Monte Carlo Event Generators

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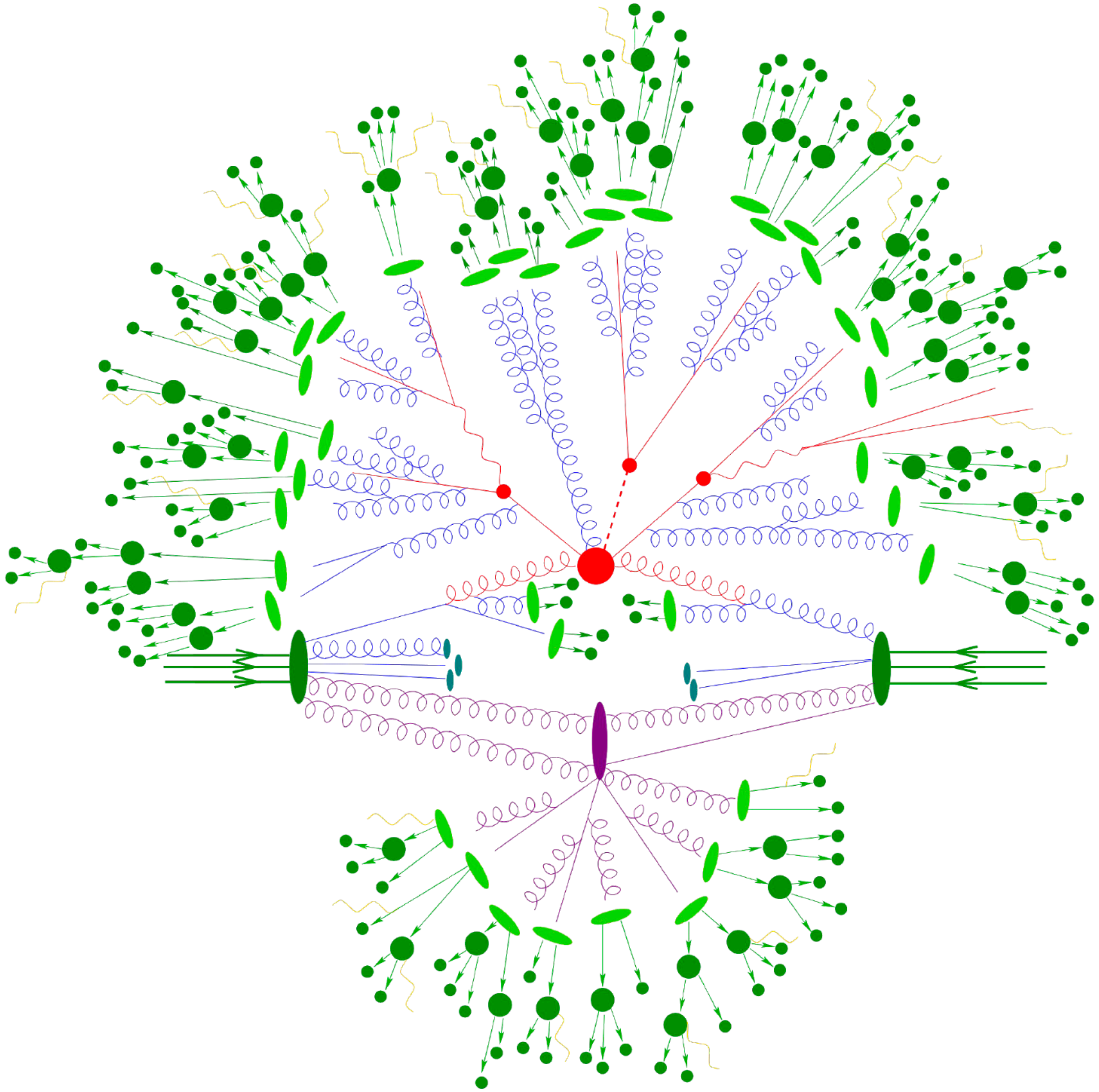
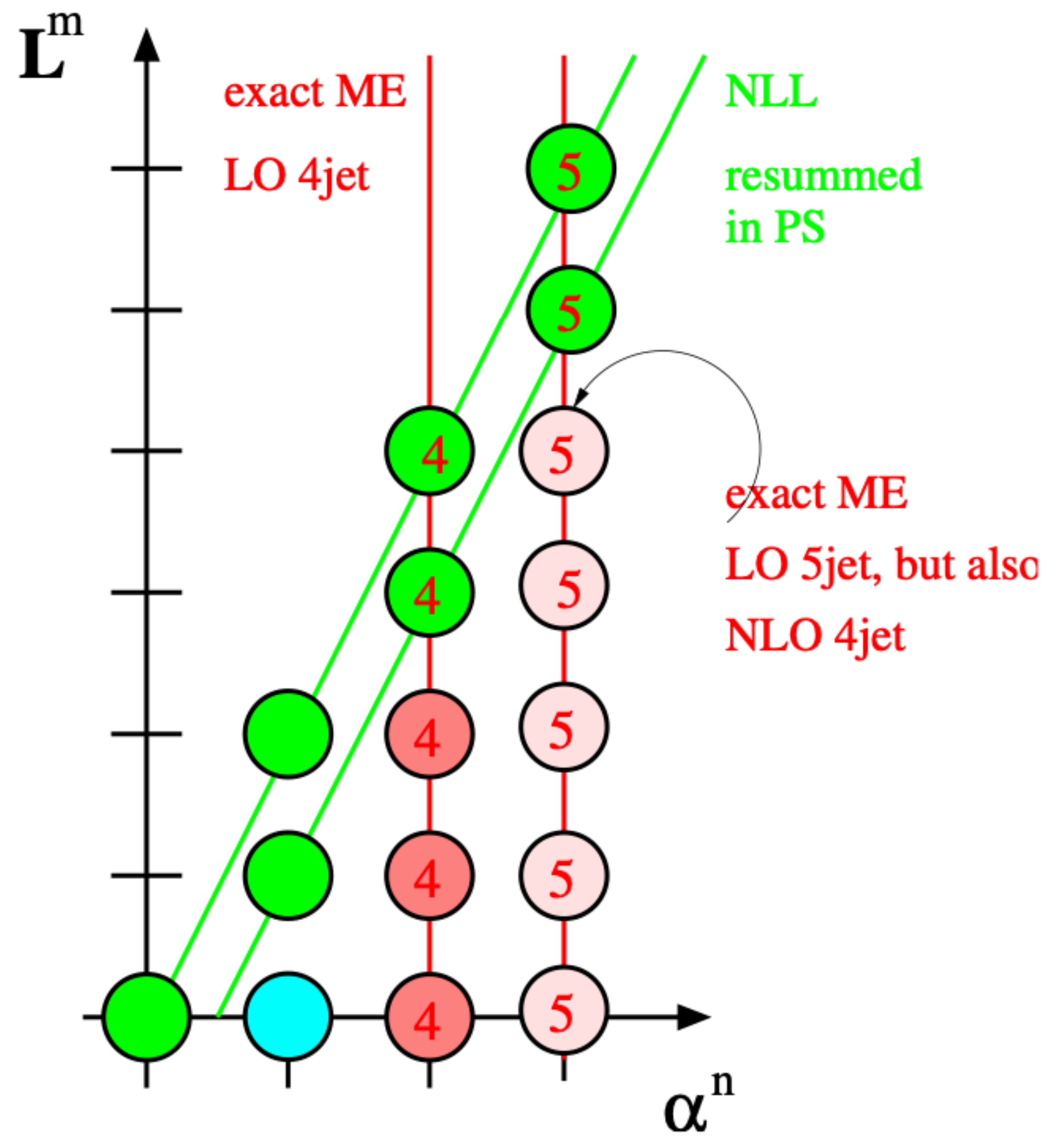
Structure of LHC Events

- Hard Interaction
- Radiative Corrections
- Hadronization
- Hadron Decays
- Underlying Event



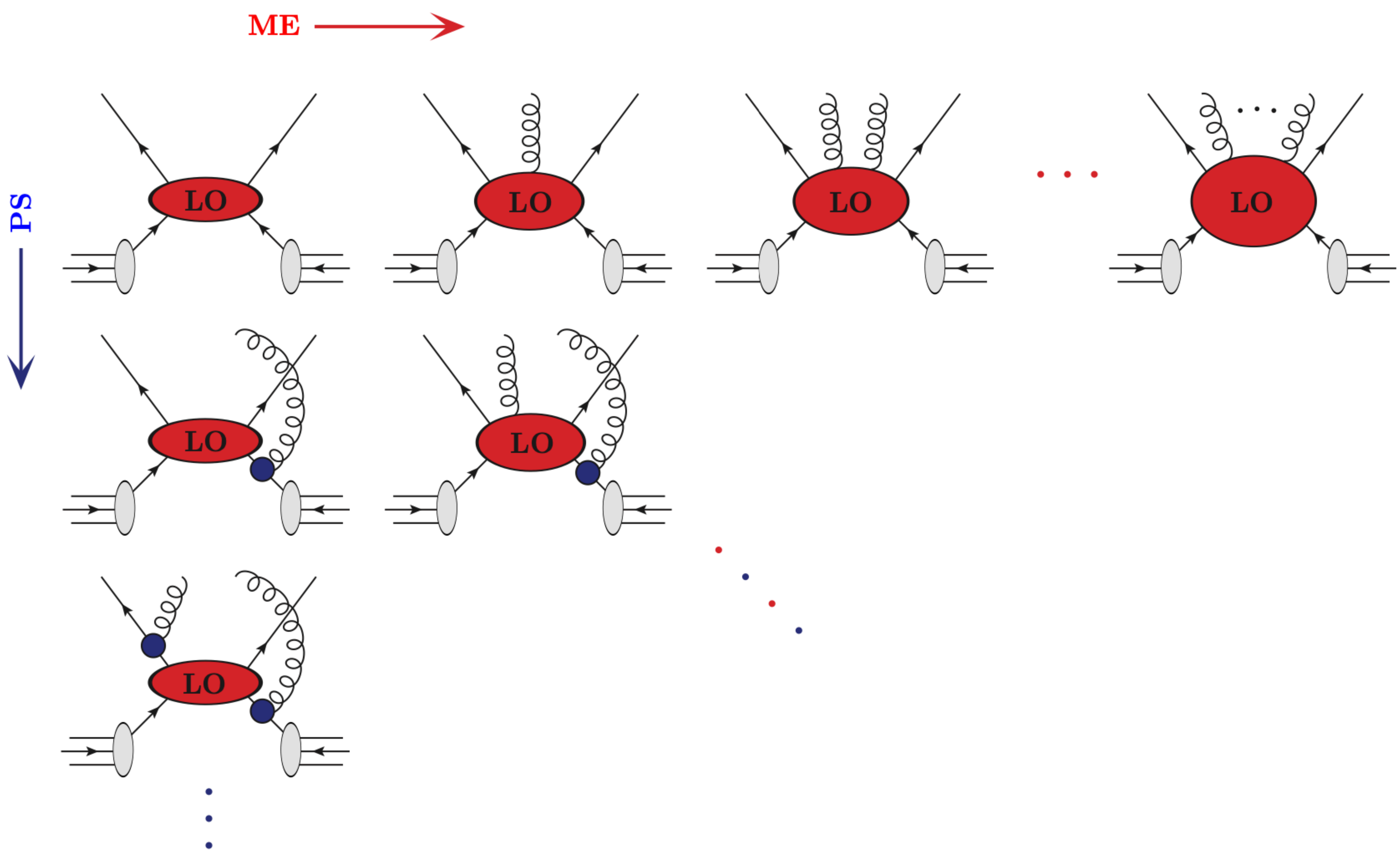
Multijet Merging

- Parton shower resums logarithms and is a good description of collinear/ soft emissions jet evolution (Large Logs)
- Matrix elements at given order is fair description of hard/large-angle emissions jet production (small logs)
- "Merge" both approaches



Matching

- Parton shower resums logarithms and is a good description of collinear/ soft emissions jet evolution (Large Logs)
- Matrix elements at given order is fair description of hard/large-angle emissions jet production (small logs)
- "Match" both approaches:
  - Cross section at **NLO accuracy** and correct the hardest emission in PS to reproduce ME element



Matching at LO

Matching at LO is essentially trivial

$$\langle O \rangle^{LO} = \int d\Phi_n \, B(\Phi_n) \, O(\Phi_n)$$

$$\downarrow$$

$$\langle O \rangle^{LOPS} = \int d\Phi_n \, B(\Phi_n) \, PS(t,0)$$

Trivial if you know how to calculate both LO ME and PS

Matching at NLO

Matching at NLO?

$$\langle O \rangle^{NLOPS} = \int d\Phi_n \left[B(\Phi_n) + V(\Phi_n) + I(\Phi_n)\right] PS(\Phi_n)$$

$$+ \int d\Phi_{n+1} \left[R(\Phi_{n+1}) PS(\Phi_{n+1}) - S(\Phi_n \otimes \Phi_1) PS(\Phi_n)\right]$$

First bracket seems fine but we have a problem in the second

R and S have different PS contributions: IR subtraction will be spoilt

Reminder

NLO cross section:

$$d\sigma_n^{NLO} = d\Phi_n \left[B(\Phi_n) + V(\Phi_n) + I(\Phi_n) + \int d\Phi_{n+1} \left(R(\Phi_{n+1}) - S(\Phi_{n+1}) \right) \right]$$

$$= d\Phi_n \bar{B}(\Phi_n)$$

Splitting Kernels:

$$d\Phi_1 \frac{R(\Phi_{n+1})}{B(\Phi_n)} \xrightarrow{\text{IR Limit}} d\Phi_1 \frac{\alpha_s}{2\pi} K_{ij,k}(\Phi_{ij,k})$$

$K_{ij,k}$ reproduces the process-independent behaviour of $\frac{R(\Phi_{n+1})}{B(\Phi_n)}$ in the soft/collinear regions of phasespace

POWHEG

[Alioli,Nason,Oleari,Re] arXiv:0812.0578

$$d\Phi_1 \frac{R(\Phi_{n+1})}{B(\Phi_n)} \longrightarrow d\Phi_1 \frac{\alpha_s}{2\pi} K_{ij,k}(\Phi_{ij,k})$$

Define a modified Sudakov Form Factor

$$\Delta_N^K(\mu_N^2, t_0) = \exp\left[-\int_{t_0}^{\mu_N^2} d\Phi_1\, K_{ij,k}(t, z, \phi)\right] \longrightarrow \Delta_N^{R/B}(\mu_N^2, t_0) = \exp\left[-\int_{t_0}^{\mu_N^2} d\Phi_1\, \frac{R(\Phi_{n+1})}{B(\Phi_n)}\right]$$

- Assumes factorization of phasespace $\Phi_{n+1} = \Phi_n \otimes \Phi_1$
- α_s will typically vary with the shower scale

POWHEG

Generate Emissions with Sudakov Form Factor

$$d\sigma^{NLO} = d\Phi_n \, \bar{B}(\Phi_n) \left[\Delta_n^{R/B}(\mu^2, t_0) + \int_{t_0}^{\mu_n^2} d\Phi_1 \, \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Delta_n^{R/B}(\mu_n^2, t(\Phi_1)) \right]$$

- Square bracket again integrates to 1: **Unitarity of PS**
- Radiation pattern now follows the real ME correction

MC@NLO

[Frixione,Webber] hep-ph/0204244

- Basic idea: divide R into **soft(S)** and **hard (H)** part

$$R = R^S + R^H = B \otimes dS_1 + H_n$$

- We can identify the subtraction term dS_1 with the kernels $dS_1 = \sum K_{ij,k}$

$$d\sigma^{NLO} = d\Phi_n \tilde{B}(\Phi_n) \left[\Delta_n^{R/B}(\mu^2, t_0) + \int_{t_0}^{\mu_n^2} d\Phi_1 \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Delta_n^{R/B}(\mu_n^2, t(\Phi_1)) \right] + d\Phi_{n+1} H(\Phi_{n+1})$$

$$\tilde{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + I(\Phi_n)$$

MC@NLO

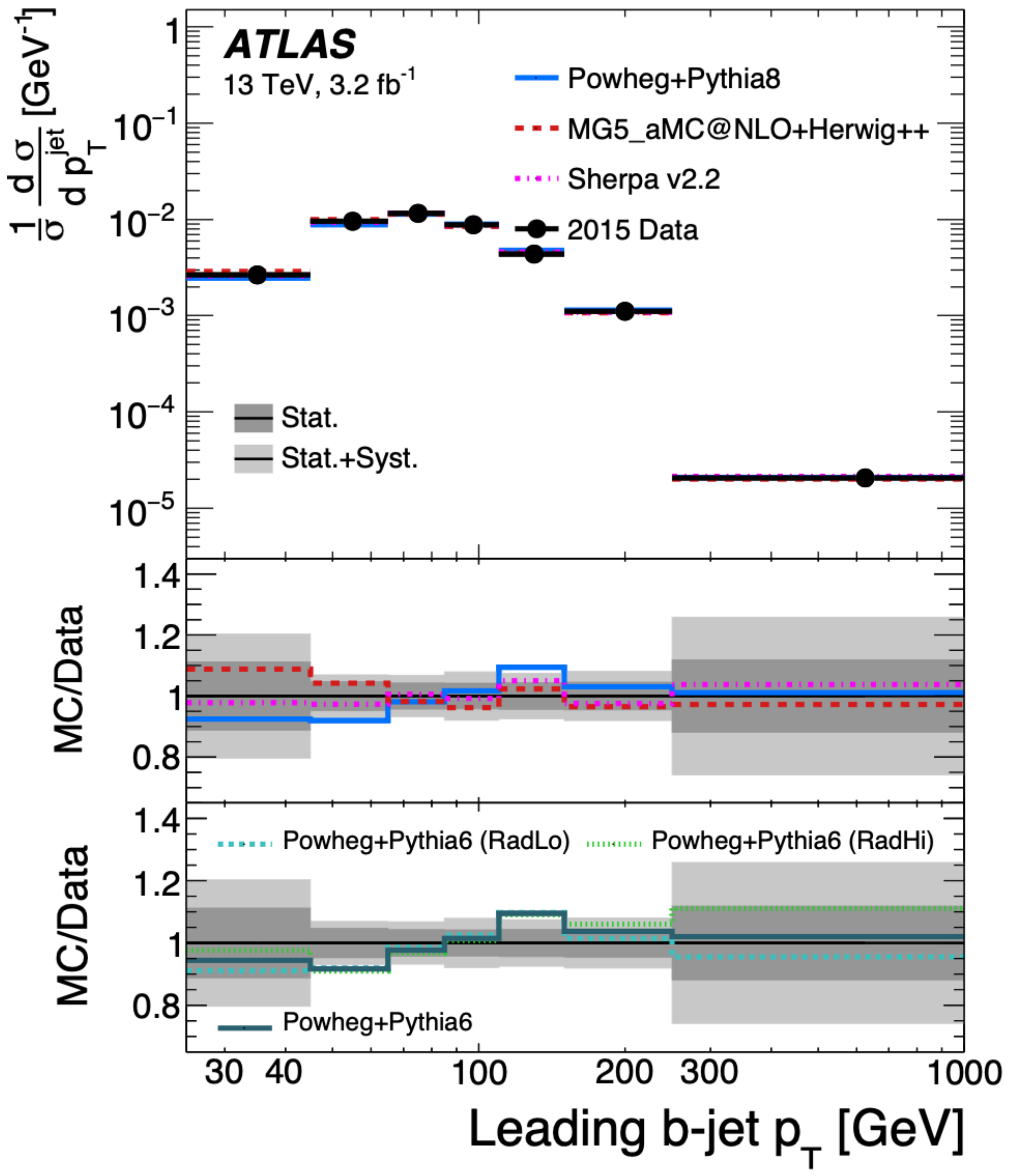
$$d\sigma^{NLO} = d\Phi_n\,\tilde{B}(\Phi_n)\left[\Delta_n^{R/B}(\mu^2, t_0) + \int_{t_0}^{\mu_n^2} d\Phi_1\,\frac{R(\Phi_{n+1})}{B(\Phi_n)}\Delta_n^{R/B}(\mu_n^2, t(\Phi_1))\right] + d\Phi_{n+1}H(\Phi_{n+1})$$

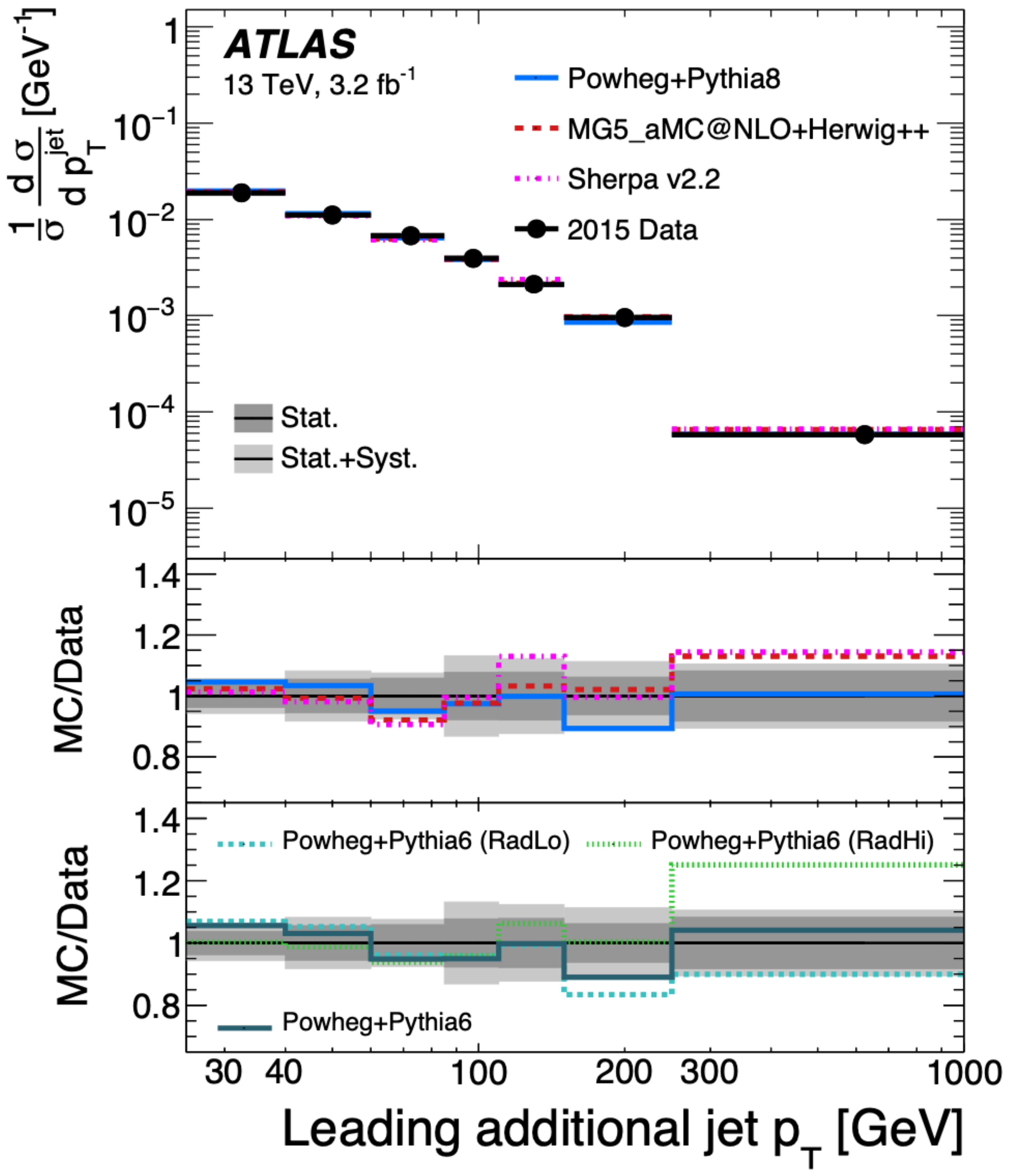
$$\tilde{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + I(\Phi_n)$$

- Essentially MC@NLO decomposes the real emission into a part driven by the shower and a hard remainder
- Virtual corrections are only applied to emissions generated by the shower
- $H(\Phi_{n+1})$ corrects for the hardest emission and fills regions of phase space inaccessible to the PS

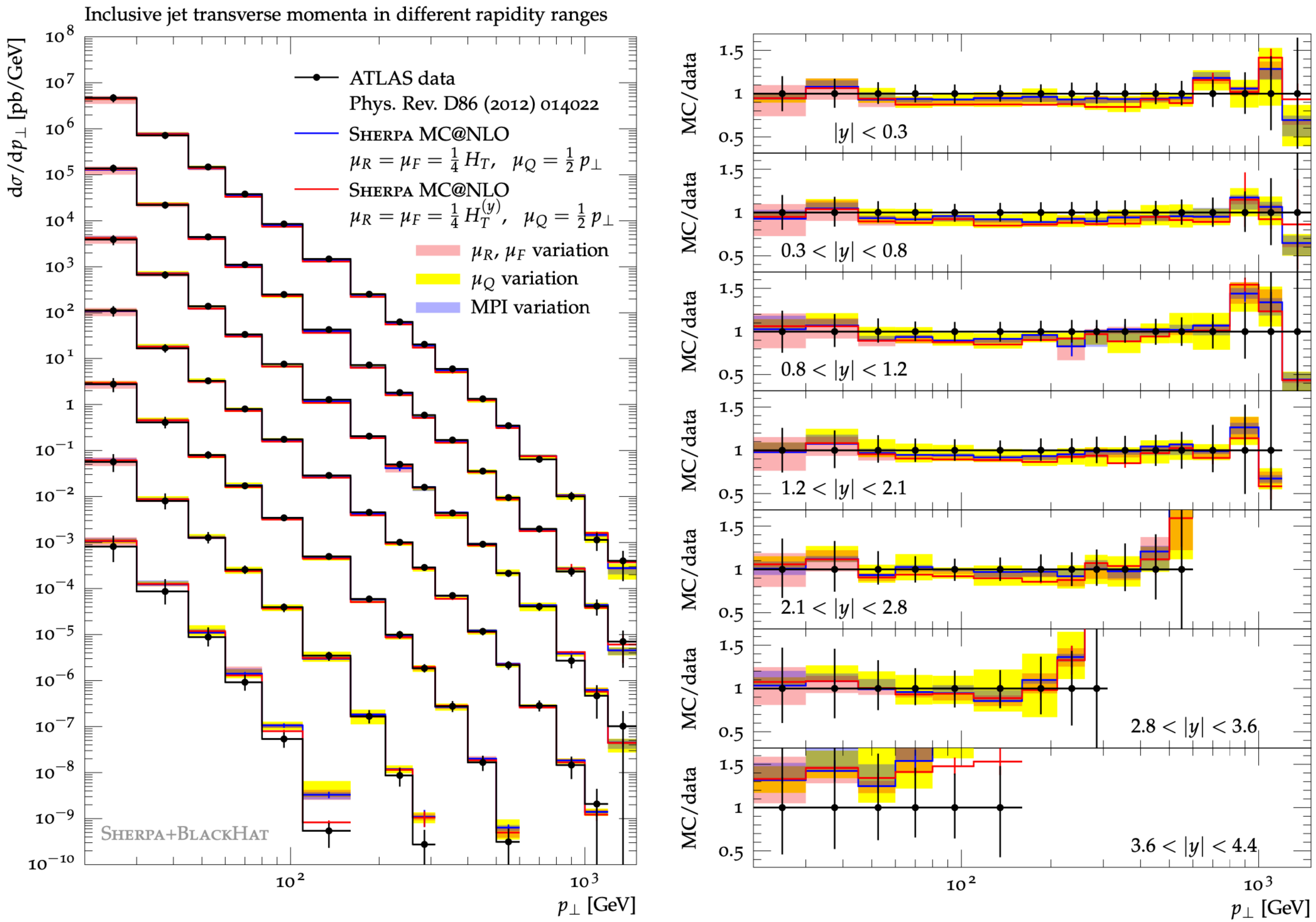
POWHEG/MC@NLO

$t\bar{t}$ production   arXiv:1610.09978



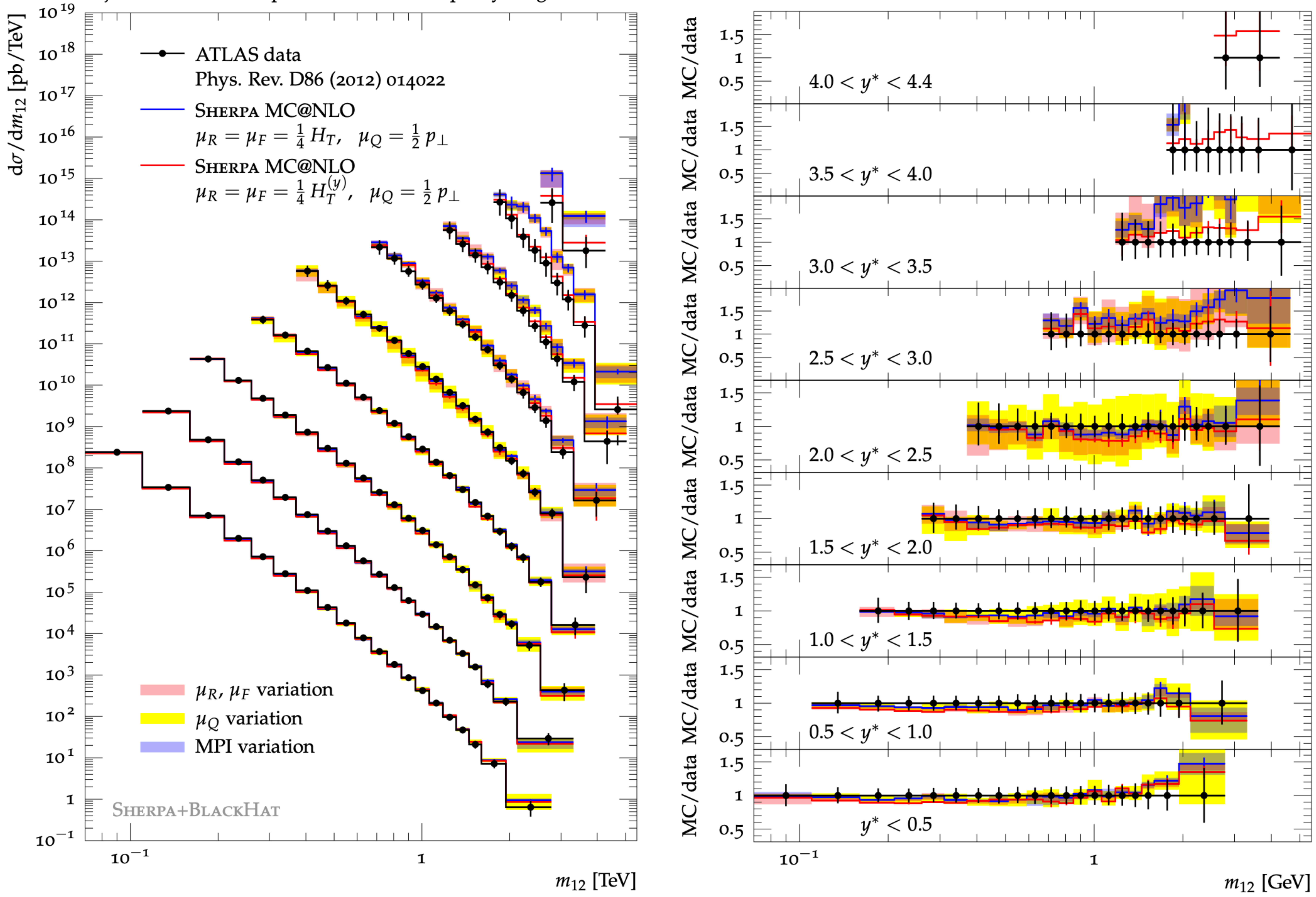


Inclusive jet production at the LHC



Inclusive jet production at the LHC

Dijet invariant mass spectra in different rapidity ranges



POWHEG/MC@NLO

POWHEG

- Positive Weights (Nearly always) **:)**
- Resummation is modified **:(**
- **POWHEG-Box**
- **HERWIH**

MC@NLO

- Resummation is unchanged :)
- Negative Weights :(
- **MC@NLO**
- **SHERPA**
- **aMC@NLO**
- **HERWIG**

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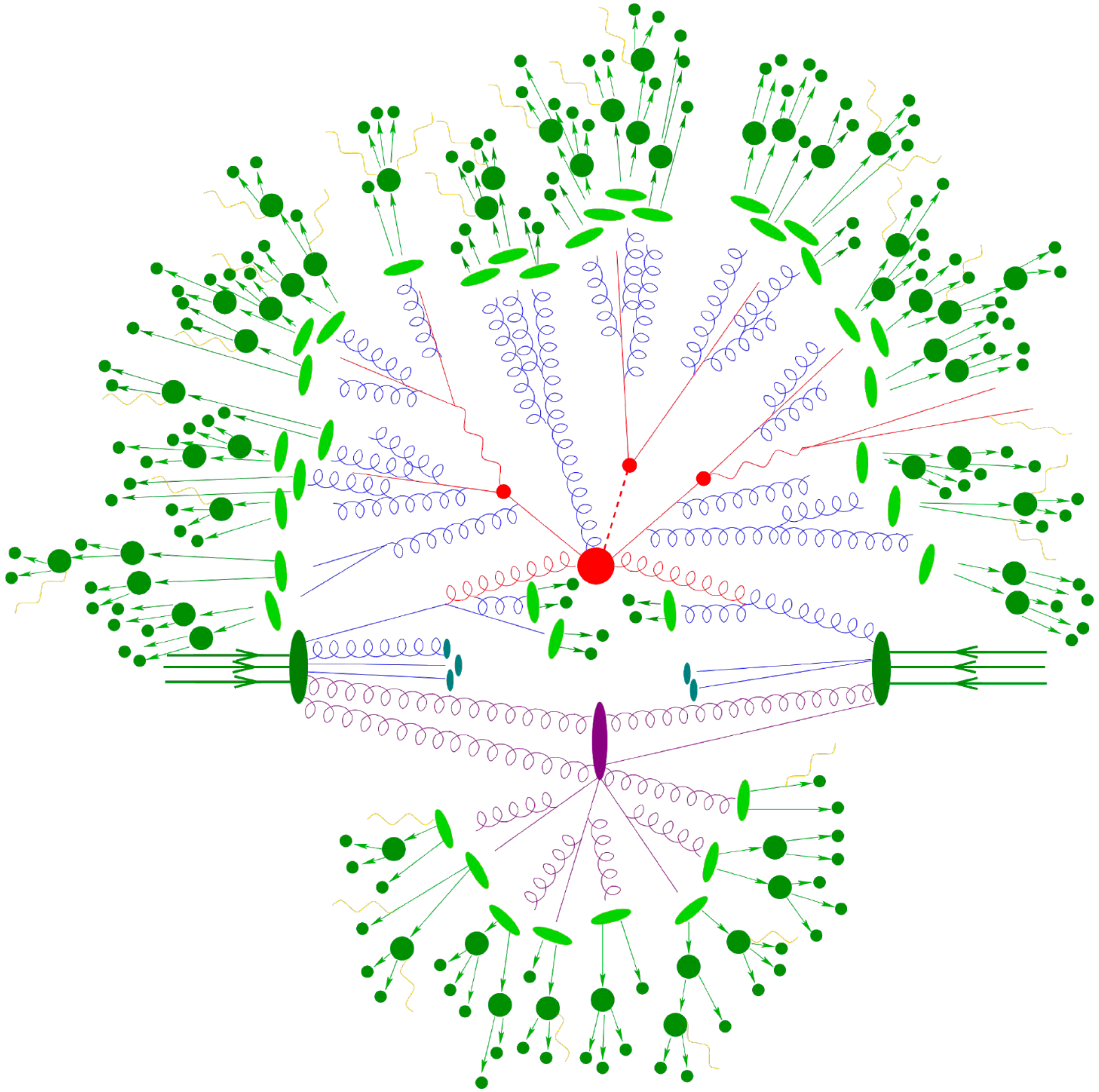
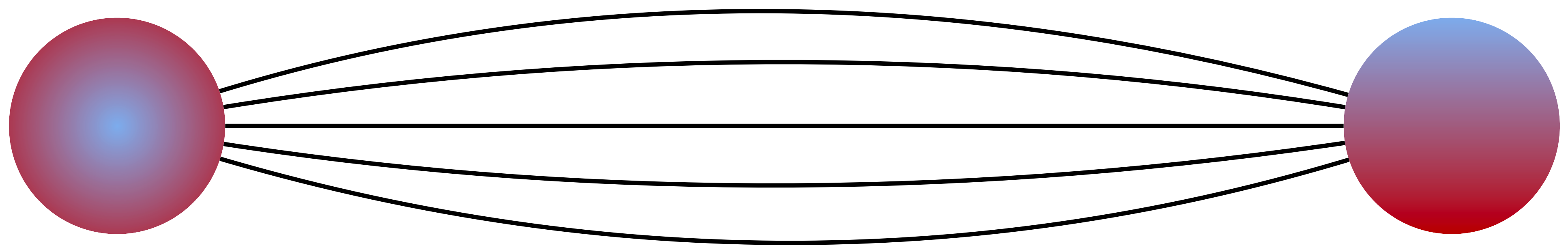
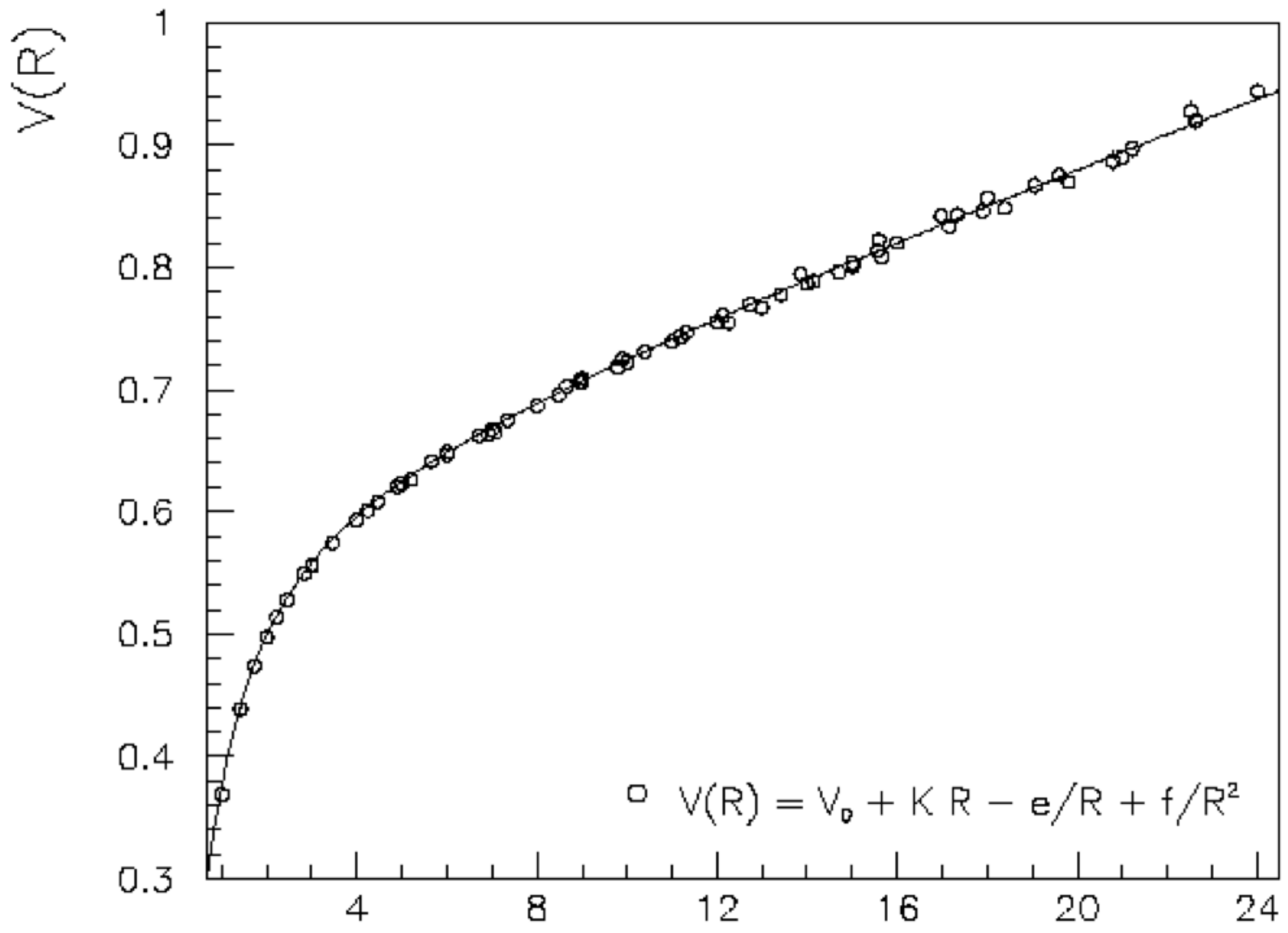


Hadronization

- At short distances $q\bar{q}$ are relatively free
- At long distances the strong forces starts to dominate
- From lattice we see that the QCD potential is approximately linear



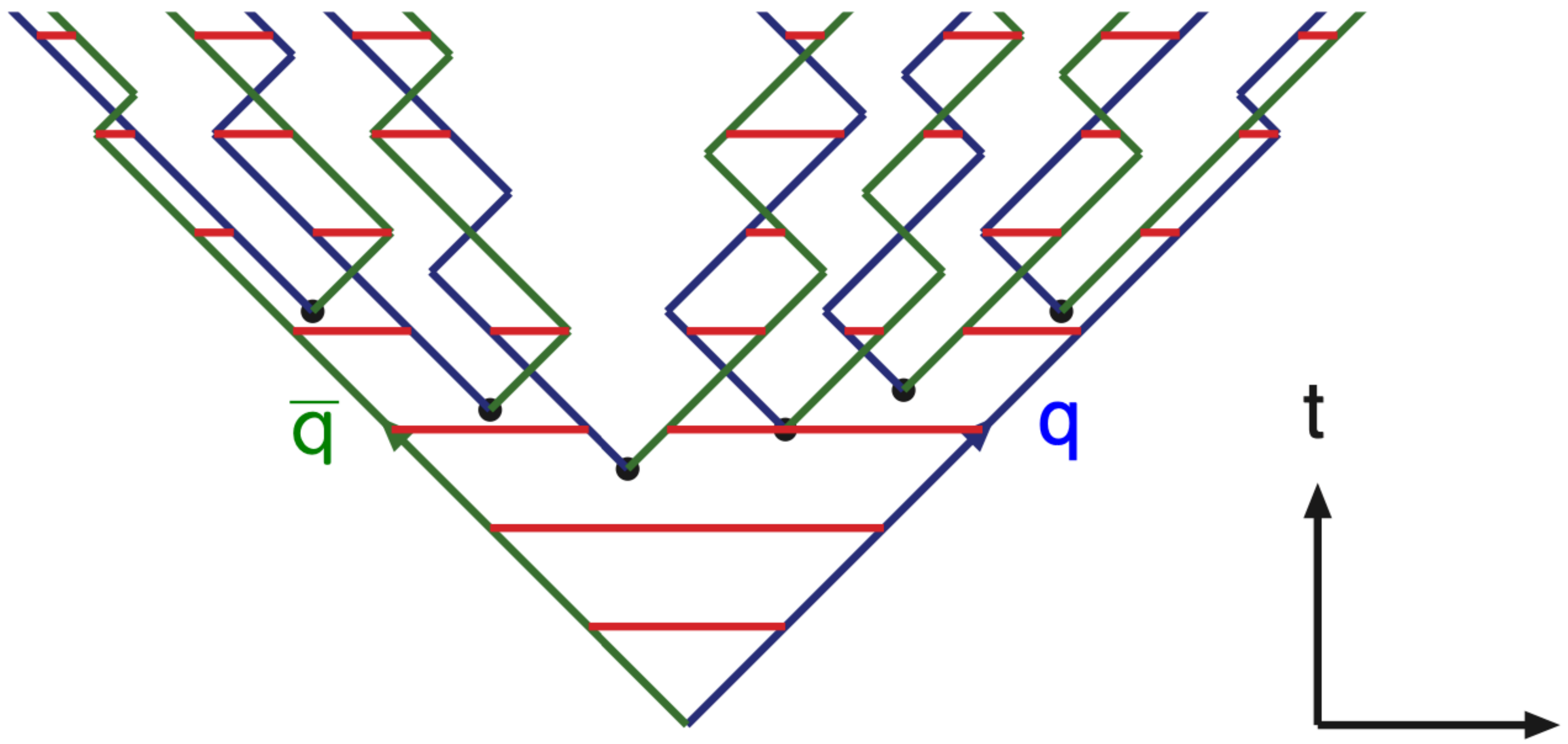
Linear Potential = Confinement



Lund String Model

Andersson,Gustafson,Ingelman,Sj¨ostrand PR97(1983)31

- Assume that light quarks are connected by "Strings"
- New $q\bar{q}$ are created by tunnelling with prob $\approx e^{-\frac{\pi m_q^2}{\sigma}}$, where σ is the string tension
- $q\bar{q}$ pairs can "yo-yo" allowing them to be more dynamical
- Hadrons are then formed from the multiple breakup of strings to more $q\bar{q}$ pairs



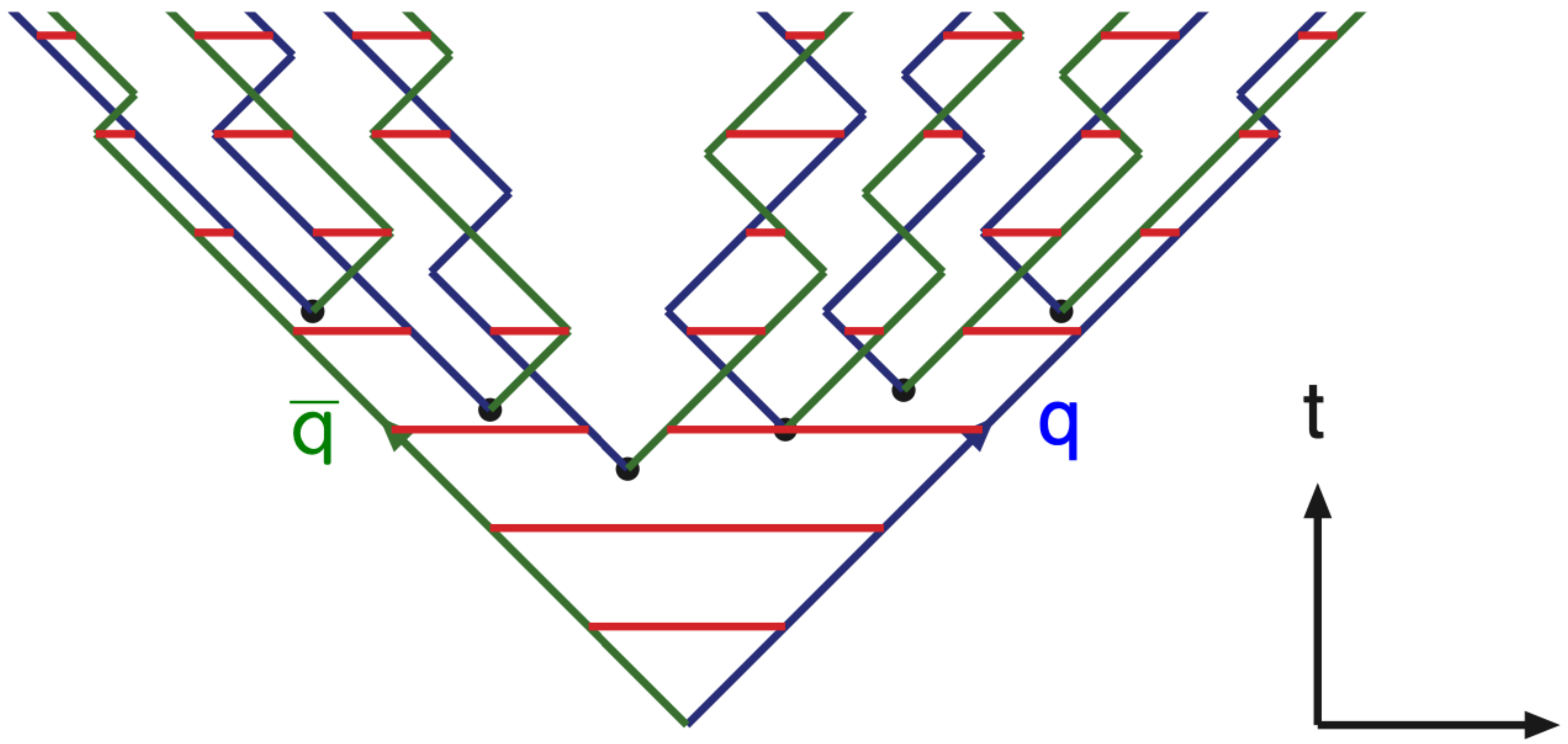
Lund String Model

Andersson,Gustafson,Ingelman,Sj¨ostrand PR97(1983)31

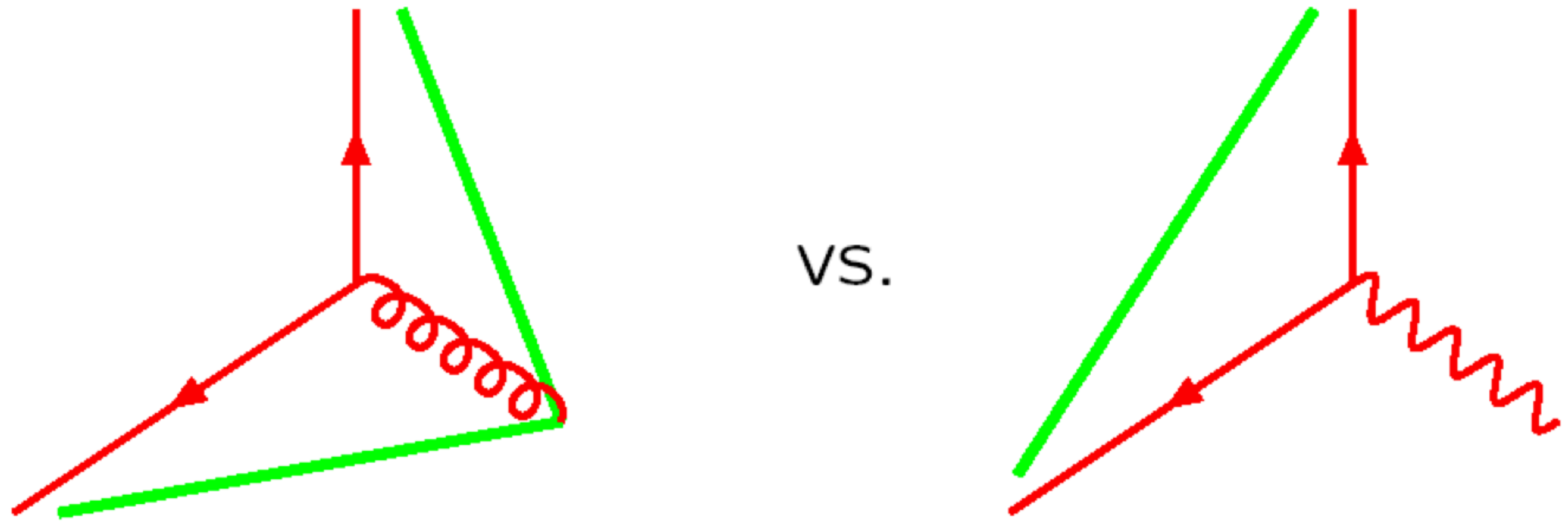
- Gluons can be considered "**kinks**" in the string, with the gluon experiencing twice the string force

- Also see this from the associated Casamir operators

$$\frac{C_A}{C_F} = \frac{9}{4} \approx 2$$



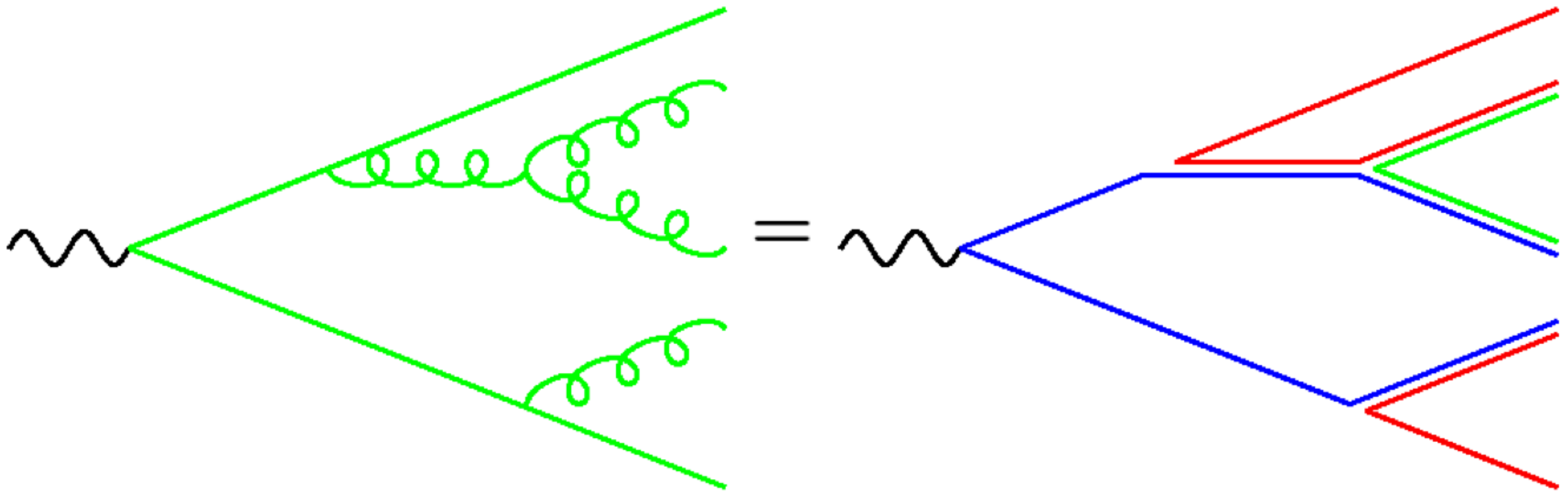
- This means hadron production is enhanced in regions dominated with qg or $g\bar{q}$ pairs while suppressed in $q\bar{q}$



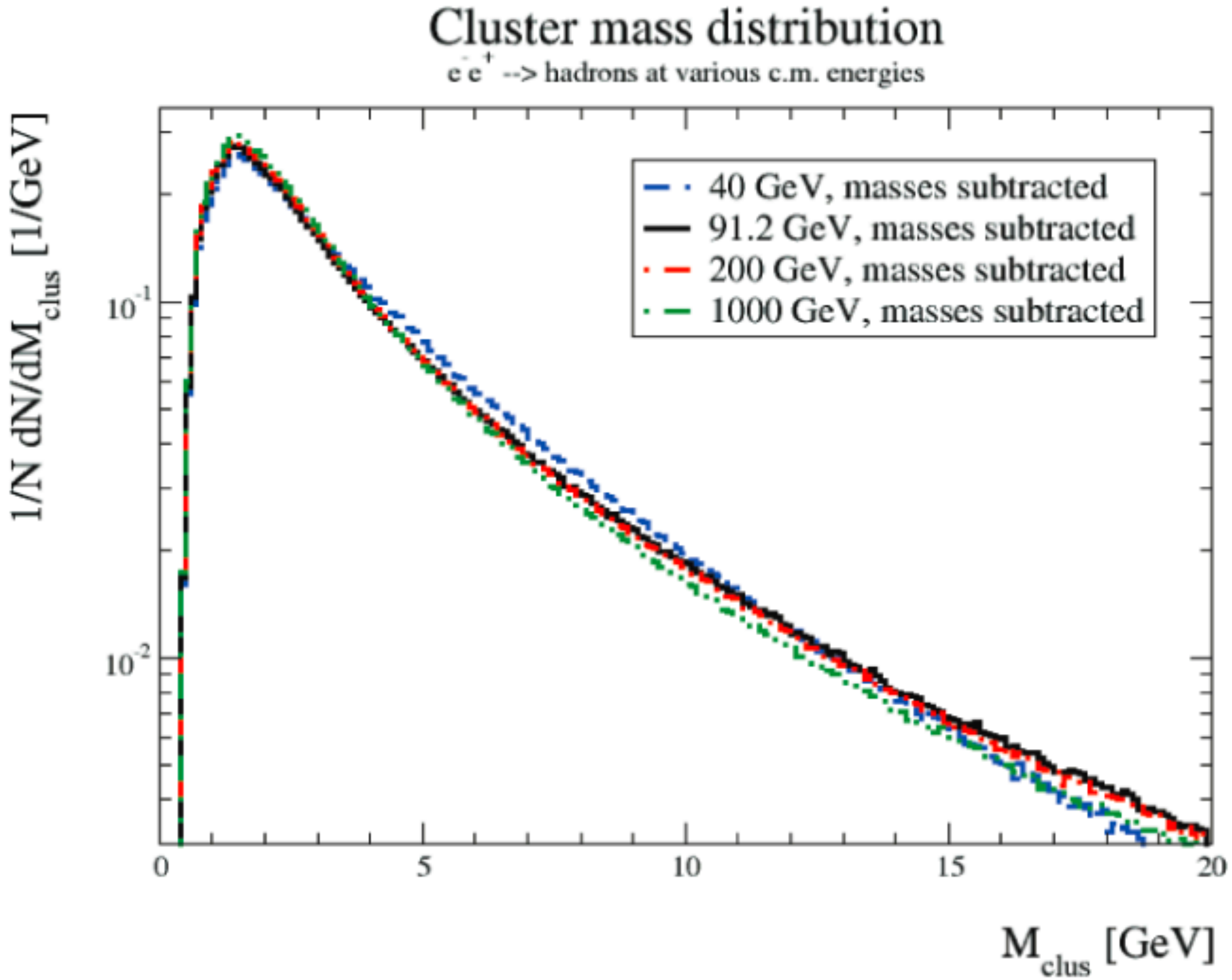
Cluster Model

[Webber] NPB238(1984)492

- Cluster models are based on the idea of **preconfinement**
- At the end of the Parton Shower all gluons are forced to split into $q\bar{q}$ pairs.
- Color pairs end-up close together in phasespace
- Phasespace tells us how the clusters decay into hadrons



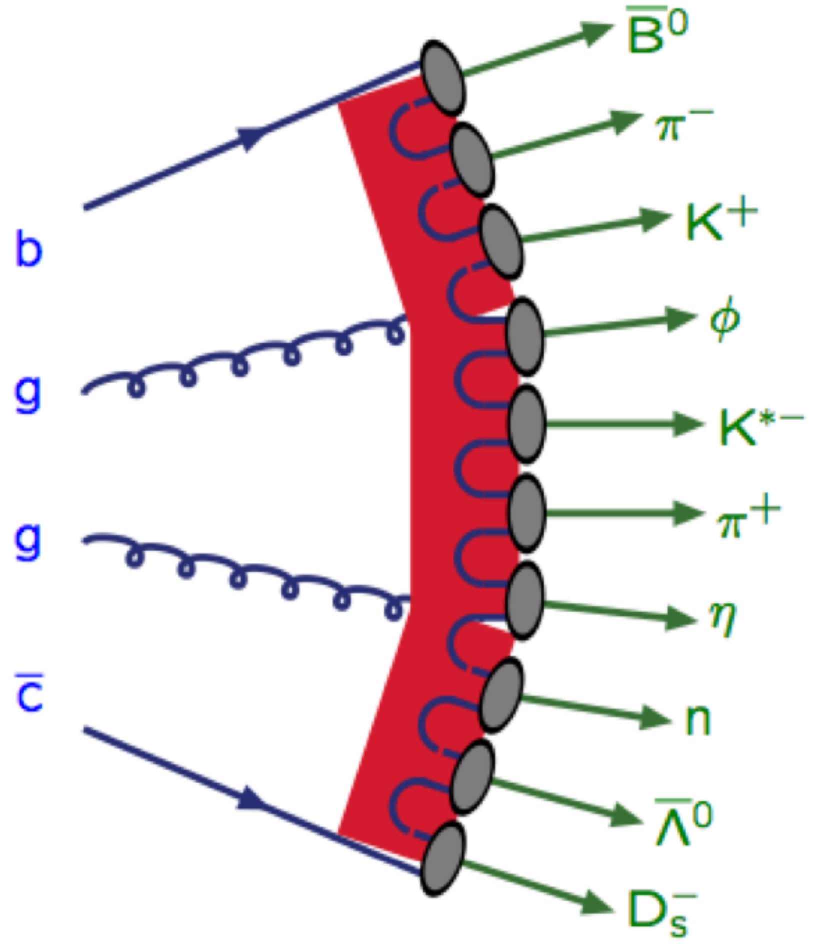
Cluster Model

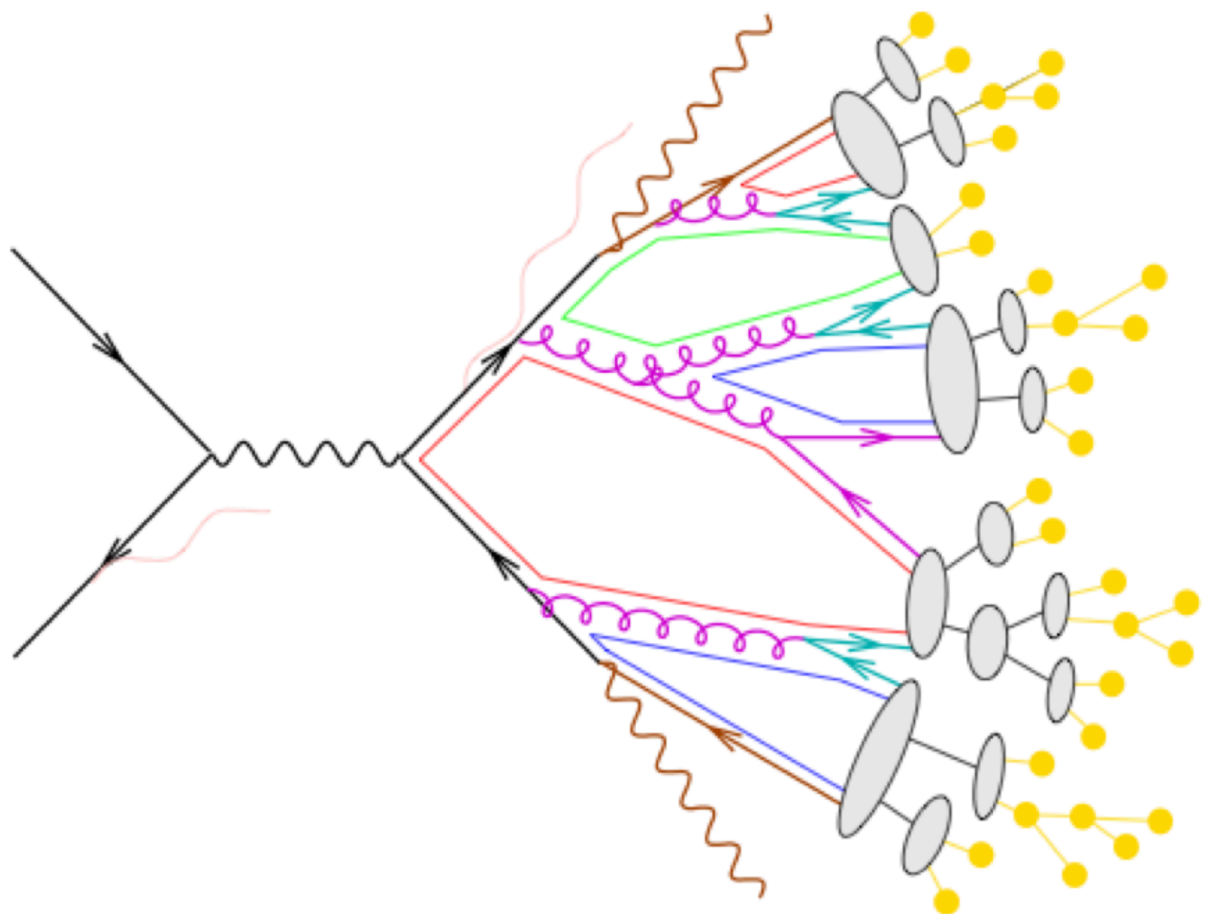


We see that the cluster mass peaks around 1GeV, regardless of the CME

This shows the independence of the cluster at the end of the Parton shower from the hard scale

String vs Cluster





[T.Sjöstrand]

program	PYTHIA	Herwig
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

"There ain't no such thing as a parameter-free *good* description"

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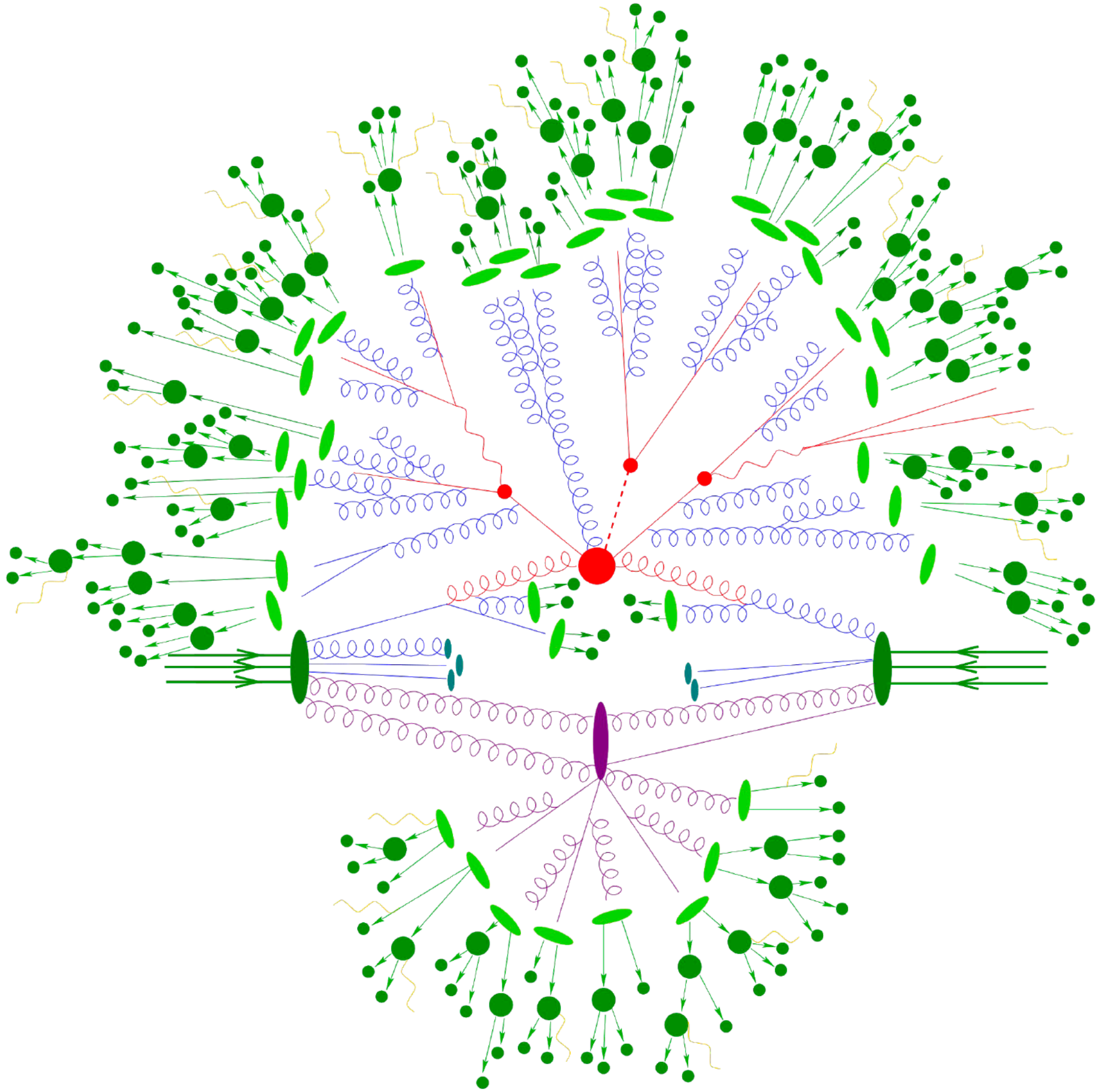
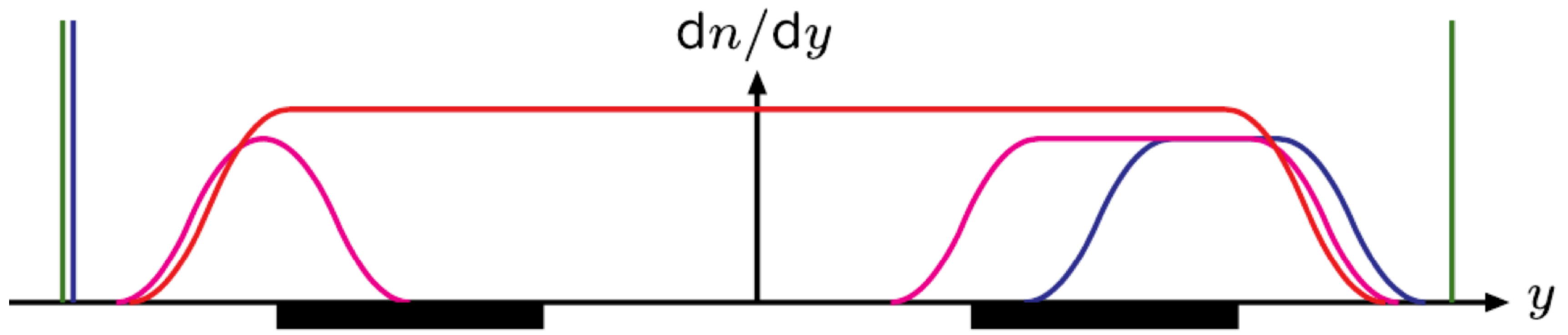
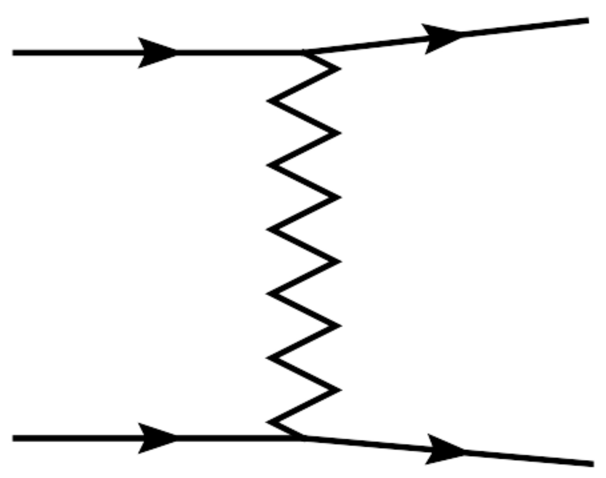


Multi-Parton Interactions

$$\sigma_{\text{total}} = \sigma_{\text{Elastic}} + \sigma_{\text{Single Diffractive}} + \sigma_{\text{Double Diffractive}} + \sigma_{\text{Non Diffractive}}$$



Underlying Event



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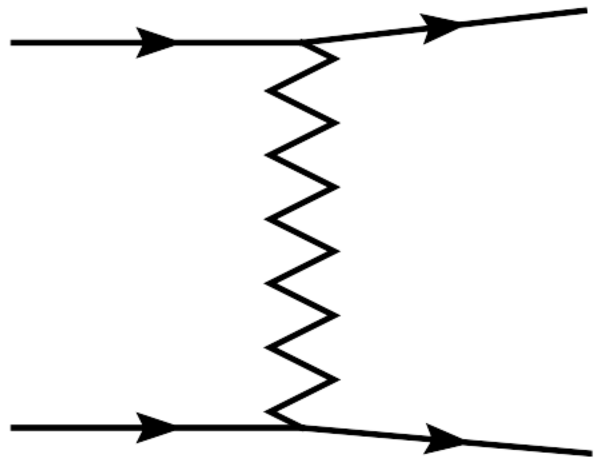
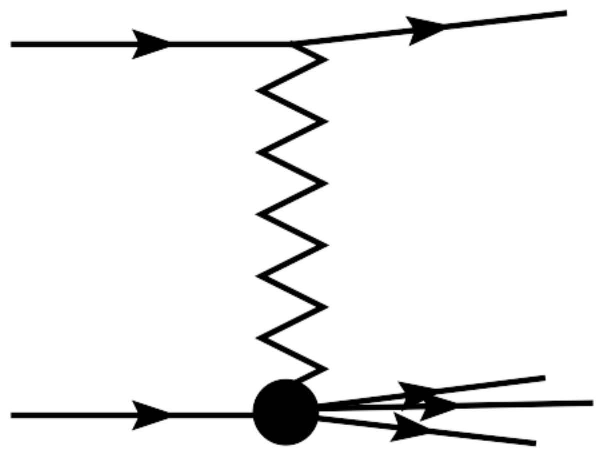
Underlying Event

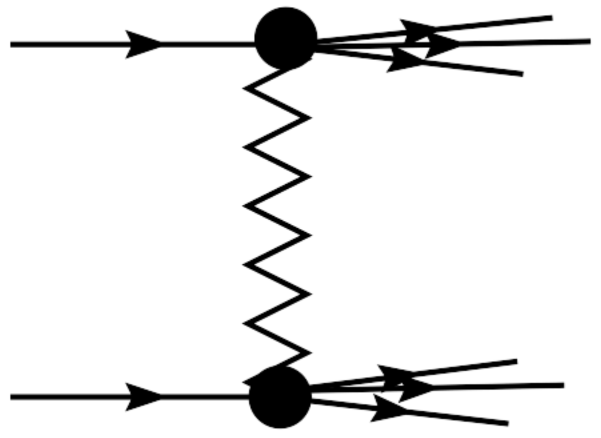
$$\sigma_{\text{total}} = \sigma_{\text{Elastic}} + \sigma_{\text{Single Diffractive}} + \sigma_{\text{Double Diffractive}} + \sigma_{\text{Non Diffractive}}$$



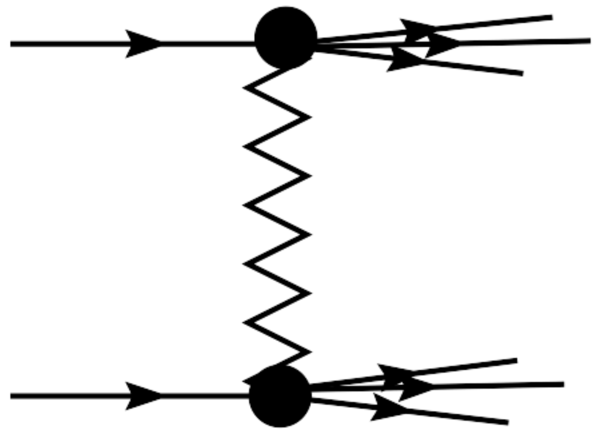


Single diffraction

Underlying Event



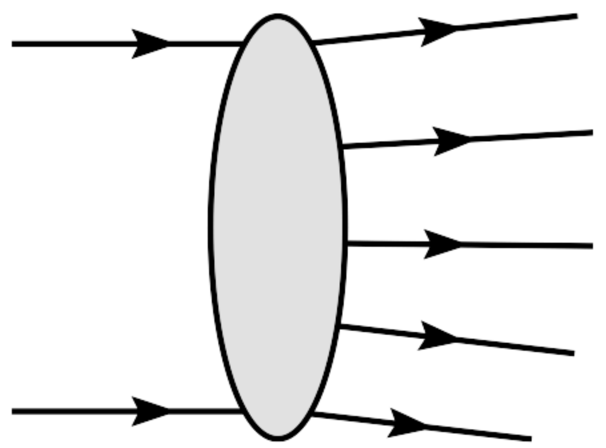
$$\sigma_{\text{total}} = \sigma_{\text{Elastic}} + \sigma_{\text{Single Diffractive}} + \sigma_{\text{Double Diffractive}} + \sigma_{\text{Non Diffractive}}$$

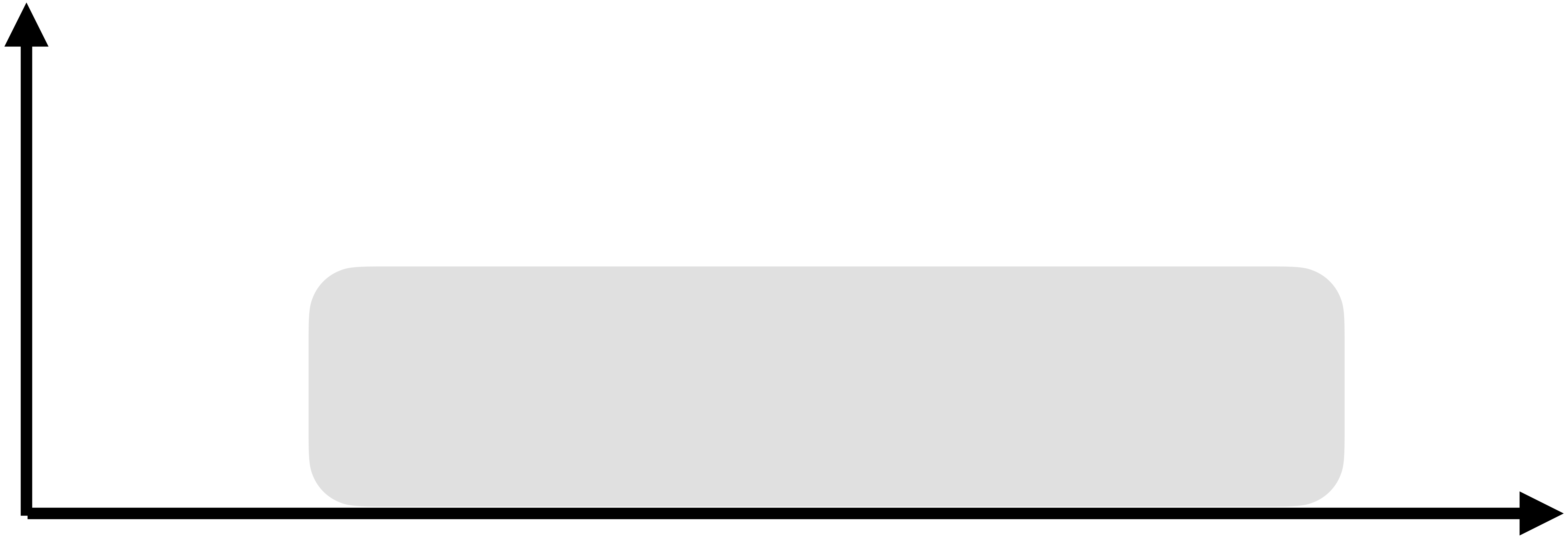


Double diffraction

Underlying Event

$$\sigma_{\text{total}} = \sigma_{\text{Elastic}} + \sigma_{\text{Single Diffractive}} + \sigma_{\text{Double Diffractive}} + \sigma_{\text{Non Diffractive}}$$

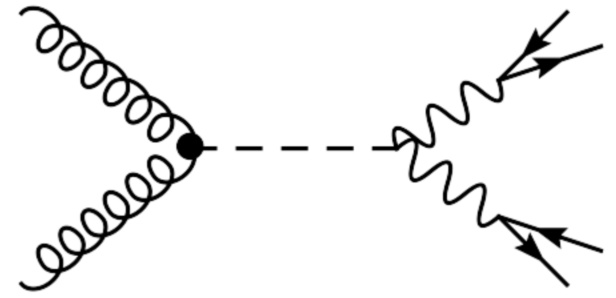


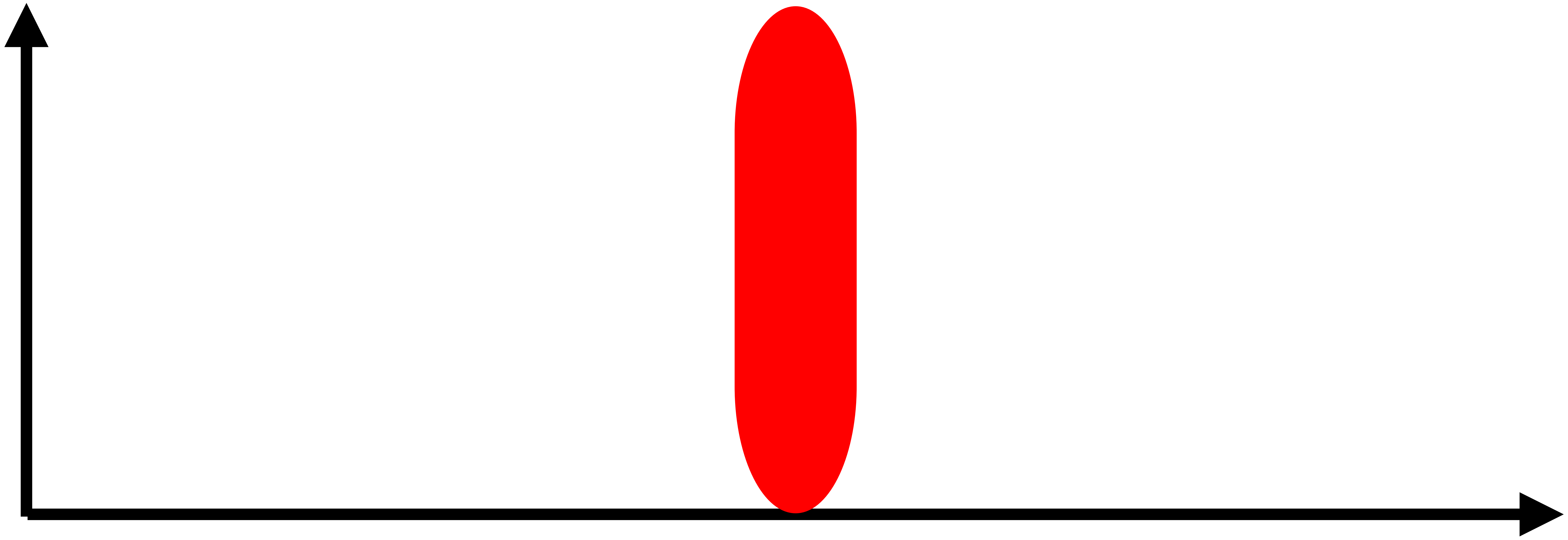


(multiple/soft) interactions

Underlying Event

$$\sigma_{\text{total}} = \sigma_{\text{Elastic}} + \sigma_{\text{Single Diffractive}} + \sigma_{\text{Double Diffractive}} + \sigma_{\text{Non Diffractive}}$$

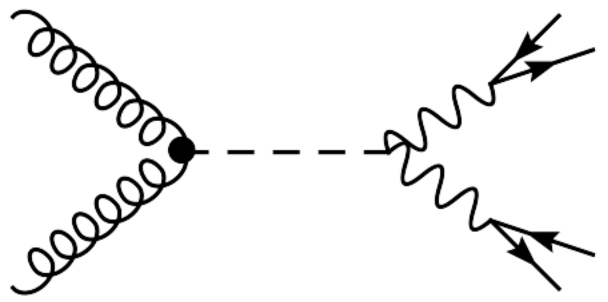


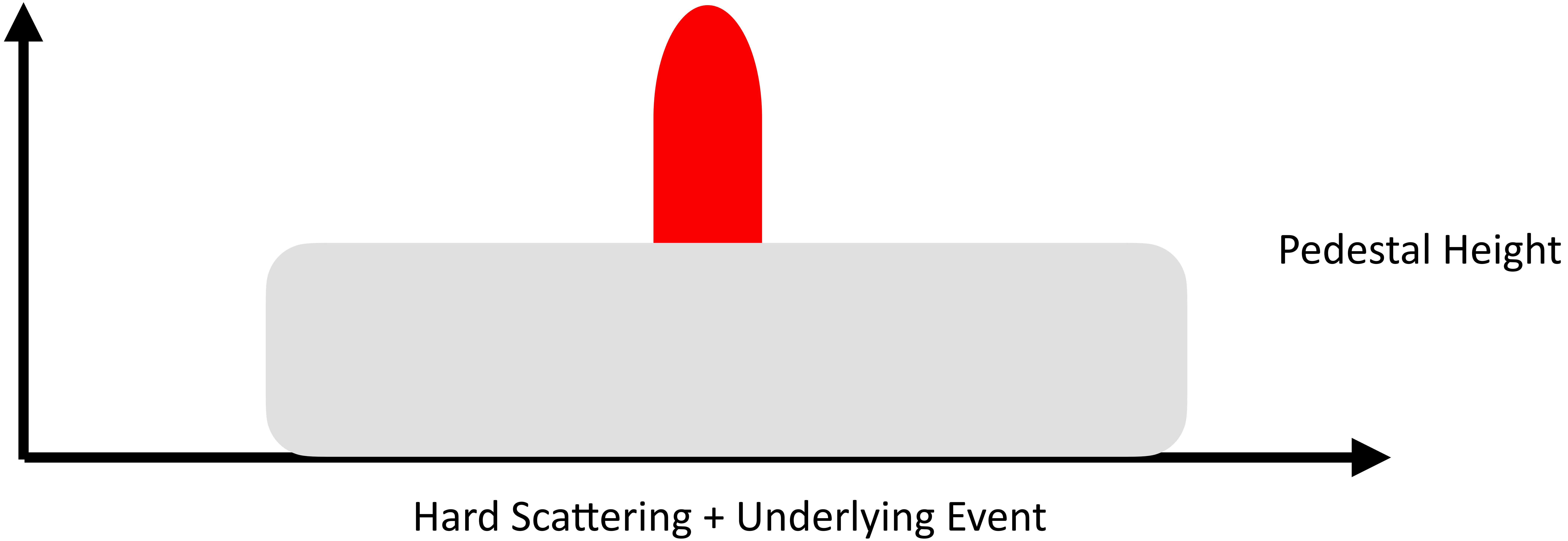


Hard Scattering

Underlying Event

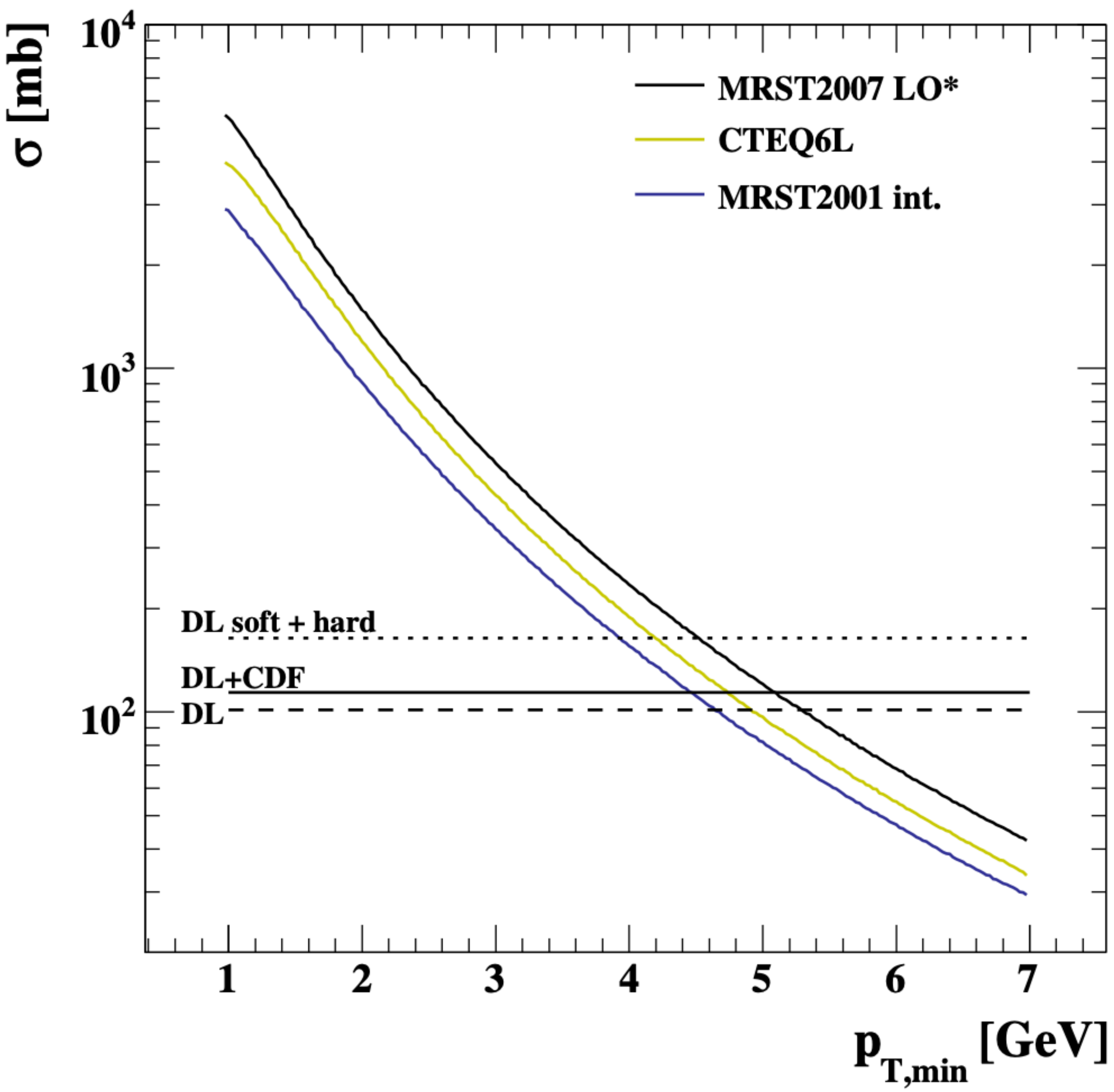
$$\sigma_{\text{total}} = \sigma_{\text{Elastic}} + \sigma_{\text{Single Diffractive}} + \sigma_{\text{Double Diffractive}} + \sigma_{\text{Non Diffractive}}$$





Modelling the Pedestal

[Sjöstrand,Zijl] PRD36(1987)2019



Total LHC cross section is exceeded at low p_T

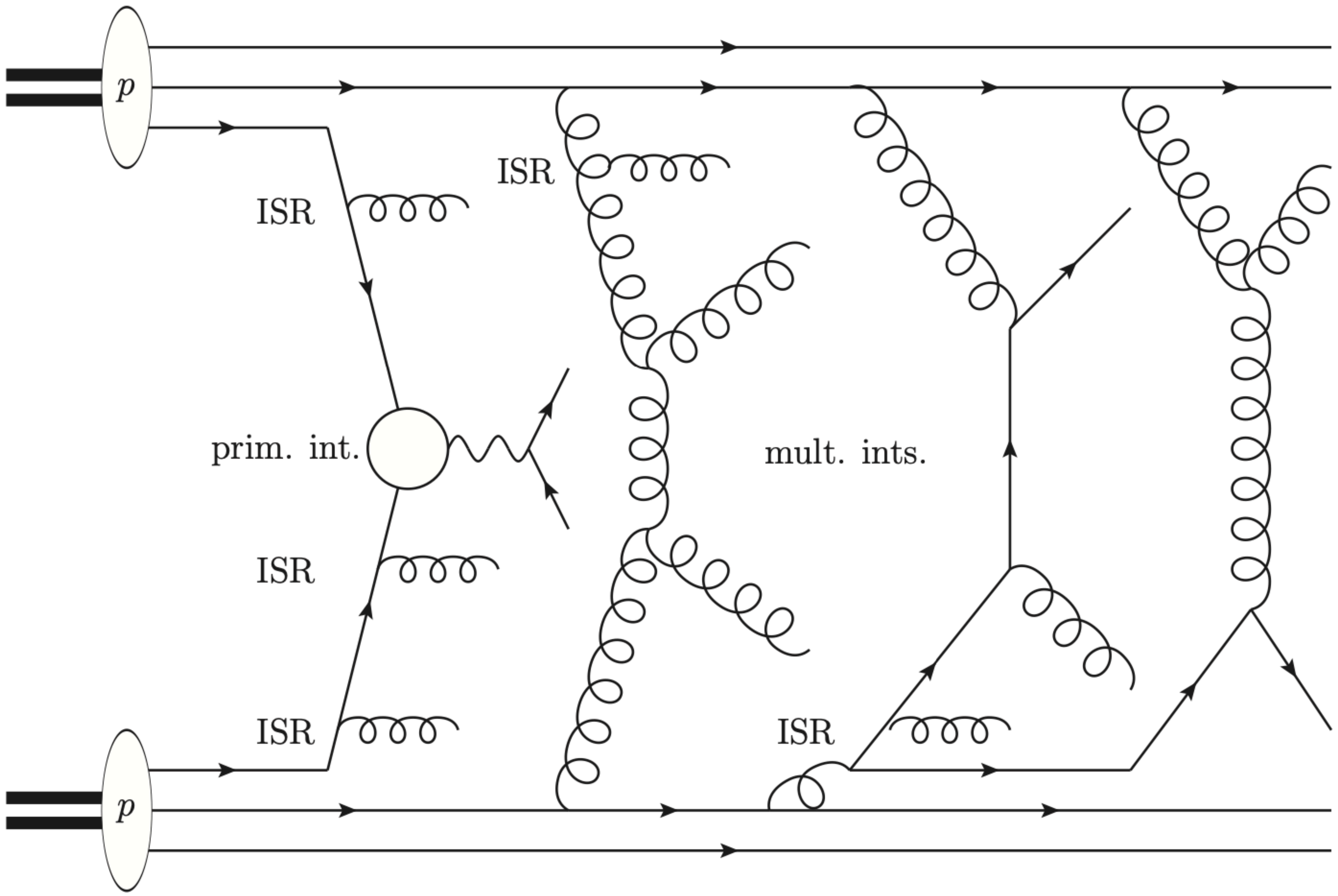
We can interpret this as additional parton-parton scattering per proton collision

$$\langle n \rangle = \frac{\sigma_{\text{Hard}}}{\sigma_{\text{Non Diffractive}}}$$

Main free parameter is P_{Tmin}

Modelling the Pedestal

[Sjöstrand,Zijl] PRD36(1987)2019

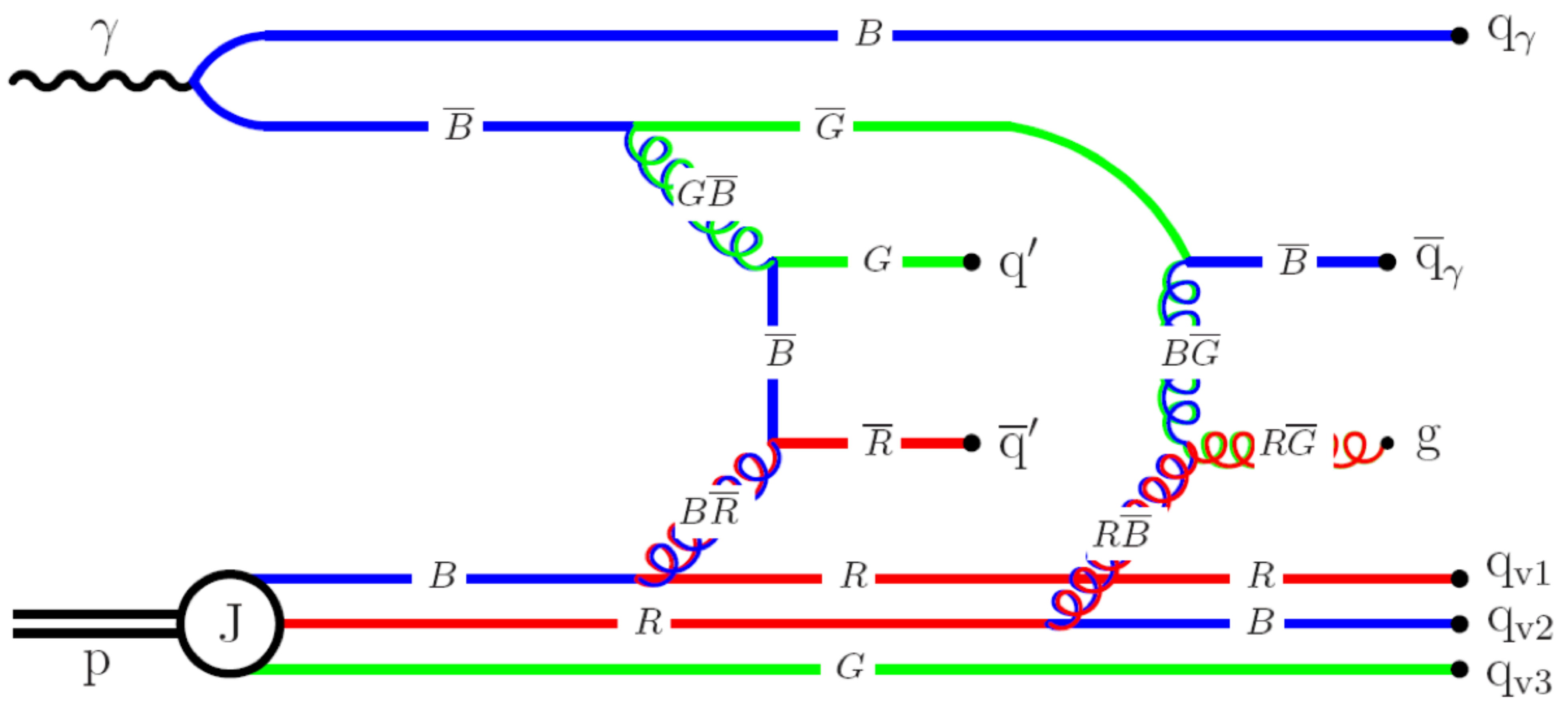


- We will have n independent secondary interactions
- Model each as a perturbative interaction with a non-perturbative form-factor correction

Color connections and beam remnants

[Sjöstrand,Skands] hep-ph/0402078

- Secondary scatterings need to be color-connected to something
- Simplest model would decouple them from proton remnants
- Newer models embed scattering into color topology



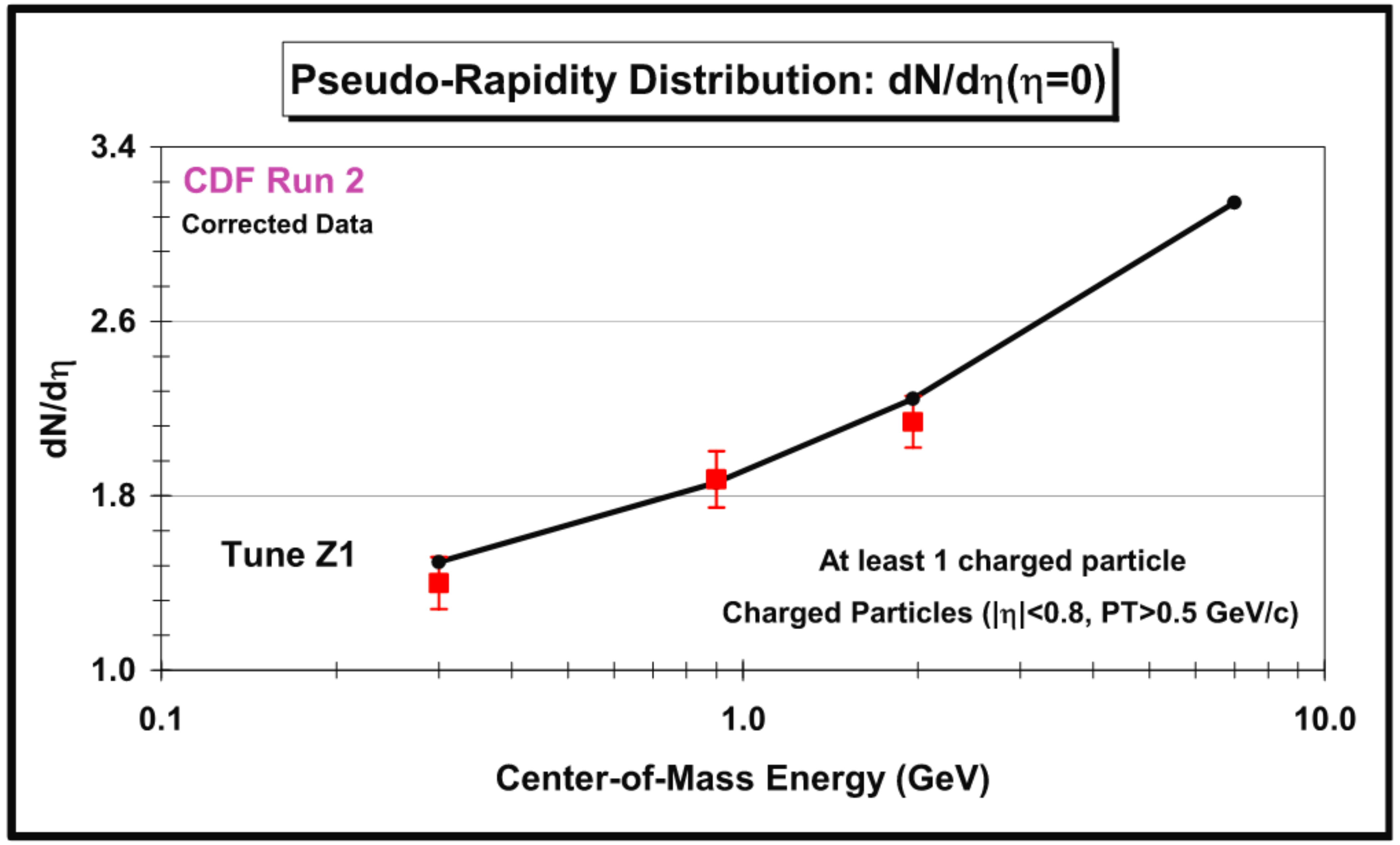
A model for minimum bias

[Butterworth,Forshaw,Seymour] hep-ph/9601371

- Peripheral collision of particles in a collision
- Take the parton distribution in a beam as

$$\frac{dn_a(x,\mathbf{b})}{d^2\mathbf{b}dx} = f_a(x)\,G(\mathbf{b})$$

$$G(\mathbf{b}) = \int \frac{d^2\mathbf{k}}{(2\pi)^2}\,\frac{\exp(\mathbf{k}\cdot\mathbf{b})}{(1+\mathbf{k^2}/\mu^2)^2}$$



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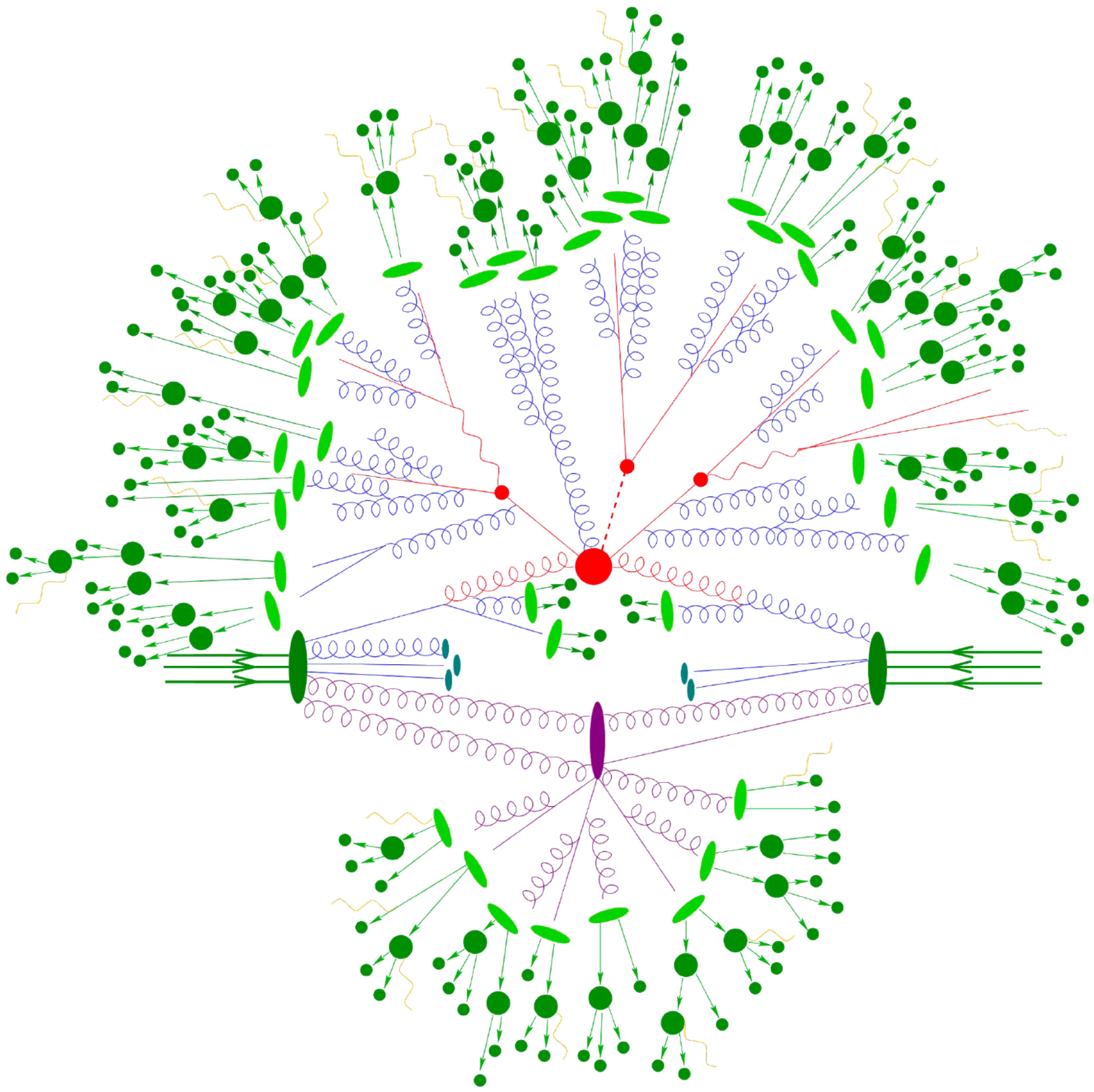

Hadron Decays

- Most hadrons are unstable and will **decay**
- In practice there are $\approx \mathcal{O}(1000)$ decay channels
- PDG contains tables of branching ratios

Issues

- Not all resonances have been measured
- BR rarely add up to 100% and some have large uncertainties
- Can lead to non-trivial effects in the hadronization, event shapes, etc..

η DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Neutral modes			
neutral modes	(71.96 ± 0.30) %	S=1.3	–
2γ	(39.36 ± 0.18) %	S=1.1	274
$3\pi^0$	(32.57 ± 0.21) %	S=1.2	179
$\pi^0 2\gamma$	$(2.55\pm0.22)\times10^{-4}$		257
$2\pi^0 2\gamma$	$< 1.2 \times10^{-3}$	CL=90%	238
4γ	$< 2.8 \times10^{-4}$	CL=90%	274
invisible	$< 1.0 \times10^{-4}$	CL=90%	–
Charged modes			
charged modes	(28.04 ± 0.30) %	S=1.3	–
$\pi^+\pi^-\pi^0$	(23.02 ± 0.25) %	S=1.2	174
$\pi^+\pi^-\gamma$	(4.28 ± 0.07) %	S=1.1	236
$e^+e^-\gamma$	$(6.9\pm0.4)\times10^{-3}$	S=1.2	274
$\mu^+\mu^-\gamma$	$(3.1\pm0.4)\times10^{-4}$		253
e^+e^-	$< 7 \times10^{-7}$	CL=90%	274
$\mu^+\mu^-$	$(5.8\pm0.8)\times10^{-6}$		253
$2e^+2e^-$	$(2.40\pm0.22)\times10^{-5}$		274
$\pi^+\pi^-e^+e^-(\gamma)$	$(2.68\pm0.11)\times10^{-4}$		235
$e^+e^-\mu^+\mu^-$	$< 1.6 \times10^{-4}$	CL=90%	253
$2\mu^+2\mu^-$	$(5.0\pm1.3)\times10^{-9}$		161
$\mu^+\mu^-\pi^+\pi^-$	$< 3.6 \times10^{-4}$	CL=90%	113
$\pi^+e^-\overline{\nu}_e$+ c.c.	$< 1.7 \times10^{-4}$	CL=90%	256
$\pi^+\pi^-2\gamma$	$< 2.1 \times10^{-3}$		236
$\pi^+\pi^-\pi^0\gamma$	$< 6 \times10^{-4}$	CL=90%	174
$\pi^0\mu^+\mu^-\gamma$	$< 3 \times10^{-6}$	CL=90%	210

S. Navas et al. (Particle Data Group), to be published in Phys. Rev. D 110, 030001 (2024)

Structure of LHC Events: Conclusion

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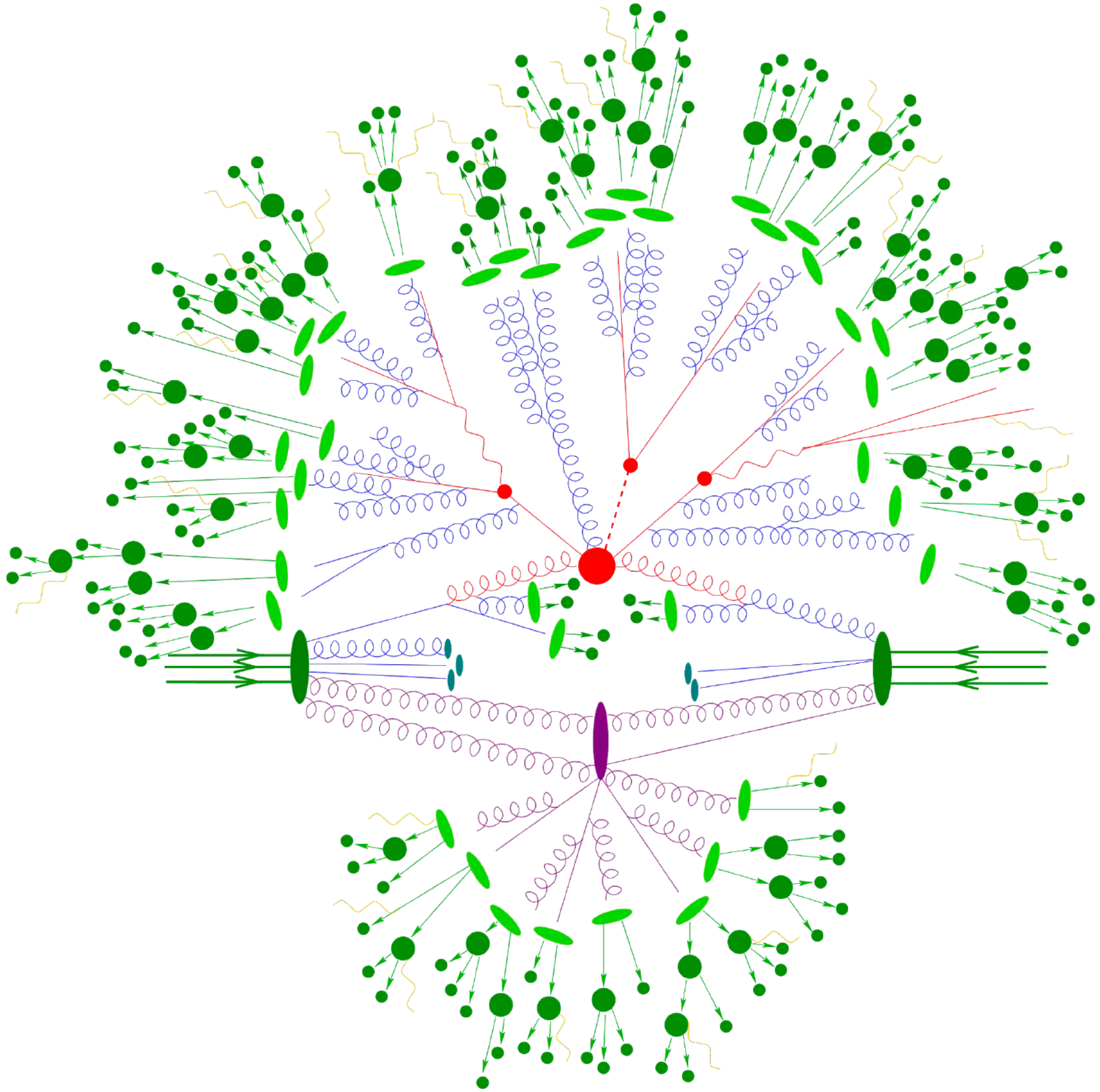


Sherpa 3.0.0 “Erebus”

- New major release of Sherpa happened this week
- Culmination of many years of work
- Issue/feature request on gitlab page

SHERPA

https://sherpa-team.gitlab.io

Sherpa 3.0.0 “Erebus”

Physics Improvements and New Capabilities

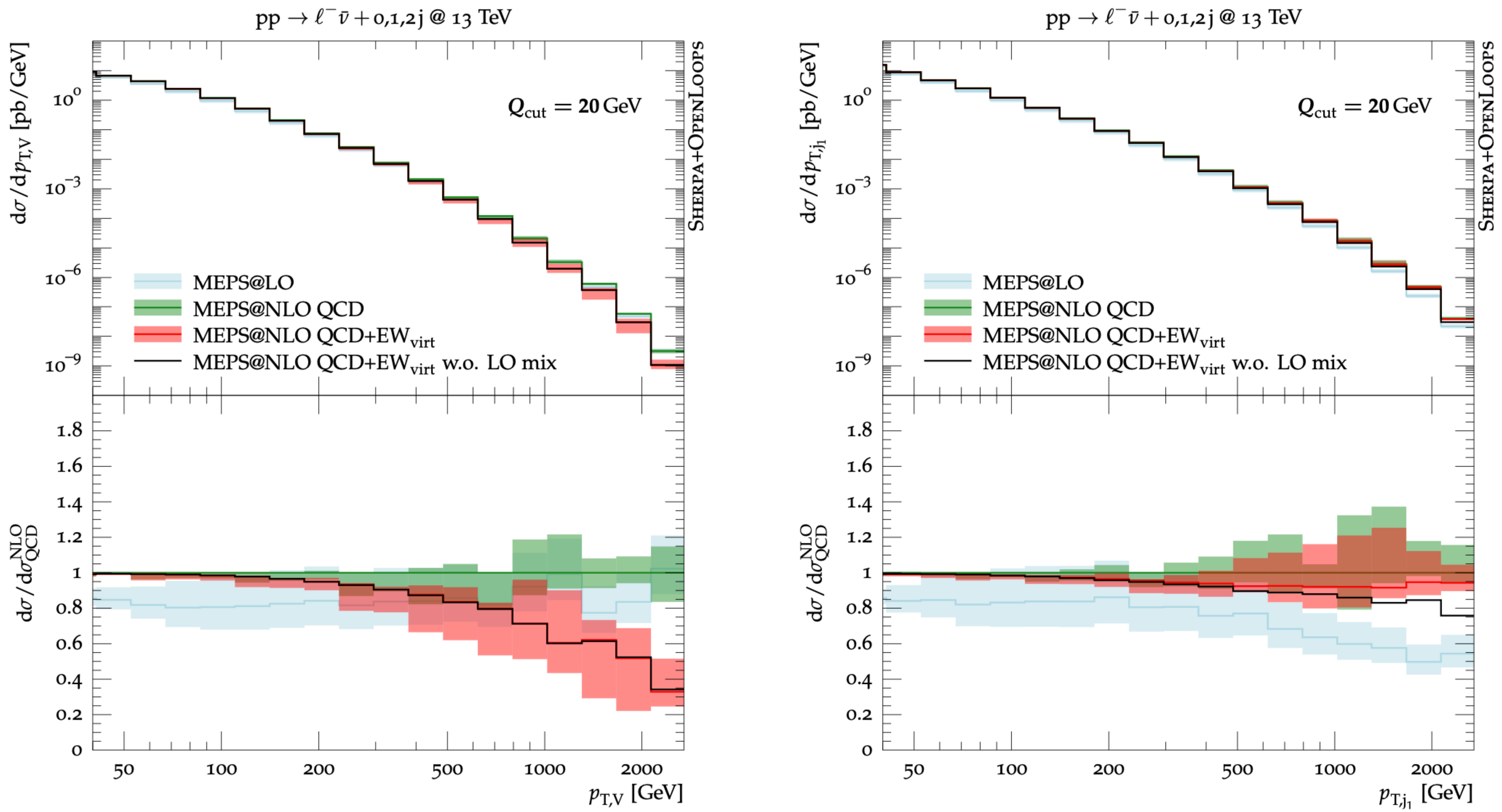
- NLO EW corrections for fixed-order predictions
- Polarized cross sections for massive vector bosons !619
- EW Sudakov logarithms (!831, !464)
- Improved scale setting for VBF processes !723
- Add Recola interface !463, including but not limited to on-/off-shell W+W+jj production for both t-channel (VBS) and s-channel (W+W+W-) production !849
- Add model for instanton production (!813, !476, !447, !366)
- Photoproduction at MC@NLO accuracy !448
- New MPI and MinBias modelling including photon MPIs !687
- Photon splittings in YFS resummation (!641, !660, !663)
- YFS for initial state radiation in lepton-lepton collisions !830
- Add simple color reconnection model (!361, !201, !173)
- Upgrade embedded Lund hadronisation implementation from Pythia 6 to Pythia 8 !774
- Implement UFO 2.0 support for handling form factors !834
- New on-the-fly variations for the merging cut (QCUT) parameter and for AlphaS(MZ). The latter can now be used instead of relying on implicit variations via PDF variations, e.g. to vary the strong coupling for lepton collider setups !295
- Additional new ME interfaces for external generators !419
    - Support for the MCFM BLHA interface
    - Support for MadLoop
    - Comix/Amegic programmatic interface to external generators
    - Support for resummation and full / leading color ME corrections
- First version of BLHA2 support (tested with GoSam for ee->bb) !390

YAML Input

```
(run){
  # general settings
  EVENTS 25000;

  # collider setup
  BEAM_1 2212; BEAM_ENERGY_1 6500;
  BEAM_2 2212; BEAM_ENERGY_2 6500;

  # generator parameters
  WIDTH[6] 0;

  # scale choice
  CORE_SCALE VAR{sqr(175)};
  HARD_DECAYS=1
  WIDTH[6] 0;

  # settings to accelerate event generation
  MI_HANDLER None;
  FRAGMENTATION Off;
}(run);

(processes){
  Process 93 93 -> 6 -6 93{1};
  CKKW sqr(20/E_CMS);
  Order (*,0);
  End process;
}(processes);
```

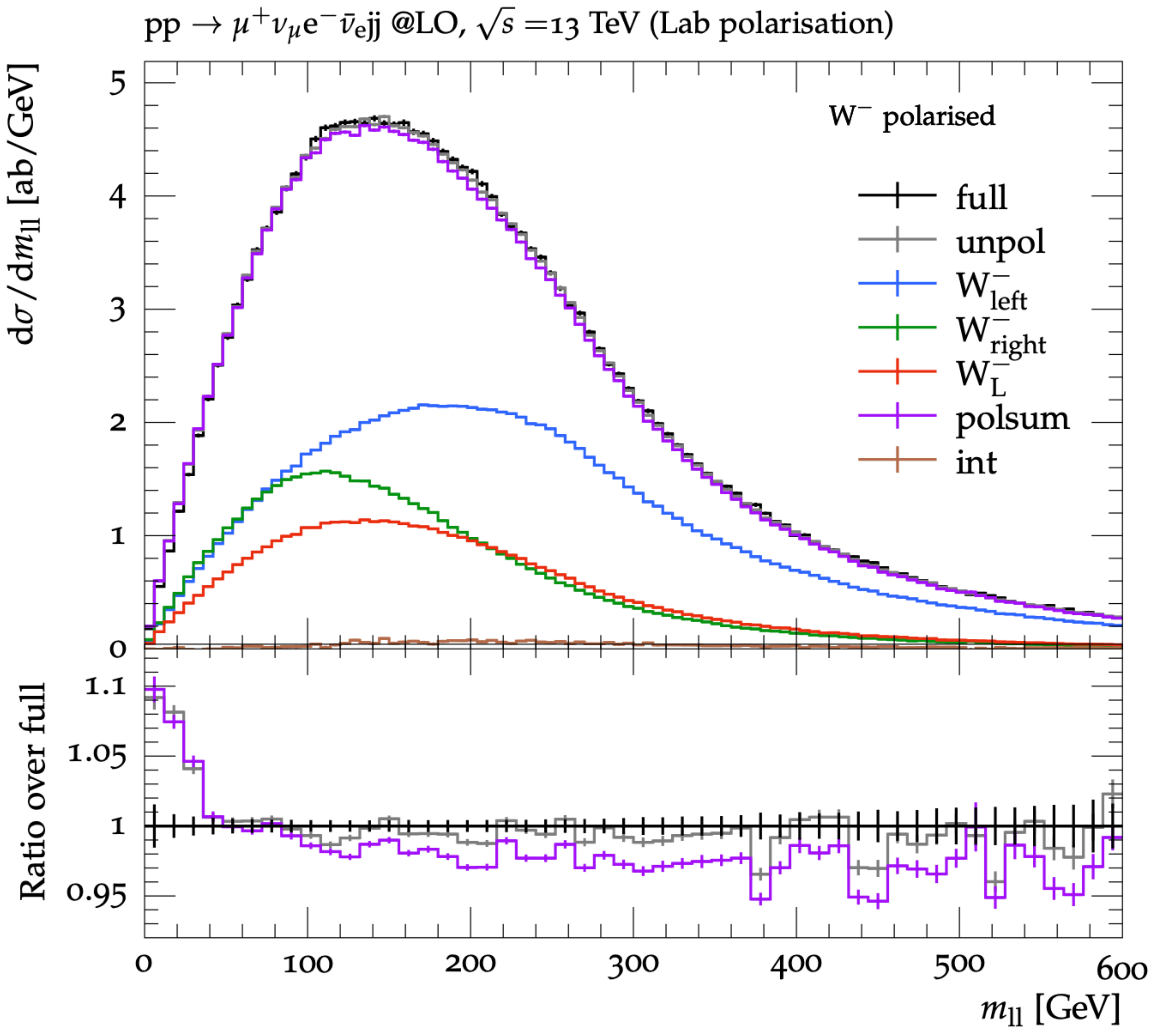
```yaml
# collider setup
BEAMS: 2212
BEAM_ENERGIES: 6500

# scales
EXCLUSIVE_CLUSTER_MODE: 1
MEPS:
  CORE_SCALE: TTBar

# me generator settings
ME_GENERATORS: [Comix, Amegic]

# decays
HARD_DECAYS:
  Enabled: true
  Channels:
    24,2,-1: {Status: 0}
    24,4,-3: {Status: 0}
    -24,-2,1: {Status: 0}
    -24,-4,3: {Status: 0}

PARTICLE_DATA:
  6: {Width: 0}

# on-the-fly variations
SCALE_VARIATIONS: 4.0*  # 7-point scale variations

PROCESSES:
- 93 93 -> 6 -6 93{1}:
    Order: {QCD: 2, EW: 0}
    CKKW: 20
```

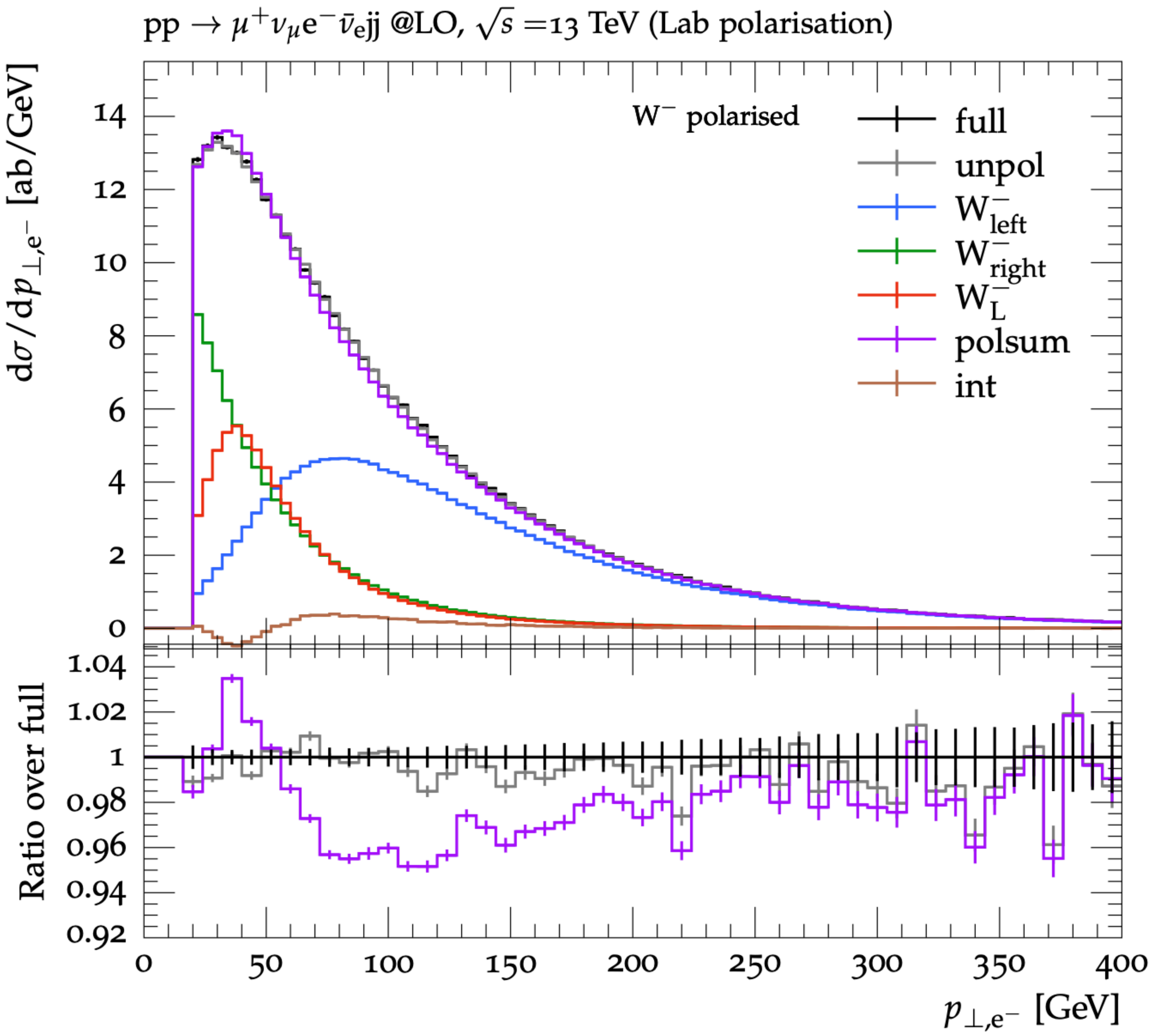
EW Corrections



Polarised Cross-Sections

Mareen Hoppe, Marek Schönherr, Frank Siegert





https://arxiv.org/pdf/2310.14803

EW Sudakovs

Bothmann, Napoletano arXiv:2006.14635

- EW Sudakov approximation for parton showered event generation