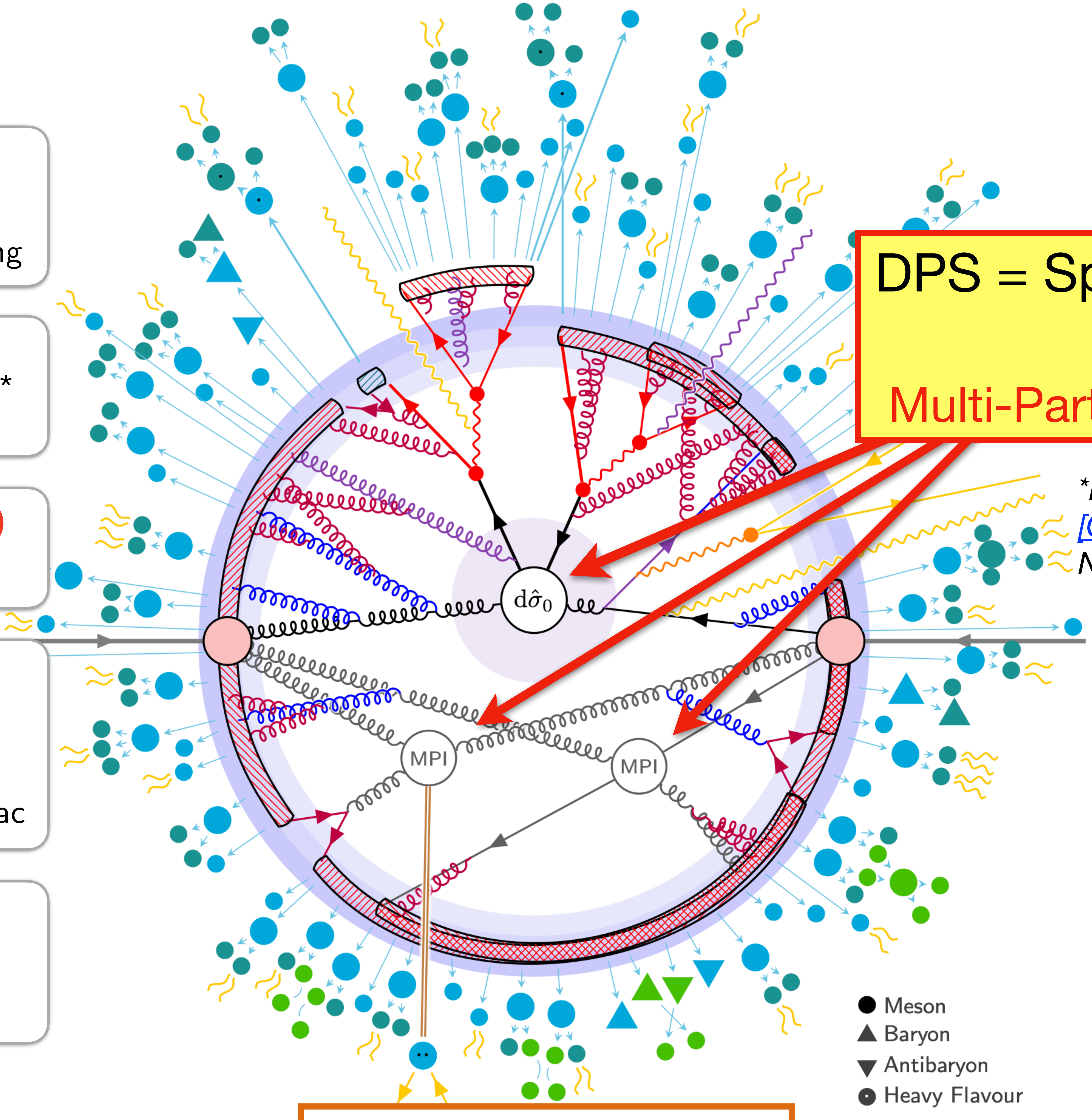
DPS in Event Generators

Hard Process	Hard Interaction Resonance Decays MECs, Matching & Merging
Parton Showers	QCD Final-State Radiation QCD Initial-State Radiation* Electroweak Radiation
Underlying Event	Multiparton Interactions Beam Remnants*
Hadronization	Strings Colour Reconnections String Interactions Bose-Einstein & Fermi-Dirac
Hadron (& τ) Decays	Primary Hadrons Secondary Hadrons Hadronic Reinteractions

(: incoming lines are crossed)*



Meson
Baryon
Antibaryon
Heavy Flavour

DPS = Special Case* of
MPI
Multi-Parton Interactions

**Except for dedicated dShower [Cabouat, Gaunt, Ostrolenk 2019]*
Not covered here

Figure from arXiv:2203.11601: $pp \to t\bar{t}$ (all-jets)

MPI

Each proton = **beam** of partons

$\Longrightarrow$ For each type of **parton-parton** scattering process, expect:

$$\frac{\sigma_{\text{parton-parton}}}{\sigma_{\text{hadron-hadron}}} \sim \langle n \rangle_{\text{parton-parton}}$$ ***per*** **hadron-hadron interaction**

QCD 2➜2 scattering dominated by t-channel gluon exchange $\propto \frac{\alpha_s^2}{\hat{p}_\perp^4}$

$\Longrightarrow$ $\langle n \rangle$ exceeds **1** for $\hat{p}_\perp \sim \mathcal{O}$(several GeV) $\Longrightarrow$ **MPI** (+ hard tails with $\langle n \rangle \ll 1$ ➜ DPS, TPS, …)

Further key building blocks ➜ next slides

IR regularisation (Unitarity/Screening/Saturation)	**Multi-parton** PDFs	**Conservation** laws
Impact-parameter (b) dependence	**Interleaved** Evolution	Colour **reconnections**

❶ IR regularisation & b dependence

[Sjöstrand & van Zijl 1987]

IR-divergent

$$\sigma_{\text{parton}-\text{parton}} \propto 1/p_T^{2n}$$

Regulated by

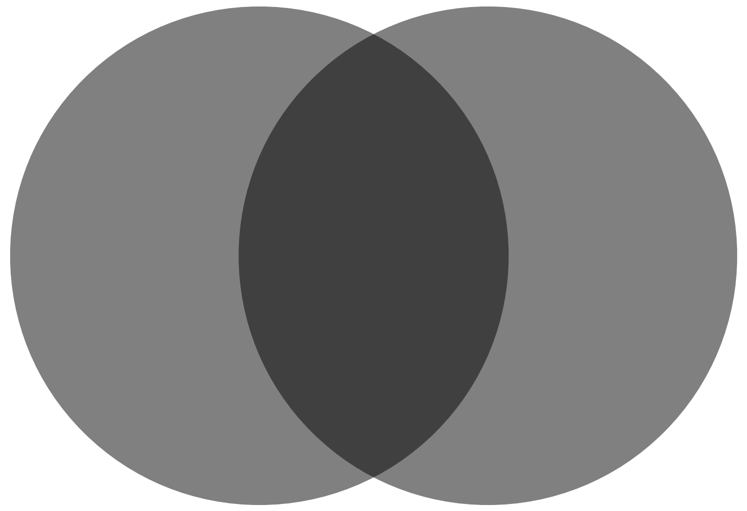
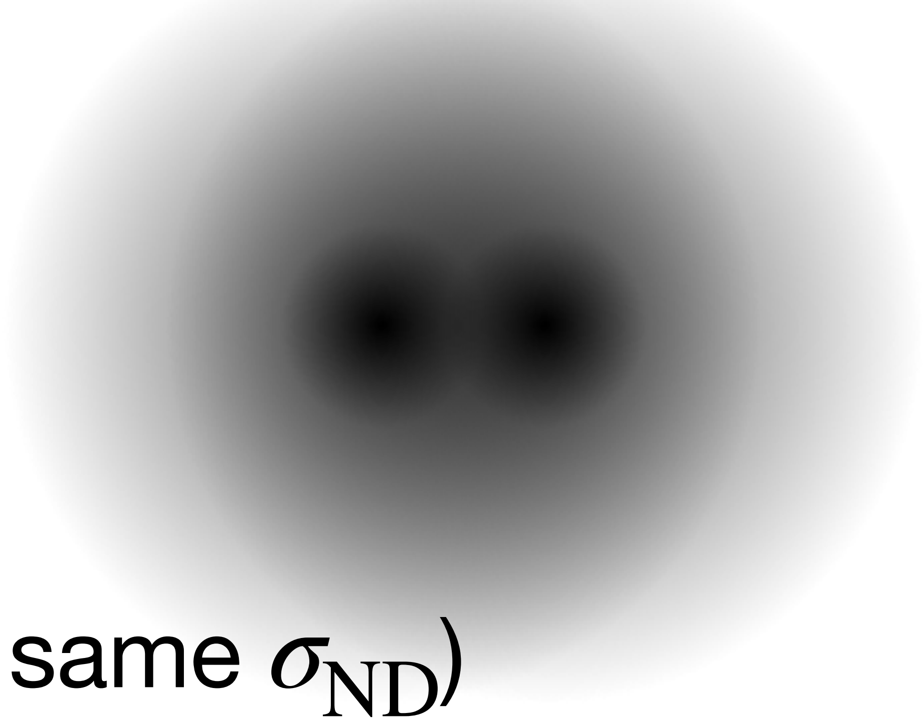
Hard cutoff $p_{T\min}$

or Smooth $p_\perp^{2n}/(p_\perp^2+p_{\perp 0}^2)^n$

Interpret as ($\sqrt{s}$-dependent) **colour-screening distance** ~ poor man's "saturation"

Ensures $\lim_{p_\perp \to 0} \langle n \rangle_{\text{MPI}}$ = finite

Smear hadron PDFs across effective transverse mass distribution

e.g.,  or 

(normalised to give same σ_{ND})

$$\langle n \rangle_{\text{MPI}} \to \langle n(b) \rangle_{\text{MPI}}$$

⇒ Triggering on **hard processes** biases selection to **small impact parameters**, with larger-than-average matter overlaps $\Longrightarrow$ higher $\langle n(b) \rangle_{\text{MPI}}$

$\Longrightarrow$ "Pedestal Effect" (UE > MB)

($\Leftrightarrow$ $\sigma_{\text{eff}} < \sigma_{ND}$ for 2nd and subsequent scatterings)

❷ Multi-parton evolution (in PYTHIA)

1987 [Sjöstrand & van Zijl, Phys.Rev.D 36 (1987) 2019]

MPI cast as Sudakov-style evolution in p_T analogous to the one for showers

2005 [Sjöstrand & Skands, Eur.Phys.J.C 39 (2005) 129]

Interleave MPI & ISR evolutions in one common sequence of p_T

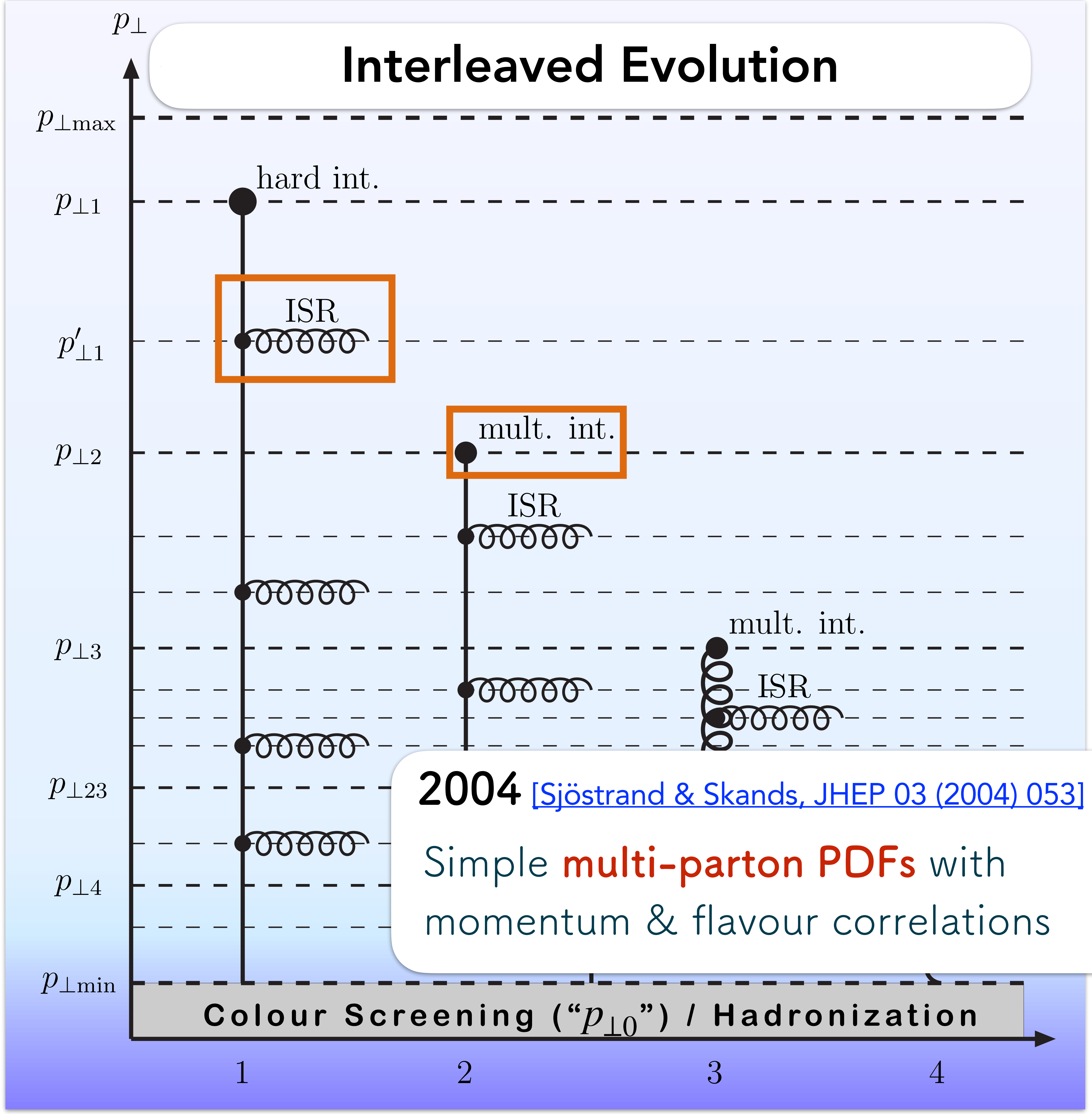
➜ ISR & MPI "compete" for the remaining available x in the proton.

2011 [Corke & Sjöstrand, JHEP 03 (2011) 032]

Also include **FSR** in interleaving

2021 [Brooks, **PS**, Verheyen, SciPost Phys. 12 (2022) 3]

Also include **Resonance Decays** in interleaving (VINCIA)



2004 [Sjöstrand & Skands, JHEP 03 (2004) 053]

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

Figure from Sjöstrand & Skands, 2005

Some observable consequences of MPI

[Sjöstrand & van Zijl 1987]

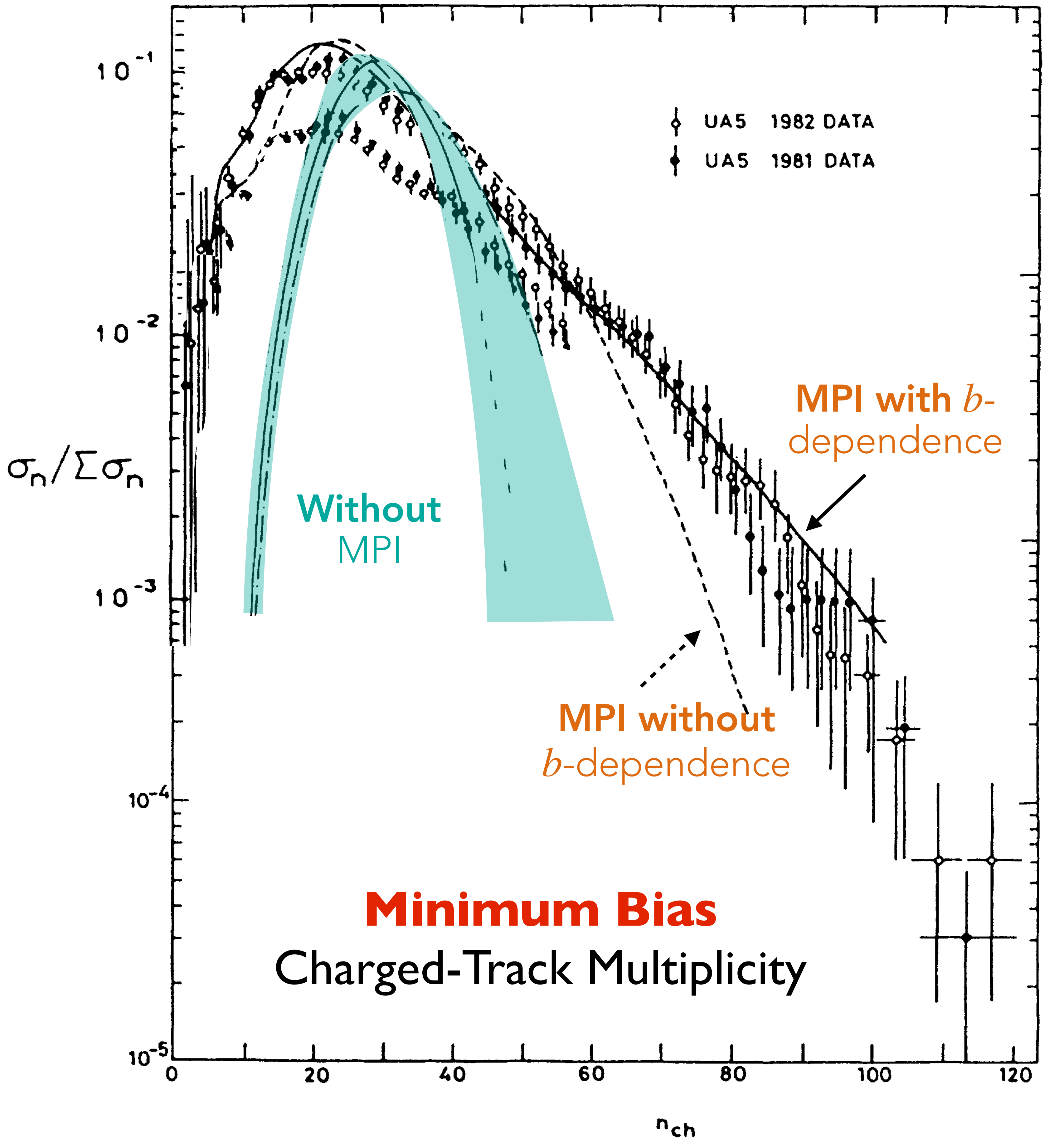
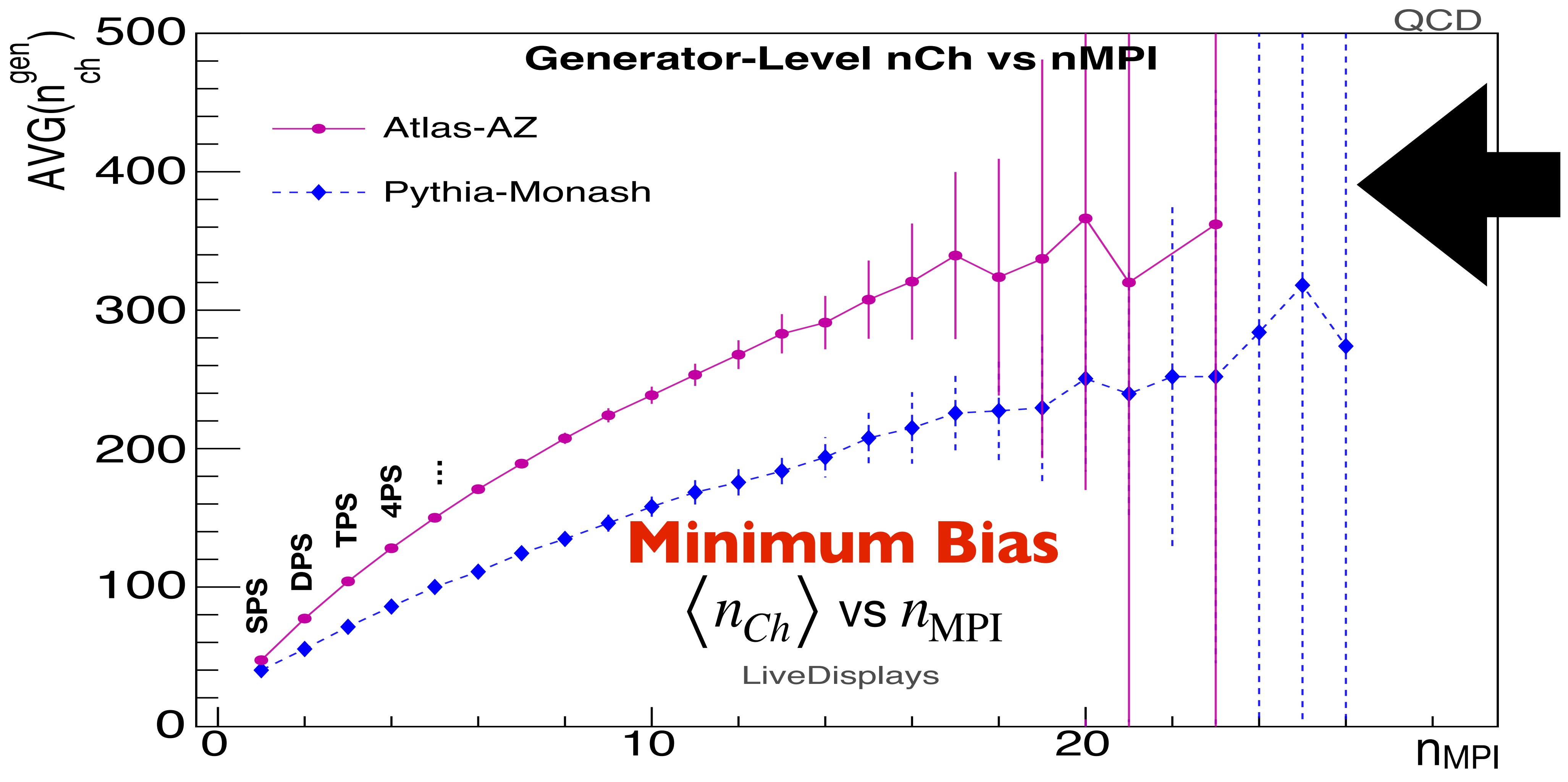
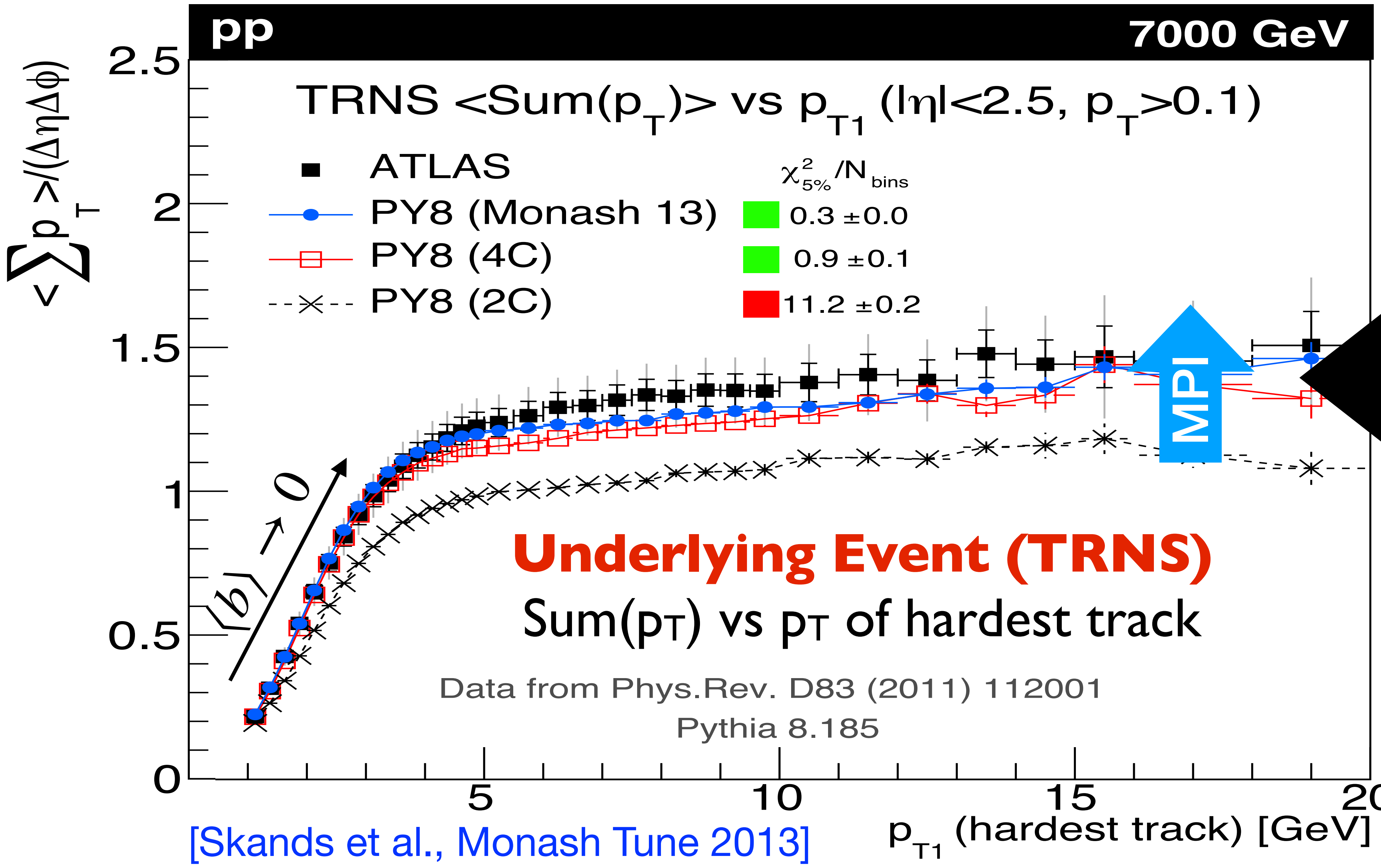


FIG. 12. Charged-multiplicity distribution at 540 GeV, UA5 results (Ref. 32) vs multiple-interaction model with variable impact parameter: solid line, double-Gaussian matter distribution; dashed line, with fix impact parameter [i.e., $\tilde{O}_0(b)$].



$\Longrightarrow n_{\mathrm{Ch}}$ widely used as an observable proxy for n_{MPI}

*(Note: here, **all** MPI are counted in n_{MPI}, including very low-p_T ones; a plot for **hard** SPS, DPS, etc, would look different.)*



[Skands et al., Monash Tune 2013]

UE plateau a.k.a. jet pedestal a.k.a. *"maximum bias"*
$\langle b \rangle \to 0$

❸ Colour Reconnections (CR)

MPI (or cut pomerons) $\Rightarrow$ lots of coloured partons scattered into final state

Who gets confined with whom?

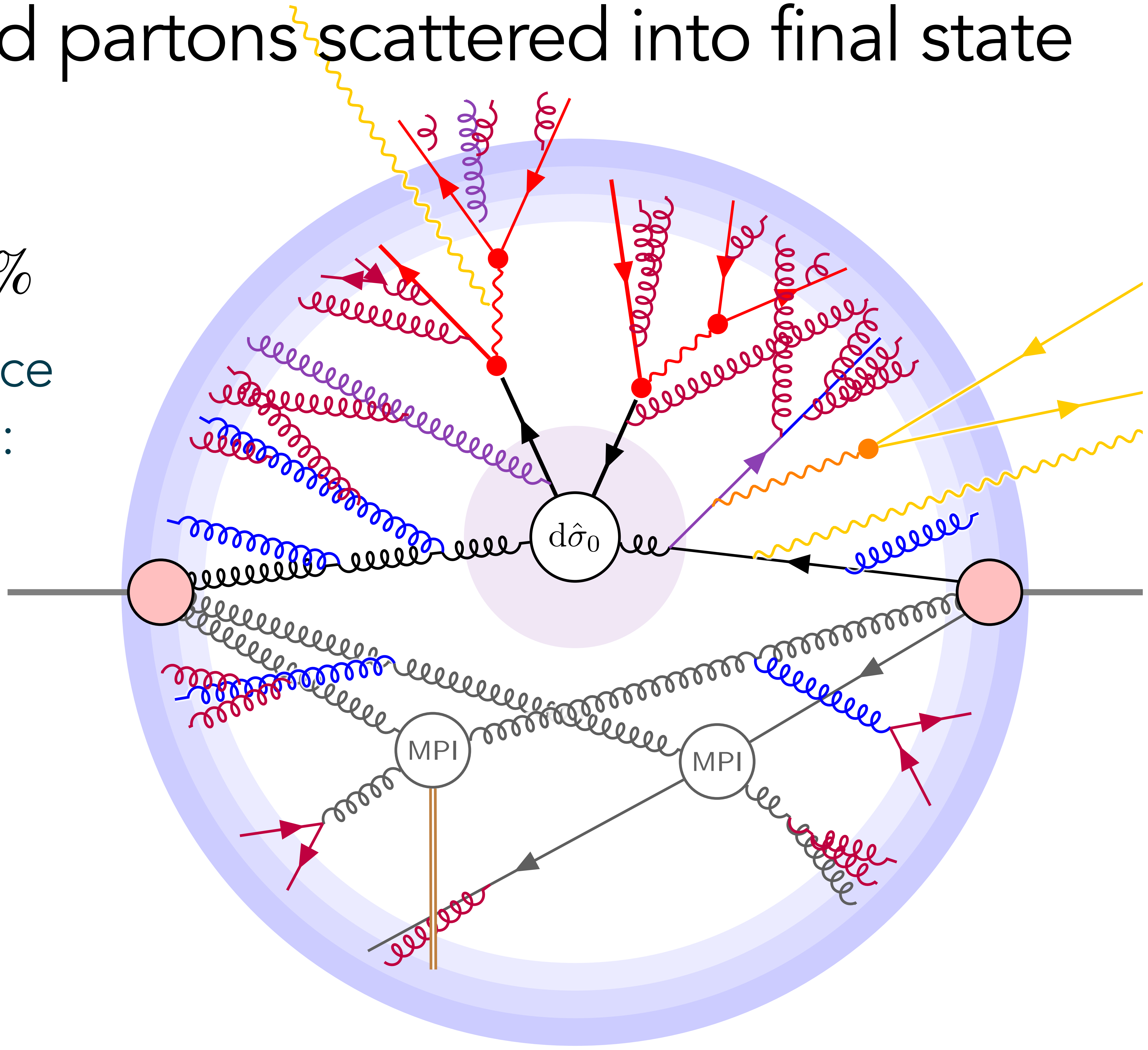
Each has a colour ambiguity $\sim 1/N_C^2 \sim 10\,\%$

QCD screening: random triplet has 1/9 chance to be in **singlet** state with **random antitriplet**:

$$3 \otimes \overline{3} = 8 \oplus 1\,, \quad 3 \otimes 3 = 6 \oplus \overline{3}\,, \quad etc.$$

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

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

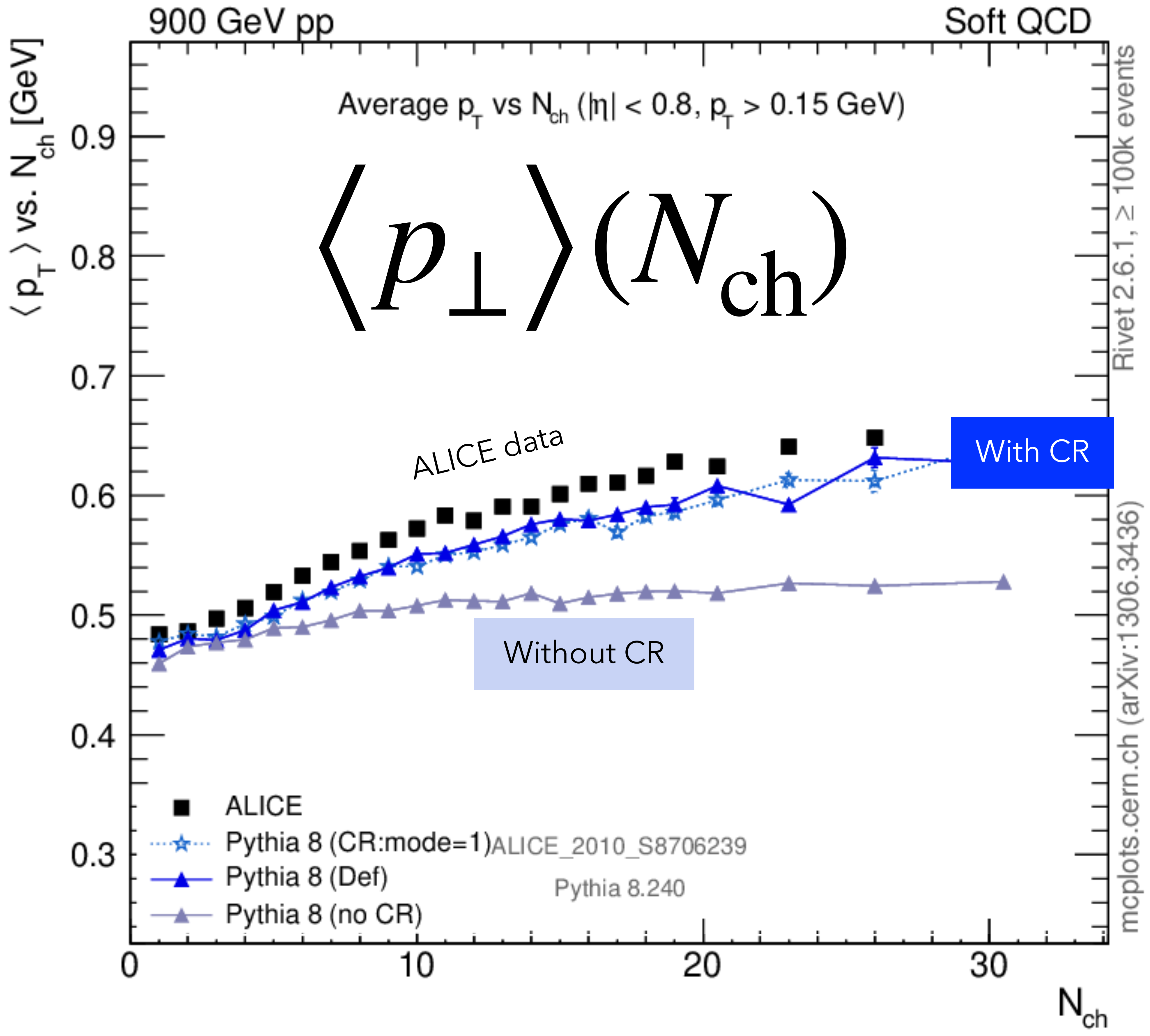


Ambiguities ➜ Several models in PYTHIA

Most advanced: QCD CR using approximate to SU(3) products [Christiansen & Skands, 2015]

Some observable consequences of CR

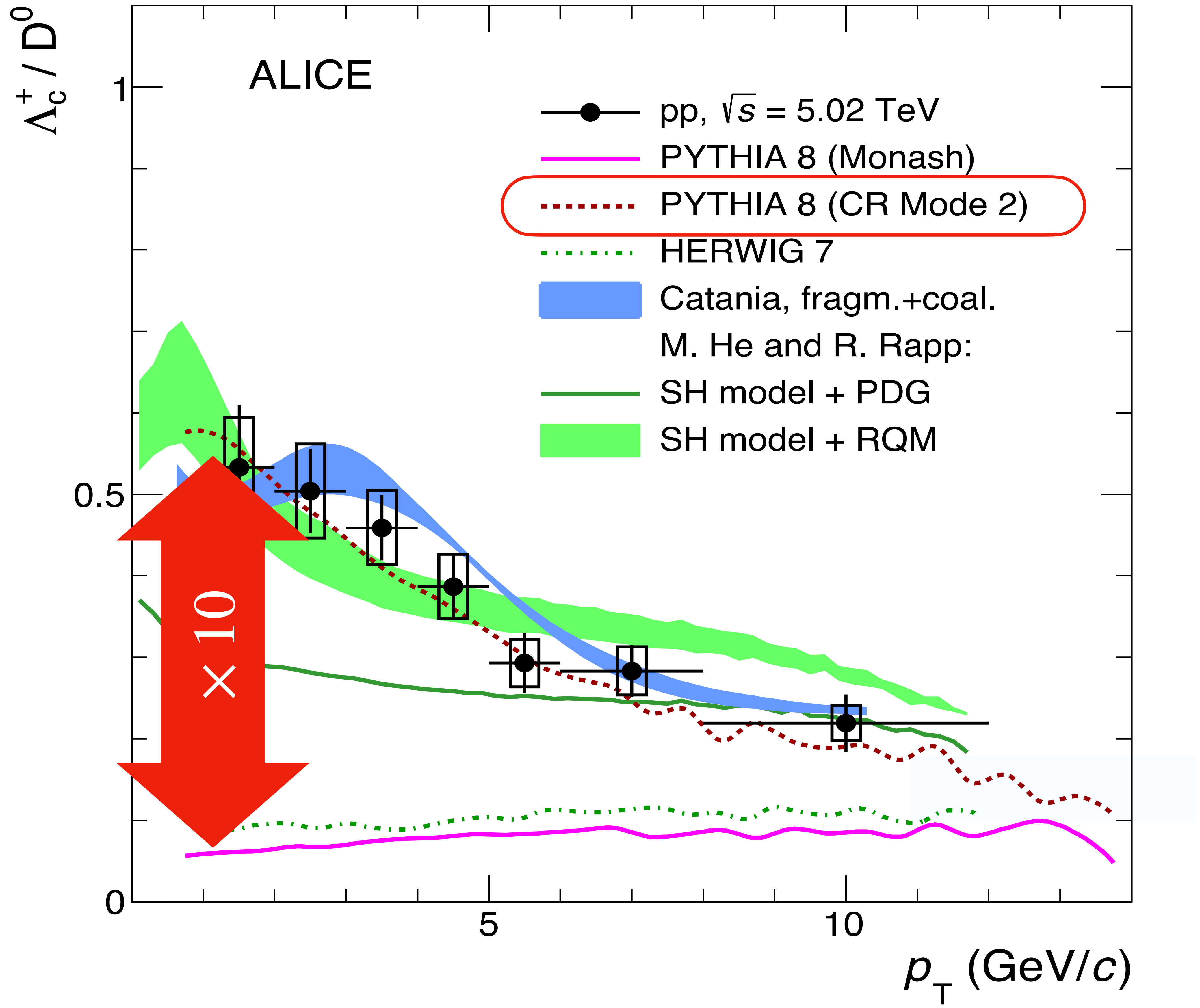
Minimum-Bias: Average track p_T vs N_{Ch}



Already noted in 1st MC MPI model [Sjöstrand & van Zijl 1987]

Plot from mcplots.cern.ch [2401.10621]

Heavy-Flavour Baryons

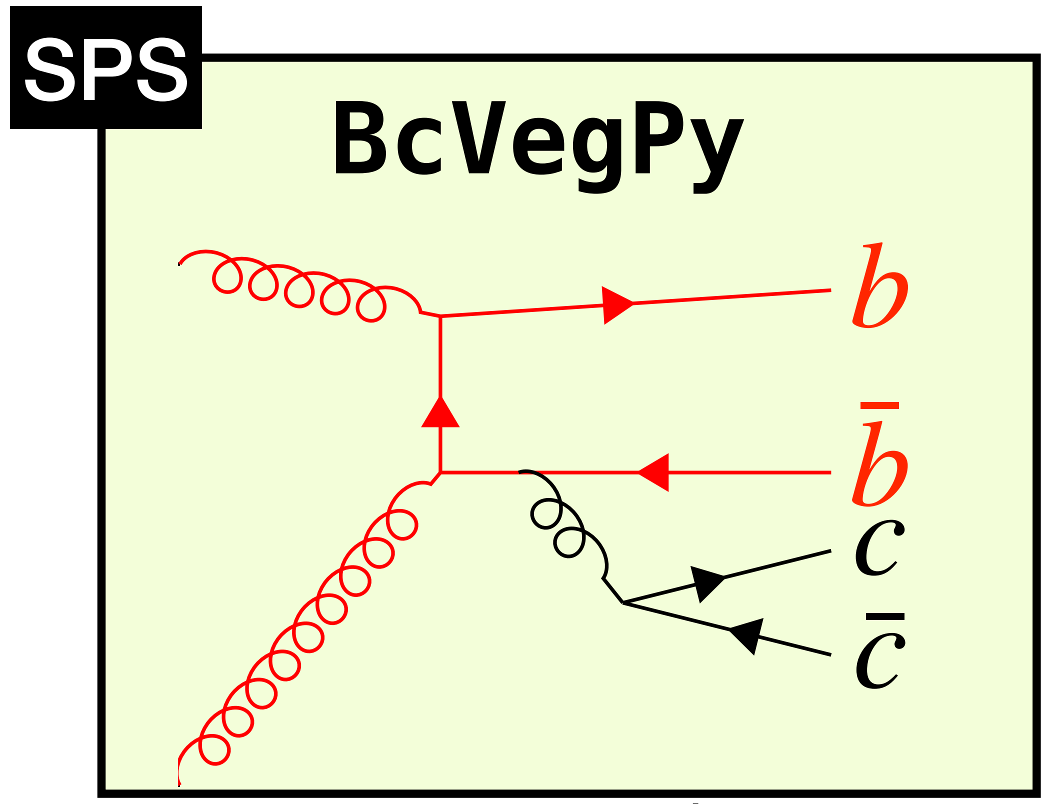


QCD CR with **"String Junctions"** [Sjöstrand & Skands 2002]

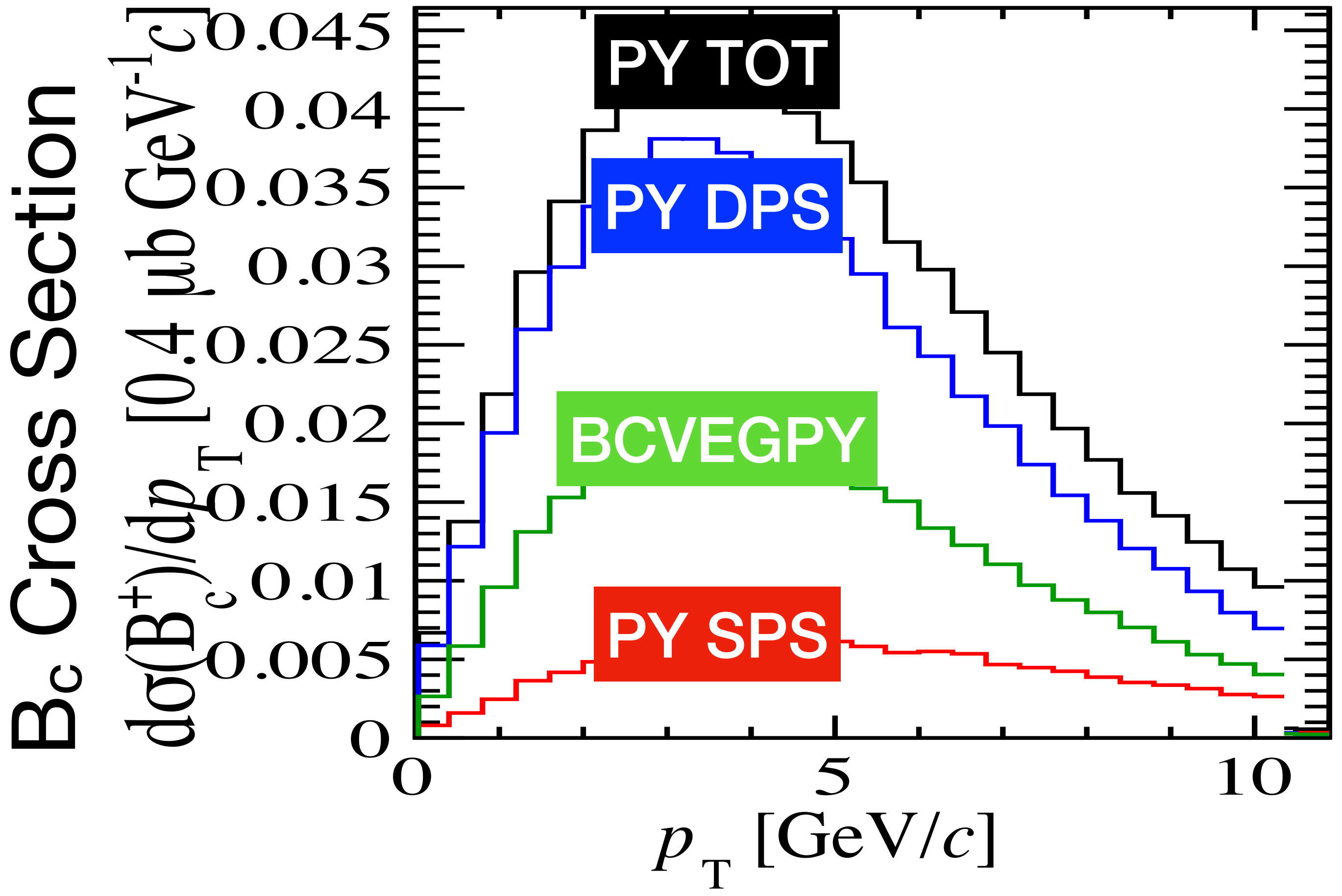
➜ new source of low-p_T **baryons** [Christiansen & Skands 2015] [Altmann & Skands 2024]

Recent case study: $B_c^{\pm}$ production

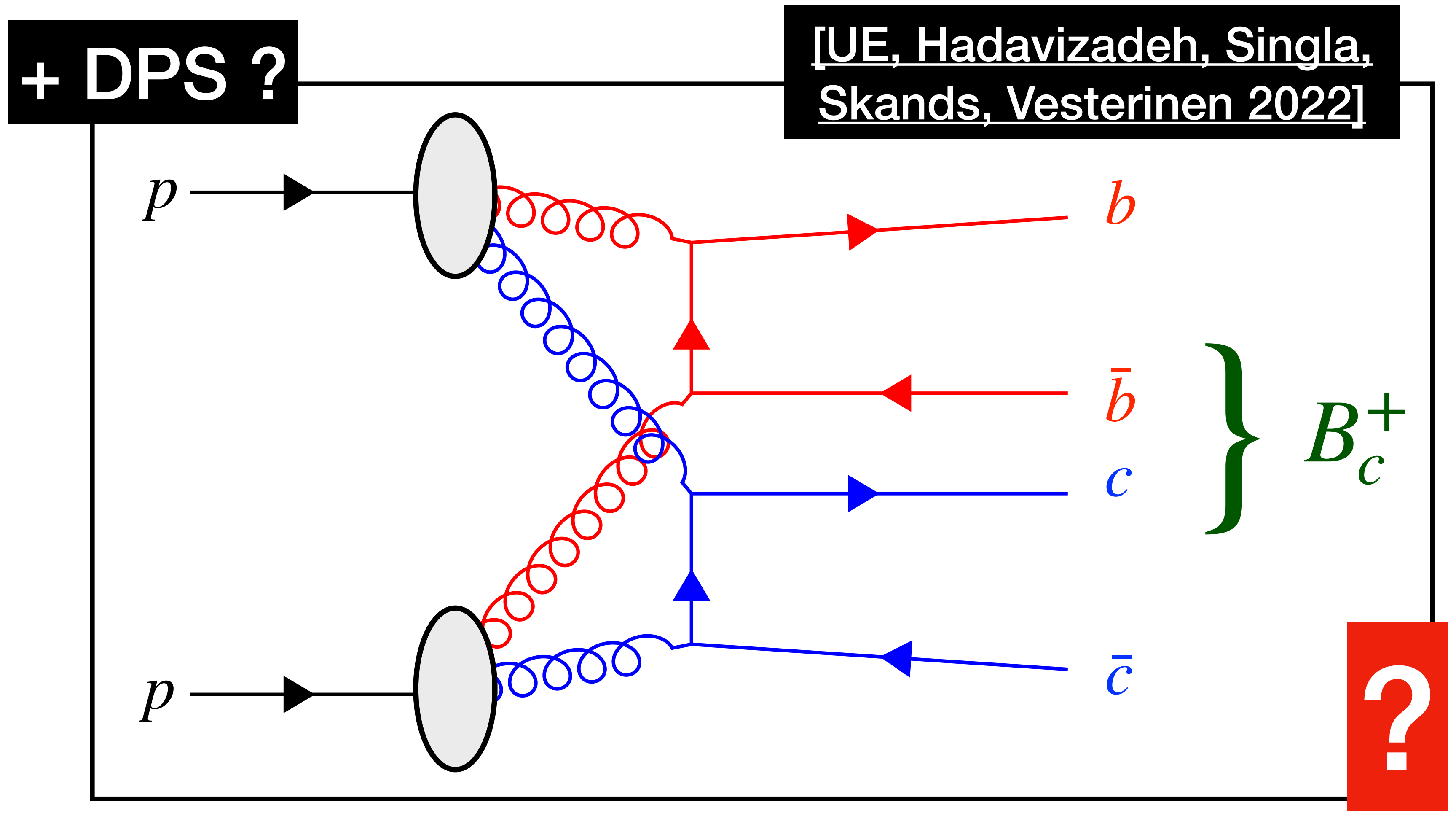
Requires production of b **and** $\bar{c}$ quark (distinct from onia which receive contributions from $g \to Q\bar{Q}_8 \to Q\bar{Q}_1$)



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



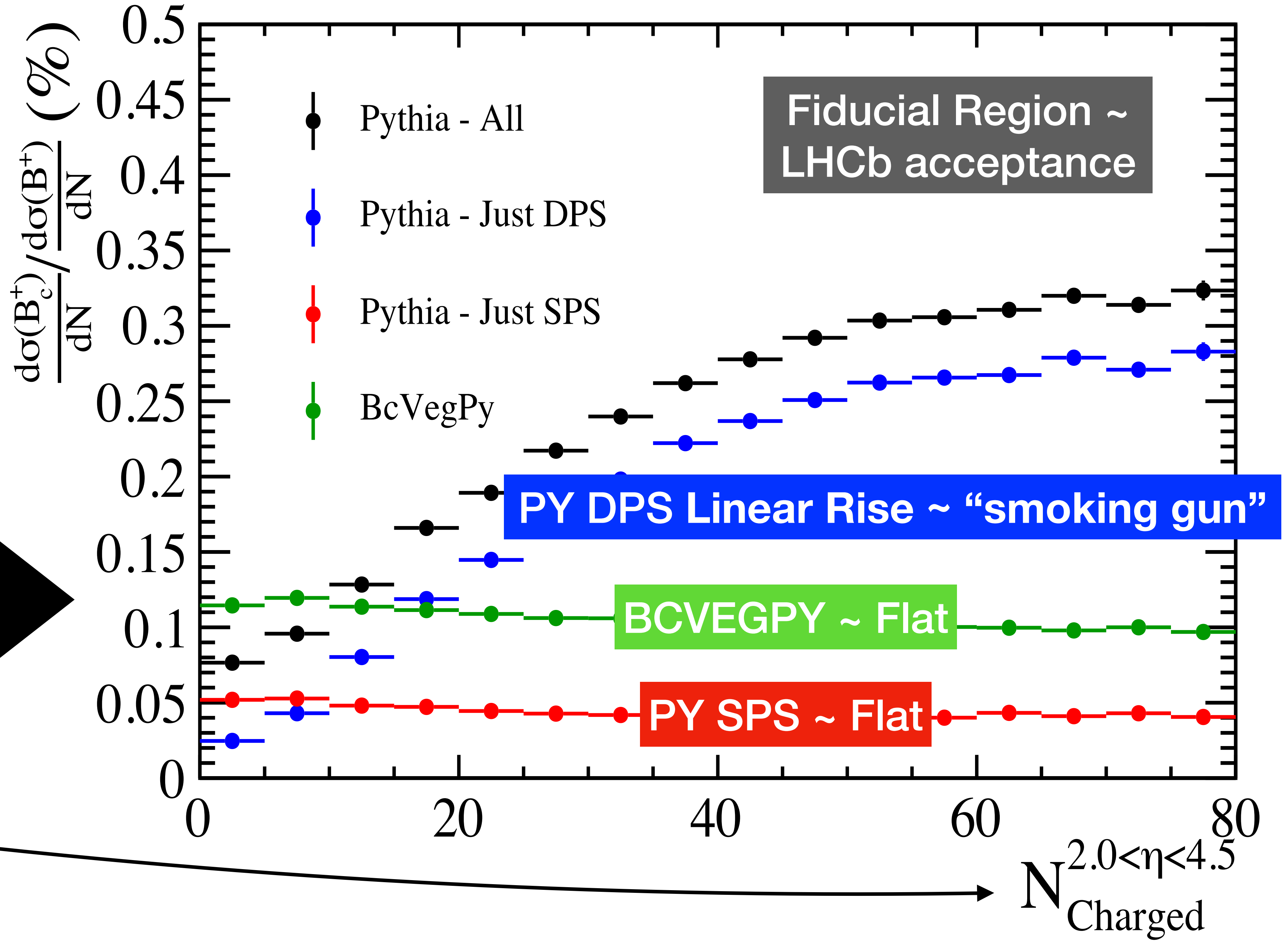
Pythia (with CR) predicts order-of-magnitude enhancements from DPS



Difficult to measure absolute $\sigma(B_c)$

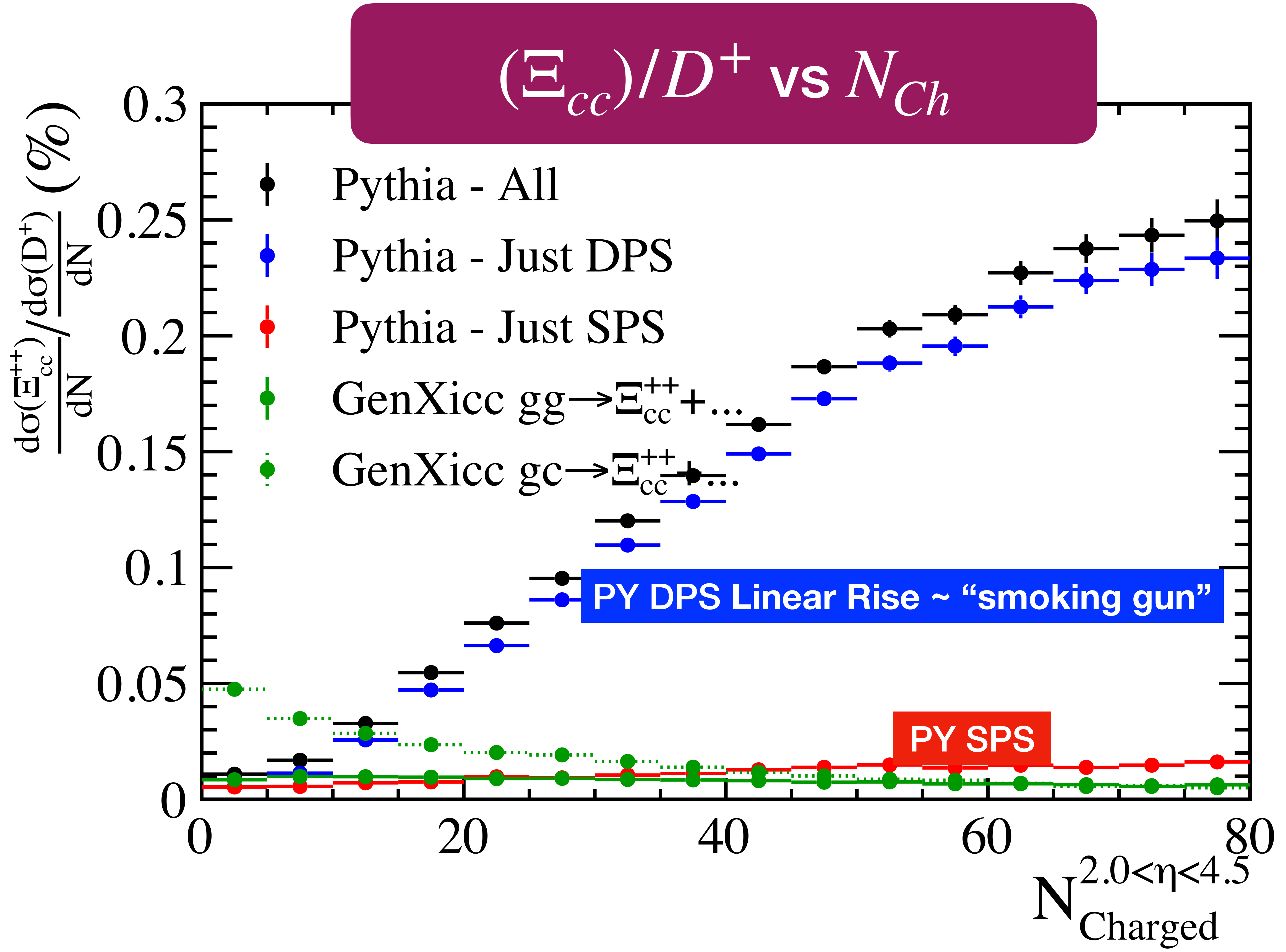
➜ **use B_c/B^+ ratio**

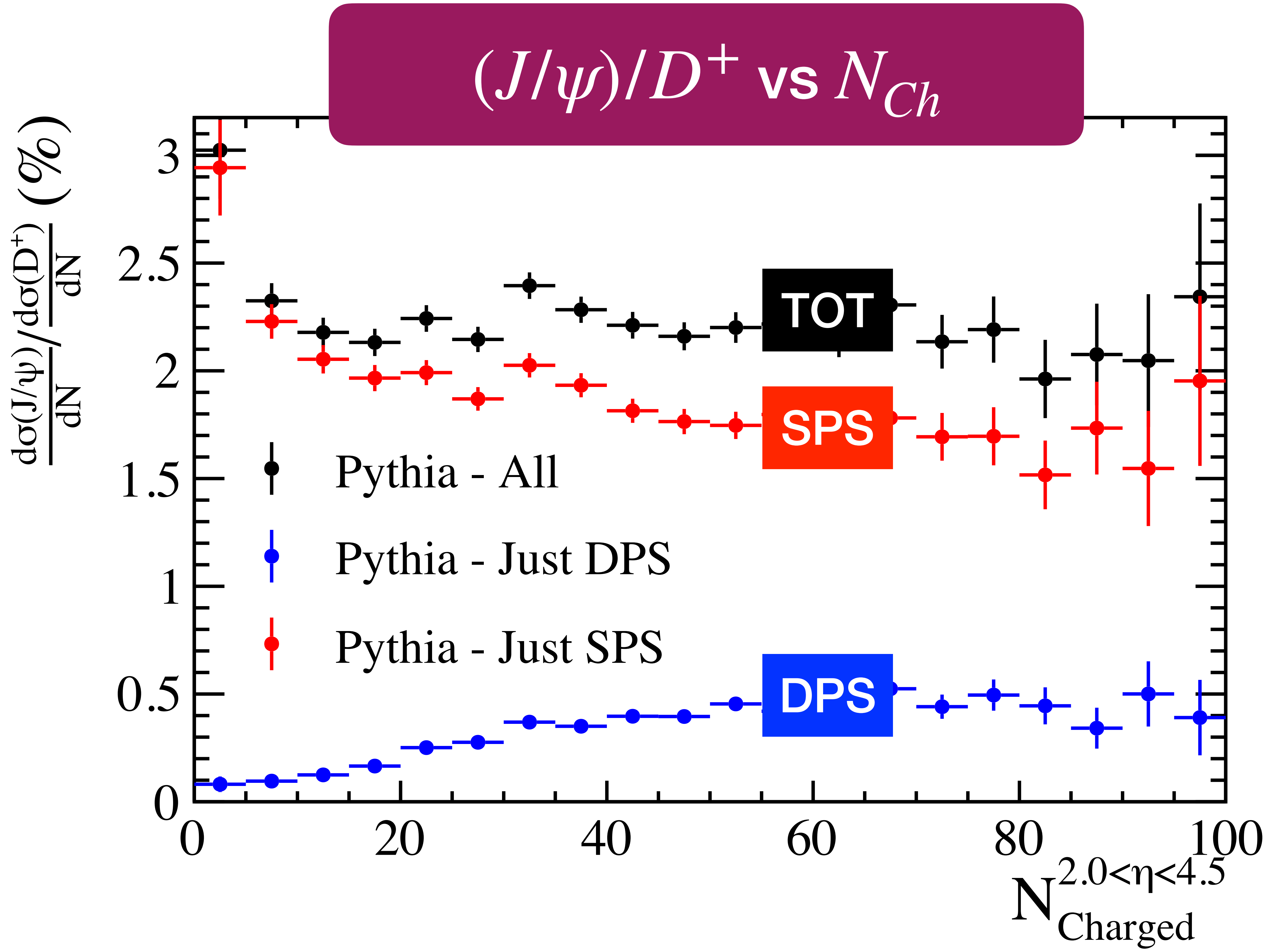
+ exploit DPS events have higher $\langle N_{Ch} \rangle$



[**UE**, Hadavizadeh, Singla, Skands, Vesterinen 2022]

Other multiply-heavy hadrons





Sensitive to baryon/junction CR

Also look at: Ξ_{bc} , …

Onia: large SPS from $g \to Q\bar{Q}_8 \to Q\bar{Q}_1$

➜ look at **associated production**: $J/\psi + X_c + X_{\bar{c}}$

[**UE**, Hadavizadeh, Singla, Skands, Vesterinen 2022]

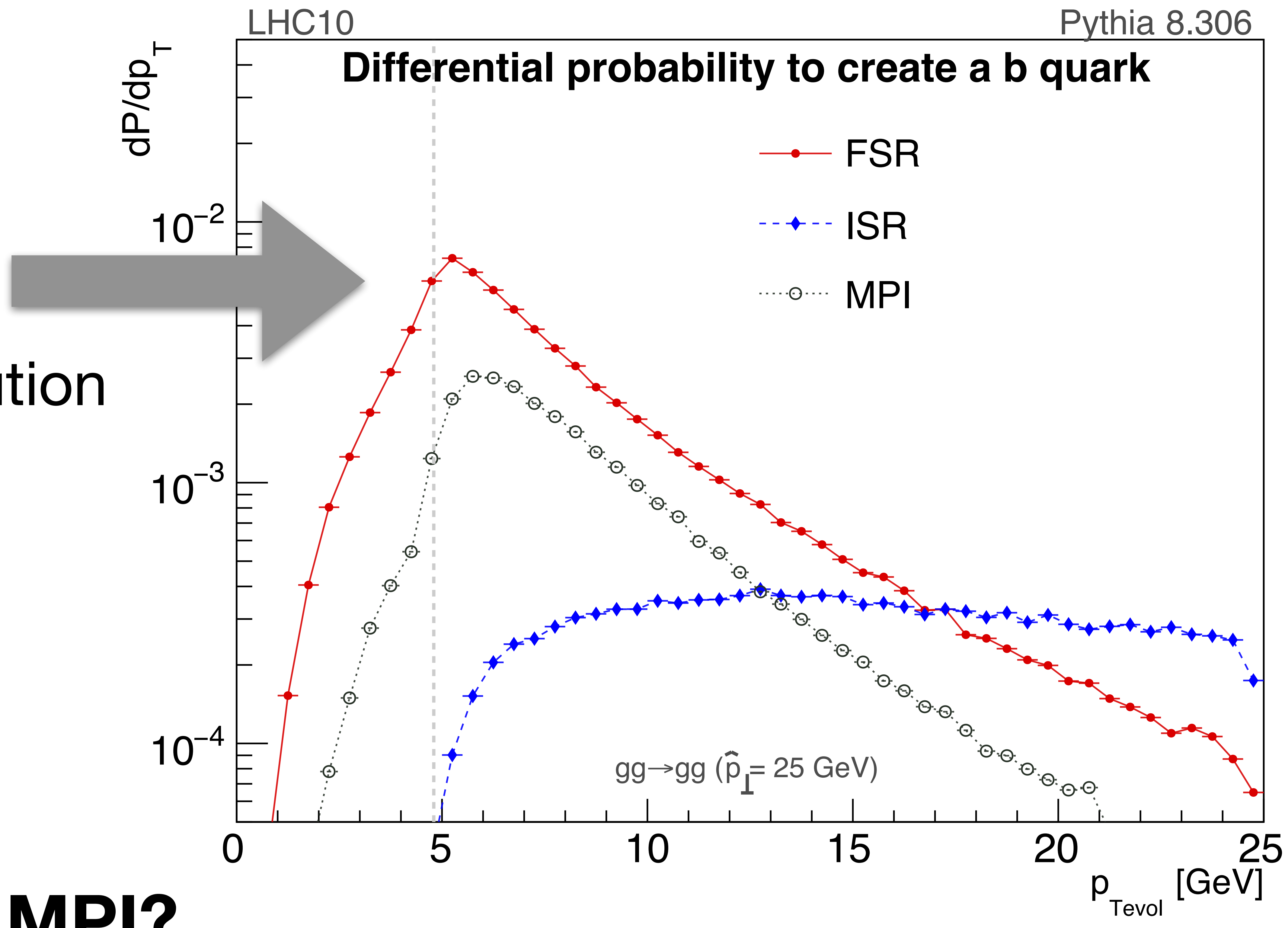
Outstanding Issues & Outlook

- **Evolution Equations & Efficiency**

  PYTHIA's FSR & MPI evolved in ~ physical p_T

  ⇒ Heavy quarks Q can be created at $p_{Tevol} < m_Q$

  Unphysical (& slow) ➜ *reformulate* FSR & MPI evolution



- **Contrast Different Physics Models?**
  - **Alternative MPI+CR implementations?**
  - **Coalescence?**
  - **Thermal (HI-inspired) Models?**

- **Suppression due to spatial separation of MPI?**
  - (arguments both for and against)

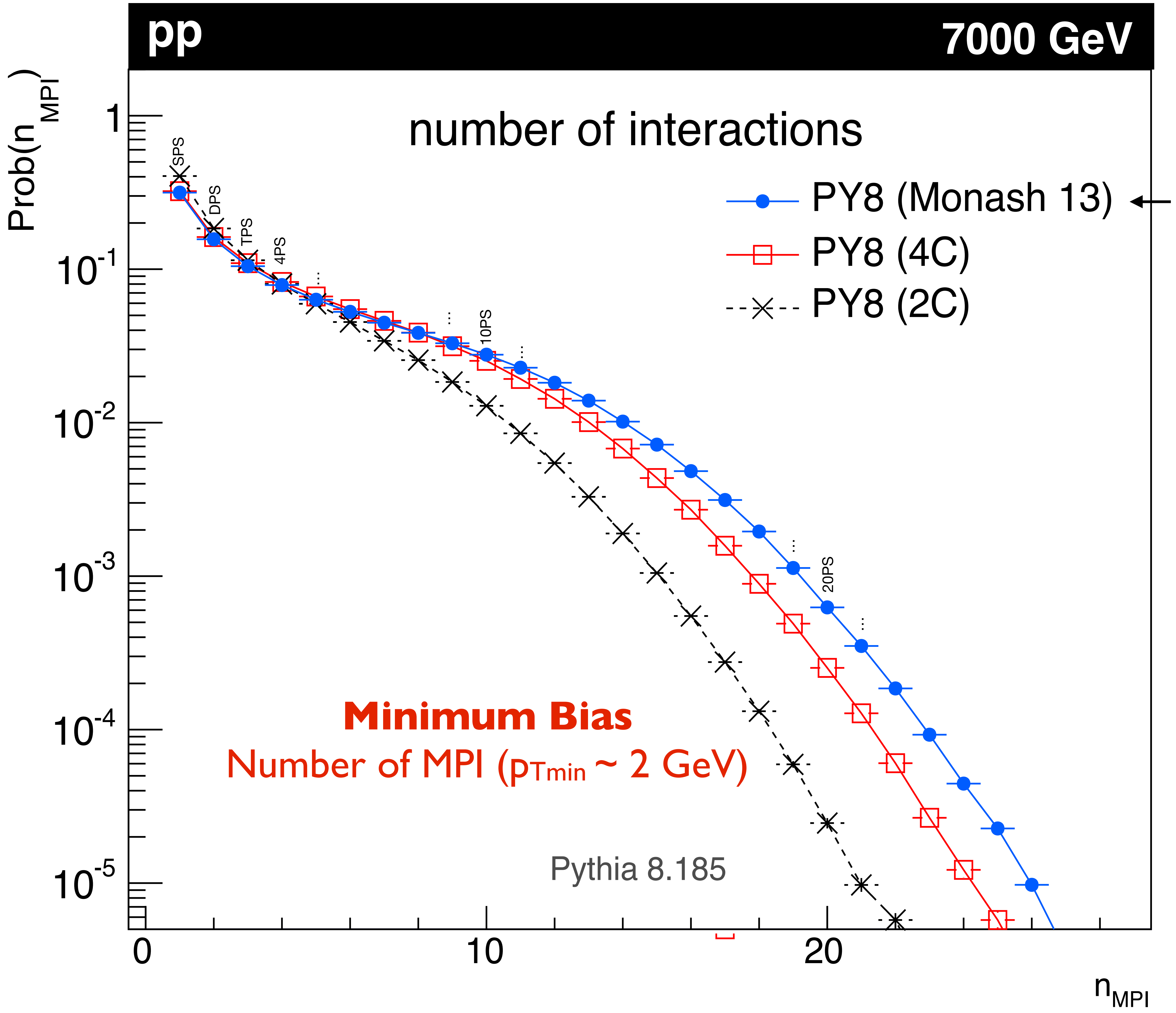
- **What does data say?** ➜ **Eagerly awaiting *measurements*!**

  + if large enhancements confirmed ➜ reevaluate physics potential for BSM sensitivity?

Extra Slides

How many MPI?

(According to PYTHIA simulation; take with a grain of salt —point is that there are *many*)



$\leftarrow p_{\perp 0} = 2.28\,\mathrm{GeV}$

Note: this is the number of **all** MPI, including low-pT ones, in an inclusive sample of inelastic non-diffractive events.

The probability for events with **hard** DPS (etc) is much smaller.