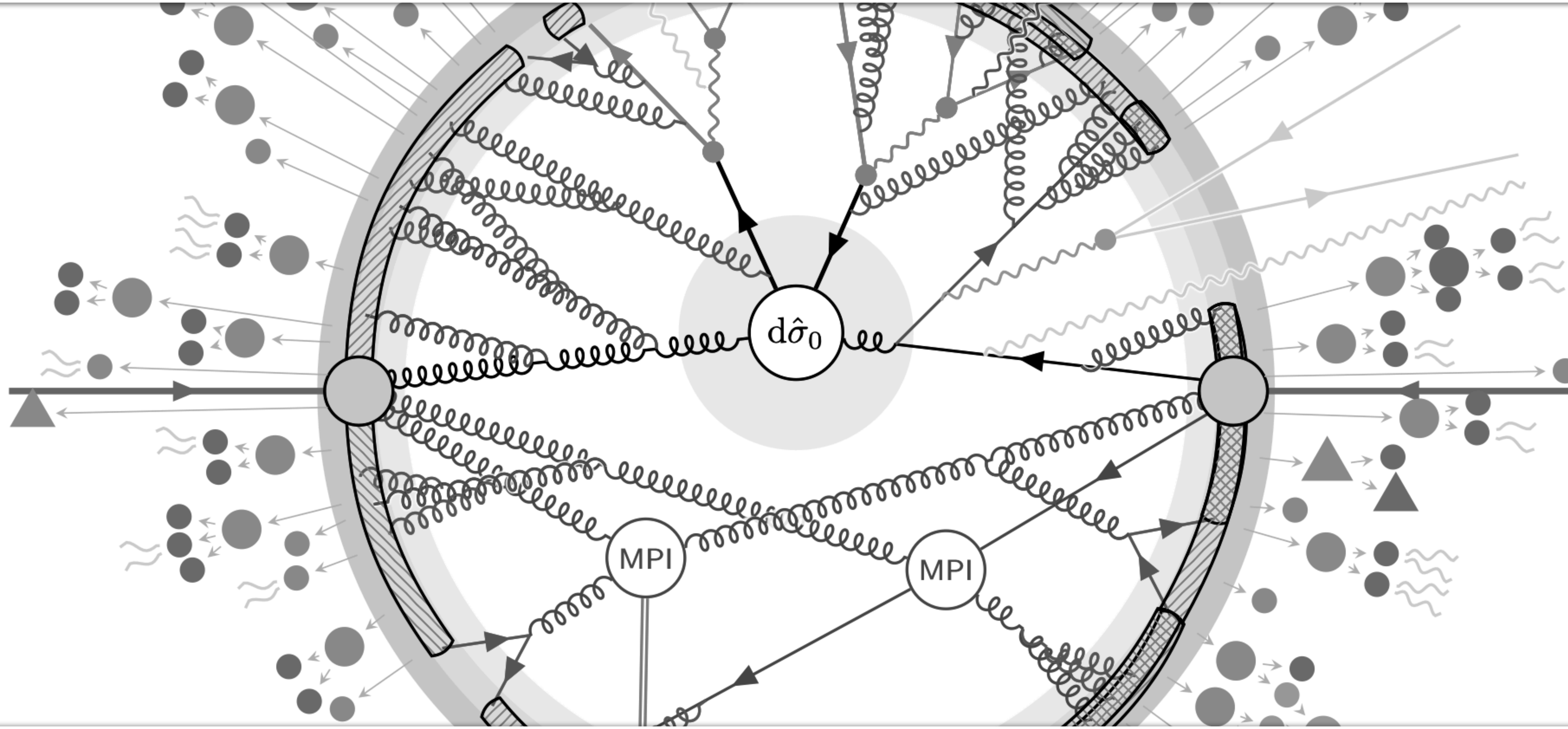
PYTHIA Overview

Peter Skands — U of Oxford & Monash U.



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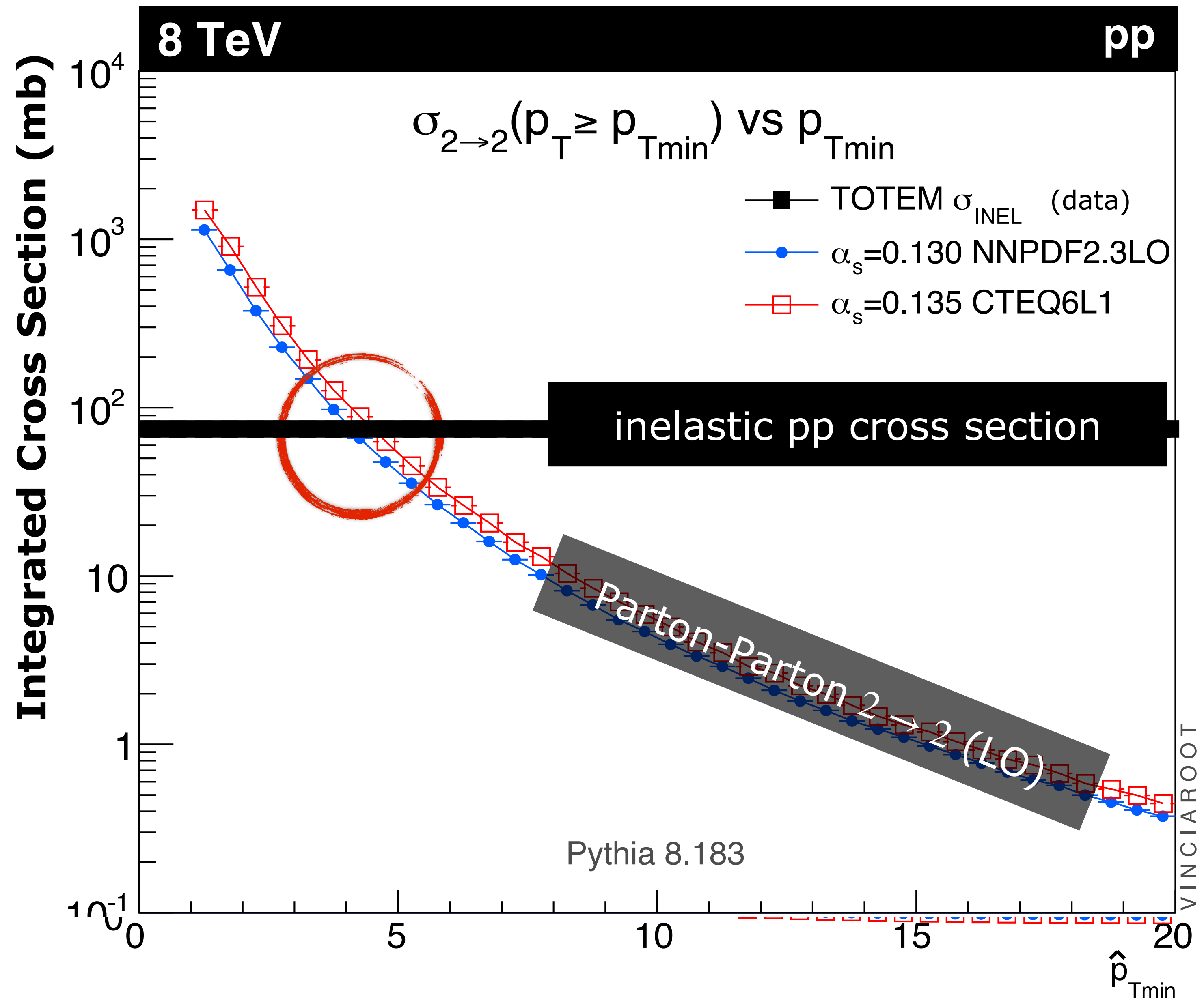
A Brief History of MPI in PYTHIA

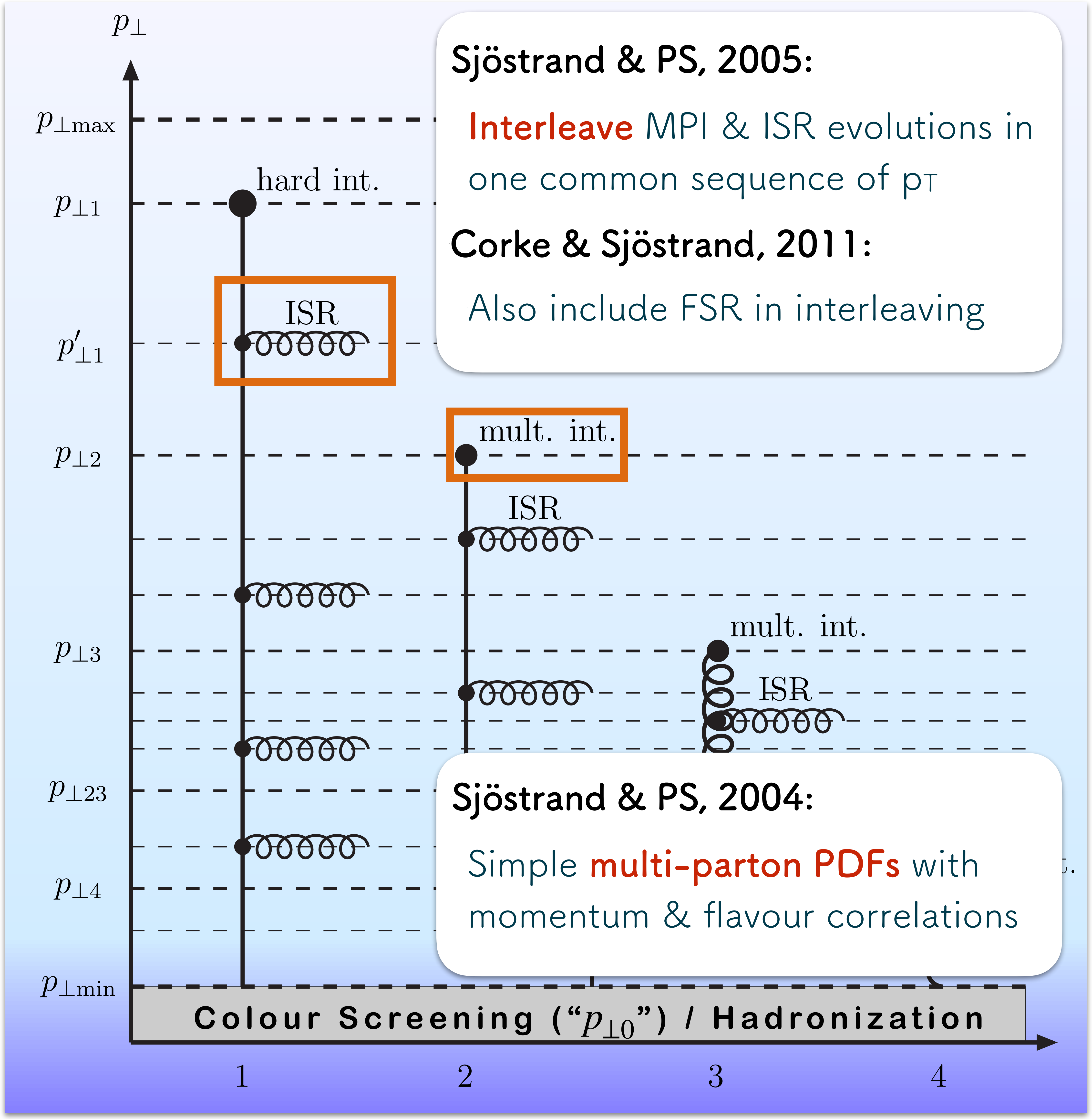
$$\frac{\sigma_{\text{parton-parton}}(\hat{p}_\perp)}{\sigma_{\text{hadron-hadron}}} > 1$$

$\Longrightarrow$ several parton-parton interactions *per* hadron-hadron interaction: **MPI**



Sjöstrand & van Zijl, 1985:

Cast as **Sudakov-style evolution equation**, analogous to the $\sigma_{X+\text{jet}}(p_\perp)/\sigma_X$ one for showers



Sjöstrand & PS, 2005:

Interleave MPI & ISR evolutions in one common sequence of pT

Corke & Sjöstrand, 2011:

Also include FSR in interleaving

Sjöstrand & PS, 2004:

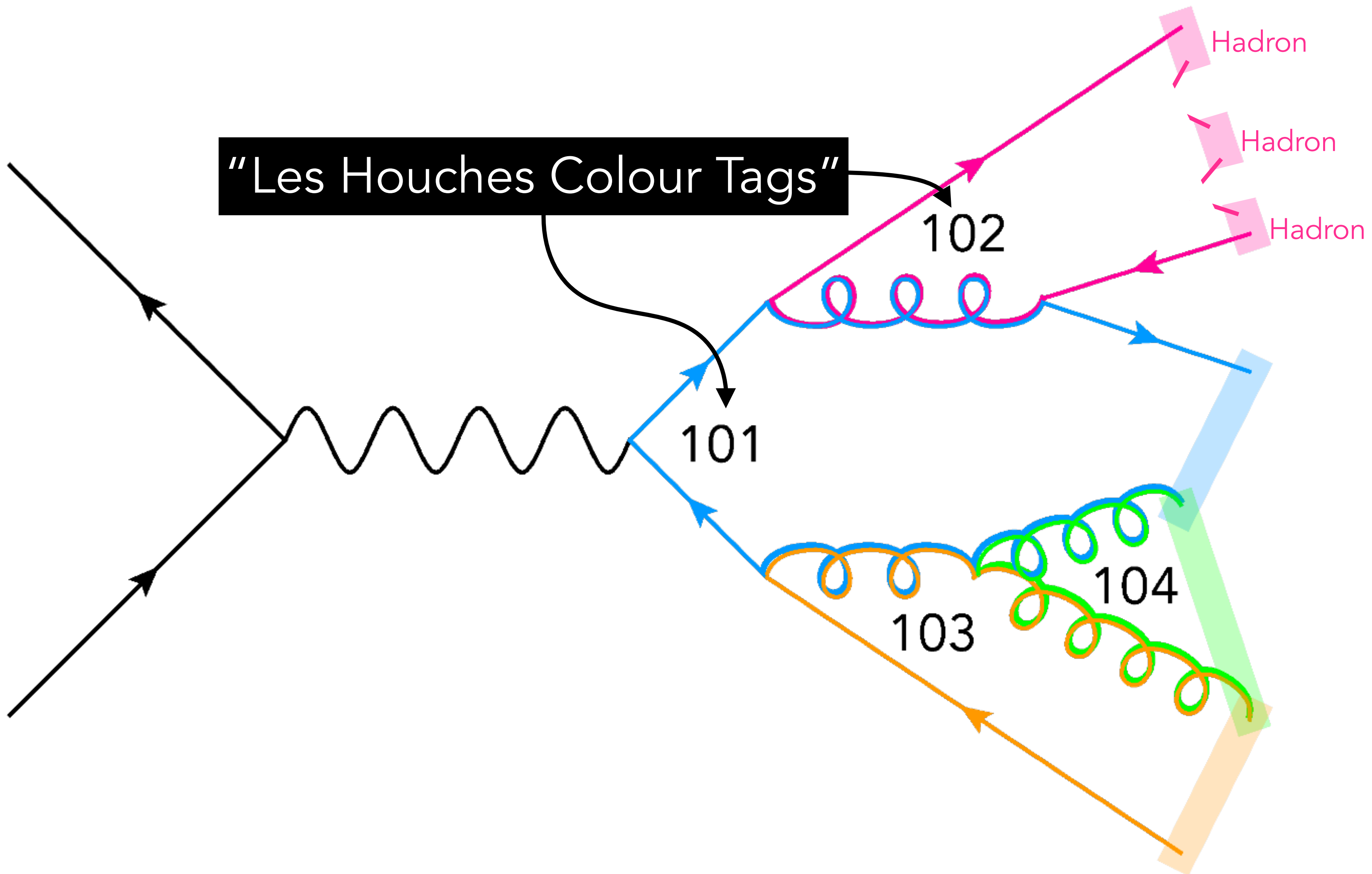
Simple **multi-parton PDFs** with momentum & flavour correlations

Figure from Sjöstrand & PS, 2005

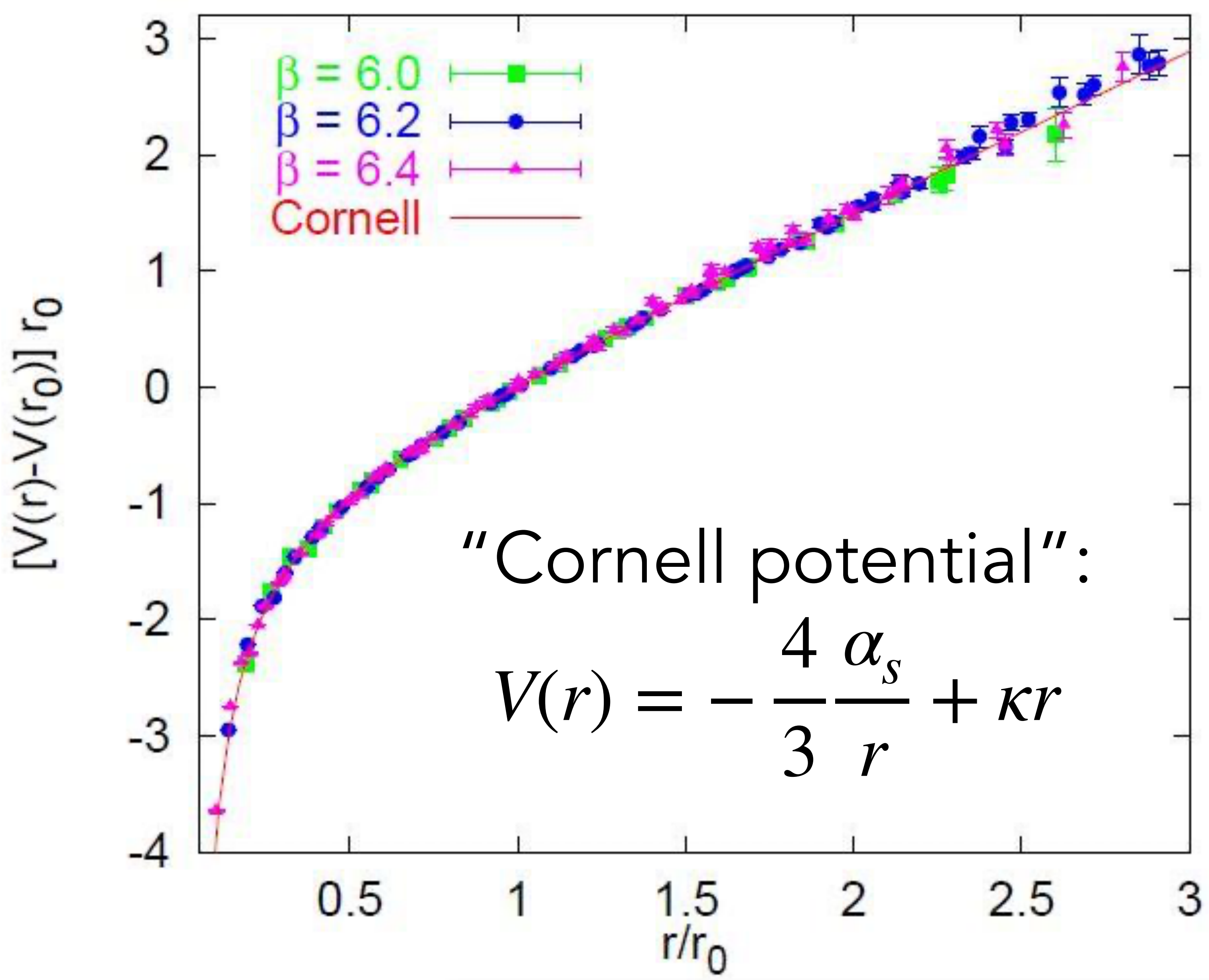
Confinement in PYTHIA: *The Lund String Model*

Using simplified ("leading-N_C") rules for "colour flow", we can determine between which partons confining potentials should be set up

Example $e^+e^- \to Z^0 \to q\bar{q}$ + parton shower



"Linear confinement"
(From Lattice & Hadron Spectroscopy)



"Cornell potential":

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \kappa r$$

Map to Strings: Quarks ➡ string endpoints; gluons ➡ "kinks"

System then evolves as a string world sheet: **area law**

Uncertainties → See talk by C. Bierlich, Thursday

+ String breaks via spontaneous $q\bar{q}$ pair creation ("Schwinger mechanism") → **hadrons**

Gaussian p_T + Lund Symmetric Fragmentation Function $f(z, m_h, p_{Th})$ + many flavour parameters

Confinement in Hadron Collisions

High-energy pp collisions with MPI + QCD bremsstrahlung

Final states with **very many** coloured partons

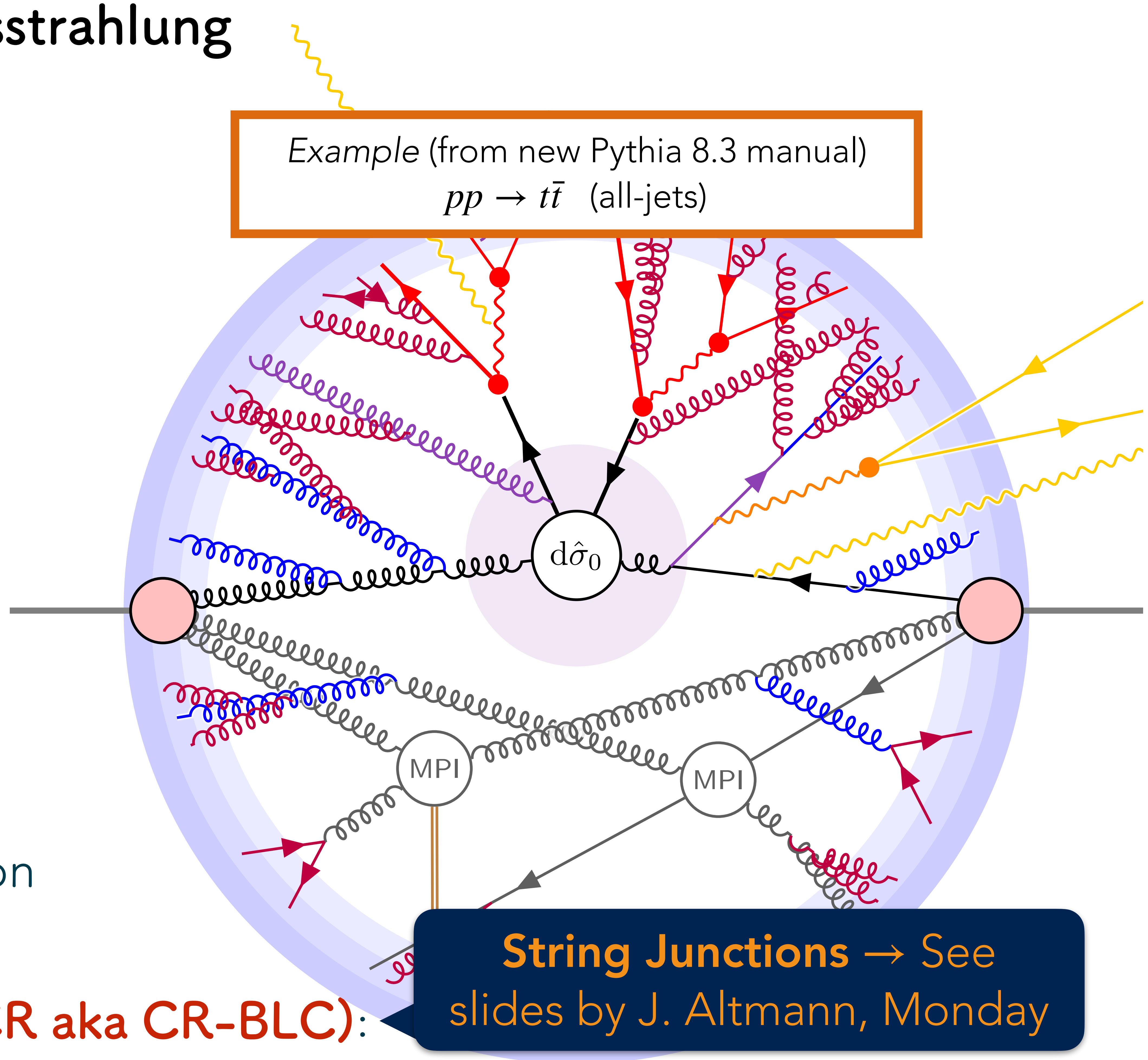
With significant overlaps in phase space

Who gets confined with whom?

If each has a colour ambiguity $\sim 1/N_C^2 \sim 10\,\%$

Colour Reconnections* **(CR)** ➜ more likely than not

$$\text{Prob(no CR)} \propto \left(1 - \frac{1}{N_C^2}\right)^{n_{\mathrm{MPI}}}$$



Colour Reconnections in PYTHIA:

Default (MPI-based): simple string-length minimisation

+ a few others (e.g., gluon-move)

Most sophisticated: Christiansen & PS, 2015 **(QCD CR aka CR-BLC)**:

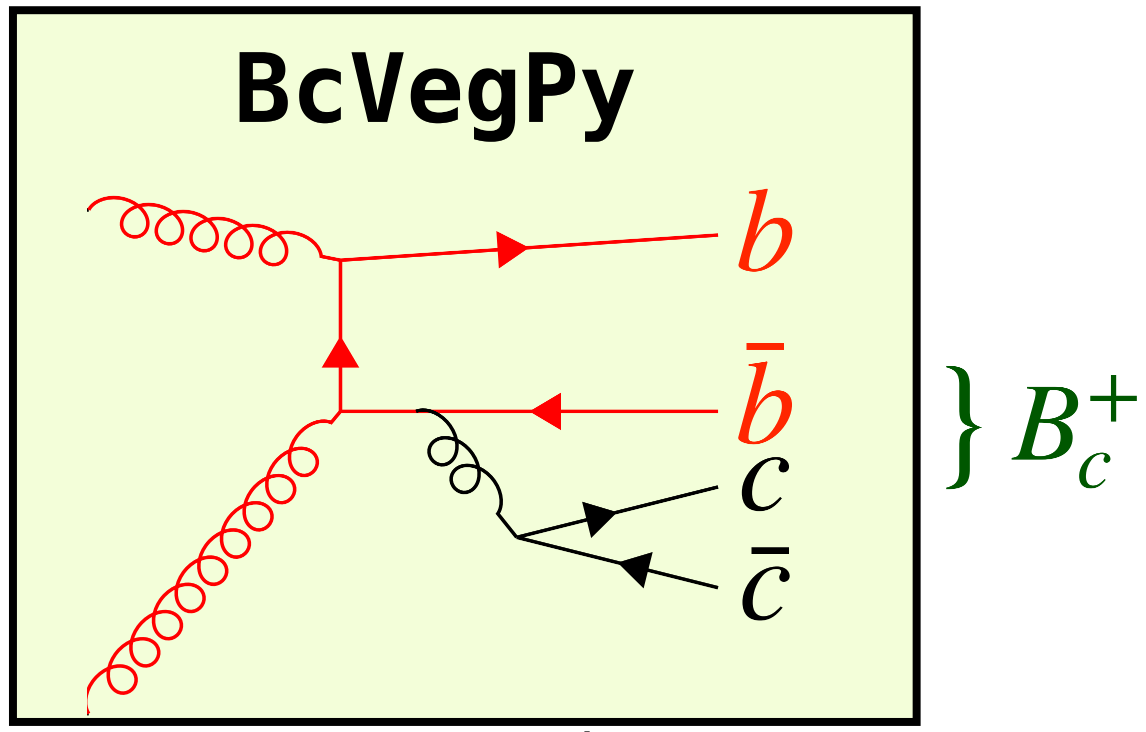
Stochastic sampling of SU(3)$_C$ correlations at end of shower + string-length minimisation

***): in this context, QCD CR simply refers to an ambiguity beyond Leading N_C, known to exist.*
But the term "CR" can also be used more broadly to incorporate further physics concepts.

Doubly-heavy hadrons in PYTHIA: B_c^+ , Ξ_{cc}^{++}, ...

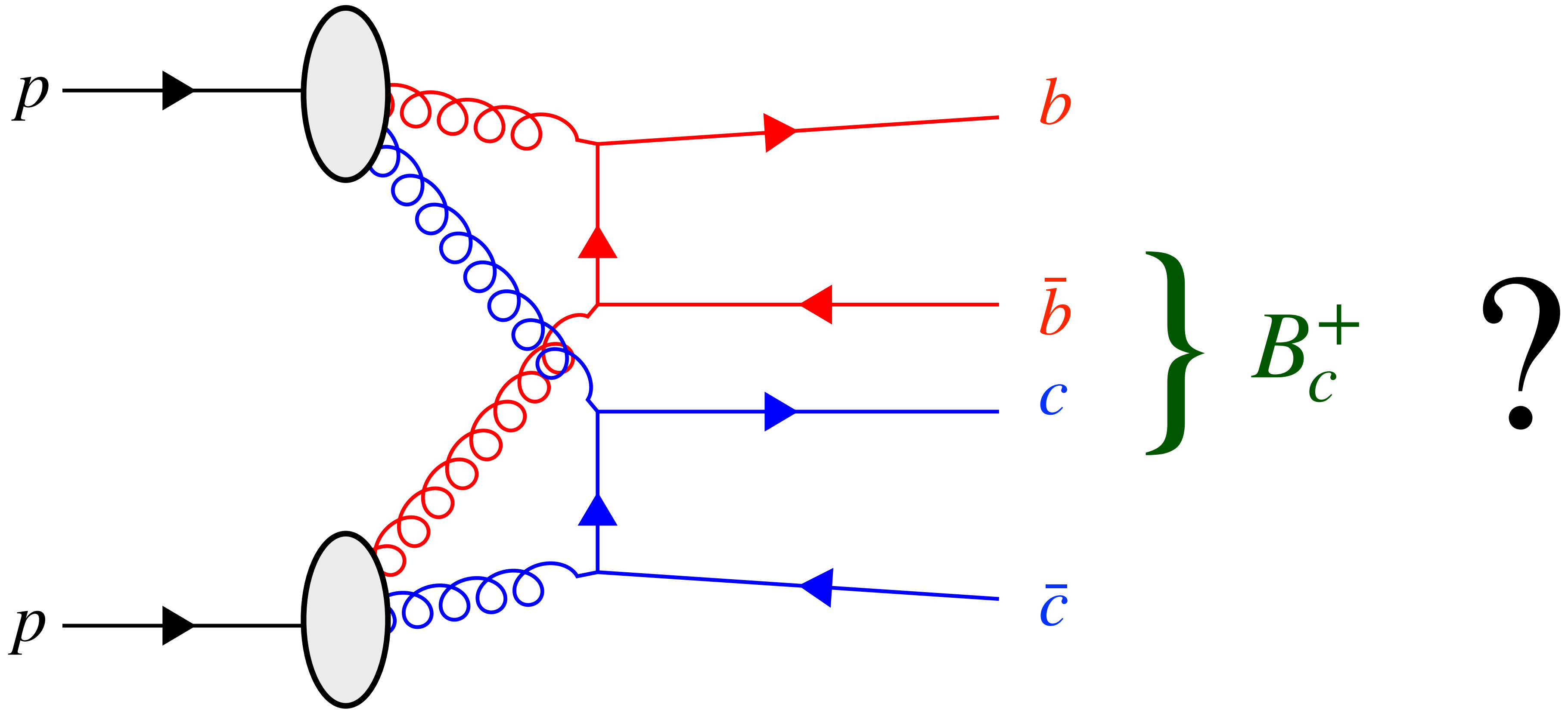
U. Egede, T. Hadavizadeh, M. Singla, PS, Eur.Phys.J.C 82 (2022) 9

Dedicated generators (BcVegPy, GenXicc) and predictions for doubly-heavy hadron production assume single parton interactions the origin of the partons



$gg \to B_c^+ b\bar{c}$

we want to test whether **double parton interactions** contribute



Experimental evidence that multiple heavy-quark pairs can be produced in MPI

Expect partons from different MPI hadronize together. **Can they form B_c^+?** (e.g., via CR?)

Expect *some* suppression since $r(B_c^+) < \langle b \rangle_{MPI}$ but how much? … **Interesting probe!**

PYTHIA Predictions for B_c^+ from MPI

U. Egede, T. Hadavizadeh, M. Singla, PS, Eur.Phys.J.C 82 (2022) 9

Measuring the absolute B_c^+ cross-section precisely is difficult

Requires theoretical input on branching fractions

Exploit the different behaviour in events with MPI

- **Ratio** of doubly-heavy hadrons to singly-heavy hadrons

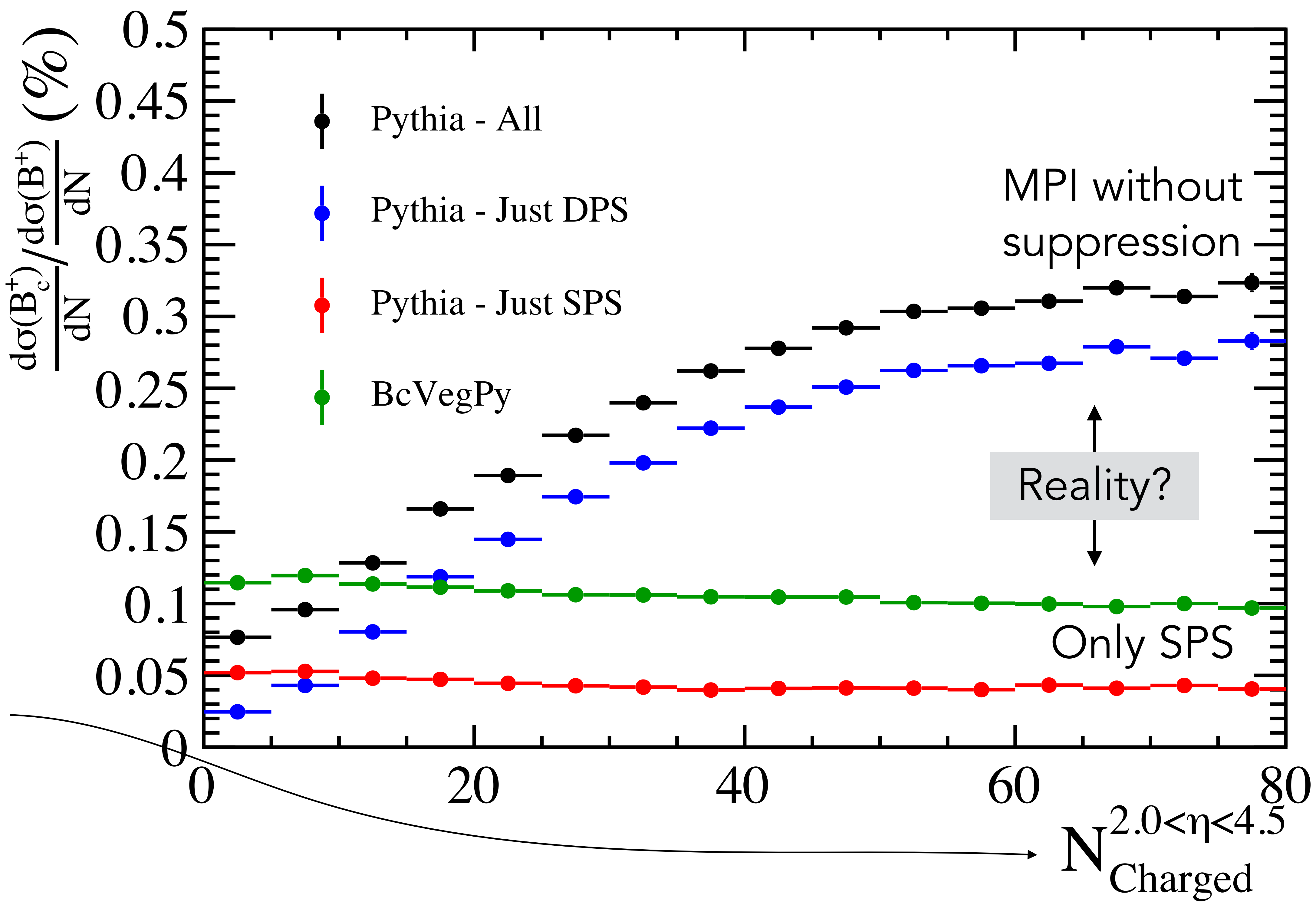
SPS

$$\frac{\sigma(B_c^+)}{\sigma(B^+)} \propto 1$$

DPS

$$\frac{\sigma(B_c^+)}{\sigma(B^+)} \propto (N-1)$$

Can't measure N_{MPI}; use multiplicity instead

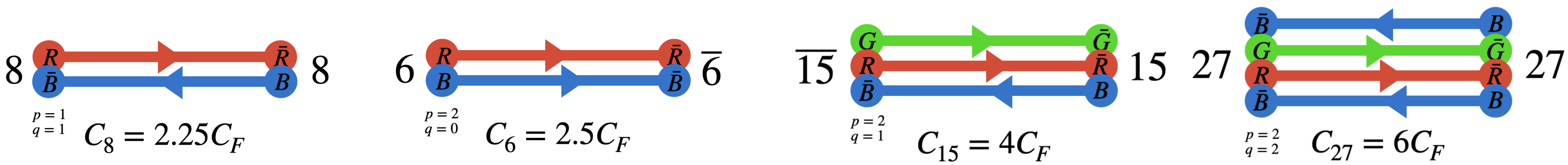


Strangeness Enhancement in PYTHIA

Clear observations of strangeness enhancements in high-multiplicity pp collisions (relative to LEP and low-multiplicity pp) [e.g., ALICE Nature Phys. 13, 535 (2017)]

1) In string context, MPI + Colour Ropes [e.g., Bierlich et al. 1412.6259] have been proposed:

Casimir scaling of effective string tension $\Longrightarrow$ **less strangeness suppression** in string breaks



2) Simplified alternative: Close-Packing [Fischer, Sjöstrand 1610.09818] string tension scales with effective background flux density ∝ n_{MPI} (global) or n_{strings} (local)

Altmann & PS (2023, in progress): rope-like **directional colour flows** (p and q) and **junction topologies** (incl physics updates to basics of string junction fragmentation, esp for heavy quarks)

Effective diquark suppression in octet-type fields ("Altmann mechanism")

& Option for **enhanced strangeness** "near" junctions ("Strange Junctions")

$\Longrightarrow$ **Can describe important observation $\langle p/\pi \rangle_{\mathrm{LHC}} \lesssim \langle p/\pi \rangle_{\mathrm{LEP}}$**

See slides by J. Altmann, Monday

Heavy-Ion Collisions in PYTHIA: *ANGANTYR*

ANGANTYR extends PYTHIA to Ion Beams (HI, Cosmic Rays, ⋯)

Main emphasis/hypothesis: collectivity **without** a medium

1) Hadron-Ion Collisions: PYTHIA for UPC and cosmic-ray air showers

→ Talk by M. Utheim, Tuesday

2) Angantyr can now include QCD CR between different nucleon-nucleon subcollisions

Lönnblad & Shah 2023 [2303.11747; coming in Pythia 8.311]

- As long as they are "close" in impact parameter $\lesssim$ 1fm

Bierlich, Gustafson, Lönnblad, Shah 2023 [2309.12452; coming in Pythia 8.311]

- Previously, **small junction systems** caused the rejection of whole events
  - Problem for QCD-CR in heavy ions: caused a skewing of the multiplicity distribution (high multiplicity => more CR => more mini-junction failures). Effects of this could also be seen in pp.
- MinistringFragmentation extended to include collapse of small junction systems

$\Longrightarrow$ Effects of QCD CR (eg junction baryons) can now be studied in AA collisions

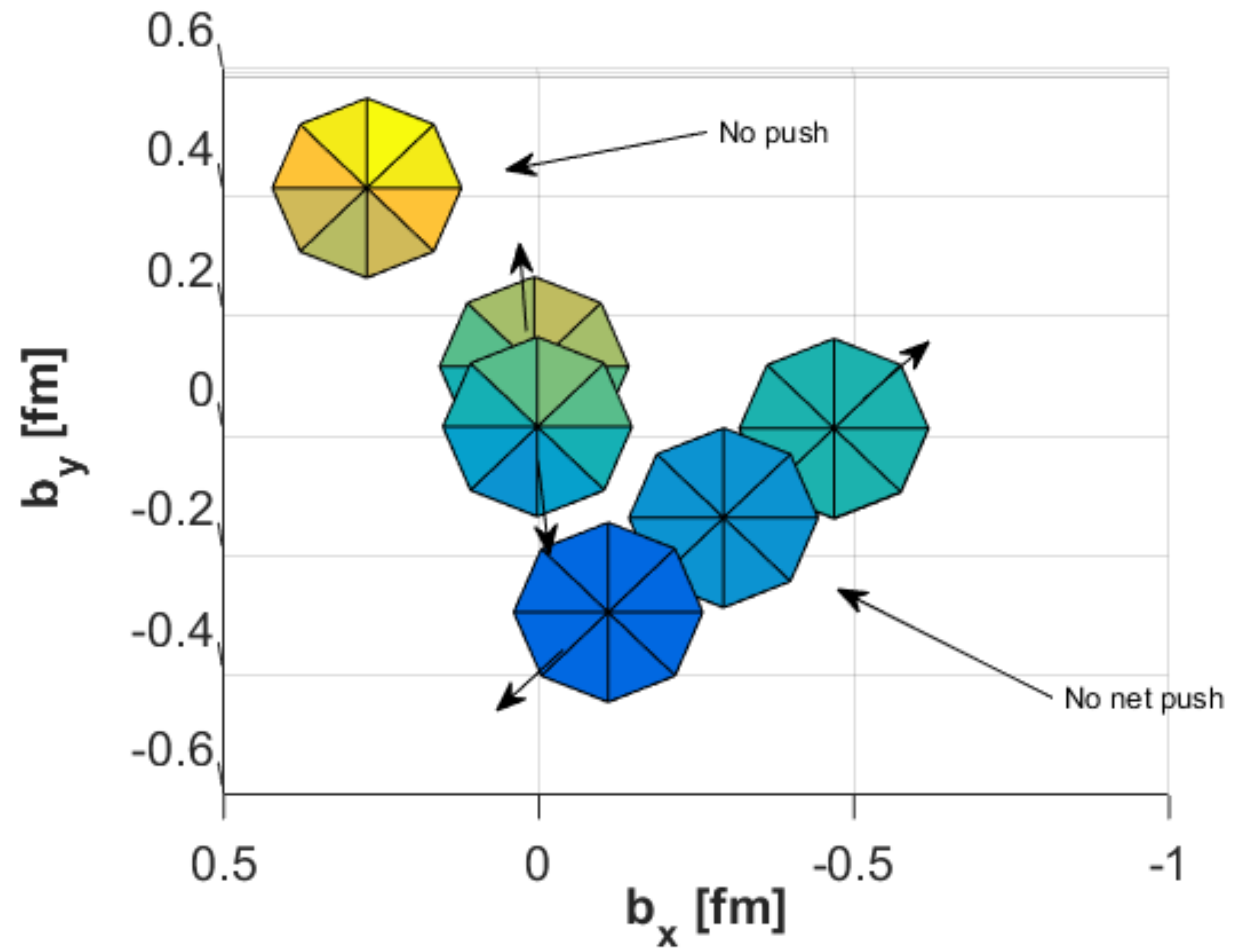
Note: CR reduces raw multiplicity → retuning needed, not done yet (interested?)

Collective Flow in PYTHIA: *String Shoving*

Bierlich, Chakraborty, Gustafson, Lönnblad, arXiv:1710.09725, 2010.07595

Strings should push each other transversely

Colour-electric fields ➜ Classical force



Model string radial shape & shoving physics

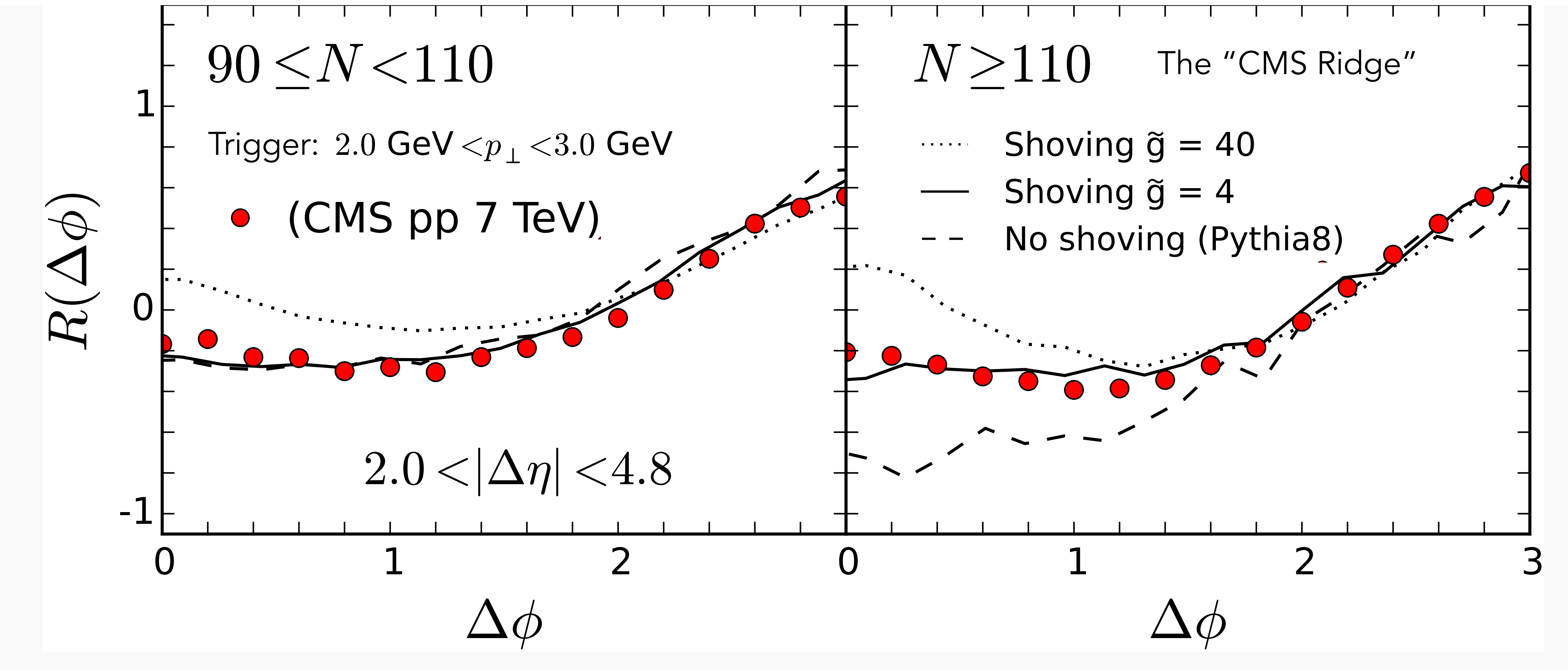
$\Longrightarrow$ force $$f(d_\perp) = \frac{g\kappa d_\perp}{R^2}\exp\left(-\frac{d_\perp^2}{4R^2}\right)$$

g: fraction of energy in field (as opposed to in condensate or magnetic flux)

$d_\perp$: transverse distance (in string-string "shoving frame")

R: string radius

κ: string tension ~ $1\,\mathrm{GeV/fm}$



CMS 1009.4122. Also: ATLAS 1906.08290, ALICE 2101.03110

MCPLOTS — New Look Coming Soon

Work in Progress: Korneeva, Karneyeu, PS

ABOUT PLOTS ▾ COMPARISON ▾ LHC@HOME

Preview at mcplots-dev.cern.ch

MCPLOTS

Online repository of Monte Carlo plots compared to experimental data

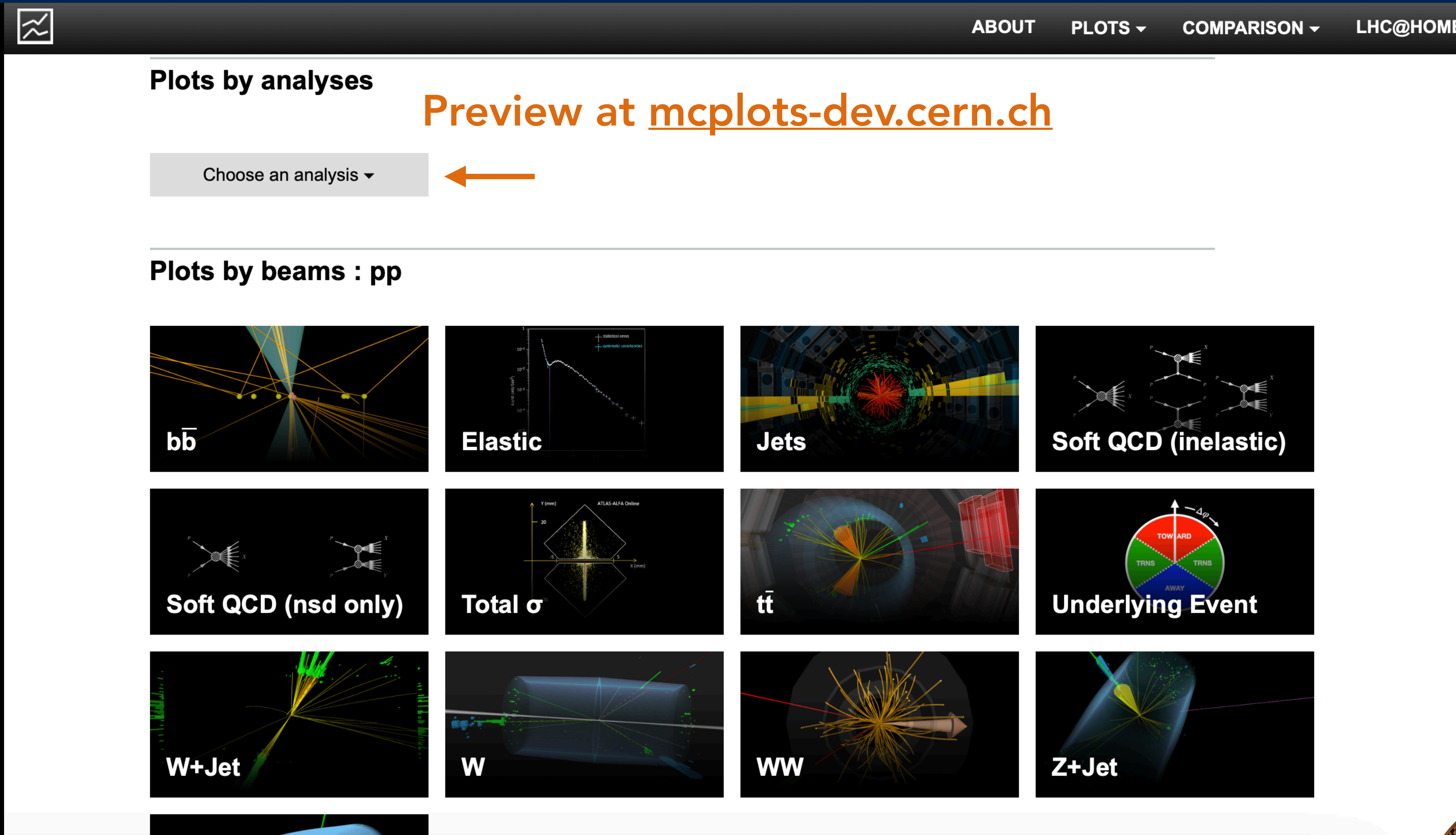
113 data analyses

126 generators

783667 plots

MCPLOTS — New Look Coming Soon

Work in Progress: Korneeva, Karneyeu, PS



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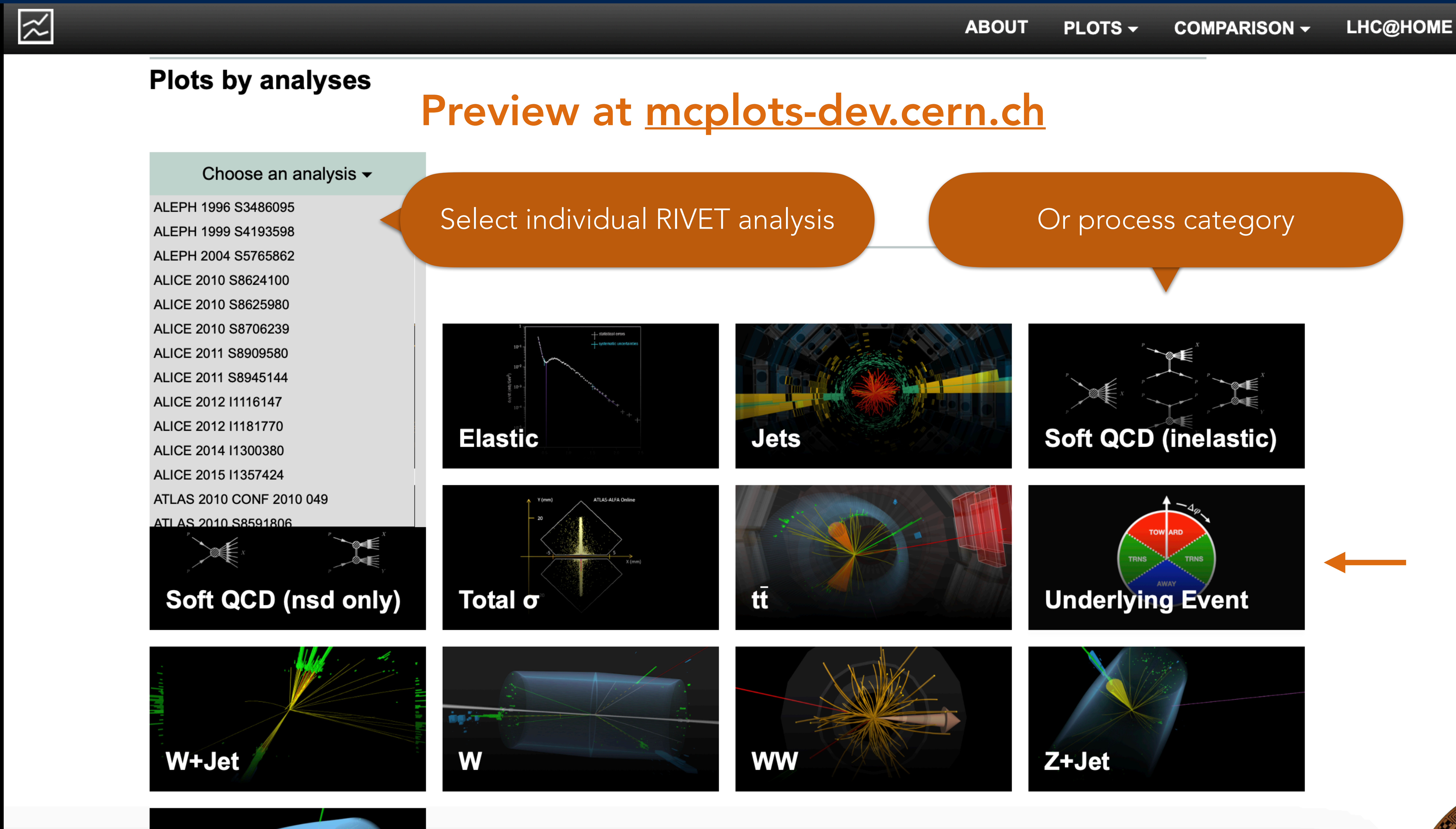

Select individual RIVET analysis

Or process category

MCPLOTS — New Look Coming Soon

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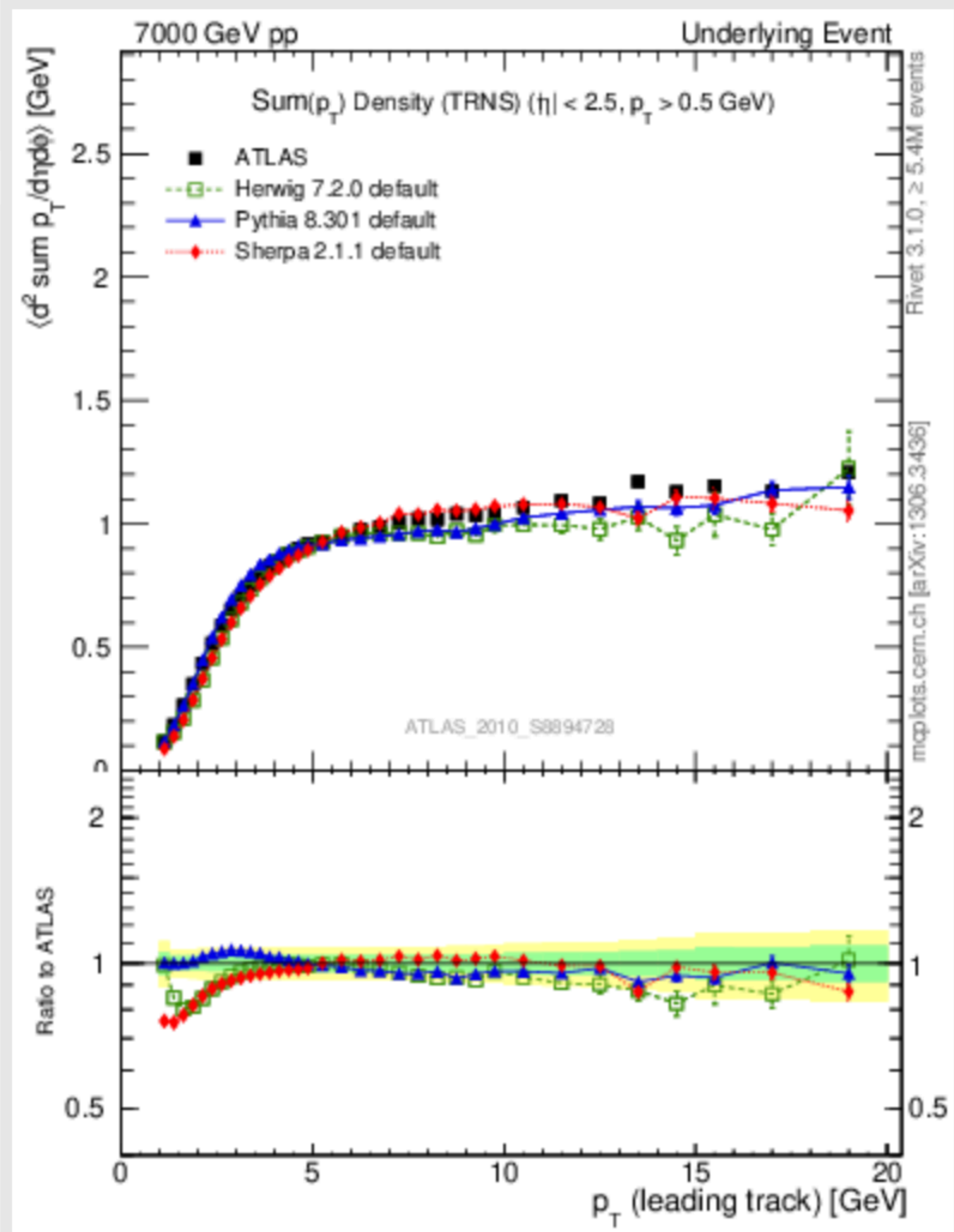
Select between all available MC generators & versions

- AWAY ▾
- TRNS ▴
  - <pT> vs Nch
  - <pT> vs pT1
  - Strange <N> vs pT1
  - Max(pT) vs pT1
  - <Nch> vs η1
  - <Nch> vs pT1
  - dNch/dpT
  - σ(Nch) vs pT1
  - σ(Σ(pT)) vs pT1
  - Σ(ET)
  - Σ(ET) vs η
  - Σ(pT) vs η1
  - Σ(pT) vs pT1
  - Strange Σ(pT) vs pT1
- TWRD ▾
- Multiplicity Distributions
- pT Distributions
- Σ(pT)
- Δφ Distributions ▾
- TRNSDIF ▾
- TRNSMAX ▾
- TRNSMIN ▾

General-Purpose MCs : Main ▾ | Customize

pp @ 7000 GeV



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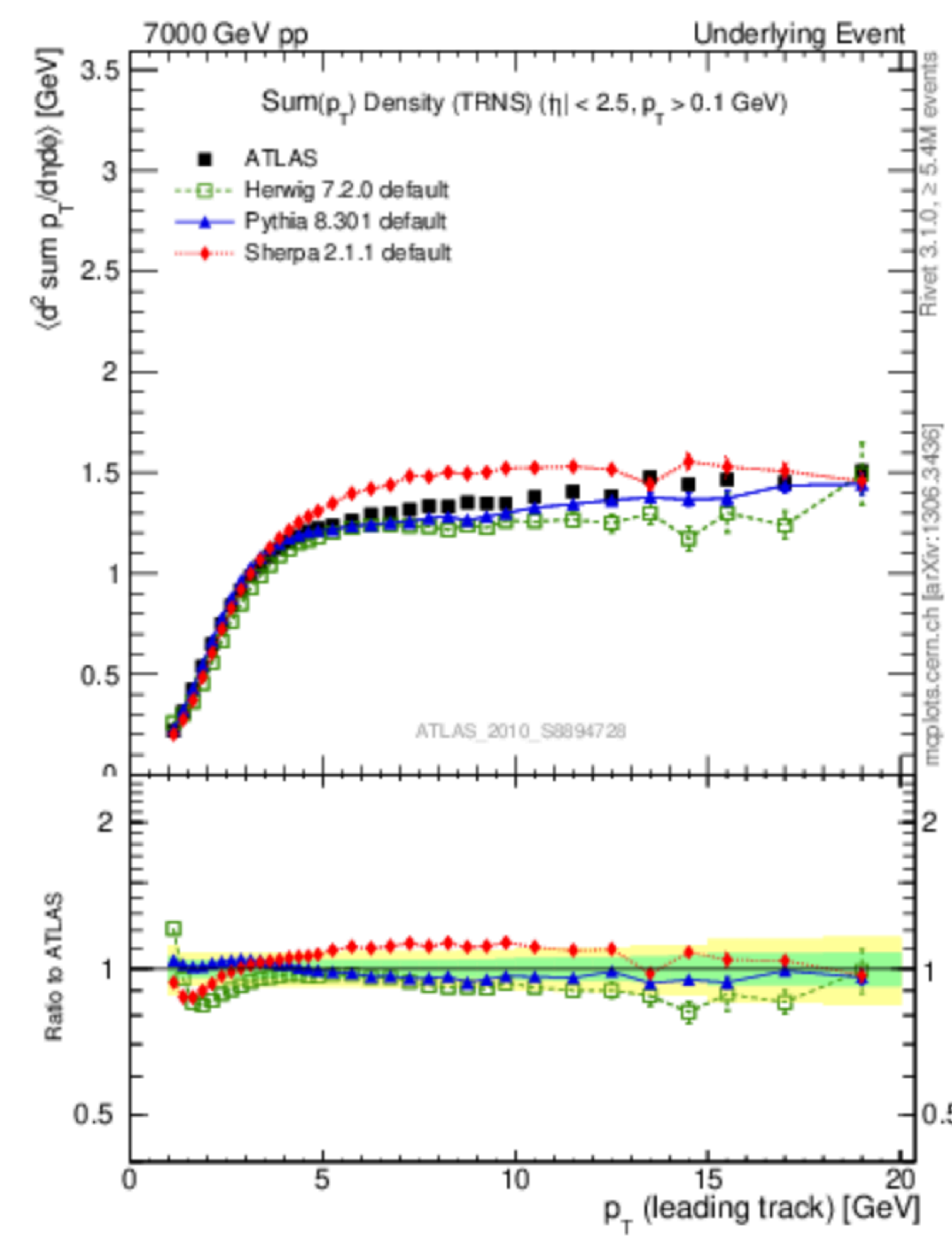

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General-Purpose MCs : Main ▾ | Customize

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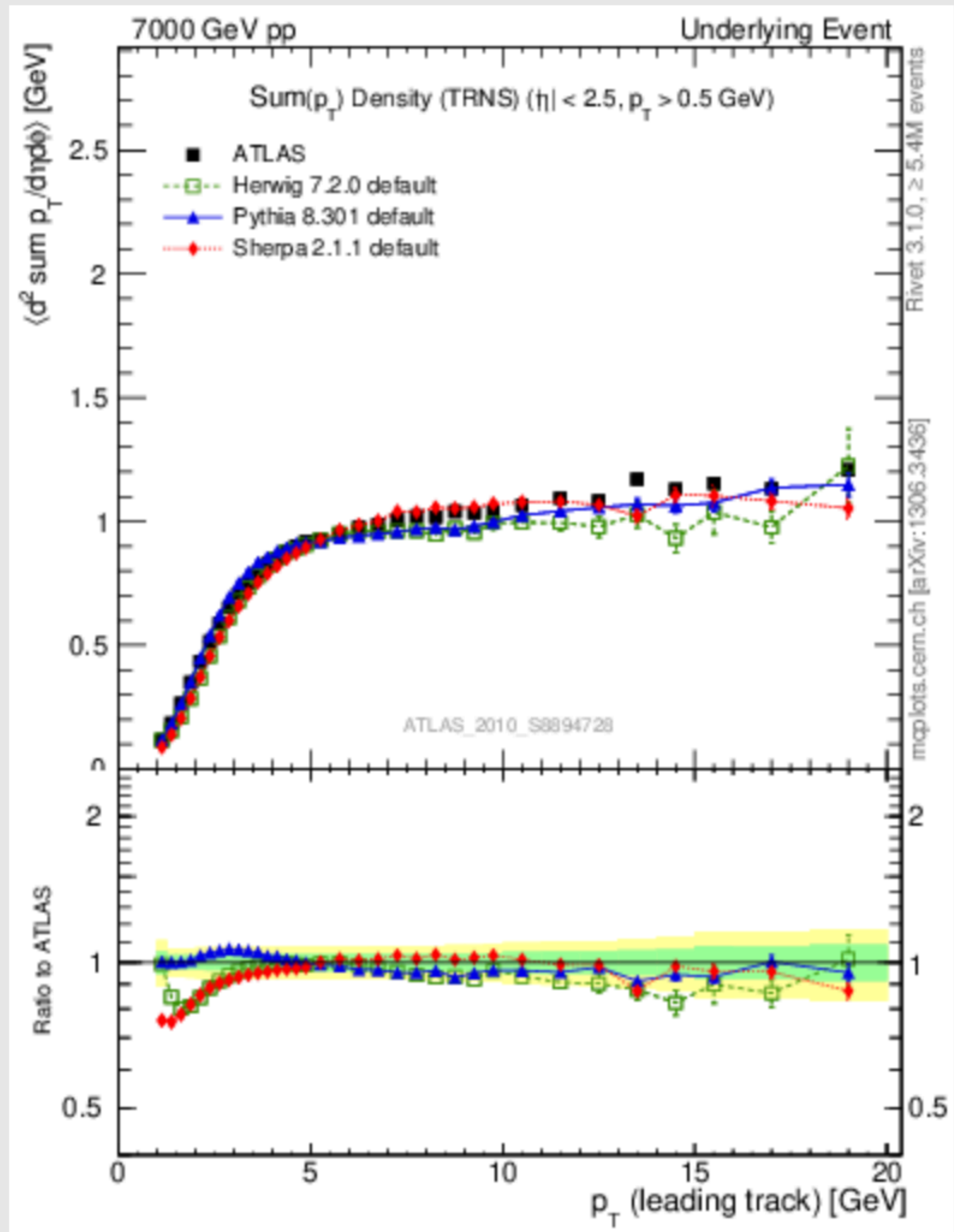

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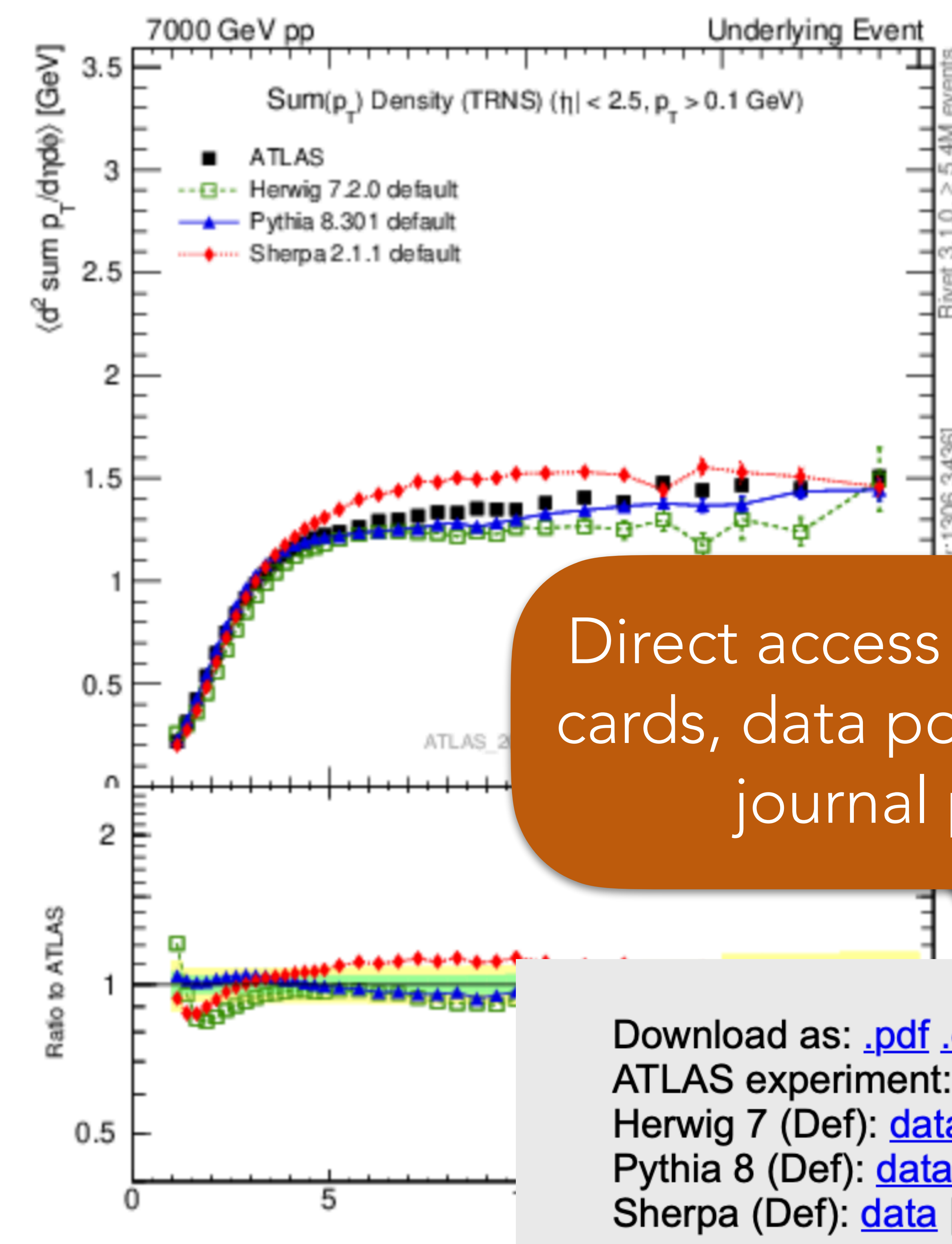

Direct access to all generator cards, data points, MC points, journal paper, etc

details

Download as: .pdf .eps .png .script.tgz #
ATLAS experiment: data | article paper
Herwig 7 (Def): data |generator card
Pythia 8 (Def): data |generator card
Sherpa (Def): data |generator card

details

Summary and Outlook

PYTHIA casts MPI as a shower-like evolution interleaved with parton showers

String Fragmentation being reexamined, esp in light of collective effects in pp

- Automated Uncertainties (2308.13459)
- String Junctions (2309.12452 + WIP)
- Thermal String Breaks (1610.09818)
- Hot strings that cool down (2005.06219)
- Flavour composition from hyperfine splitting (2201.06316)
- Overlapping strings: ropes/close-packing, shoving (many!)
- Hadronic Rescattering (2103.09665, 2108.03481)
- Efficient production of Heavy Flavours (2205.15681)

QCD CR Model looks promising; work ongoing to extend and optimise it → new default?

ANGANTYR extension to Ion Beams (HI, Cosmic Rays, ···)

Main emphasis/hypothesis: collectivity **without** a medium

Join MCPLOTS

https://lhcathome.web.cern.ch/projects/test4theory

MCPLOTS volunteer cloud: LHC@home Test4Theory — runs when computer is idle

Join the PYTHIA Team!

Apply Now! Post Doc openings at Monash U. and at Jyväskyla U.

Notes on PDFs for MPI Models

The issue with NLO gluons at low x

(Summary of note originally written by T. Sjöstrand, from discussions with R. Thorne though any oversimplifications or misrepresentations are our own)

Low-x gluon

Key constraint: DIS F_2

Low x: $\mathrm{d}F_2/\mathrm{d}\ln(Q^2)$ driven by $g \to q\bar{q}$

LO $P_{q/g}(z)$ ~ flat $\Longrightarrow$ x of measured quark closely correlated with x of mother gluon.

NLO Integral over $P_{q/g}(z) \propto 1/z$ for small z $\Longrightarrow$ approximate $\ln(1/x)$ factor.

➤ Effectively, the NLO gluon is probed more “non-locally” in x.

$\mathrm{d}\ln F_2/\mathrm{d}Q^2$ at small x becomes too big unless positive contribution from medium-to-high-x gluons (derived from $\mathrm{d}\ln F_2/\mathrm{d}Q^2$ in that region, and from other measurements) is combined with a negative contribution from low-x gluons.

Mathematically (toy NLO Calculation with just one x):

$$\frac{\mathrm{ME_{NLO}}}{\mathrm{ME_{LO}}} = 1 + \alpha_\mathrm{s}(A_1 \ln(1/x) + A_0)$$

$\ln(1/x)$ largely compensated in def of NLO PDF:

$$\frac{\mathrm{PDF_{NLO}}}{\mathrm{PDF_{LO}}} = 1 + \alpha_\mathrm{s}(B_1 \ln(1/x) + B_0)$$

➤ Product well-behaved at NLO if we choose $B_1 \approx A_1$

Cross term at $\mathcal{O}(\alpha_s^2)$ is beyond NLO accuracy ··· ⟶

For large x and small $\alpha_s(Q^2)$, e.g. $\alpha_s A_1 \ln(1/x) \sim 0.2$:

$$\frac{\mathrm{ME_{NLO}\,PDF_{NLO}}}{\mathrm{ME_{LO}\,PDF_{LO}}} = (1+0.2)(1-0.2) = 0.96$$

👍 log terms cancel

But if x and Q^2 are small, say $\alpha_s A_1 \ln(1/x) \sim 2$:

$$\frac{\mathrm{ME_{NLO}\,PDF_{NLO}}}{\mathrm{ME_{LO}\,PDF_{LO}}} = (1+2)(1-2) = -3$$

👎 Cross term dominates; The PDF becomes negative

Not so important for high-p_T processes because 1) DGLAP evolution fills up low-x region, 2) kinematics restricted to higher x, 3) smaller α_s

Some Desirable Properties for PDFs for Event Generators

General-Purpose MC Generators are used to address very diverse physics phenomena and connect (very) high and (very) low scales ➤ **Big dynamical range!**

1. Stable (& positive) evolution to **rather low Q^2 scales**, e.g. $Q_0 \lesssim 1\,\mathrm{GeV}$

   ISR shower evolution and MPI go all the way down to the MC IR cutoffs ~ 1 GeV

2. **Extrapolates sensibly to very low $x \sim 10^{-8}$** (at LHC), especially at low $Q \sim Q_0$.

   "Sensible" ~ positive and smooth, without (spurious) structure

   Constraint for perturbative MPI: $\hat{s} \geq (1\,\mathrm{GeV})^2 \implies x_{\mathrm{LHC}} \gtrsim 10^{-8}$ $(x_{\mathrm{FCC}} \geq 10^{-10})$

   Main point: MPI can probe a **large range of x**, beyond the usual $\sim 10^{-4}$

   (Extreme limits are mainly relevant for ultra-forward / beam-remnant fragmentation)

3. **Photons** included as partons

   Bread and butter for part of the user community

4. **LO** or equivalent in some form (possibly with α_s^{eff}, relaxed momentum sum rule, $\cdots$)

   Since MPI Matrix Elements are LO; ISR shower kernels also LO (so far)

5. Happy to have **N^{n}LO** ones in a similar family.

   E.g., for use with higher-order MEs for the hard process.

   Useful (but possible?) for these to satisfy the other properties too?