Establishing Center-of-Mass Energy Dependance for the Primordial Transverse Momentum in PYTHIA

Ioannis Polychronakos

In collaboration with:

C. Bierlich, C. Preuss, P. Skands, M. Szewc

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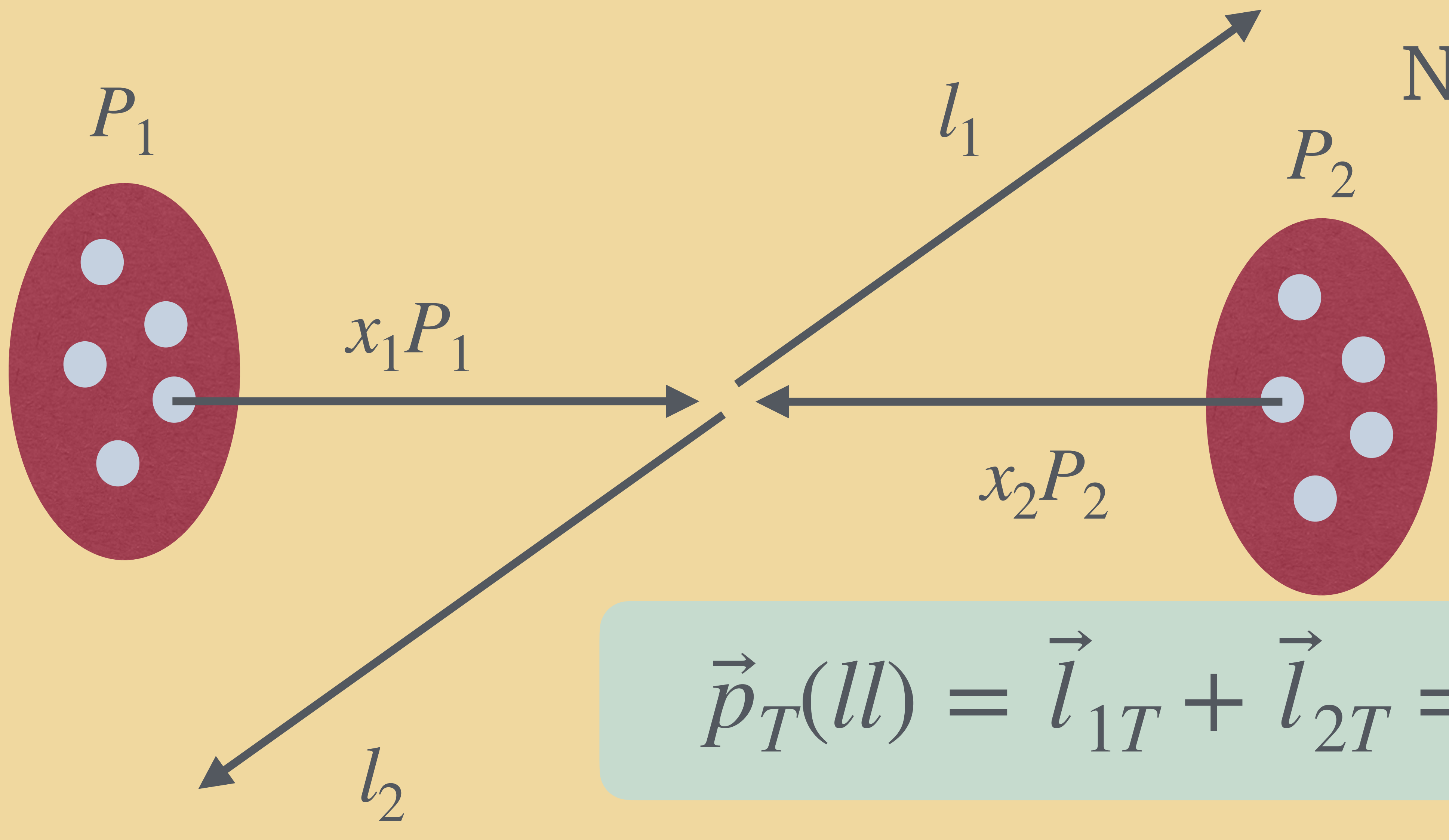
ioannis.polychronakos@fysik.lu.se

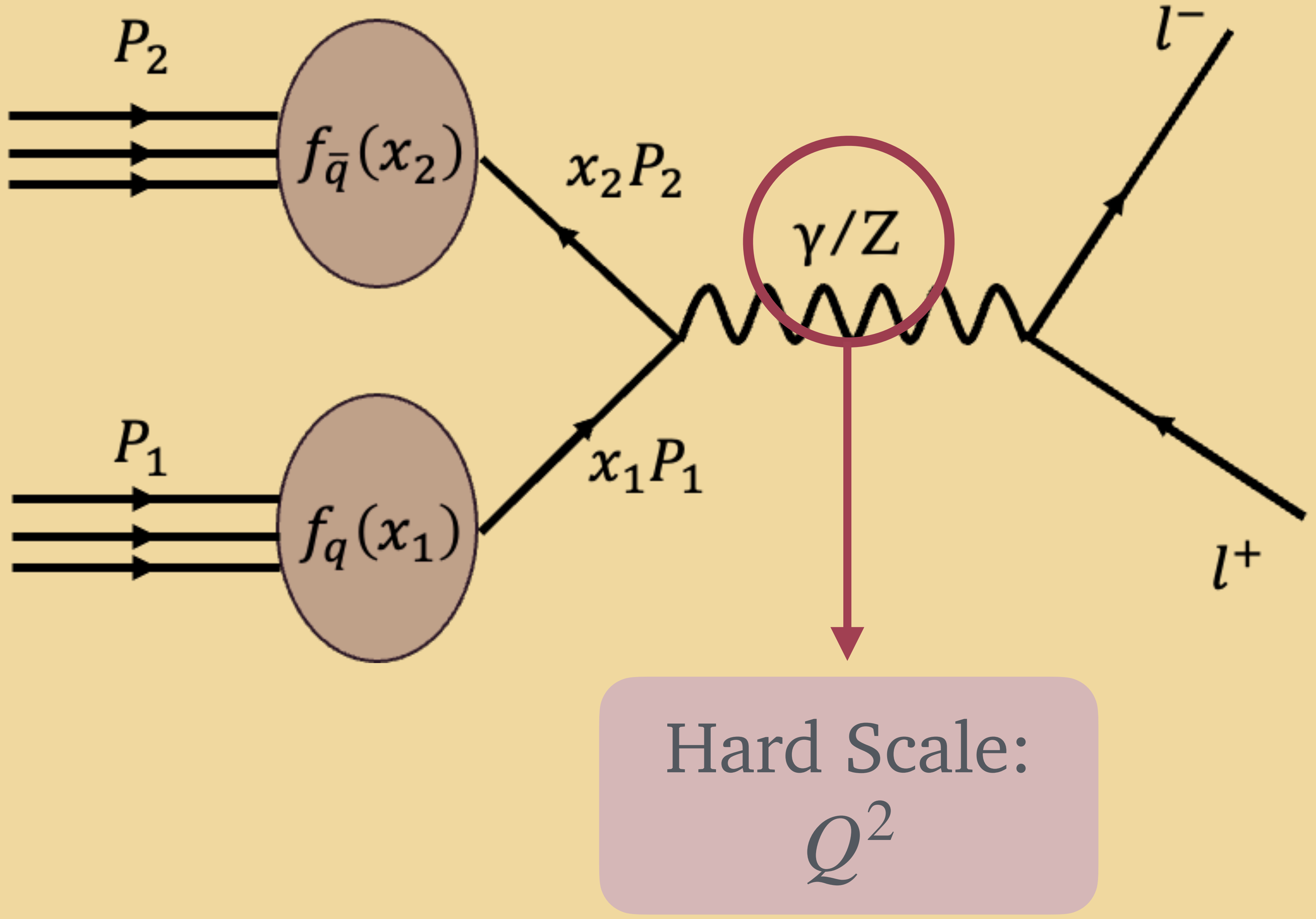
How do we measure primordial transverse momentum?

No primordial kT



$$\vec{p}_T(ll) = \vec{l}_{1T} + \vec{l}_{2T} = \vec{0}$$

A Drell-Yan sketch



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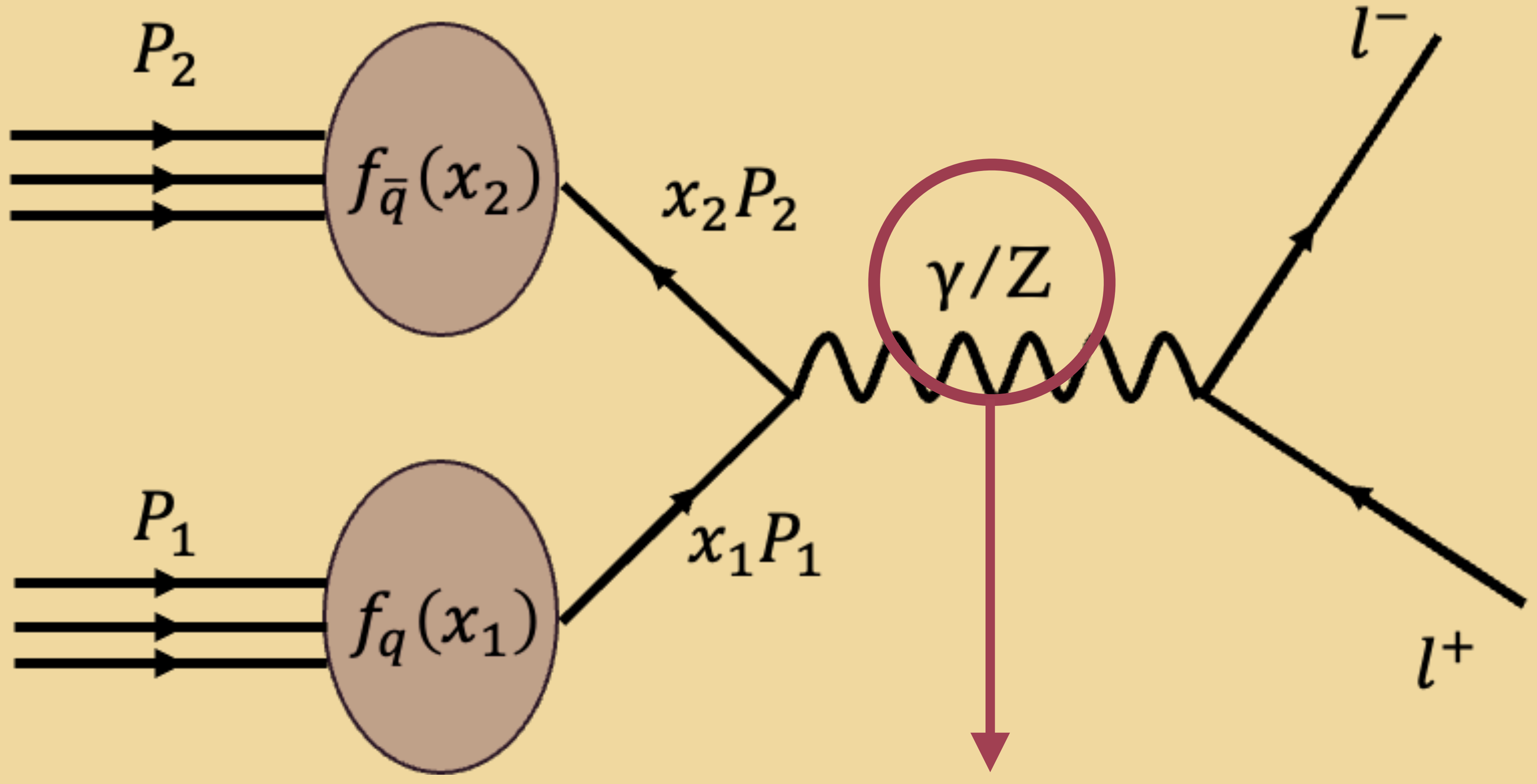
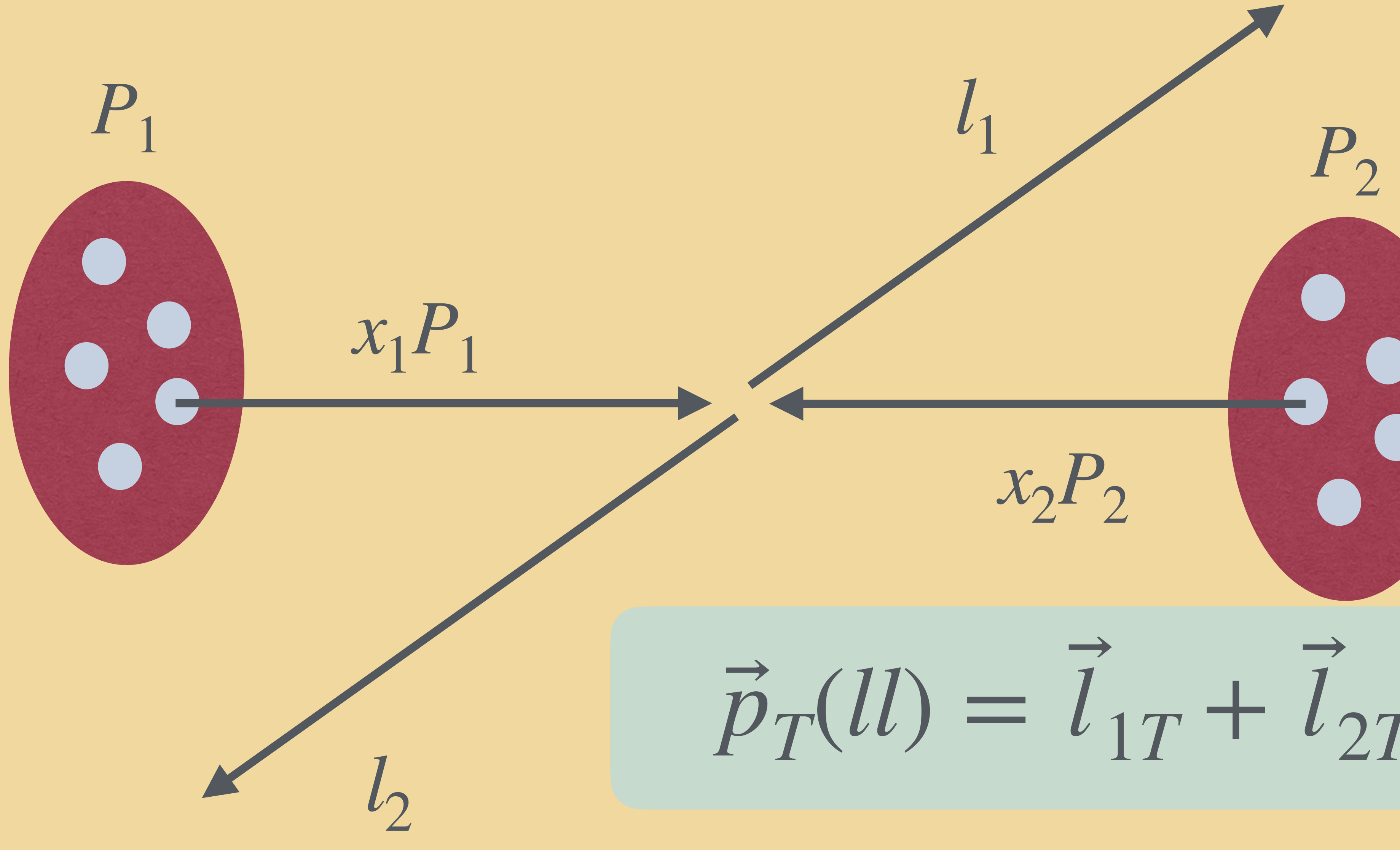


Hard Scale:
Q^2

No primordial kT



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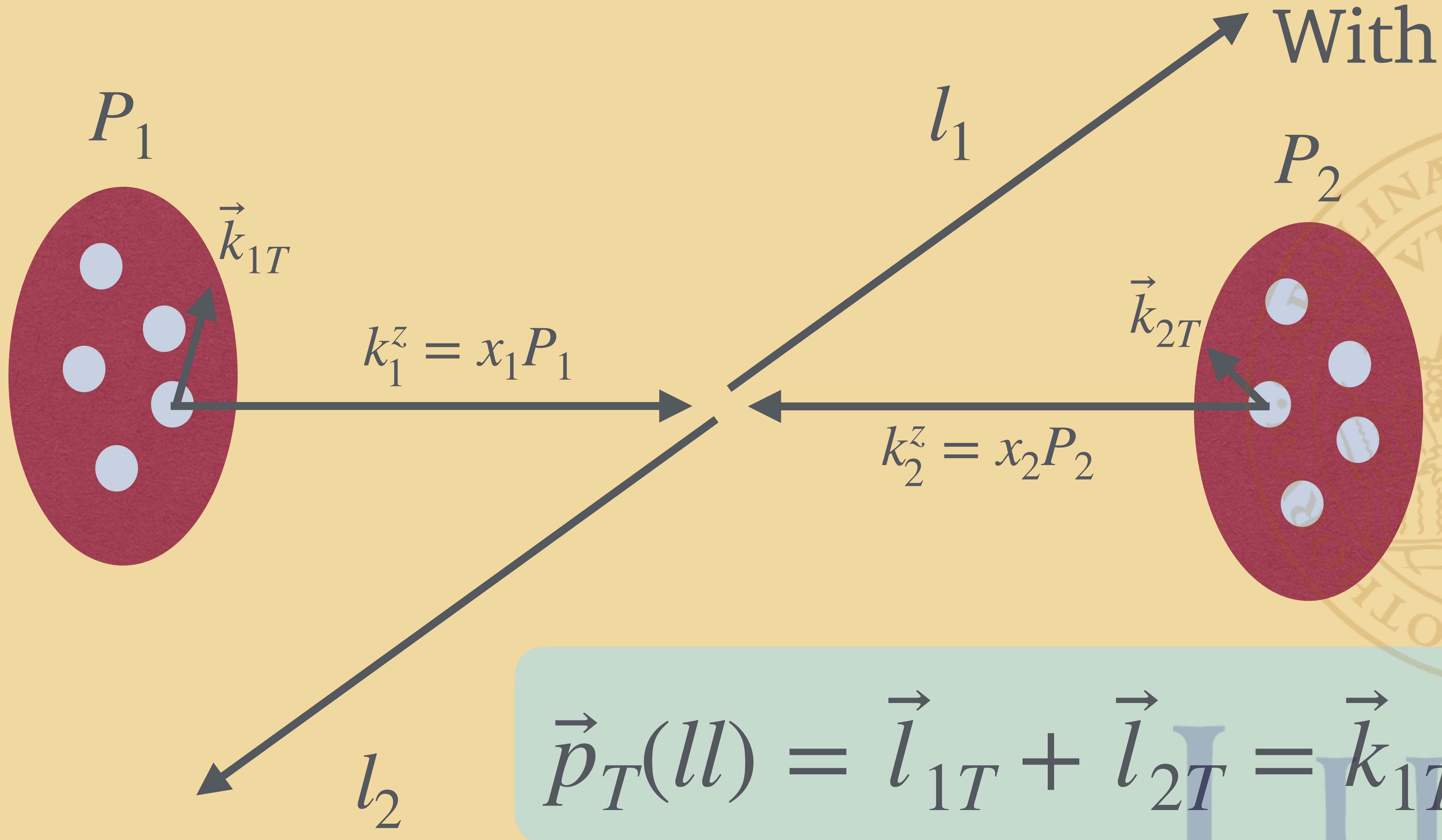
With primordial kT



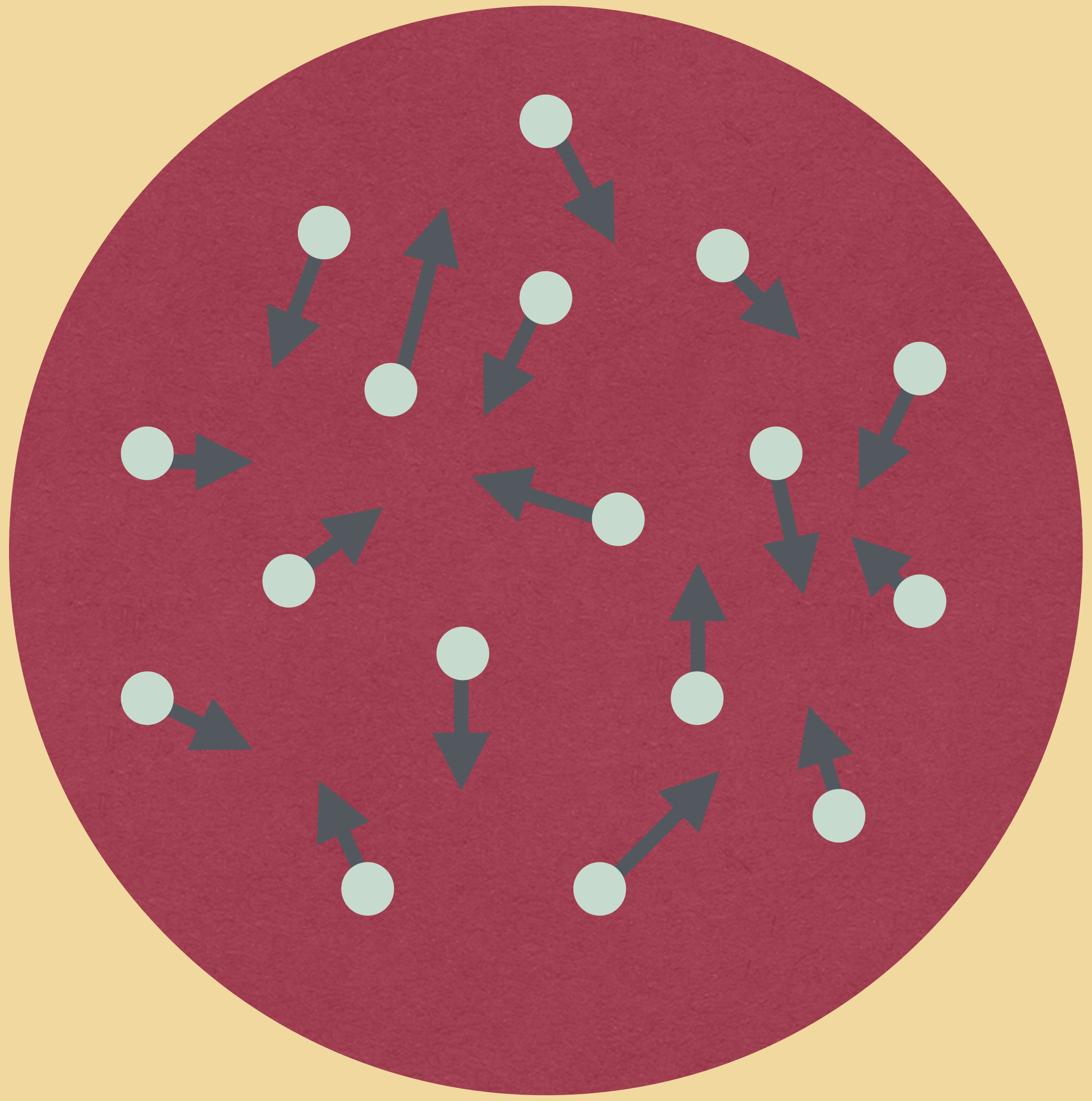
$$\vec{p}_T(ll) = \vec{l}_{1T} + \vec{l}_{2T} = \vec{k}_{1T} + \vec{k}_{2T}$$

Primordial kT as Fermi Motion

The primordial kT inside the proton at rest should be the Fermi motion of its constituent partons.

From heuristic arguments:

$$\Delta k_x \sim \Lambda_{QCD} \Rightarrow \sigma \sim 0.3\ GeV$$

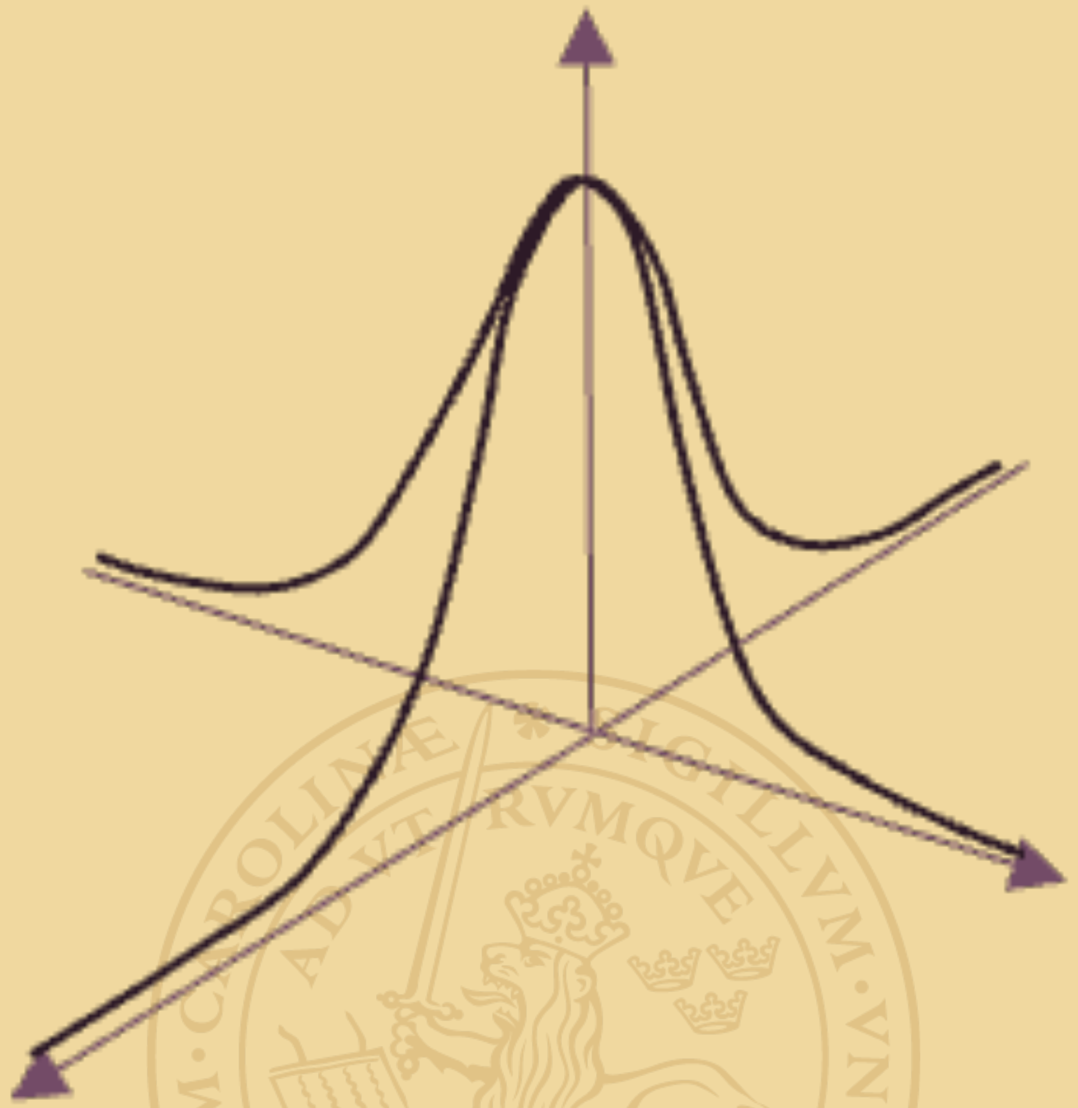


Modeled by a Gaussian:

$$G(k_T, \sigma) = \frac{1}{2\pi\sigma^2} e^{-\frac{k_T^2}{2\sigma^2}}$$

The variance controls the kT:

$$< k_T > = \sqrt{\frac{\pi}{2}}\sigma$$



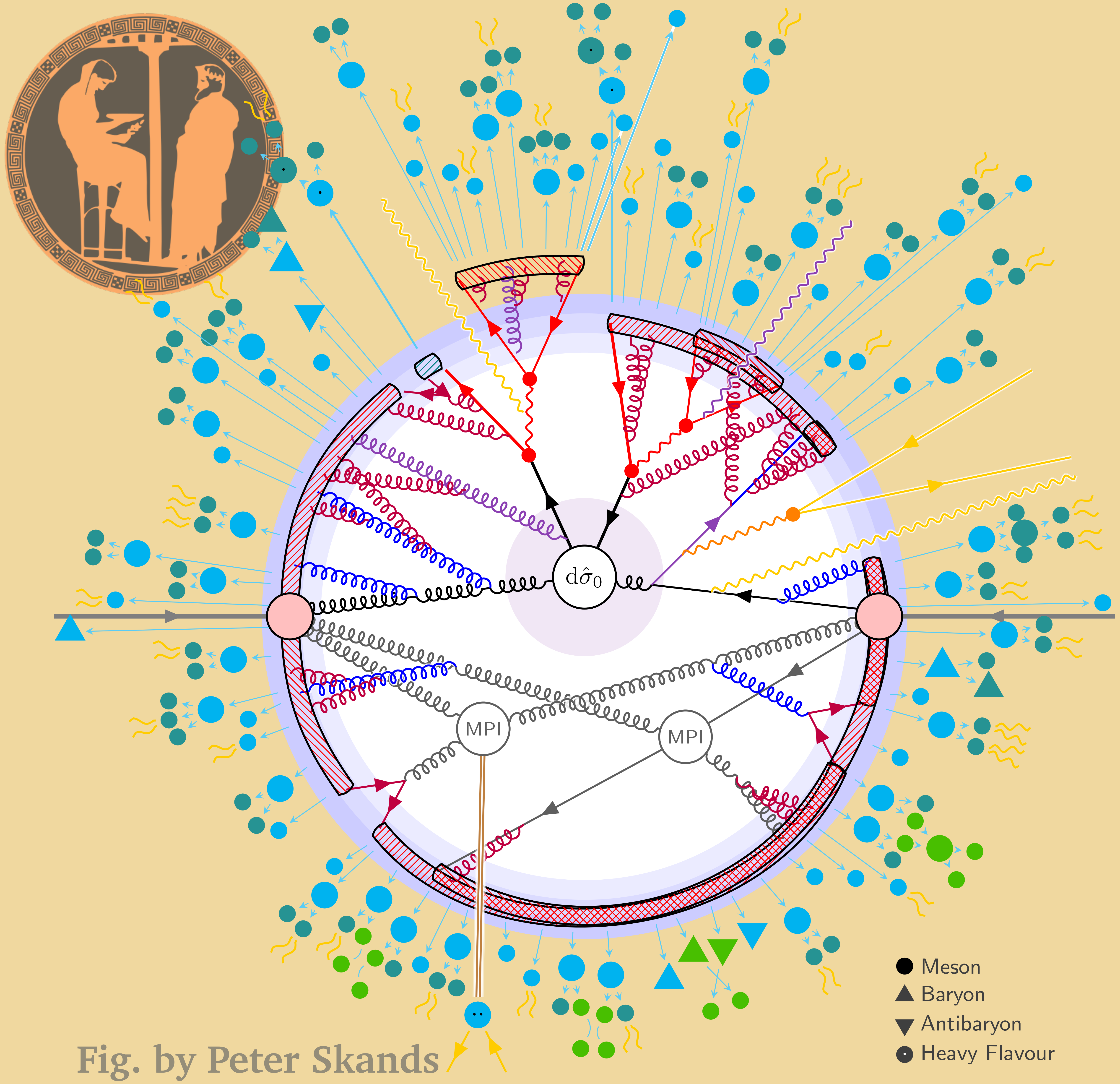
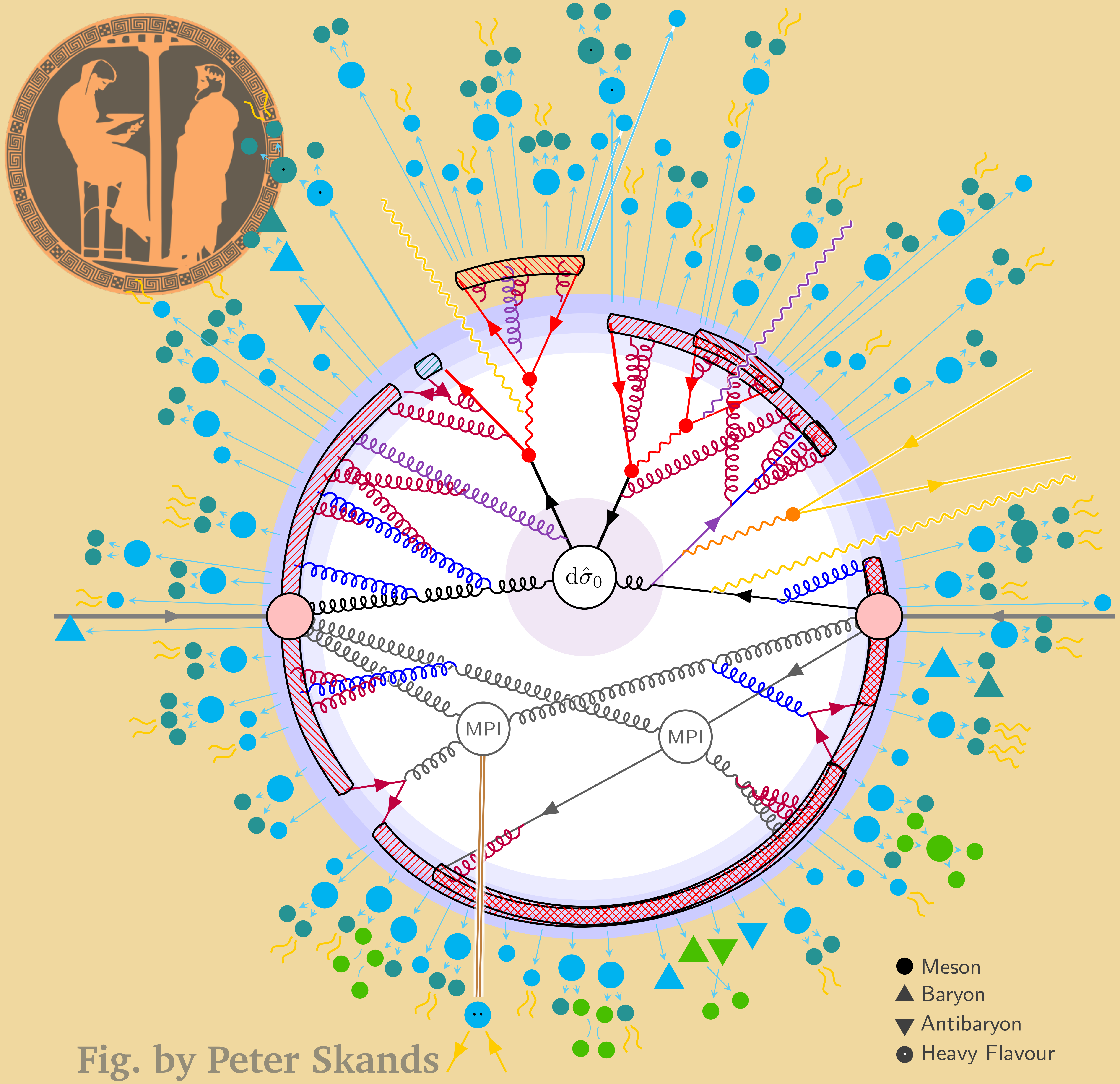


Fig. by Peter Skands

The **primordial kT** is an effective model that encapsulates:

- **Fermi Motion of partons**
- **Soft gluon emissions below the parton shower cut-off.**

$$\sigma_{pyth} \sim 1.8\ GeV$$



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Monte Carlo Event Generators contain a lot of “free” parameters.

The exact values are determined by **tuning** to data:

χ^2 **minimization procedure**

Available Data for Tuning

The last tune of PYTHIA (Monash) used three histograms.

Q/E_{CM}	38.8	62	200	1.8 TeV	1.96 TeV	2.76 TeV	7 TeV	8 TeV	13 TeV
4.2 - 5.2									
5.2 - 6.2									
6.2-7.2									
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10.85-12.85									
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Similar Studies: arXiv:2412.05221v2 arXiv:2409.17770v2

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Experimentally unexplored region!

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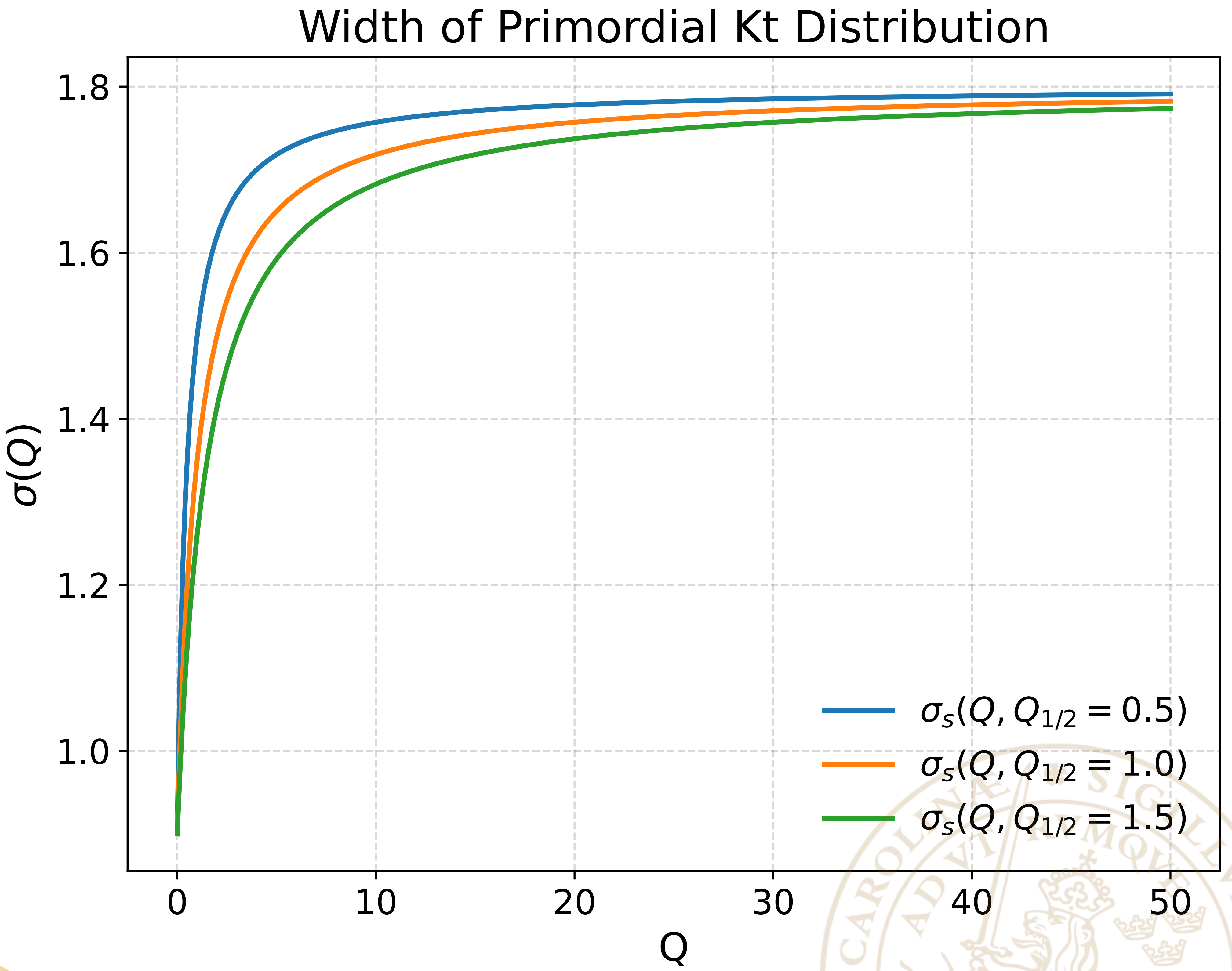
Technical Dampening Factor

$$\sigma(Q) = \frac{(\sigma_{soft}Q_{half} + \sigma_{hard}Q)}{(Q_{half} + Q)} \frac{m}{(m + m_{half}y_{damp})}$$



5 parameters ($\sigma_{soft}, \sigma_{hard}, Q_{half}, m_{half}, y_{damp}$):

$$Q_{half} = 1.5 \longrightarrow Q_{half} = 0.0$$

$$m_{half} = 1.0 \longrightarrow m_{half} = 0.0$$

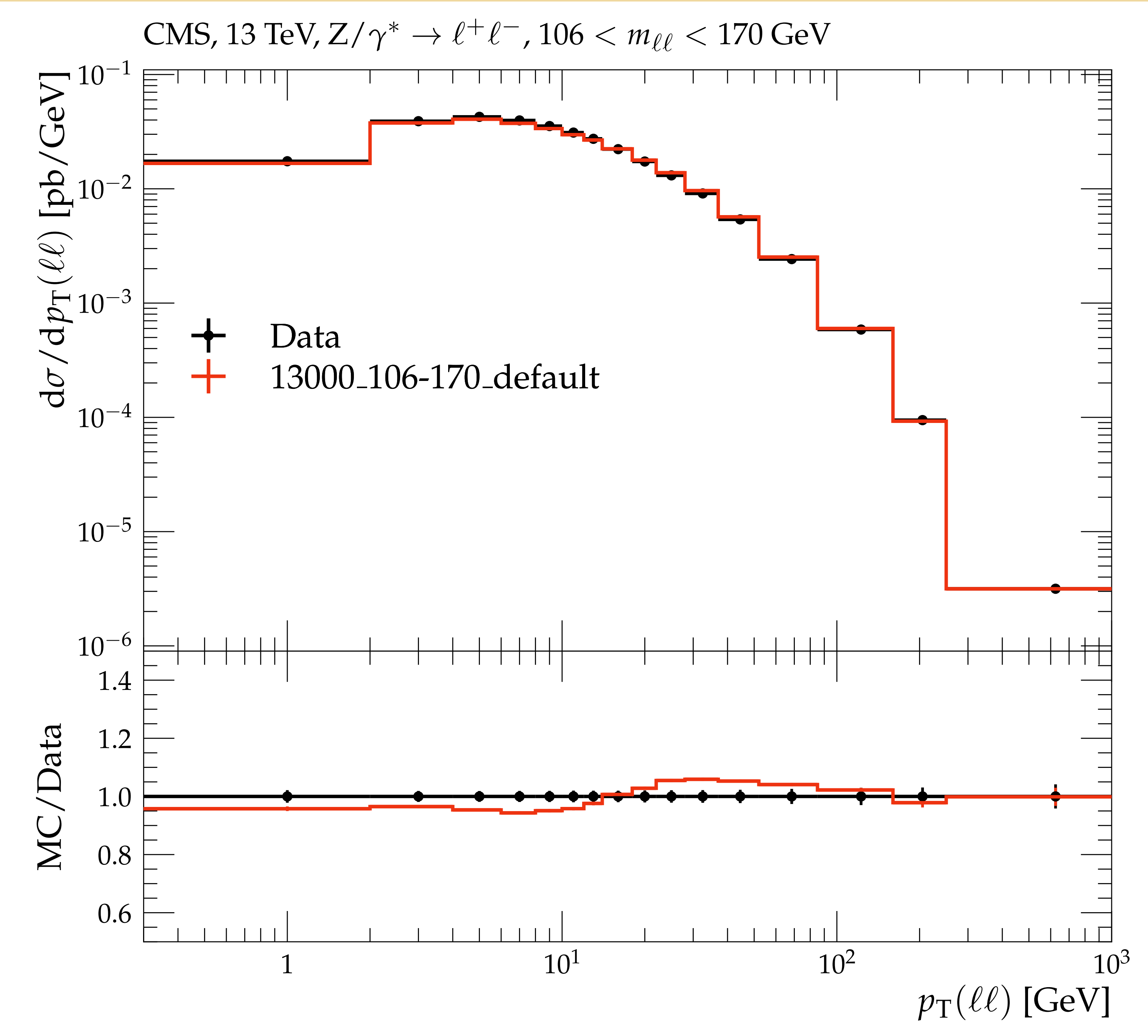
Model reduces to a single parameter that can be tuned:

$$\sigma = \sigma_{hard}$$

$$\sigma(Q) = \frac{(\sigma_{soft}Q_{half} + \sigma_{hard}Q)}{(Q_{half} + Q)}$$

Step 1: Normalize Histograms

We look at the shapes since total cross section has NLO and NNLO contributions.



Step 1: Normalize Histograms

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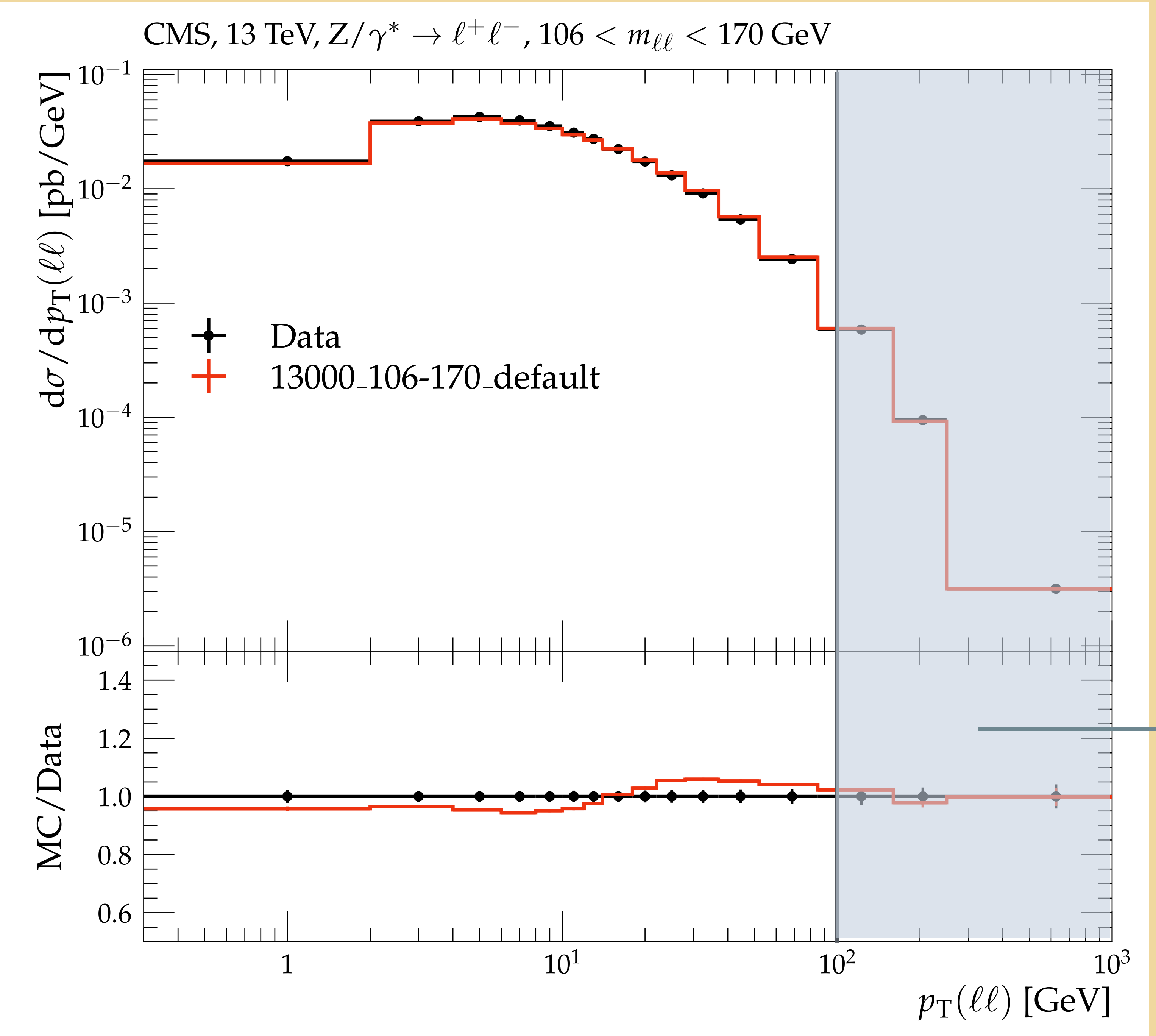
Step 2: Tune ISR α_S on the tail for all high energy data (>1TeV)

The tails affect the low pT bins because of unitarity.



Tail region

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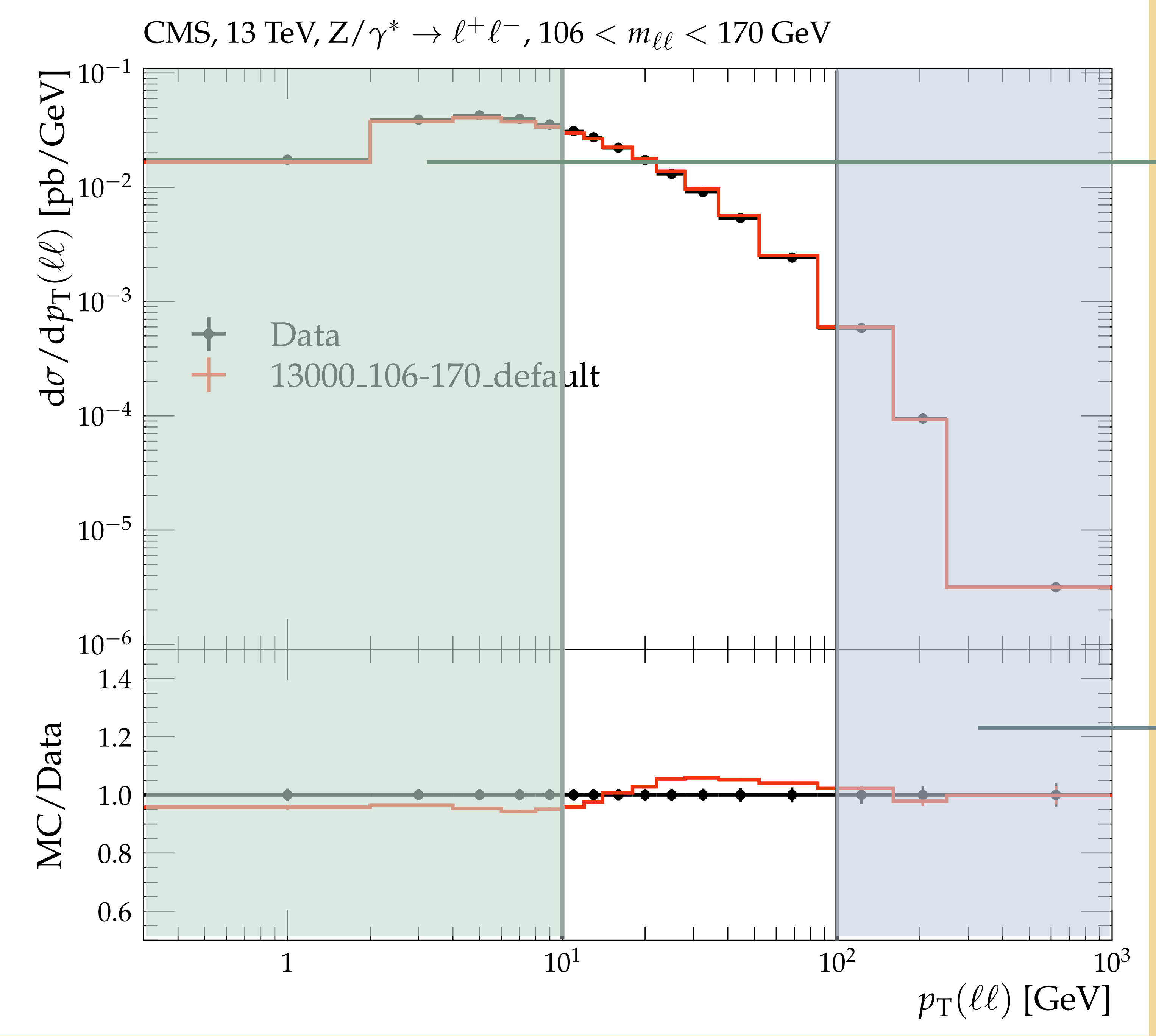

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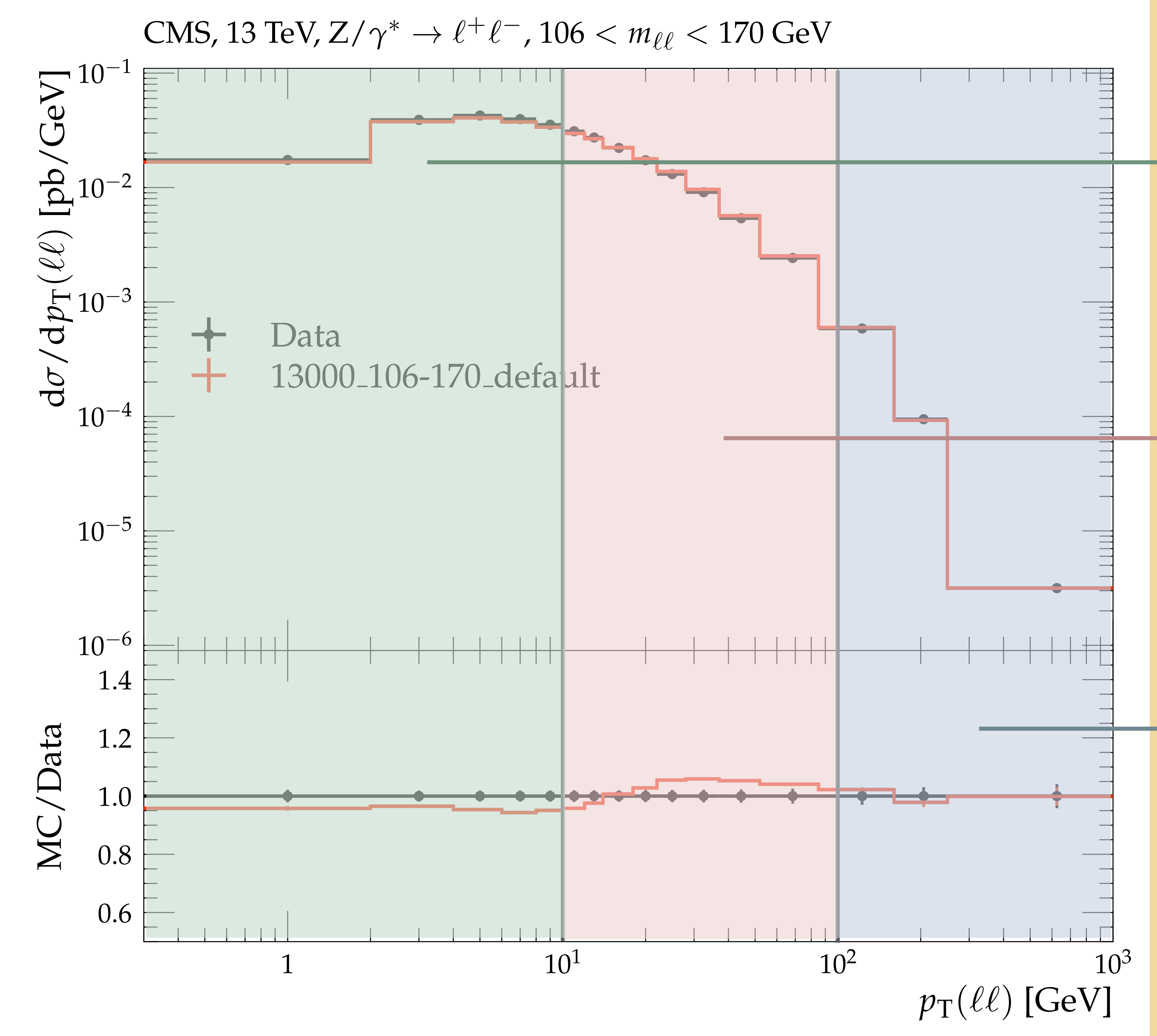

Low pT region

Sudakov region

Tail region

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Principled

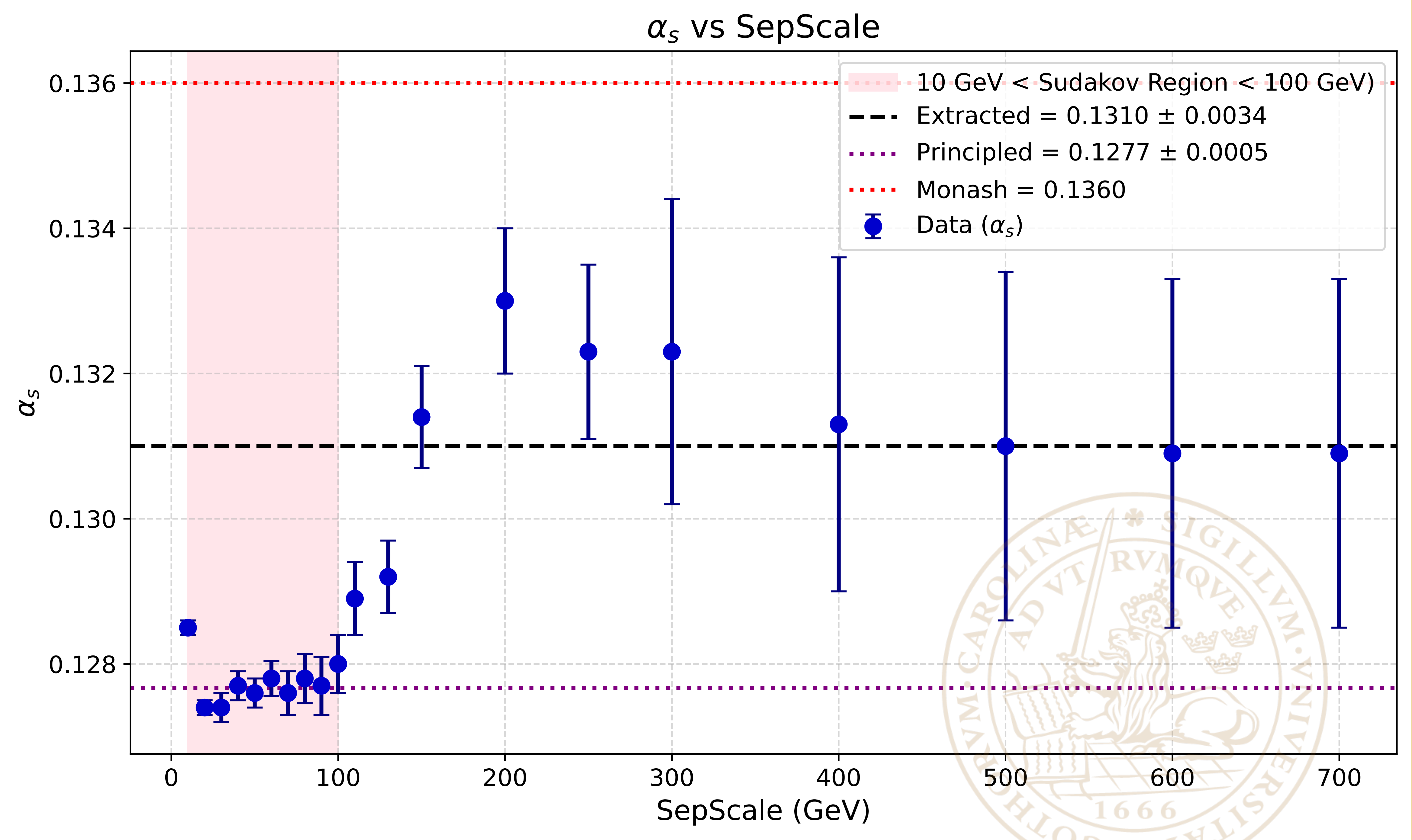
Pragmatic

Tune α_S only to the “Sudakov” region and recover CMW value.
$\alpha_S = 0.1260$

Tune α_S the tail of the distributions to capture HO effects.
$\alpha_S = 0.1310$

Pick random values or something.

Push the α_s higher (Monash) to describe data over the whole range.
$\alpha_S = 0.1360$



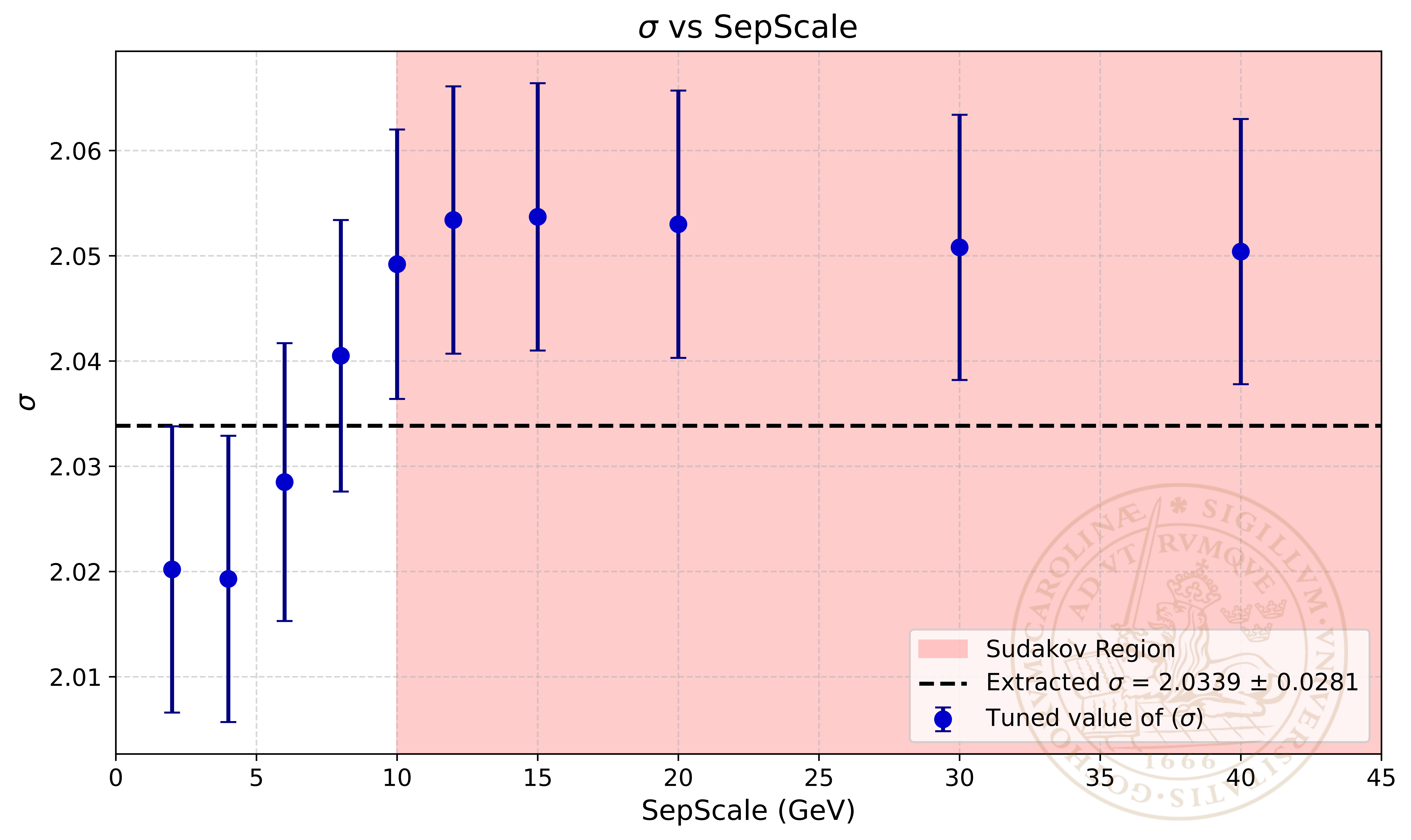
1. Take all bins for a set of (E_{CM}, Q).

2. For Q < 10 GeV, define an arbitrary separation scale.

3. Tune all bins at and below the separation scale.

4. Vary the scale and repeat.

5. Extract a σ value from an envelope below 10 < GeV.



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Tuning Procedure for σ

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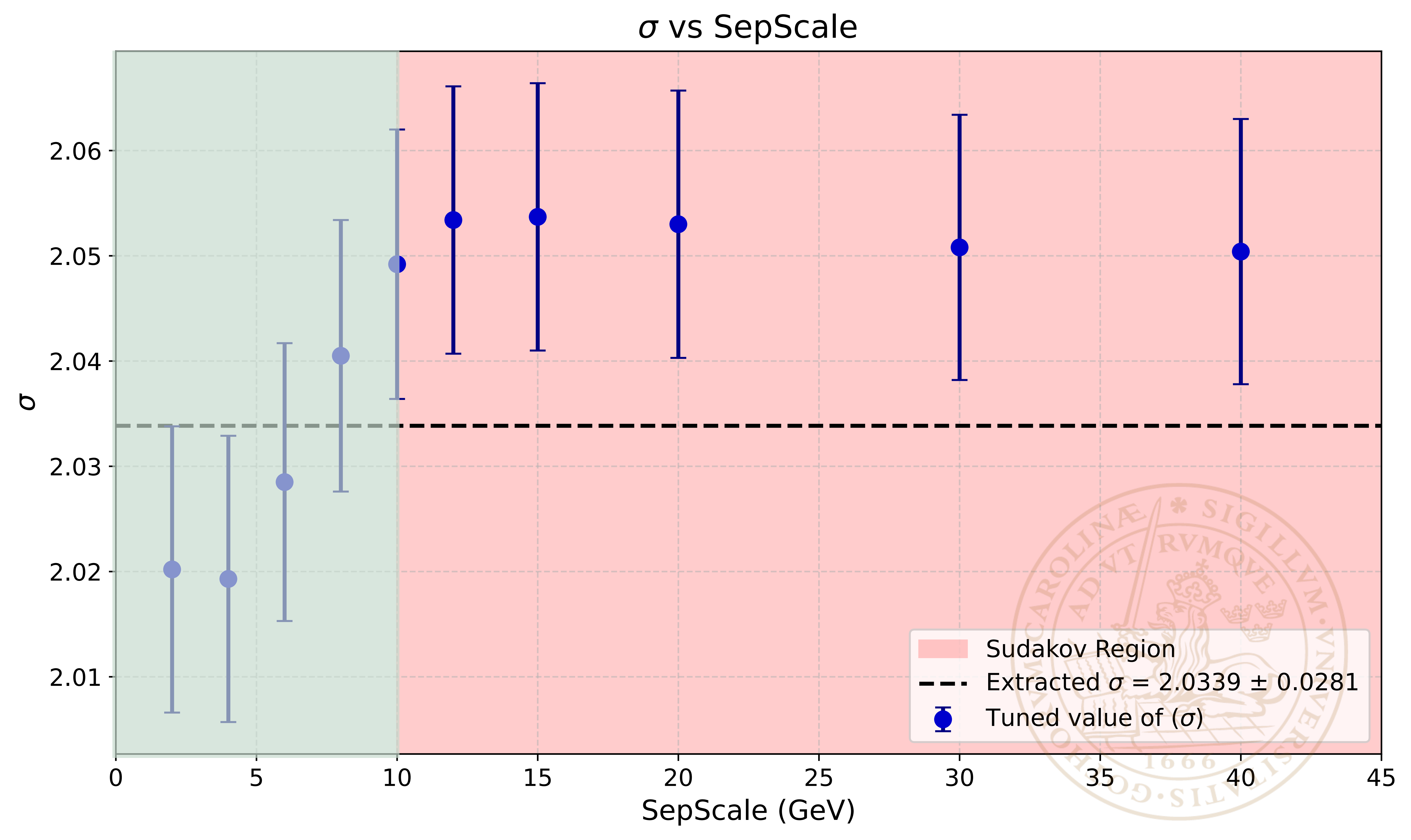

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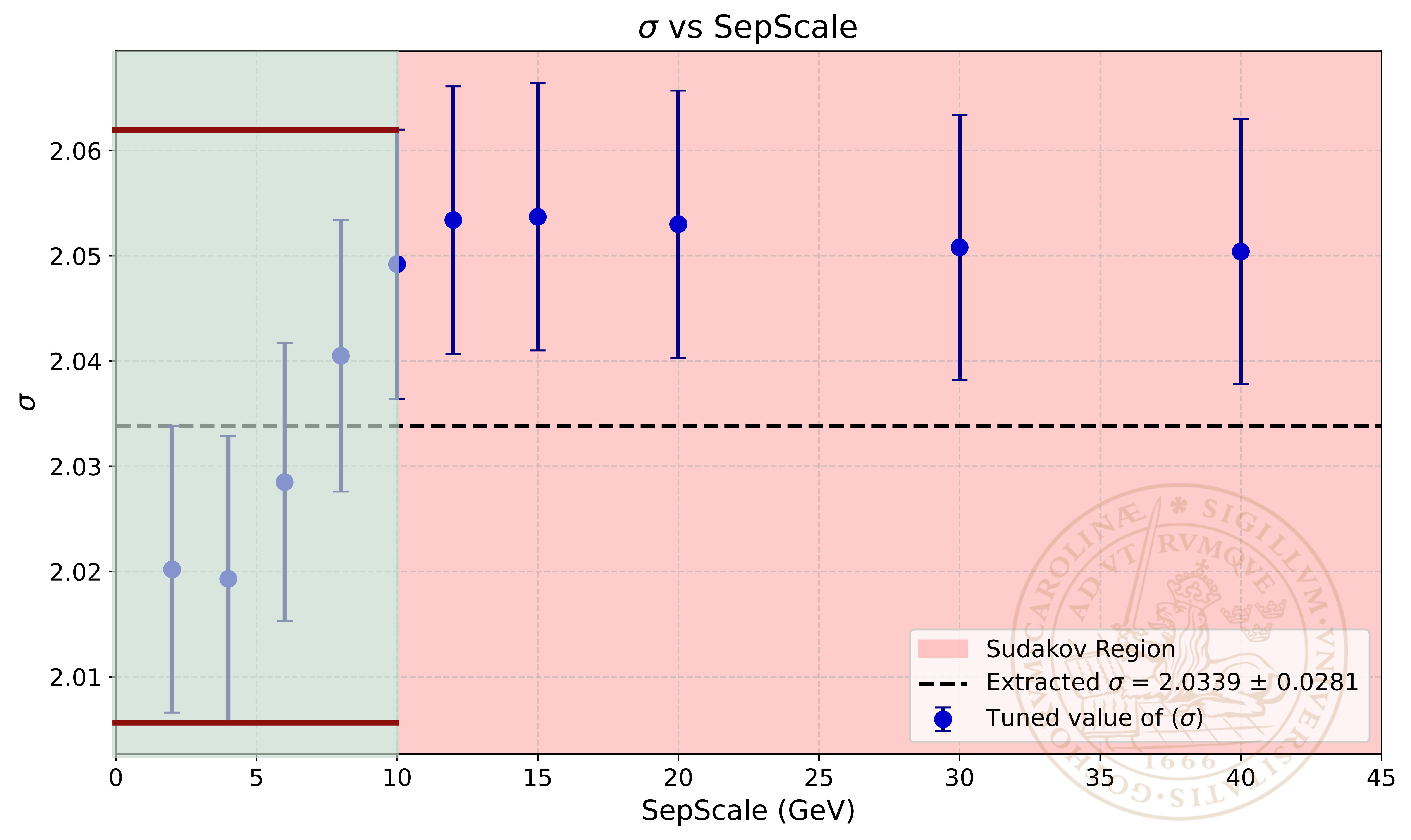

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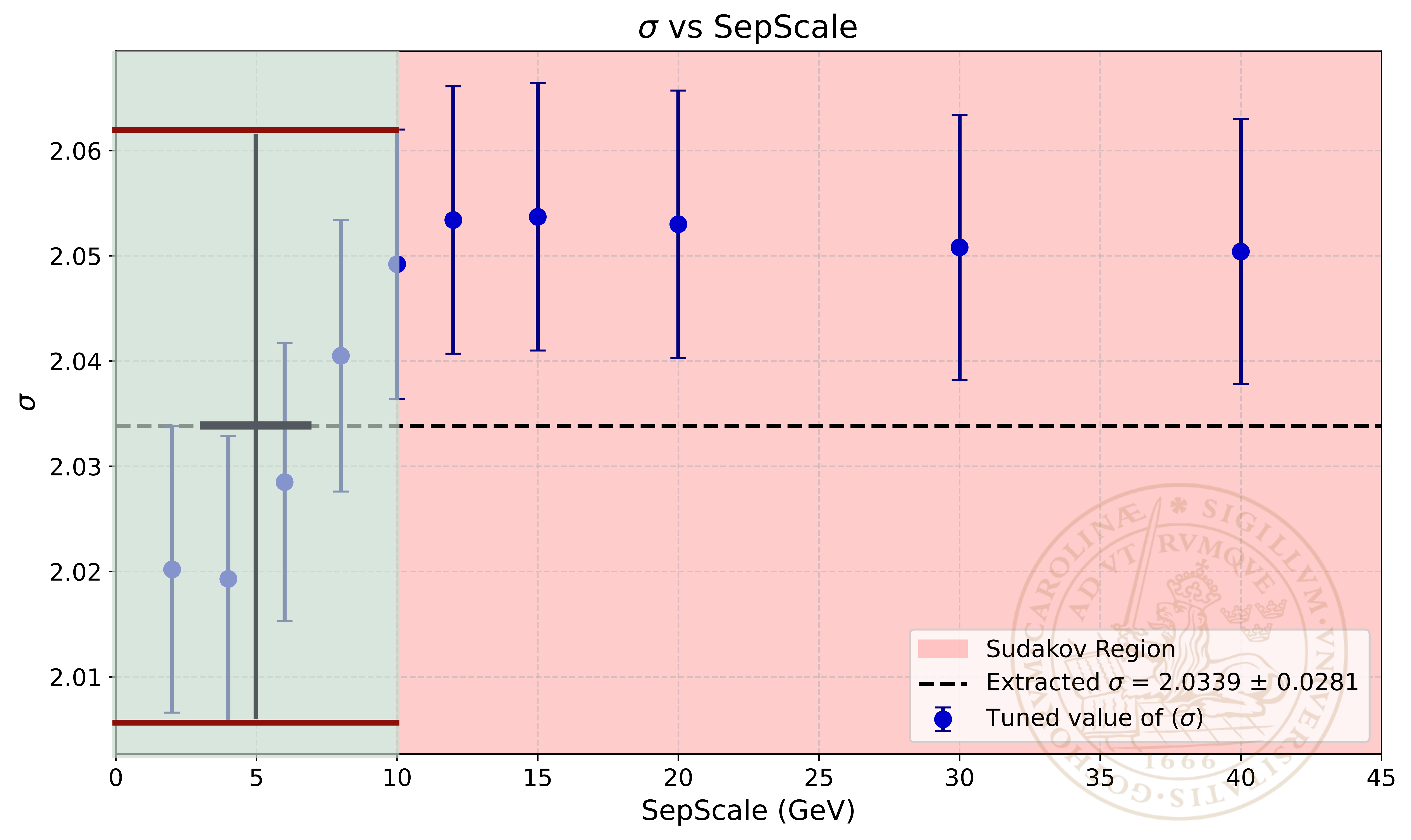

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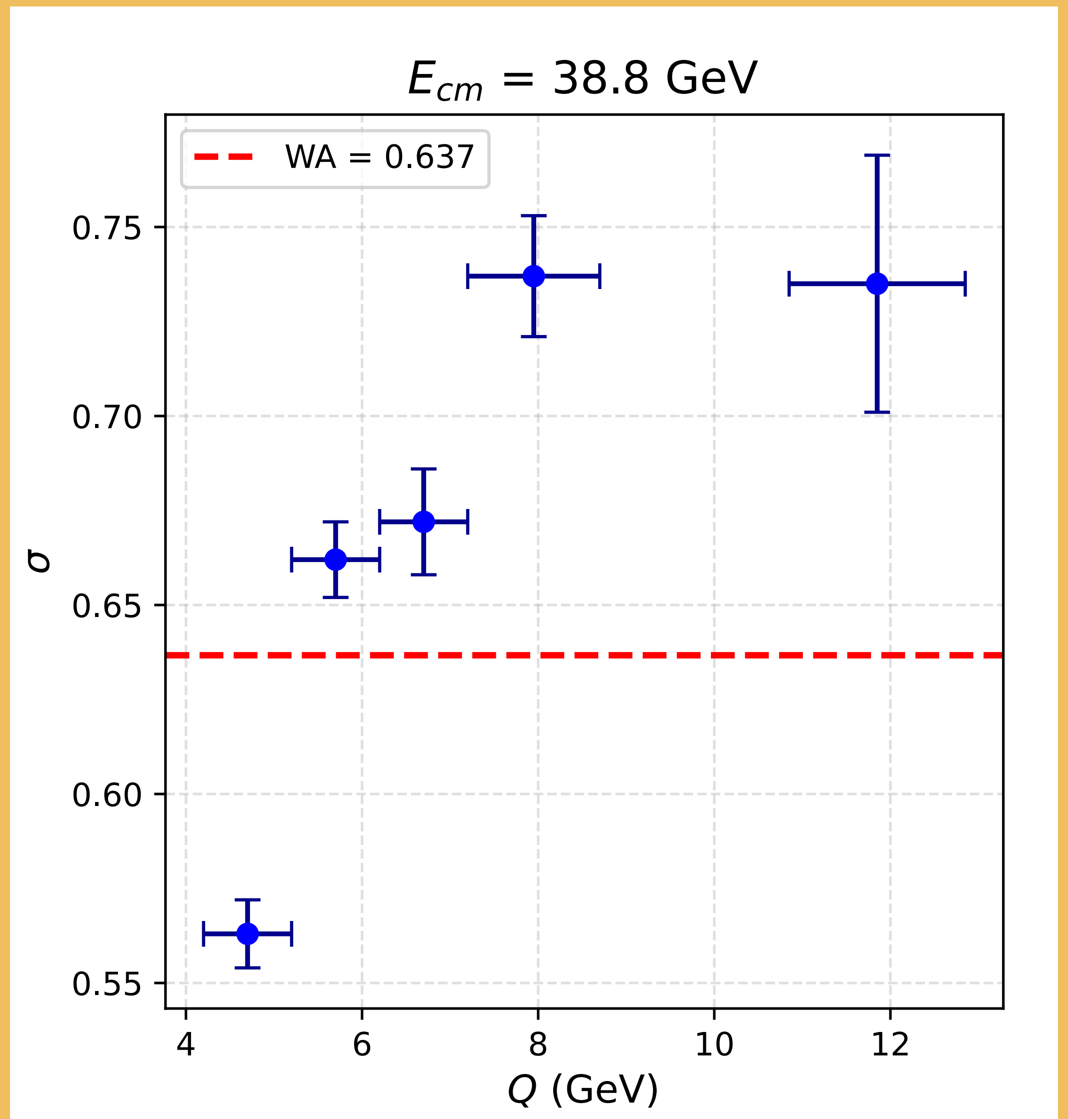
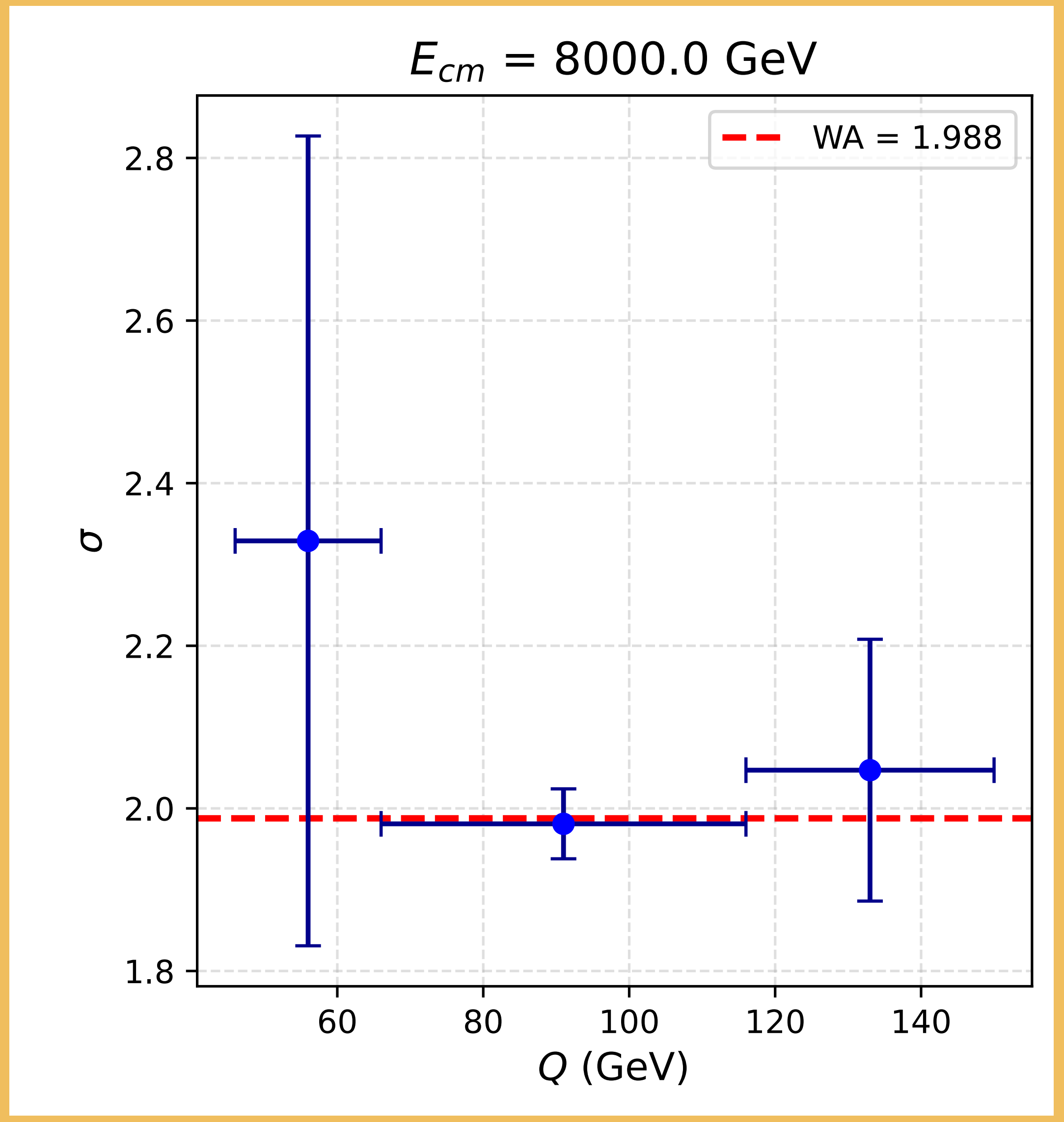
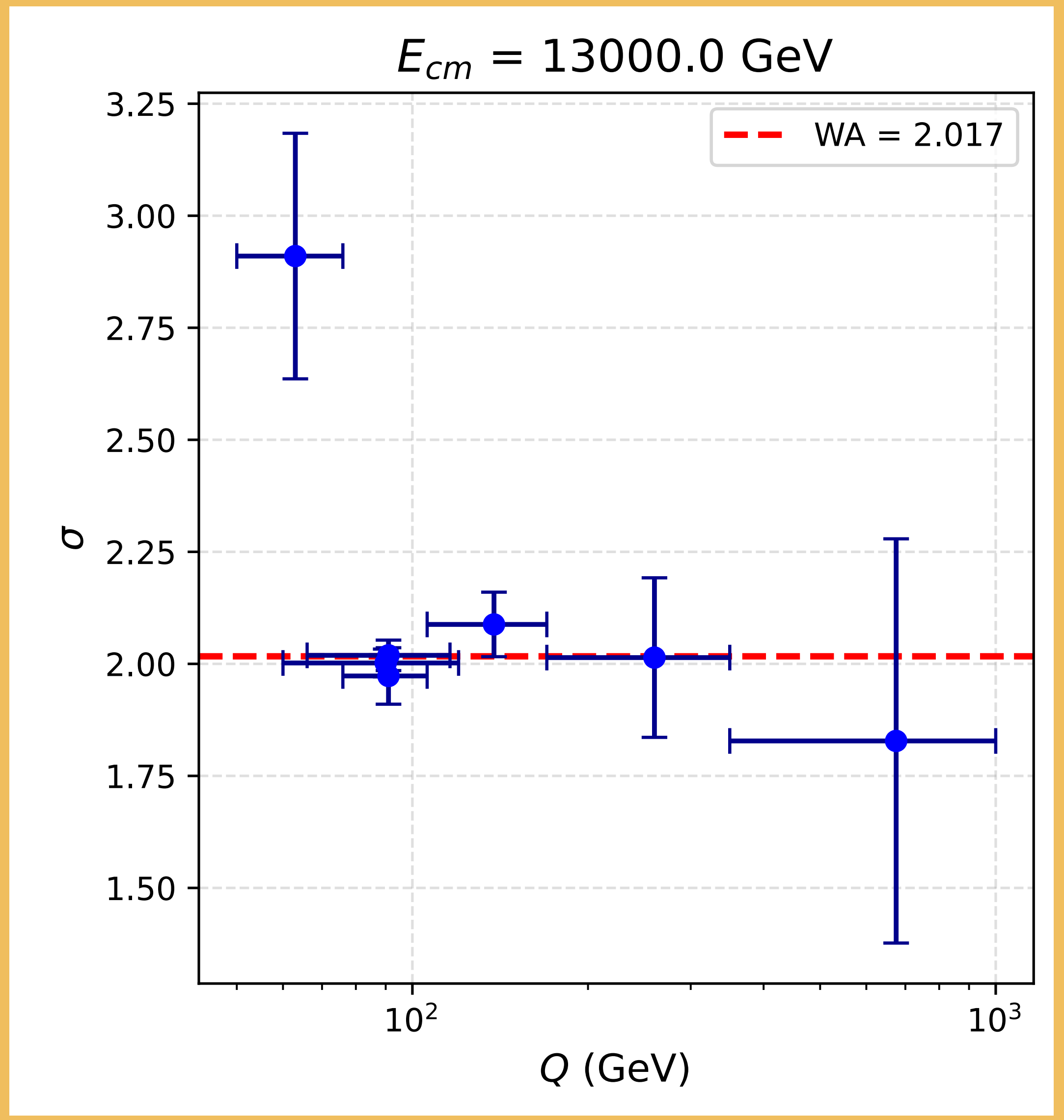


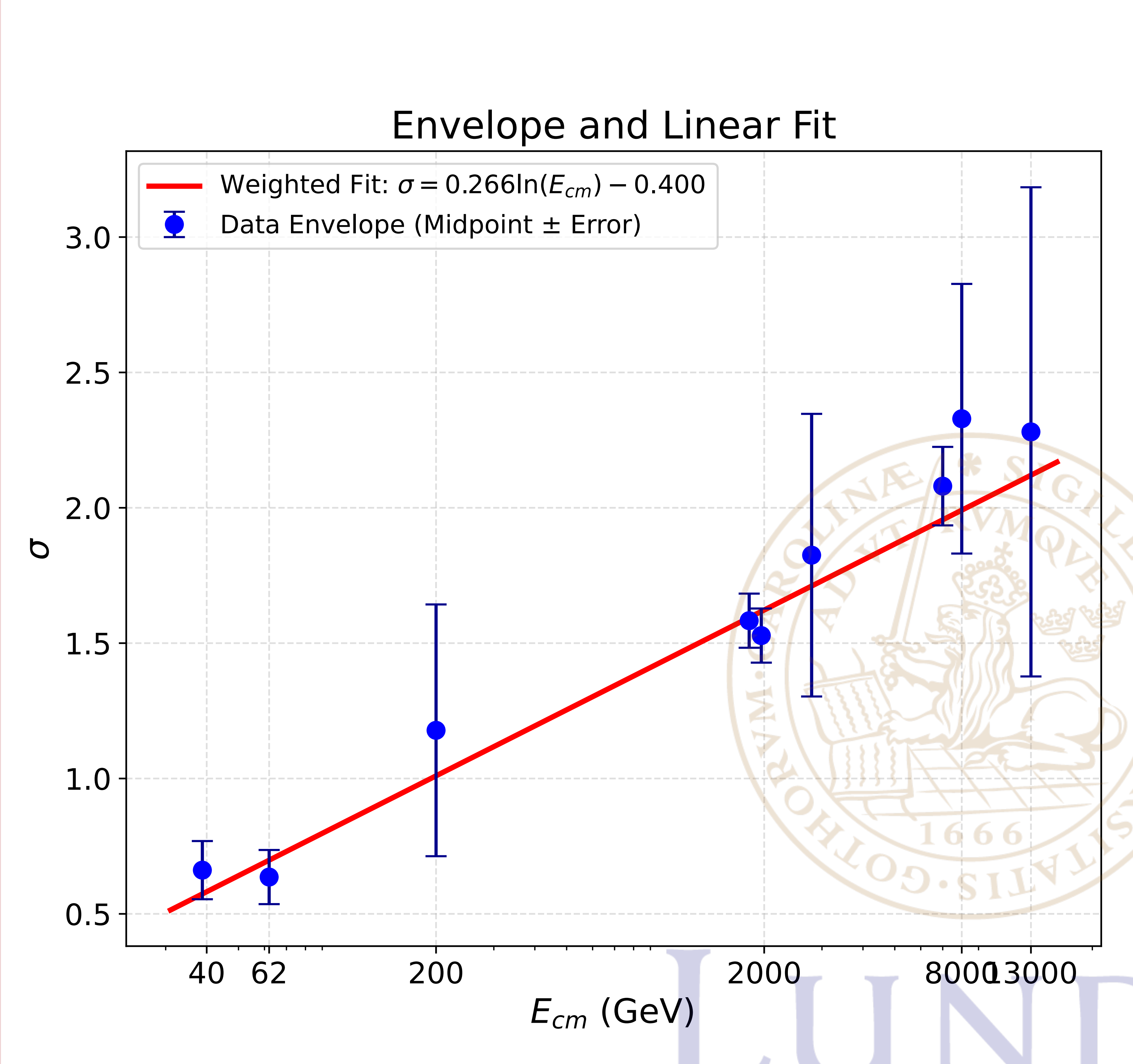


The parameter σ shows little to no dependance if the uncertainties fully are accounted for.



The primordial kT width depends on E_{CM} and a 2 parameter form improves description:

$$\sigma = A + Bln(E_{CM})$$



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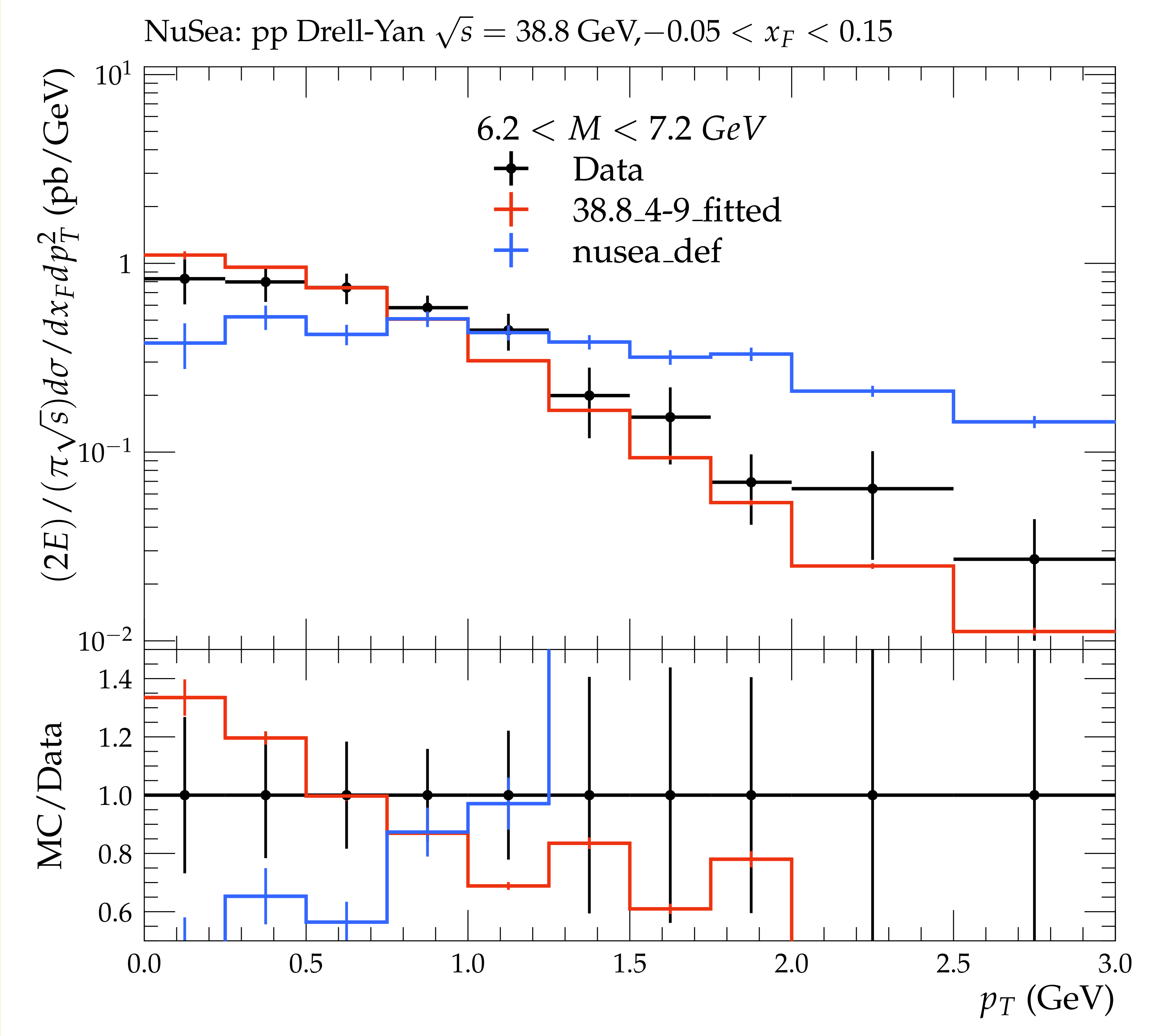
PRELIMINARY Tuning Results

$E_{CM} = 38.8\ GeV,\ Q = [6.2,\ 7.2]\ GeV$

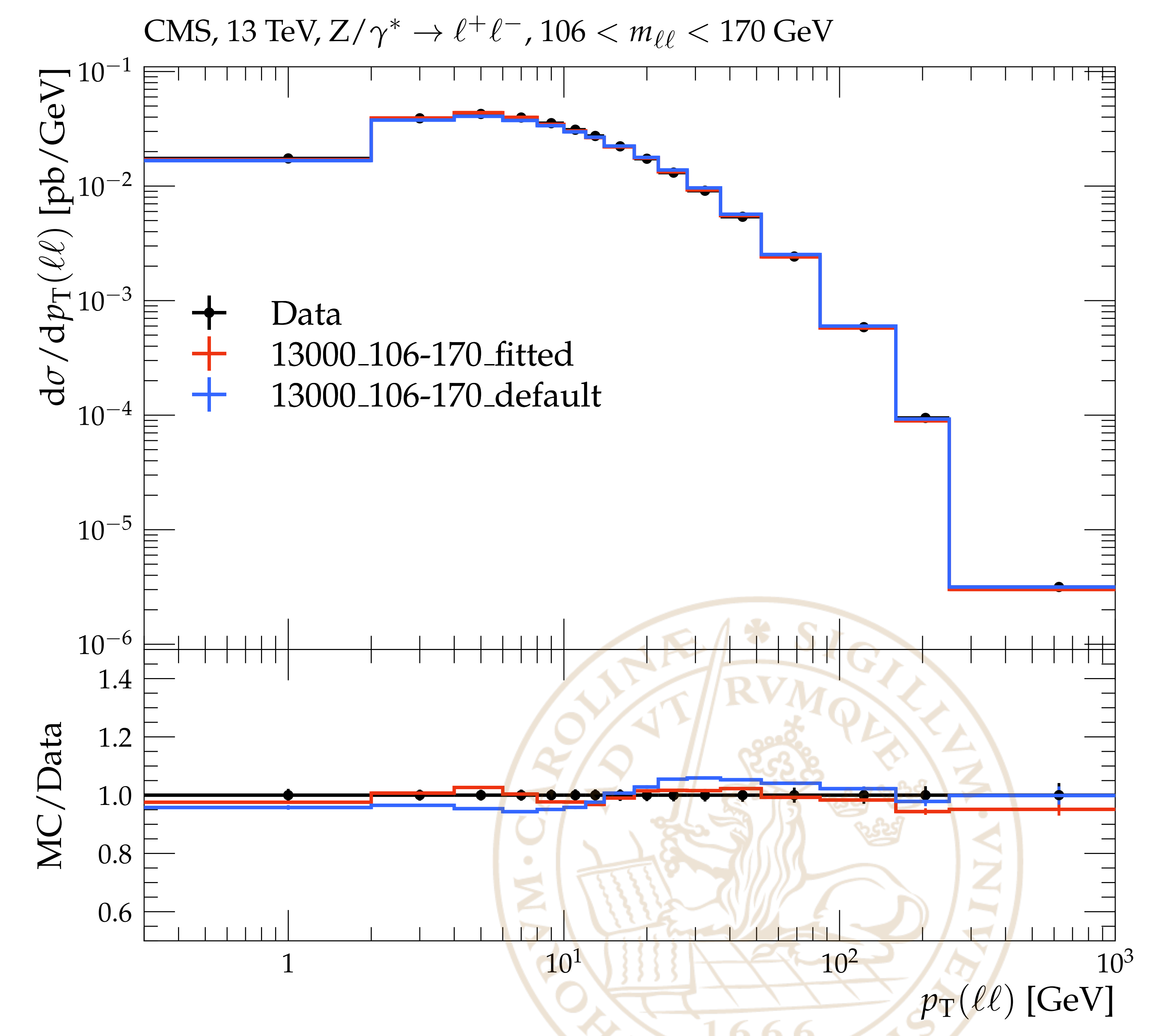


Better description of data for a bigger range of E_{CM} and Q with 2 parameters.

62, 200, 1800, 1960, 2760, 7000, 8000 GeV

$Q \in [4.2,\ 1000]$ GeV

$E_{CM} = 13\ TeV,\ Q = [106,\ 170]\ GeV$



Red line better than blue line!

- Primordial kT in PYTHIA has a center-of-mass energy dependance and little to no hard scale dependance.
- New parametrization that improves agreement with data.
- Tuning methodology that will go in a larger tuning effort.

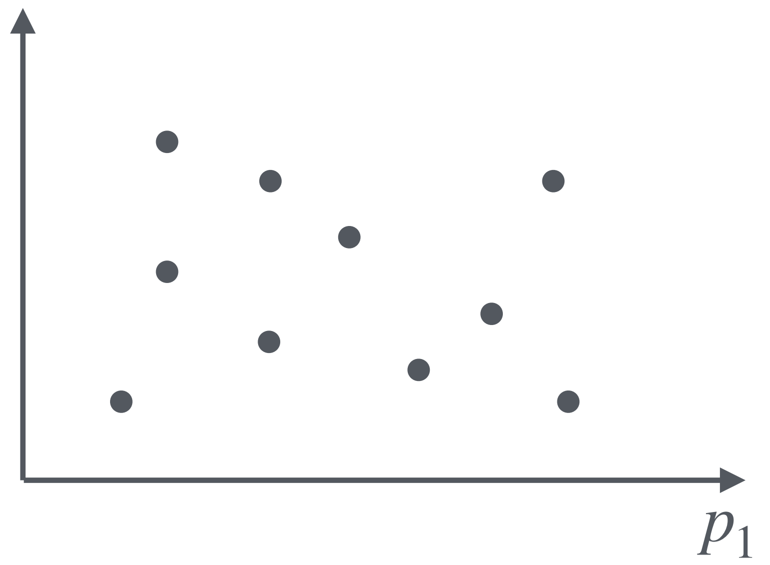
- Physical interpretation and connection with other approaches in the literature.
- Better estimation of uncertainties and completely reproducible tune.
- Publication with detailed description of the primordial kT model in PYTHIA and the new tune under construction.

Thank you all for your attention!

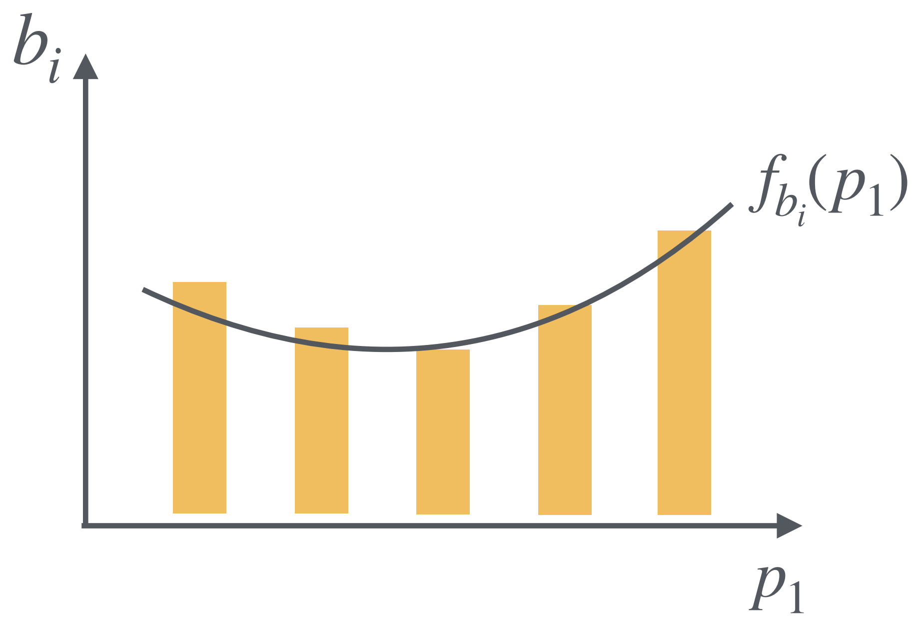
Back Up Slides…

Professor2

Parameter Space Sampling



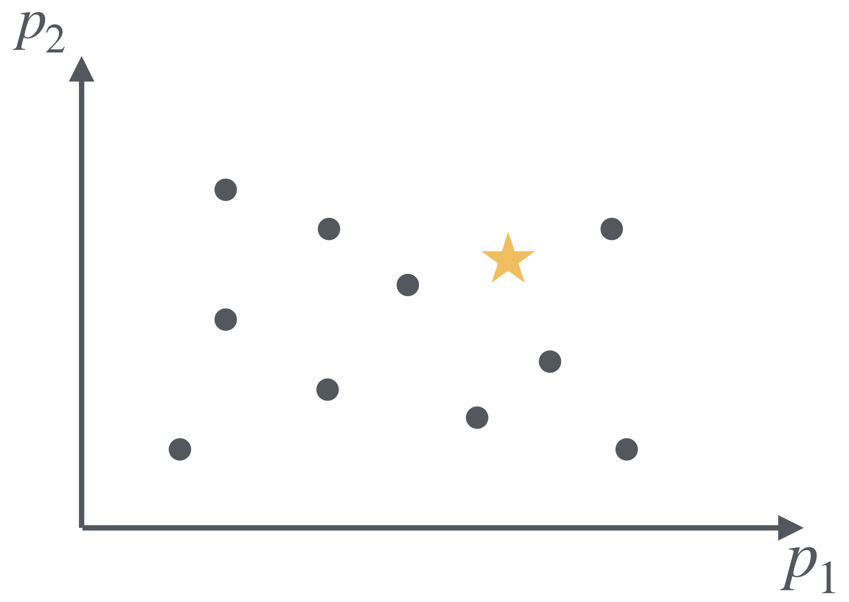
Bin-by-Bin Polynomial Interpolation



χ^2 Minimization

$$\chi^2(\vec{p}) = \sum_b \frac{(f_b(\vec{p}) - R_b)^2}{\Delta R_b^2}$$

Prediction



Custom Scripts: Bash/python for automation and plotting

Reproducibility

Rivet+YODA

Analysis/Post-processing

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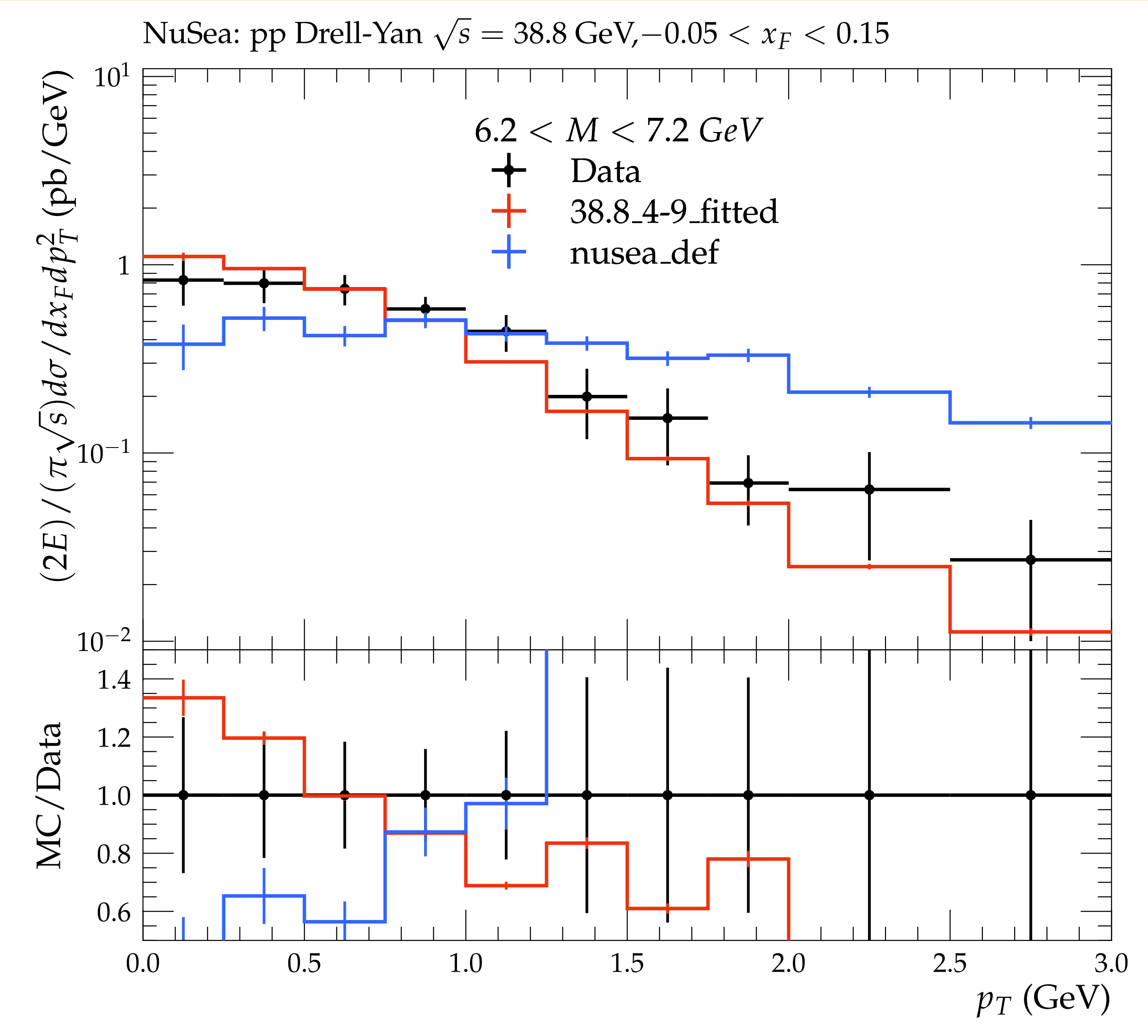
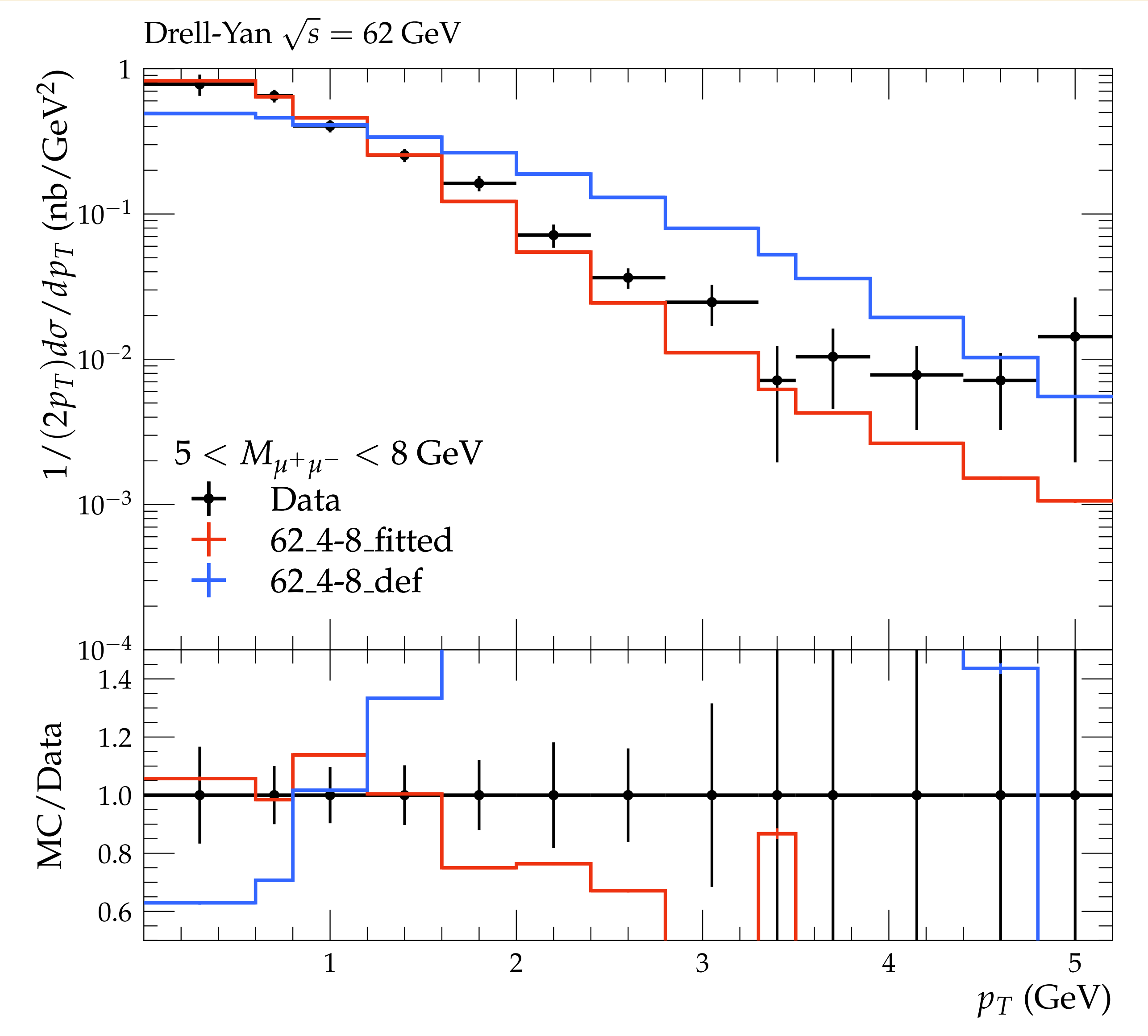
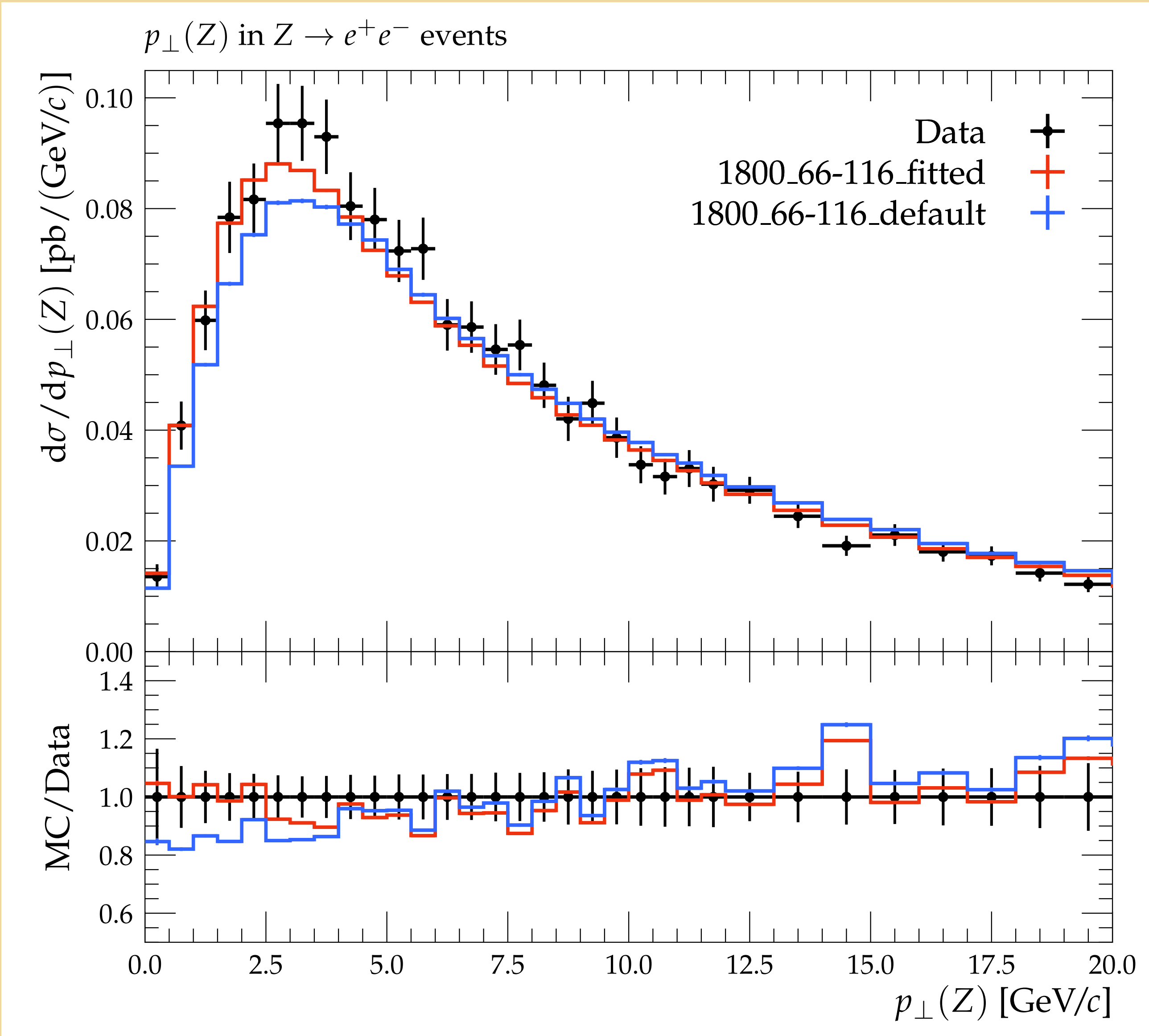
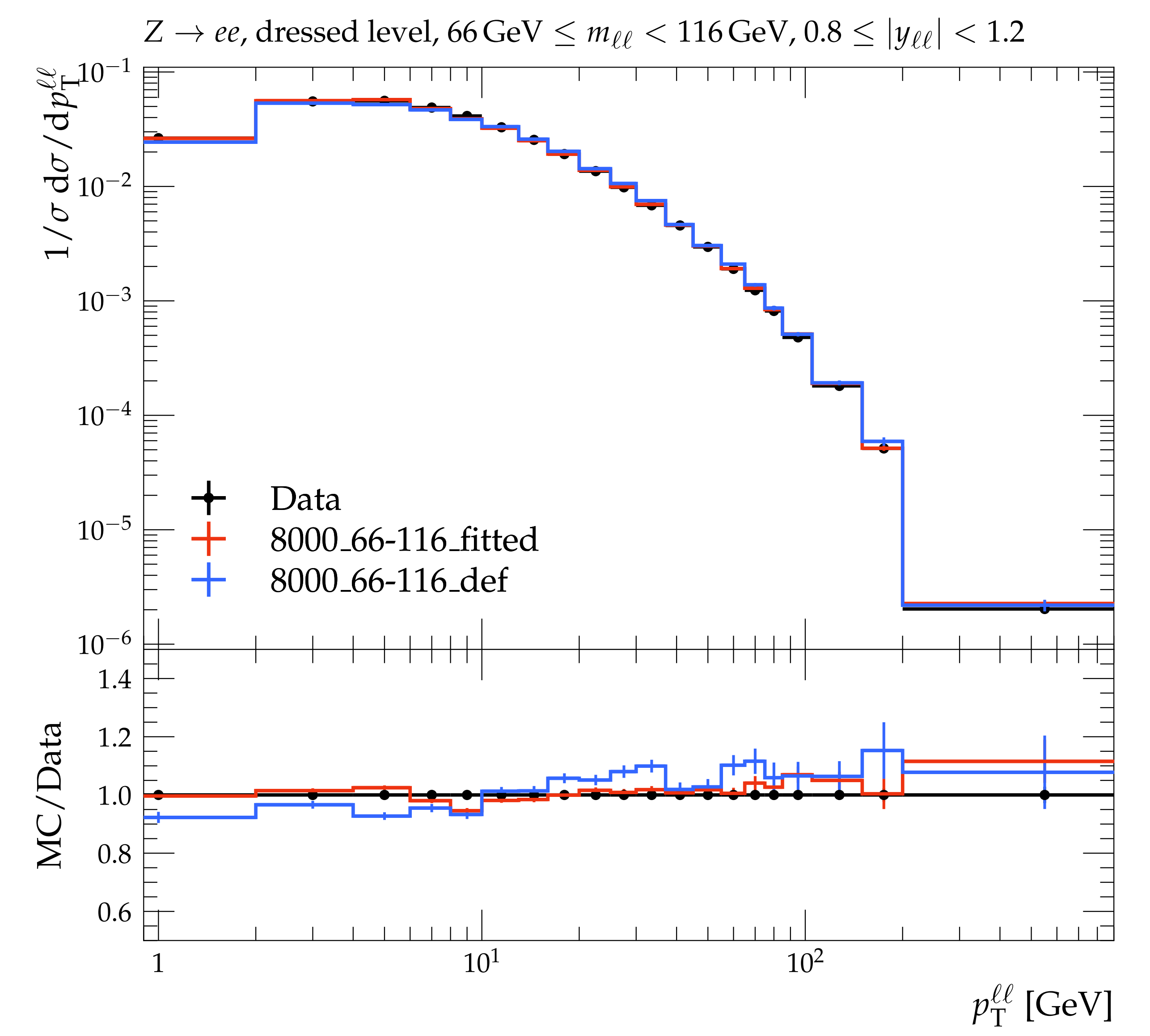
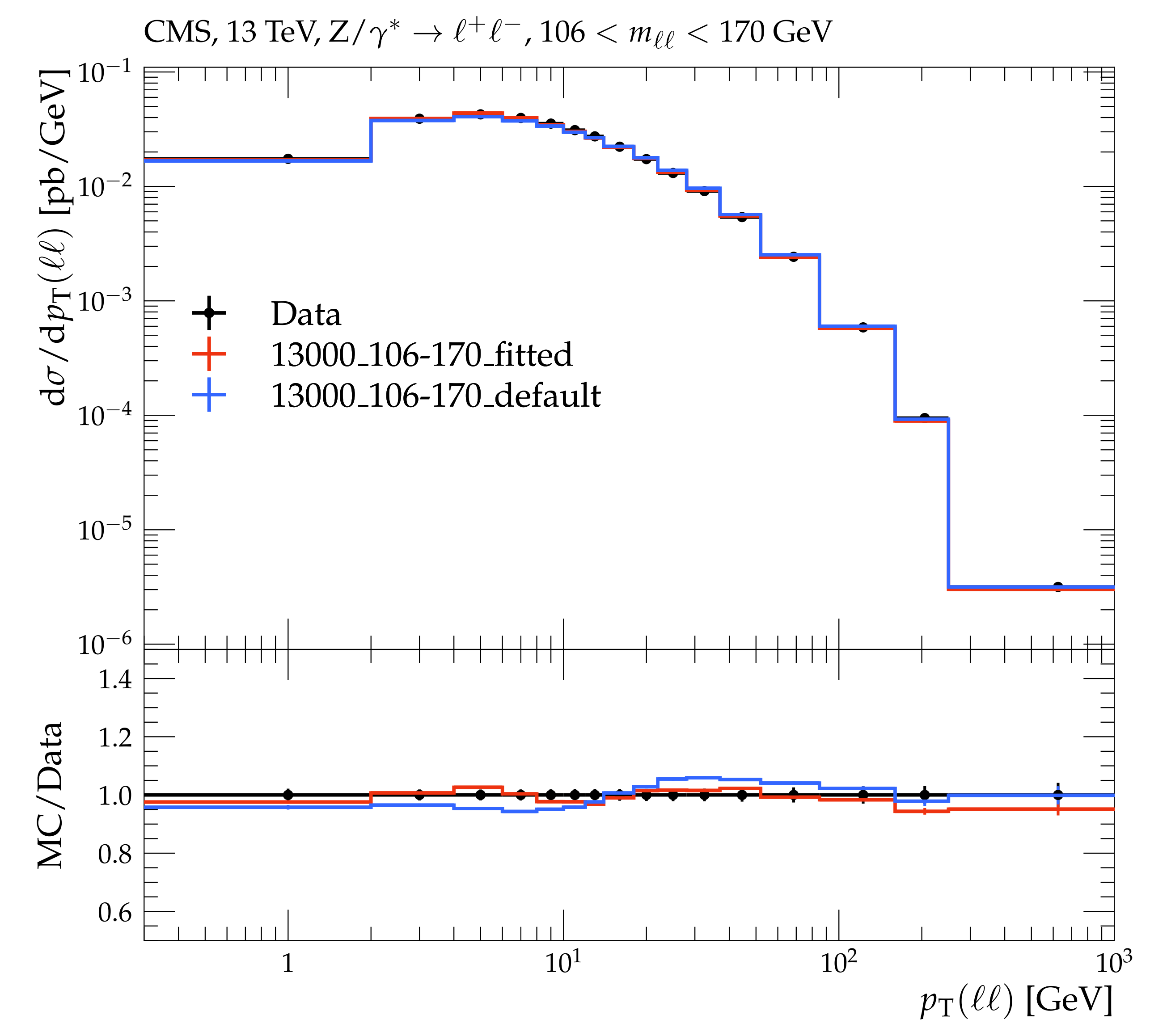
More PRELIMINARY Tuning Results

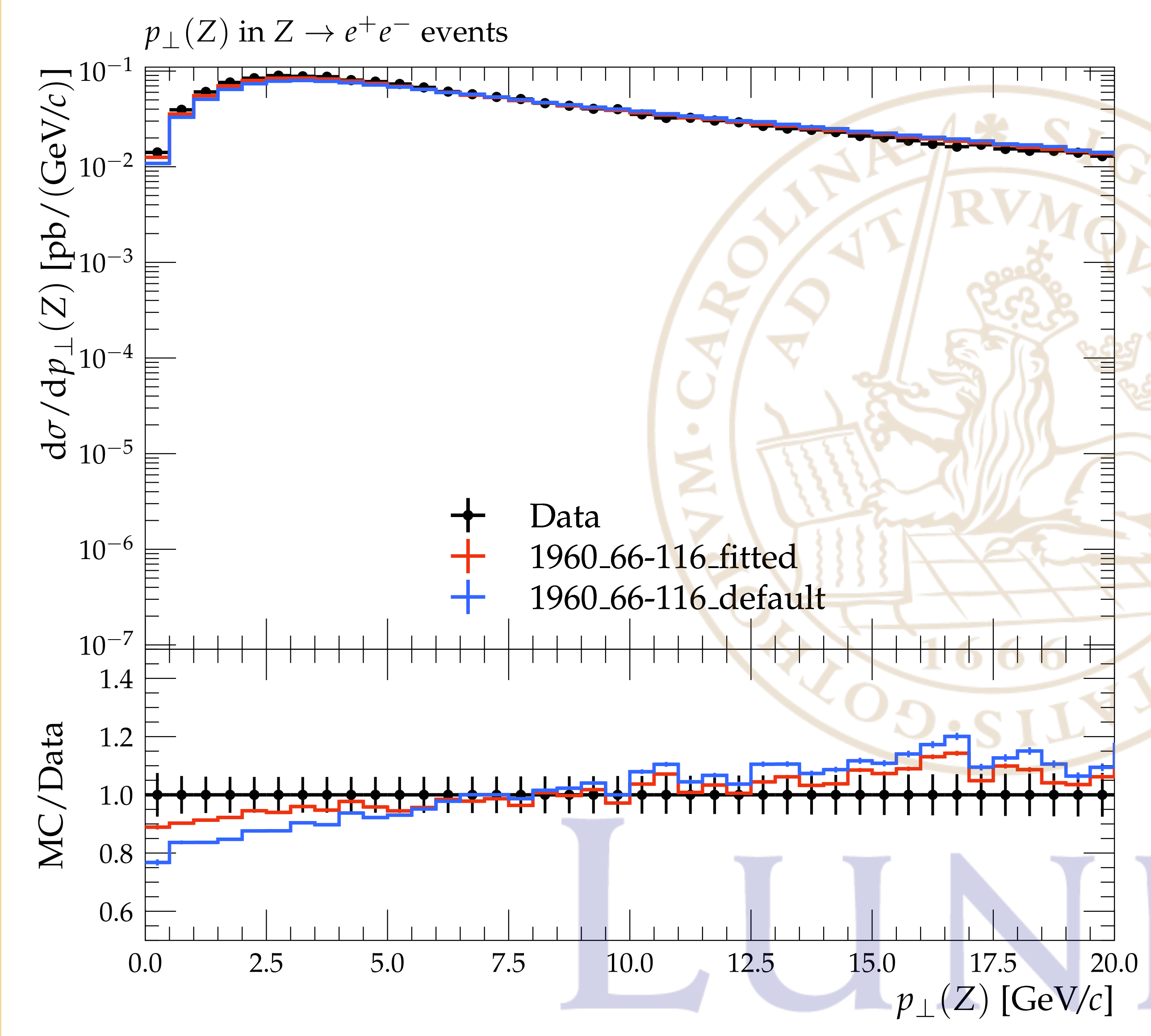




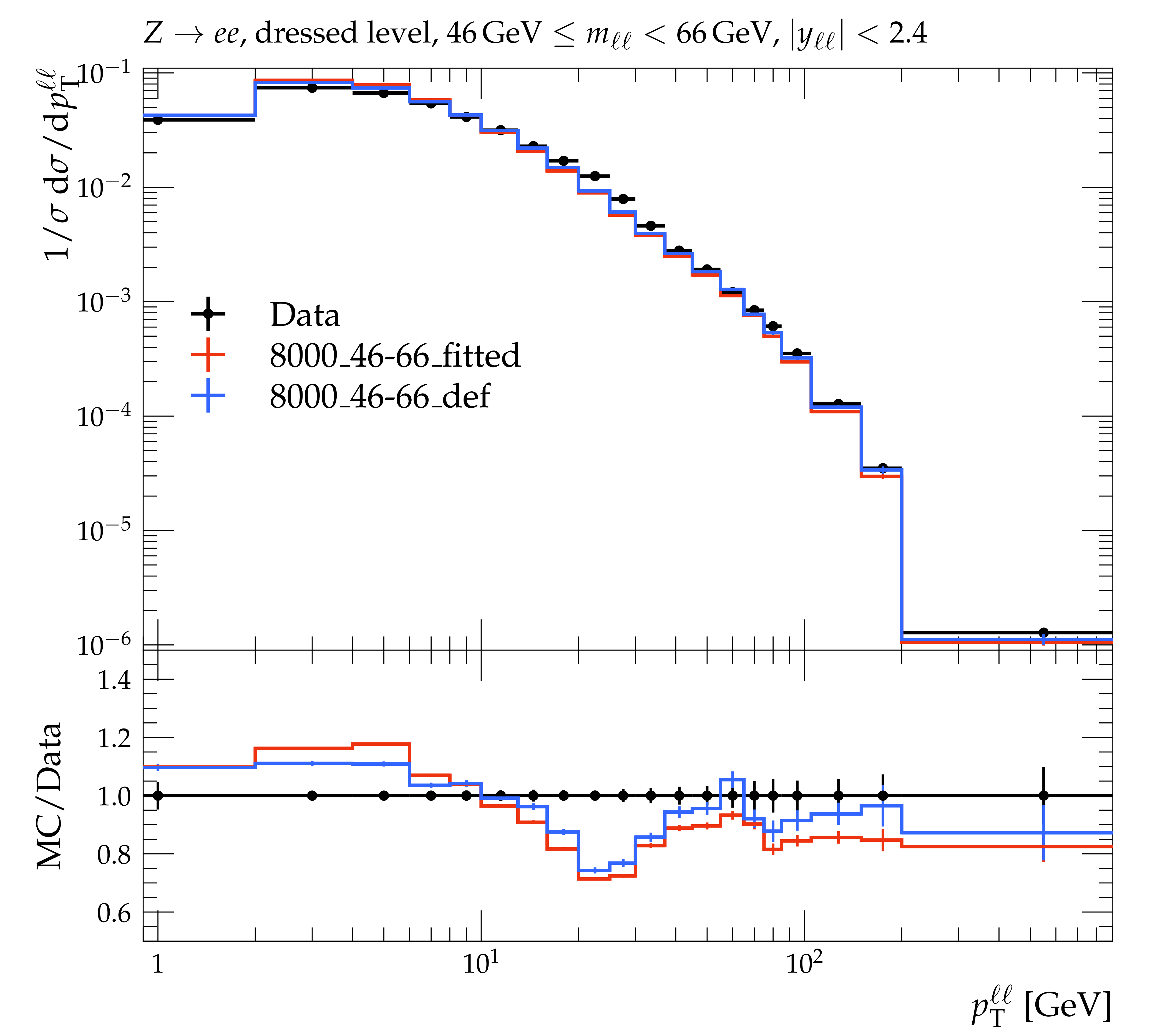


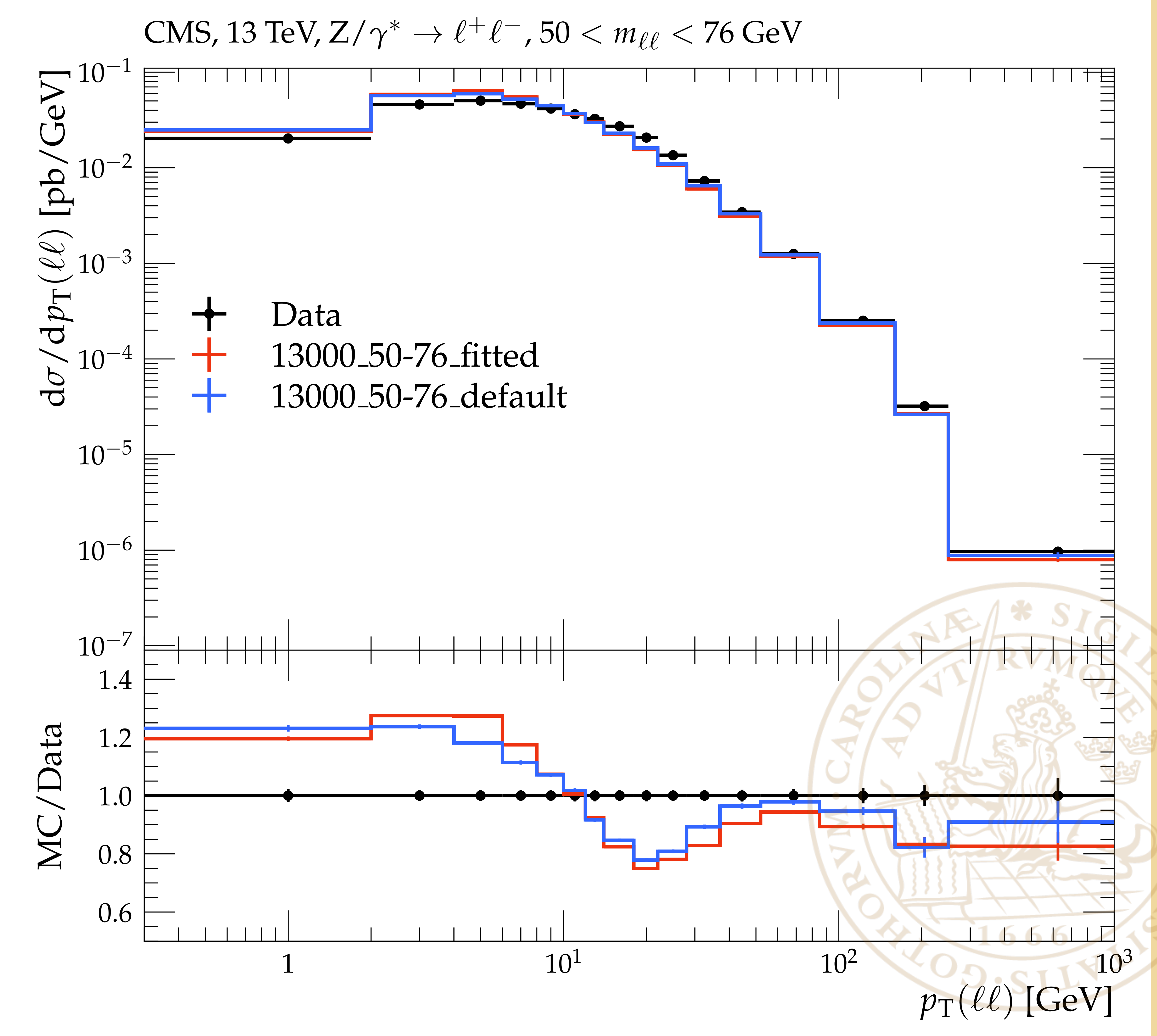






Outlier Histograms





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σ vs Parton shower cut-off