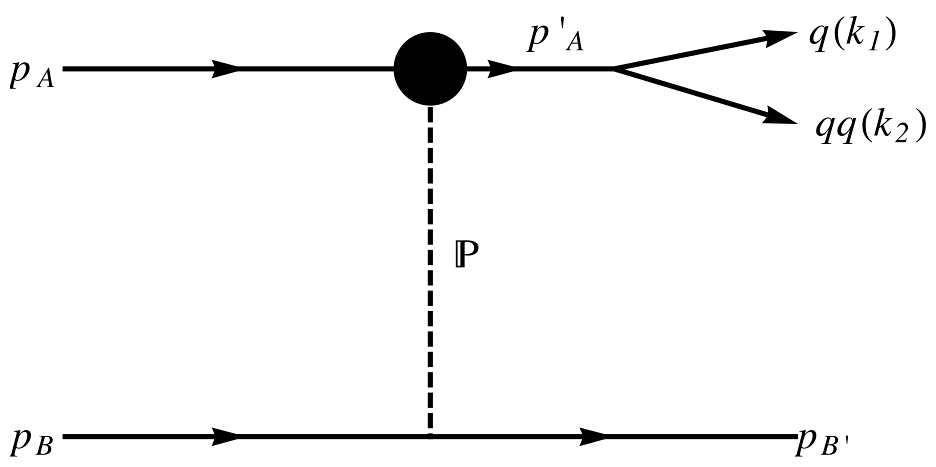
- Inelastic cross-section $\sigma_{\rm inel}(s)$ sums up to

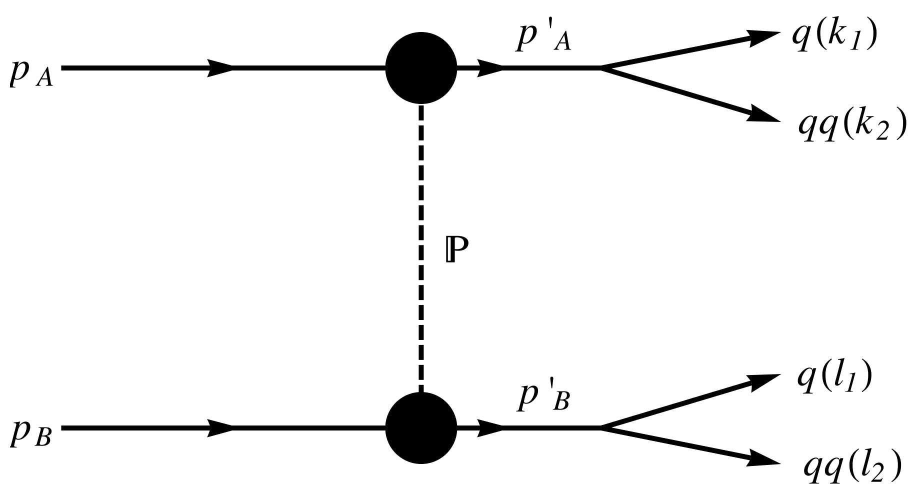
$$\sigma_{\rm inel}(s) \equiv \sigma_{\rm inel}^{\rm non-diff}(s) = \sigma_{\rm tot}(s) - \sigma_{\rm el}(s) - \sigma_{\rm diff}(s)$$

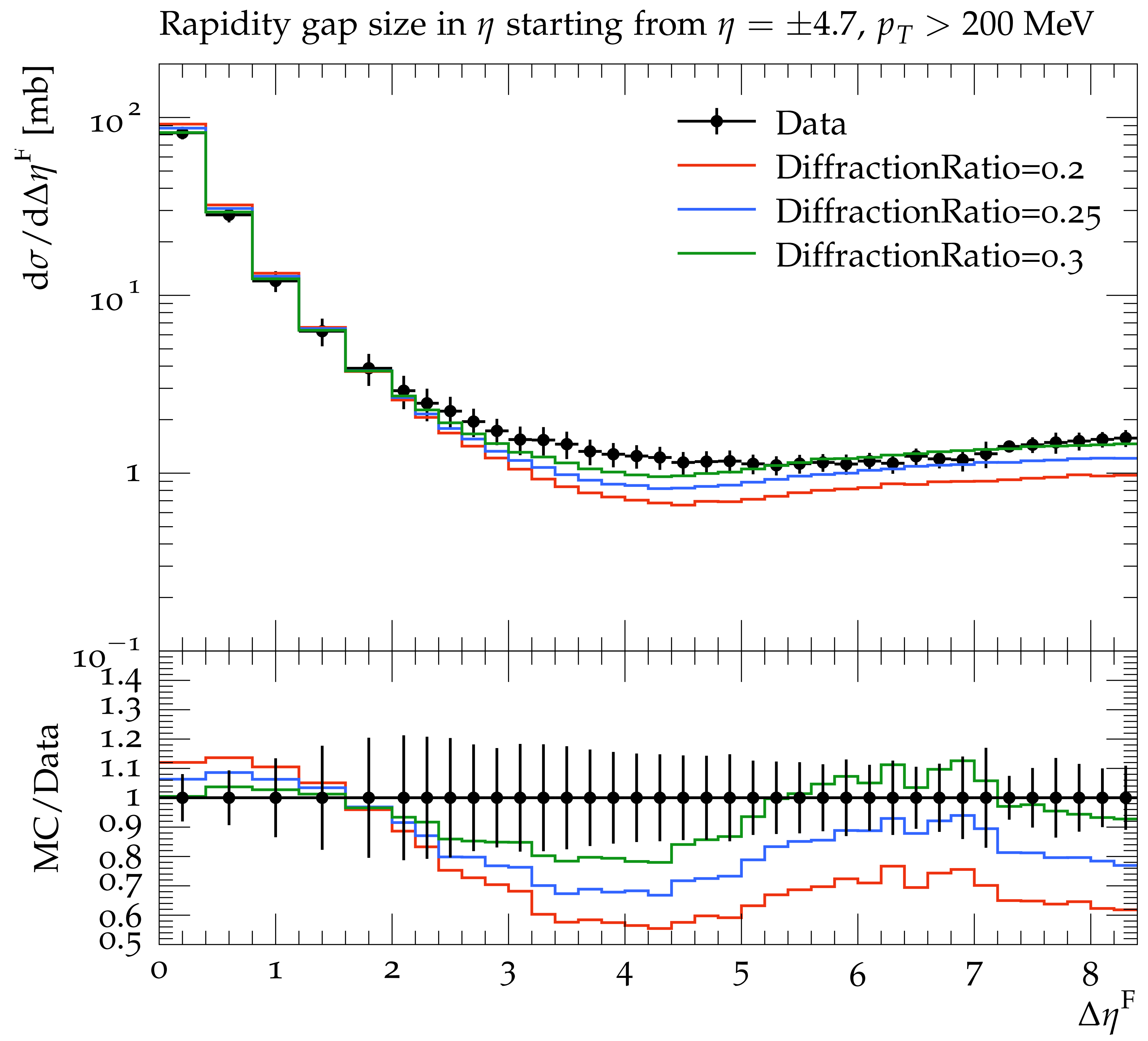
- Diffractive cross-section given by

$$\sigma_{\rm diff}(s) = R_{\rm diff}\sigma_{\rm tot}(s)$$

- $R_{\rm diff}$ can be tuned to data (e.g 7 TeV ATLAS)







[ATLAS, Eur. Phys. J. C72 (2012) 1926]

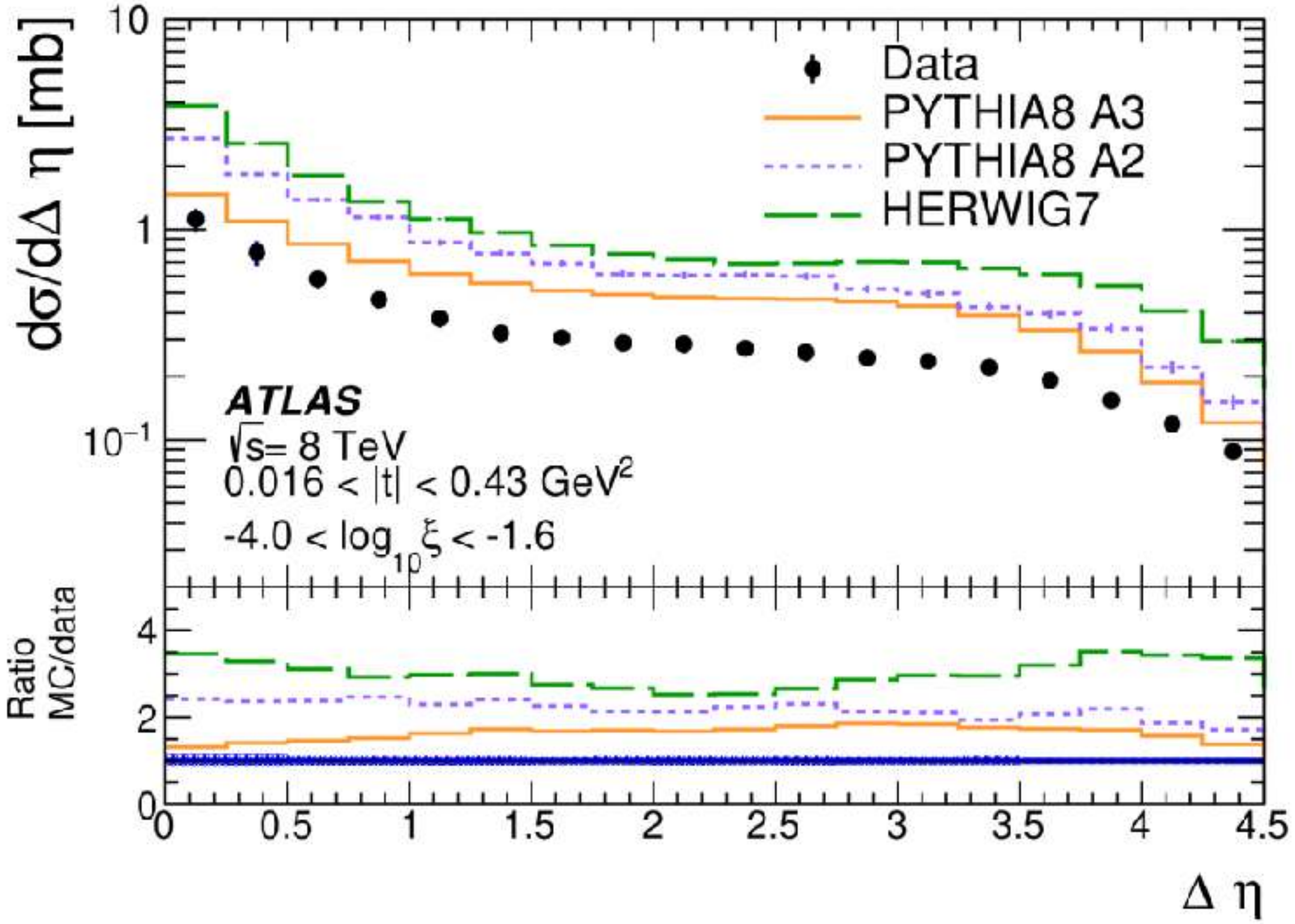
Diffraction in Herwig

- Problem: energy dependence not described
- No predictions possible

Twi-channel eikonal model including enhanced pomeron diagrams

↓

Diffractive cross-sections $\sigma_{\mathrm{SD}}(s)$ and $\sigma_{\mathrm{DD}}(s)$



[ATLAS, JHEP 02 (2020) 042, 2020]

Two-channel eikonal model

Eigenvalues of the eikonal matrix $\chi^{(\alpha)}$

- Cross-sections

$$\sigma_{\text{tot}}(s) = 2\int \mathrm{d}^2b \langle pp| \left(1 - e^{-\hat{\chi}(s,b)}\right) |pp\rangle$$

$$\sigma_{\text{el}}(s) = \int \mathrm{d}^2b \, |\langle pp| \left(1 - e^{-\hat{\chi}(s,b)}\right) |pp\rangle|^2$$

$$\sigma_{\text{inel}}^{\text{nd}}(s) = \int \mathrm{d}^2b \langle pp| \left(1 - e^{-2\hat{\chi}(s,b)}\right) |pp\rangle$$

- Cross-sections for low-mass diffraction

$$\sigma_{\text{sd},a}^{\text{lm}}(s) = \int \mathrm{d}^2b \, |\langle p^*p| 1 - e^{-\hat{\chi}(s,b)} |pp\rangle|^2$$

$$\sigma_{\text{sd},b}^{\text{lm}}(s) = \int \mathrm{d}^2b \, |\langle pp^*| 1 - e^{-\hat{\chi}(s,b)} |pp\rangle|^2$$

$$\sigma_{\text{dd}}^{\text{lm}}(s) = \int \mathrm{d}^2b \, |\langle p^*p^*| 1 - e^{-\hat{\chi}(s,b)} |pp\rangle|^2$$

- After diagonalization

$$\sigma_{\text{tot}}(s) = \frac{1}{2}\int \mathrm{d}^2b \sum_{\alpha=1}^{4} (1 - e^{-\chi^{(\alpha)}})$$

$$\sigma_{\text{el}}(s) = \frac{1}{16}\int \mathrm{d}^2b \left| \sum_{\alpha=1}^{4} (1 - e^{-2\chi^{(\alpha)}}) \right|^2$$

$$\sigma_{\text{inel}}^{\text{nd}}(s) = \frac{1}{4}\int \mathrm{d}^2b \sum_{\alpha=1}^{4} (1 - e^{-2\chi^{(\alpha)}})$$

$$\sigma_{\text{sd},a}^{\text{lm}}(s) = \frac{1}{16}\int \mathrm{d}^2b \left| e^{-\chi^{(1)}} - e^{-\chi^{(2)}} - e^{-\chi^{(3)}} + e^{-\chi^{(4)}} \right|^2$$

$$\sigma_{\text{sd},b}^{\text{lm}}(s) = \frac{1}{16}\int \mathrm{d}^2b \left| e^{-\chi^{(1)}} - e^{-\chi^{(2)}} + e^{-\chi^{(3)}} - e^{-\chi^{(4)}} \right|^2$$

$$\sigma_{\text{dd}}^{\text{lm}}(s) = \frac{1}{16}\int \mathrm{d}^2b \left| e^{-\chi^{(1)}} + e^{-\chi^{(2)}} - e^{-\chi^{(3)}} - e^{-\chi^{(4)}} \right|^2$$

Two-channel eikonal model

- Total eikonal matrix

$$\hat{\chi} = \hat{\chi}_S + \hat{\chi}_H + \hat{\chi}_{TP,a} + \hat{\chi}_{TP,b} + \hat{\chi}_{LP} + \hat{\chi}_{DP}$$

$$\chi^{(\alpha)} = \chi_S^{(\alpha)} + \chi_H^{(\alpha)} + \chi_{TP,a}^{(\alpha)} + \chi_{TP,b}^{(\alpha)} + \chi_{LP}^{(\alpha)} + \chi_{DP}^{(\alpha)}$$

- Eikonal functions

$$\chi_S = \frac{1}{2} A(b, \mu_S)\, \sigma_S^{\text{inc}}(s) \qquad \chi_H = \frac{1}{2} A(b, \mu_H)\, \sigma_H^{\text{inc}}(s, p_\perp^{\text{min}})$$

$$\chi_i = \frac{1}{2} A(b, \mu_S)\, \sigma_i(s) \text{ with } i = TP_a, TP_b, LP, DP$$

- Soft cross-section parametrized with

$$\sigma_S^{\text{inc}}(s) = g_{p\mathbb{P}}^2 \left(\frac{s}{s_0} \right)^{\alpha(0)-1}$$

- Cross-sections $\sigma_i(s)$ calculated with Gribov Reggon Field theory

[Engel, Ranft, PRD 54 (1996)] [Capella, Tran Thanh Van, Kaplan, Nucl. Phys. B97 (1975)]

Low-mass diffractive cross-sections

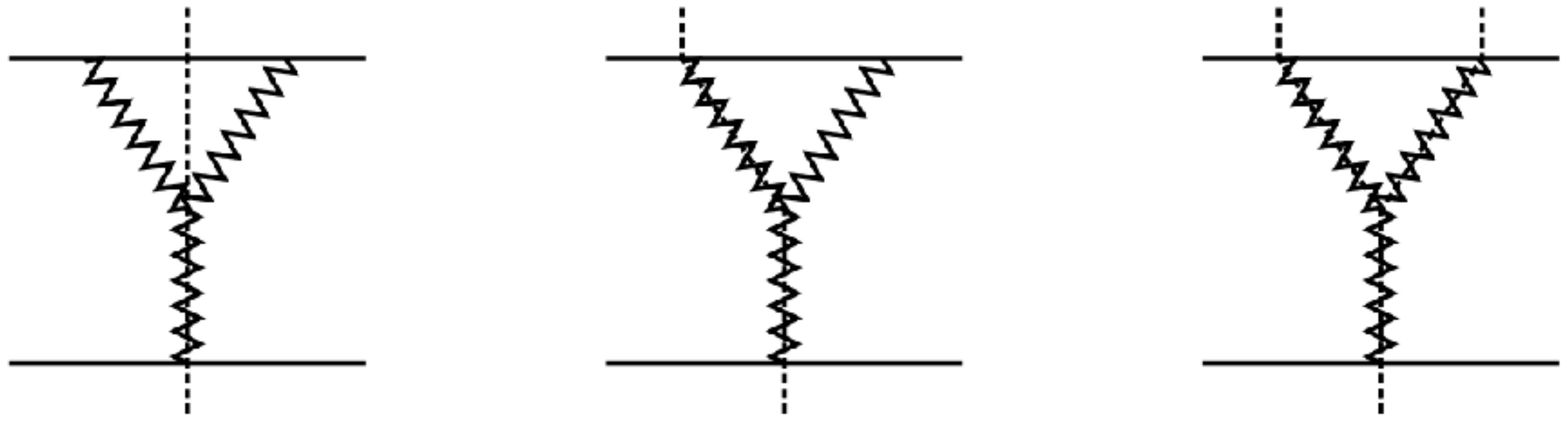
$$\sigma^{\mathrm{lm}}_{\mathrm{sd},a}(s) = \frac{1}{16}\int \mathrm{d}^2 b \, \left| e^{-\chi^{(1)}} - e^{-\chi^{(2)}} - e^{-\chi^{(3)}} + e^{-\chi^{(4)}} \right|^2$$

$$\sigma^{\mathrm{lm}}_{\mathrm{sd},b}(s) = \frac{1}{16}\int \mathrm{d}^2 b \, \left| e^{-\chi^{(1)}} - e^{-\chi^{(2)}} + e^{-\chi^{(3)}} - e^{-\chi^{(4)}} \right|^2$$

$$\sigma^{\mathrm{lm}}_{\mathrm{dd}}(s) = \frac{1}{16}\int \mathrm{d}^2 b \, \left| e^{-\chi^{(1)}} + e^{-\chi^{(2)}} - e^{-\chi^{(3)}} - e^{-\chi^{(4)}} \right|^2$$

Resolved and unresolved cross-sections

- Unitarity cuts of enhanced diagrams can be assigned to different final states



High-mass diffraction

Multiperipheral particle production

- Resolved cross-sections for the $jklnmo$ final state ($soft, hard, sd_a, sd_b, dd, cd$)

$$\sigma_{jklmno}(s) = \sum_{\alpha=0}^{j} \sum_{\beta=0}^{j-\alpha} \sum_{\gamma=0}^{j-\alpha-\beta} \sum_{\delta=0}^{j-\alpha-\beta-\gamma} \sum_{\epsilon=0}^{l} \sum_{\zeta=0}^{m} A^{\alpha}_{l+\alpha-\epsilon} A^{\beta}_{m+\beta-\zeta} A^{\gamma}_{n+\gamma} C^{\delta\epsilon\zeta}_{o+\delta+\epsilon+\zeta} \; \tilde{\sigma}_{j-\alpha-\beta-\gamma-\delta,k,l+\alpha-\epsilon,m+\beta-\zeta,n+\gamma,o+\delta+\epsilon+\zeta}(s)$$

- Contributing unresolved cross-sections ($\mathbb{P}_S, \mathbb{P}_H, TP_a, TP_b, LP, DP$)

$$\tilde{\sigma}_{jklnmo}(s) = \frac{1}{4} \sum_{\alpha=1}^{4} \int \mathrm{d}^2 b \frac{(2\chi_S^{(\alpha)})^j}{j!} \frac{(2\chi_H^{(\alpha)})^k}{k!} \frac{(2\chi_{TP_a}^{(\alpha)})^l}{l!} \frac{(2\chi_{TP_b}^{(\alpha)})^m}{m!} \frac{(2\chi_{LP}^{(\alpha)})^n}{n!} \frac{(2\chi_{DP}^{(\alpha)})^o}{o!} e^{-2\chi^{(\alpha)}}$$

[C.Röhr, PhD 2014]

Example: cross-section for 1 soft interaction

$$\sigma_{jklmno}(s) = \sum_{\alpha=0}^{j} \sum_{\beta=0}^{j-\alpha} \sum_{\gamma=0}^{j-\alpha-\beta} \sum_{\delta=0}^{j-\alpha-\beta-\gamma} \sum_{\epsilon=0}^{l} \sum_{\zeta=0}^{m} A^{\alpha}_{l+\alpha-\epsilon} A^{\beta}_{m+\beta-\zeta} A^{\gamma}_{n+\gamma} C^{\delta\epsilon\zeta}_{o+\delta+\epsilon+\zeta} \; \tilde{\sigma}_{j-\alpha-\beta-\gamma-\delta,k,l+\alpha-\epsilon,m+\beta-\zeta,n+\gamma,o+\delta+\epsilon+\zeta}(s)$$

$$\sigma_{100000}(s) = \tilde{\sigma}_{100000}(s) + 4\tilde{\sigma}_{000001}(s) + 2\left(\tilde{\sigma}_{001000}(s) + \tilde{\sigma}_{000100}(s) + \tilde{\sigma}_{000010}(s)\right)$$

- Gets absorptive and additive contributions dependent of triple pomeron coupling

High-mass diffractive cross-sections

- High-mass diffractive cross-sections

$$\sigma_{sd,a}^{hm}(s) = \sigma_{001000}(s) = -\tilde{\sigma}_{001000}(s) - 2\tilde{\sigma}_{000001}(s)$$

$$\sigma_{sd,b}^{hm}(s) = \sigma_{000100}(s)$$

$$\sigma_{dd}^{hm}(s) = \sigma_{000010}(s)$$

- Single and double diffractive cross-sections then the sum of low- and high-mass diffractive cross-section

$$\sigma_{sd}(s) = \sigma_{sd}^{lm}(s) + \sigma_{sd}^{hm}(s)$$

$$\sigma_{dd}(s) = \sigma_{dd}^{lm}(s) + \sigma_{dd}^{hm}(s)$$

Pomeron cross-sections

- Cross-sections of enhanced pomeron diagrams

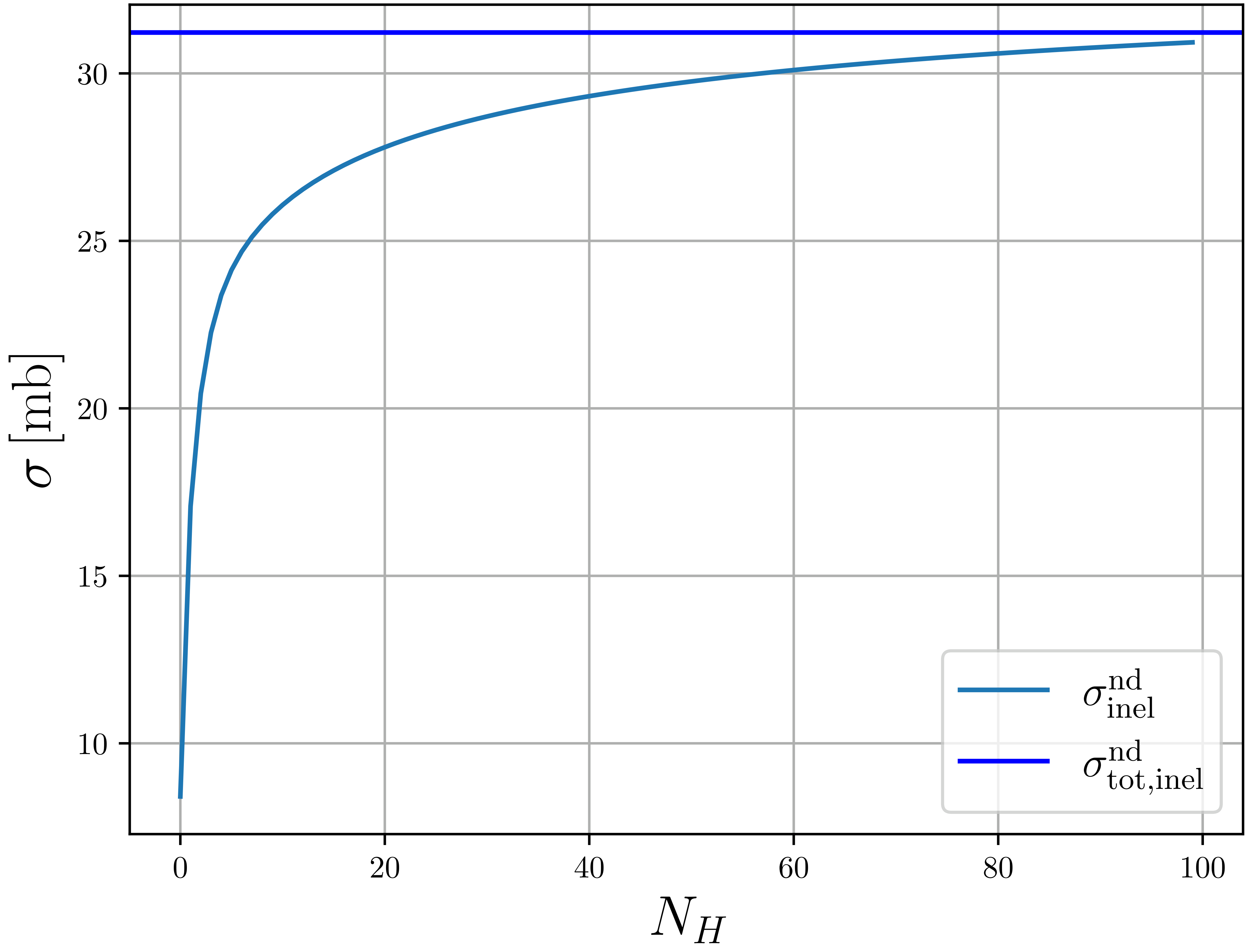
$$\sigma_{TP}(s) = -\frac{g_{p\mathbb{P}}^3 g_{3\mathbb{P}}}{2\alpha' 16\pi(\hbar c)^2}\left(\frac{s}{s_0}\right)^{\Delta_{\mathbb{P}}} \exp\left(-\frac{b_{p\mathbb{P}}+b_{3\mathbb{P}}}{2\alpha'}\Delta_{\mathbb{P}}\right) \times \left\{ \mathrm{Ei}\left[\left(\frac{b_{p\mathbb{P}}+b_{3\mathbb{P}}}{2\alpha'} + \ln\frac{s}{\Sigma_L}\right)\Delta_{\mathbb{P}}\right] - \mathrm{Ei}\left[\left(\frac{b_{p\mathbb{P}}+b_{3\mathbb{P}}}{2\alpha'} + \ln\Sigma_U\right)\Delta_{\mathbb{P}}\right]\right\}$$

$$\sigma_{LP}(s) = -\frac{g_{p\mathbb{P}}^2 g_{3\mathbb{P}}^2}{2\alpha' 16\pi(\hbar c)^2}\left(\frac{s}{s_0}\right)^{\Delta_{\mathbb{P}}} \exp\left(-\frac{b_{3\mathbb{P}}}{\alpha'}\Delta_{\mathbb{P}}\right) \times \left[C_1 \mathrm{Ei}(C_1\Delta_{\mathbb{P}}) - C_1 \mathrm{Ei}(C_2\Delta_{\mathbb{P}}) + \frac{1}{\Delta_{\mathbb{P}}}\exp(C_2) - \frac{1}{\Delta_{\mathbb{P}}}\exp(C_1\Delta_{\mathbb{P}})\right]$$

$$\frac{d\sigma_{DP}(s)}{dM_{CD}^2} = \frac{g_{p\mathbb{P}}^4}{512\pi^2(\hbar c)^4\alpha' M_{CD}^2}\sigma_{\mathbb{P}\mathbb{P}}(M_{CD}^2)\left(\frac{s}{M_{CD}^2}\right)^{2\Delta_{\mathbb{P}}} \times \left(b_{p\mathbb{P}} + b_{3\mathscr{P}} + \alpha' \ln\left(\frac{s}{M_{CD}^2}\right)\right)^{-1} \times \ln\left(\frac{b_{p\mathbb{P}} + b_{3\mathbb{P}} + 2\alpha' \ln((1-x_F^{min})s/M_{CD}^2)}{b_{p\mathbb{P}} + b_{3\mathbb{P}} - 2\alpha' \ln(1-x_F^{min})}\right)$$

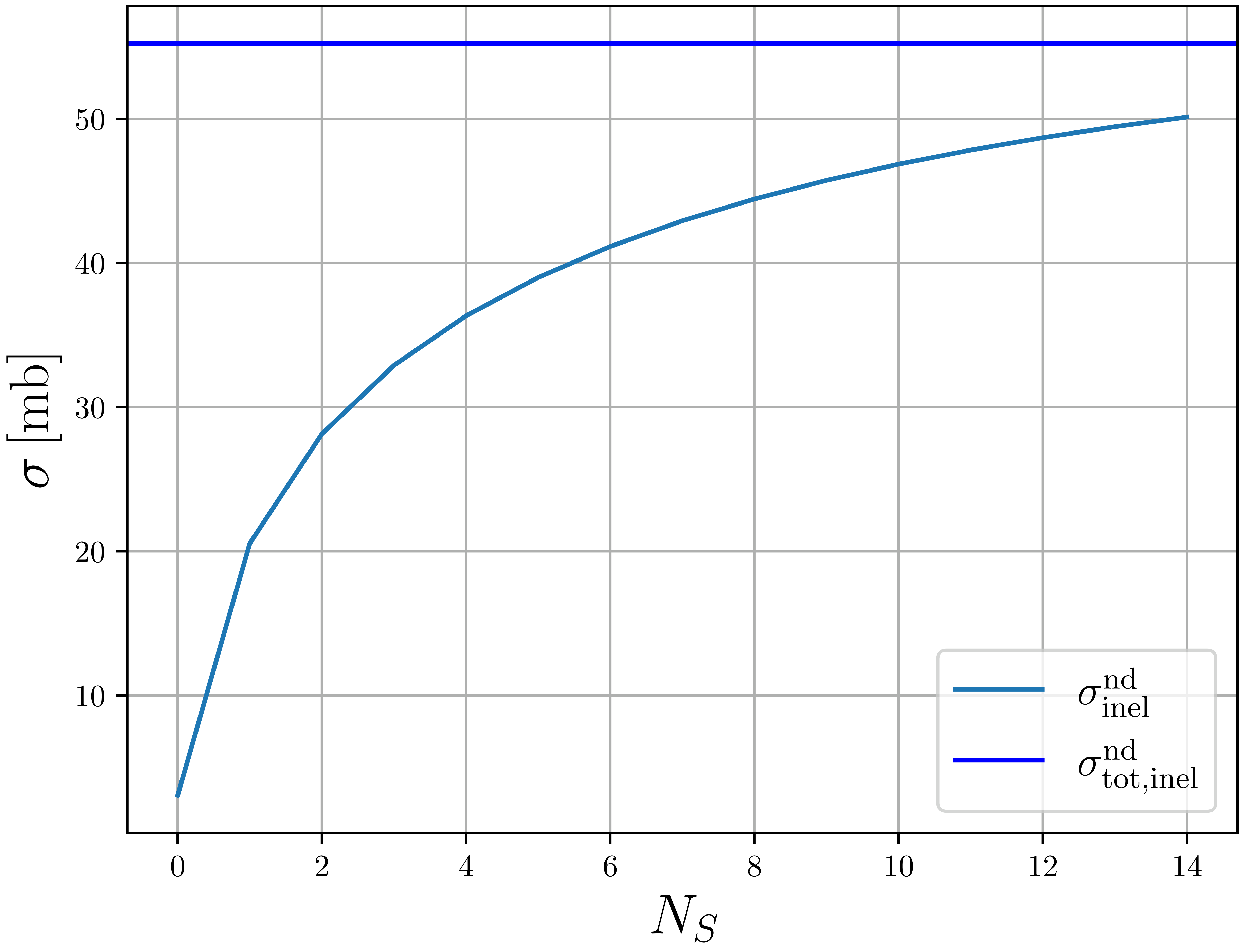
- Many parameters. Especially interesting g3p (triple pomeron coupling)

Convergence for g3p=0 (no enhanced pomeron diagrams)



$$\sum_{j,k}^{\infty} \sigma_{jk0000}(s) \to \sigma^{\text{nd}}_{\text{inel}}(s) = \frac{1}{4}\int \mathrm{d}^2 b \sum_{\alpha=1}^{4} (1 - e^{-2\chi^{(\alpha)}})$$

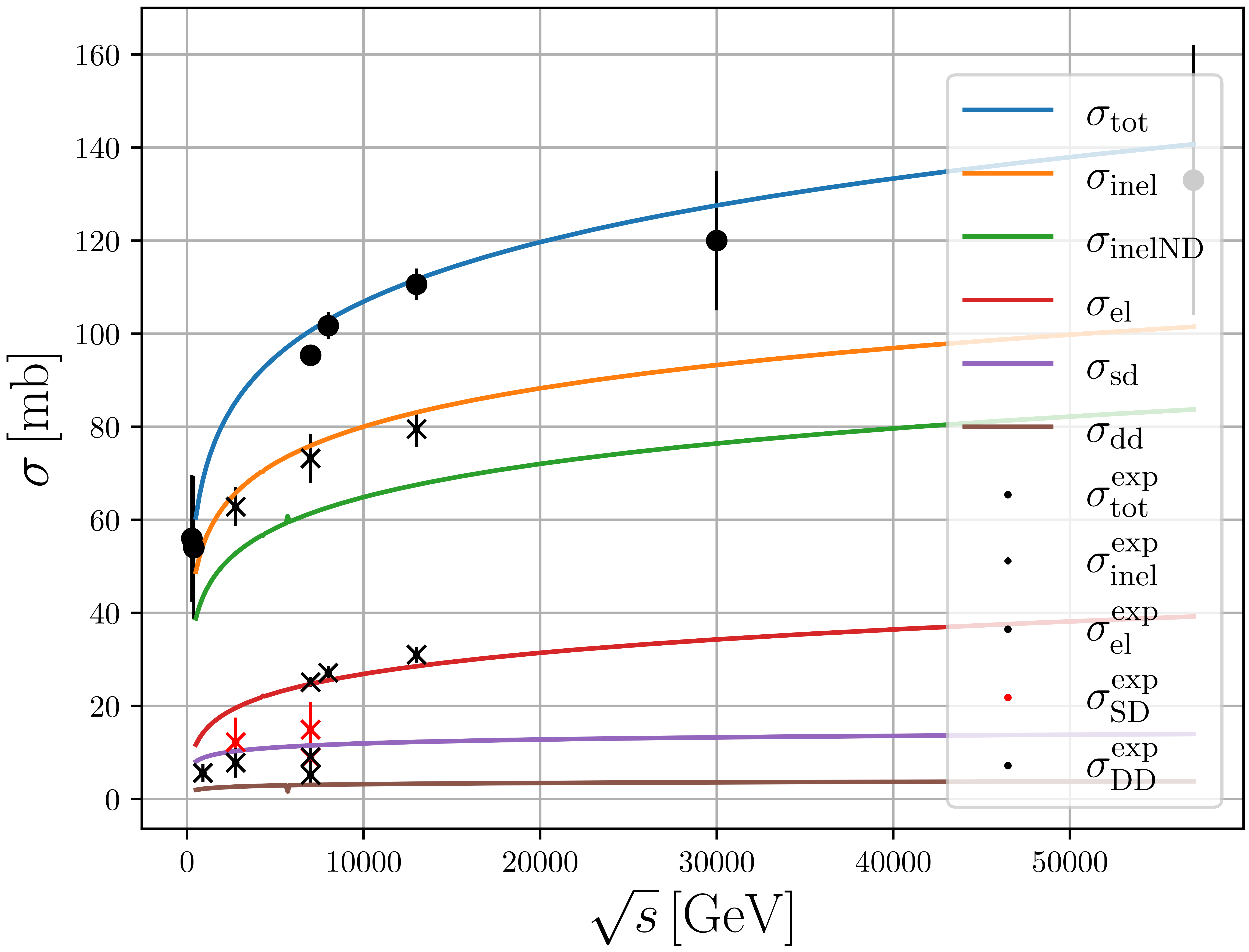
Convergence for g3p!=0



~ ✓

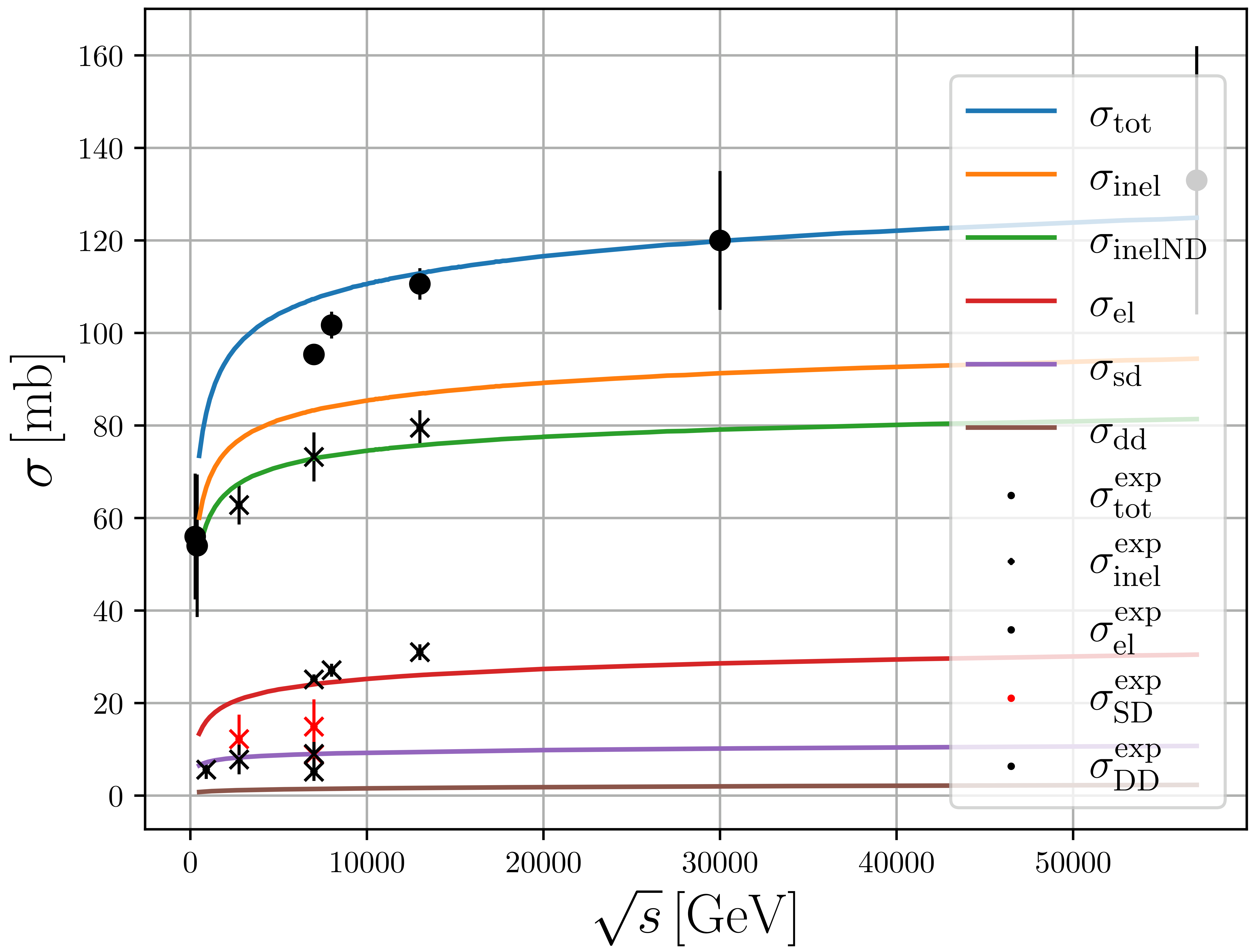
- Computation expensive for python but should be no problem for c++
- Converges for large j,k values

Cross-sections in the Two-Channel eikonal model



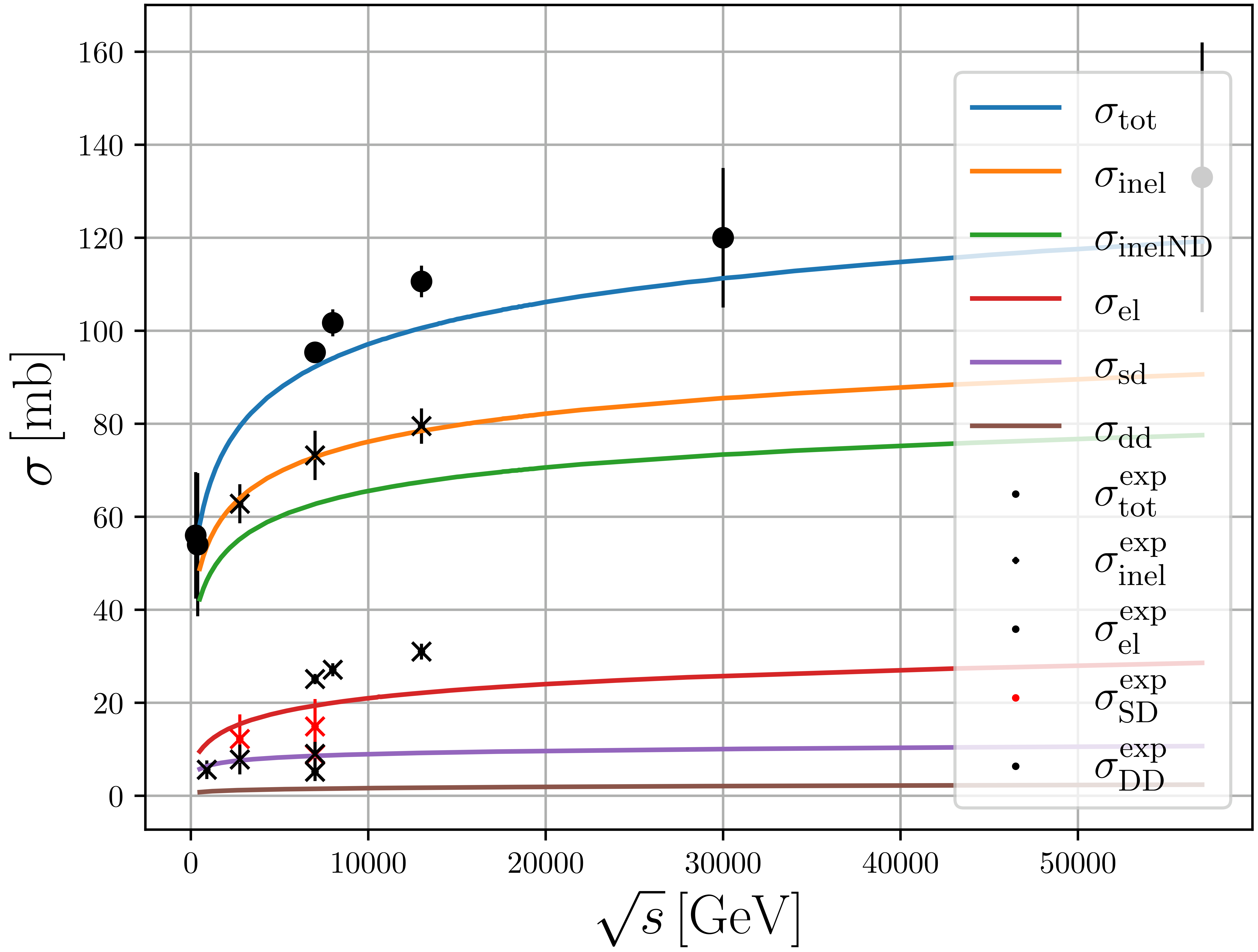
- g3p=0

Cross-sections in the Two-Channel eikonal model



- g3p!=0

Cross-sections in the Two-Channel eikonal model



- g3p!=0
- Different pTmin param.

Summary and outlook

- So far best description of cross sections for g3p=0
- Cross sections as predictions of the model (no DL parametrisation)
- Good extrapolation of energy dependence of diffractive xsec
- Tune/validation/push code to repo…

Rapidity gap survival probability

Cross-section for central diffraction

$$\sigma_{000001}(s)$$

Central diffraction without rapidity gap

$$\sigma_{jk0001}(s) \text{ for all } j, k$$