Energy Scaling Behaviour of Intrinsic k_T in Drell-Yan events

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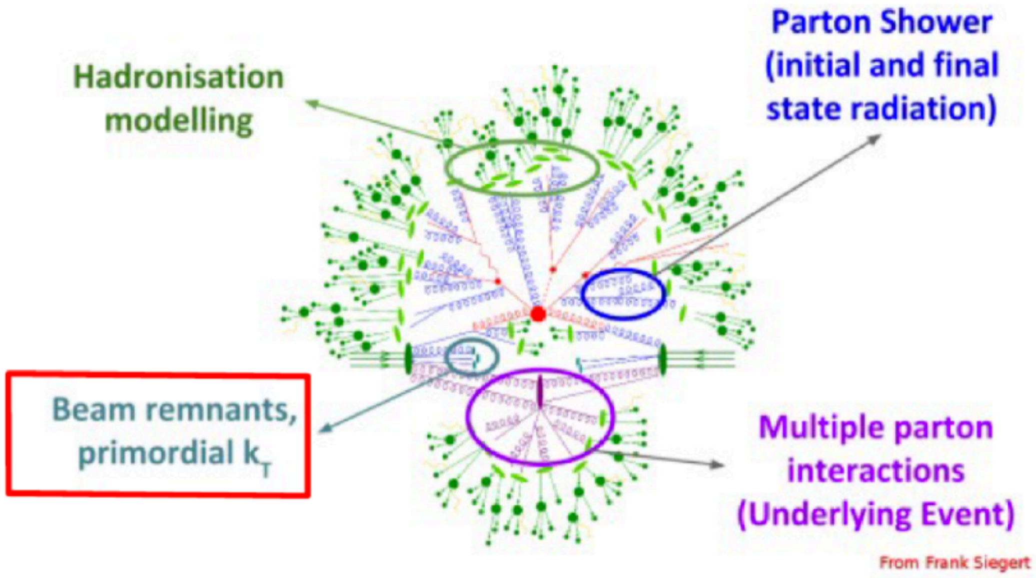
Physic analysis summary: https://cds.cern.ch/record/2895223/files/GEN-22-001-pas.pdf

Intrinsic k_T model in generators



From Frank Siegert

Intrinsic (primordial) kT:

The **transverse momenta** of the partons in the incoming colliding hadrons

→ **Not calculable** in perturbative QCD

→ Described by **phenomenological models**

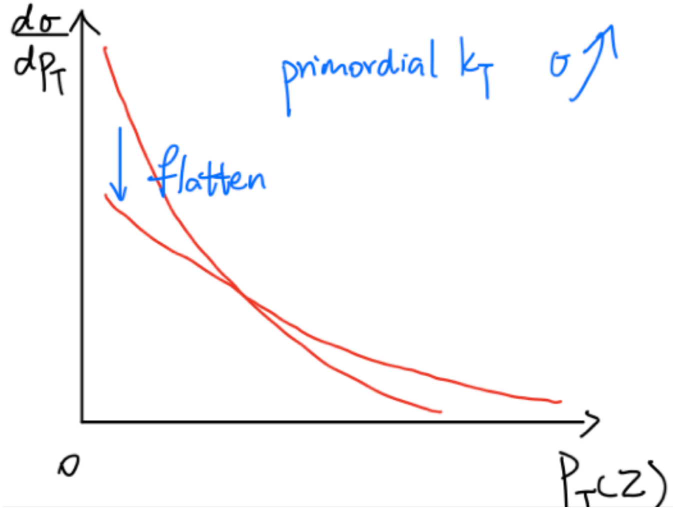
Free parameters to determine

In PYTHIA & HERWIG:

The intrinsic kT is modelled by **Gaussian** distributions

→ **Width (σ)** of the distribution determined from **tuning to data**

PYTHIA parameter: σ = √2 * BeamRemnants:primordialKThard
HERWIG parameter: σ = ShowerHandler:InstrinsicPTGaussian



Intrinsic k_T + parton shower → $p_T(Z/\gamma)$

σ ↑ → smears the intrinsic k_T → low $p_T(Z/\gamma)$ flattened

Intrinsic k_T tune to $p_T(Z/\gamma)$ has both **non-perturbative** & **perturbative** QCD effects

Fermi motion of partons, non-resolvable gluon emissions…

parton shower models

Tune to DY data in a wide range

Tuning strategy:

Underlying event (UE) and **intrinsic kT** tune can be **decoupled**
UE parameters are tuned for **various colliding energies**

⇨

Fix the **PDF & UE** parameters
Tune intrinsic kT to DY pT at **various √s** individually

Data used for the tunes

Center of mass energy	Experiments	Q [GeV] (dilepton mass)
38.8 GeV	E866/NuSea pp fixed target	4 - 12.85
62 GeV	R209 pp collisions	5 - 8
200 GeV	PHENIX pp collisions	4.8 - 8.2
1.8 TeV	CDF/D0 p+p- collisions	Z mass
1.96 TeV	D0 p+p- collisions	Z mass
2.76 TeV	CMS pPb collisions	Z mass
8 TeV	ATLAS pp collisions	46 - 150
8.16 TeV	CMS pPb collisions	15 - 120
13 TeV	CMS/LHCb pp collisions	50 - 1000 / Z mass

√s from 38.8 GeV to 13 TeV

Dilepton mass from a few to 1000 GeV

Tune with various generator setups

Instrinsic kT tune under various **generator** & **UE** setups

Generator	UE tune	PDF	α_S	Shower model
Pythia 8	CP5	NNPDF3.1 NNLO	0.118	pT+ ISR rapidity order
	CP4	NNPDF3.1 NNLO	0.118	pT order
	CP3	NNPDF3.1 NLO	0.118	pT order
Herwig 7	CH2	NNPDF3.1 NNLO (PS) NNPDF3.1 LO (MPI)	0.118	angular order
	CH3	NNPDF3.1 NNLO (PS) NNPDF3.1 LO (MPI)	0.118 (PS) 0.13 (MPI)	angular order

DY ME:

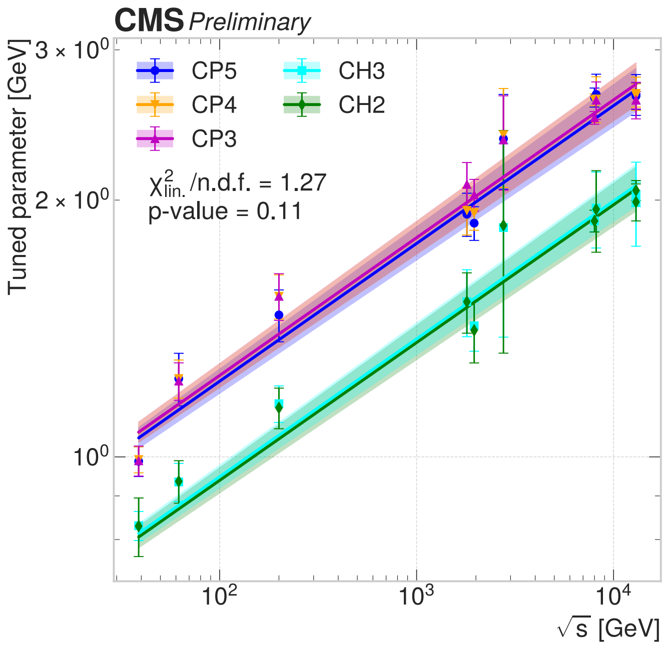
MadGraph5 MC@NLO
at NLO QCD

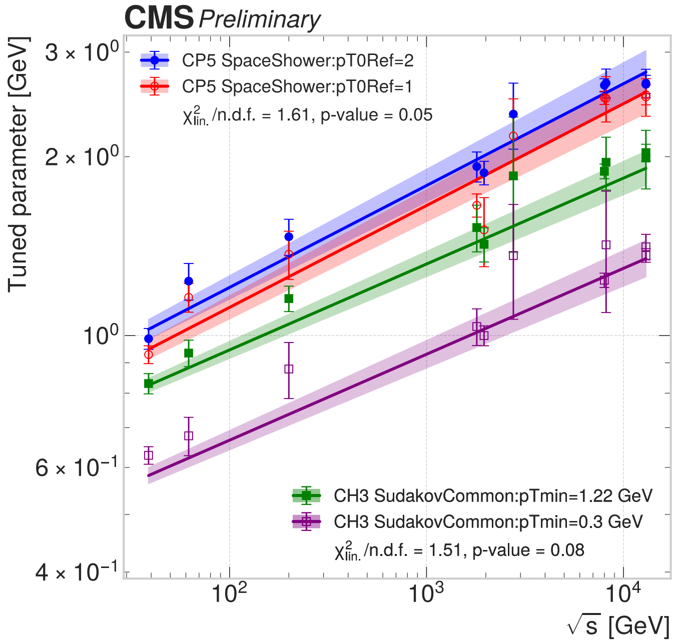
Showering:

- Pythia / Herwig
- QCD NLO α_S
- Various PDF
- Different shower models
- Different UE tune parameters

Study the intrinsic kT behaviours under these different conditions

Dependence of intrinsic k_T tunes on collision energy





Intrinsic kT

Initial-state radiation

DY pT distribution

intrinsic kT parameter compensates **ISR** in describing DY pT

- Identical slopes (~0.16) for all different shower models
- Different intercepts

The **ISR starting scale** is regularised in the generators:

- *SpaceShower:pT0Ref* in Pythia (default=2)
- *SudakovCommon:pTmin* in Herwig (default=1.22)

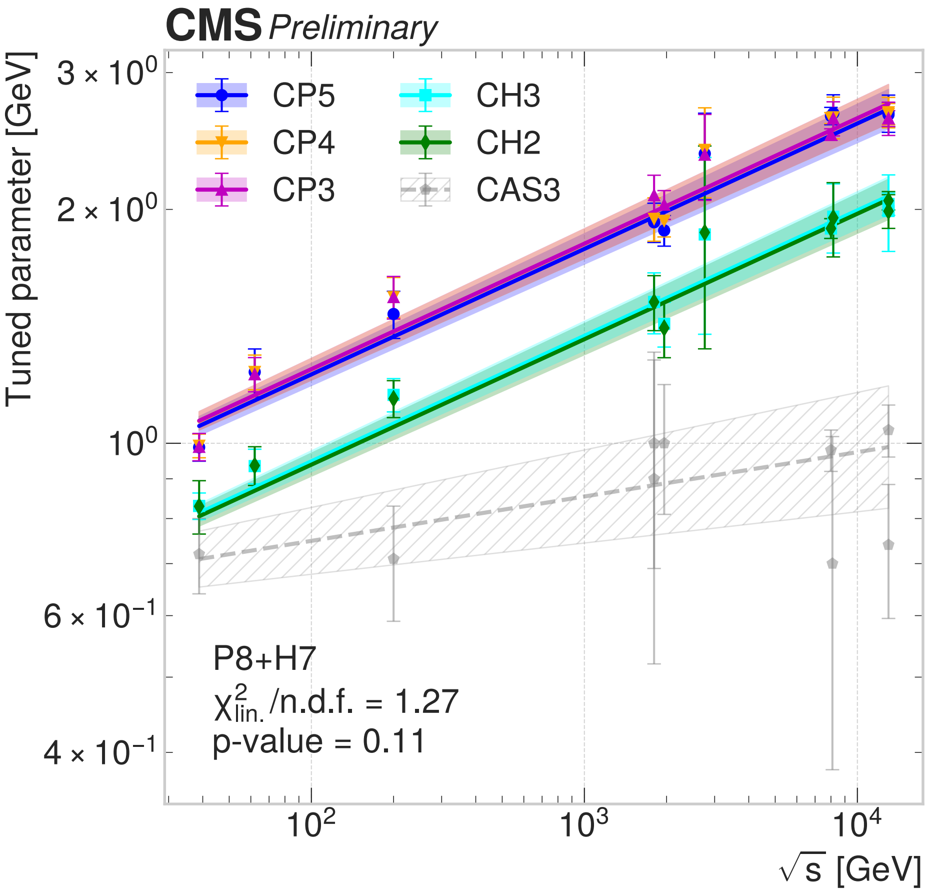
→ Intrinsic kT compensates the ISR below the cutoff

Change the **ISR cutoff** to **lower** values
→ **lower intrinsic kT** tunes
→ we did not see significant change in the slopes

⇔

More ISR allowed
→ **less intrinsic kT needed** to describe DY pT

Interpretation of the tuning results



Collinear MC generator (e.g. Pythia, Herwig):
Initial-state shower handles the parton shower from the **soft cutoff** to the **hard-scattering scale**

→ Missing contribution: the soft parton emissions not generated
→ **non-perturbative** & **perturbative** components

non-resolvable gluon emissions

cut on parton emissions by the regularization factor in the generator

We observe:

- **The slope** is identical for all shower models and setups of **Pythia & Herwig**
- **Cascade tunes:** (arXiv:2309.11802)
  - Include non-perturbative Sudakov form factor
  - Accounting for more non-resolvable gluon emissions
  - Weaker √s dependence

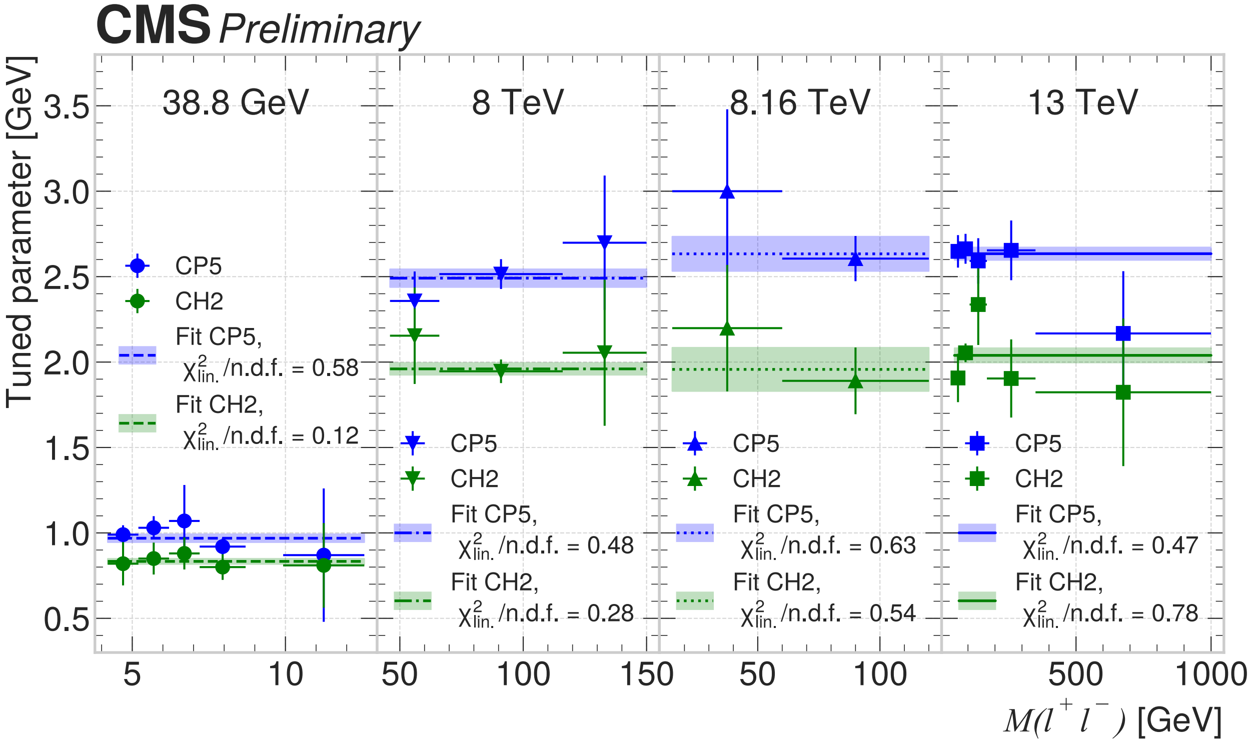
→ The slope reflects **non-perturbative** effects

Impacts of hard-scattering scale on the intrinsic kT tune

$M(l^+l^-)$ in DY events ~ **hard scattering scale**

Does it affect the intrinsic kT tune?

The 38.8 GeV, 8 TeV, 8.16 TeV and 13 TeV measurements provide $p_T(l^+l^-)$ data at various $M(l^+l^-)$ ranges
→ Tune the intrinsic kT to the data in these ranges individually



The tune results are **identical** in **different $M(l^+l^-)$** ranges at the **same $\sqrt{s}$**

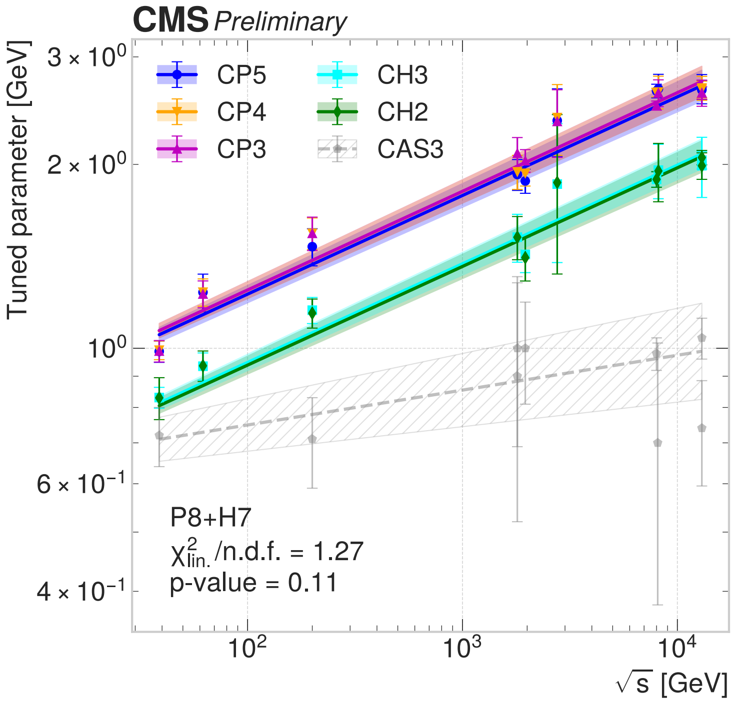
The hypothesis is supported by the goodness of fit (χ^2/ndf)

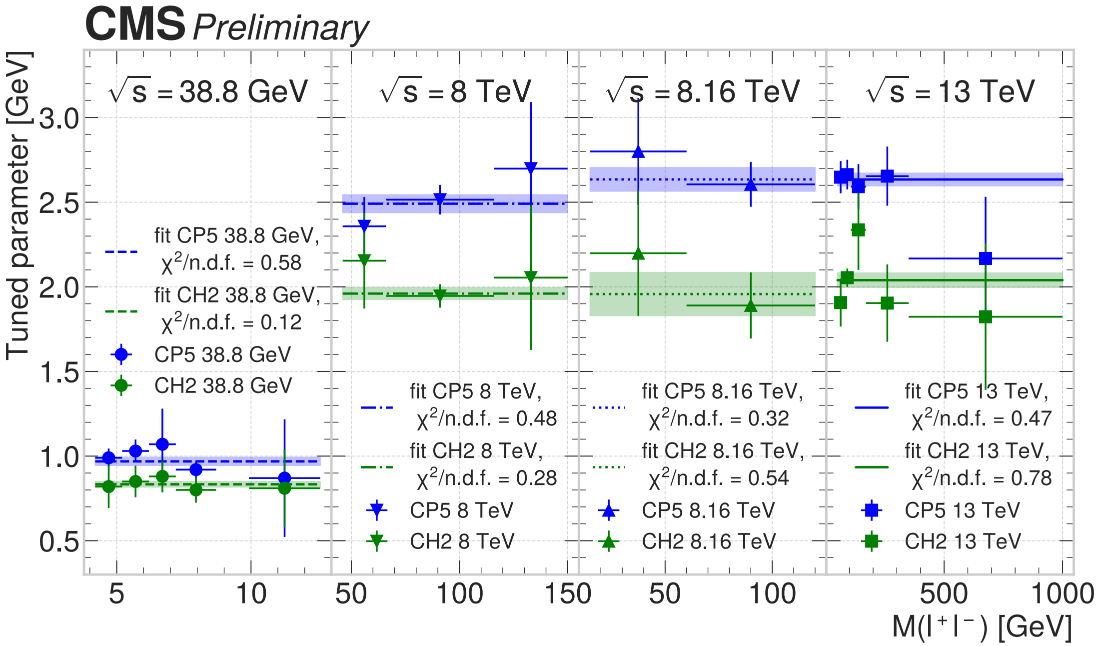
Weak/no dependence of intrinsic kT on the **$M(l^+l^-)$ range**

$M(l^+l^-) = x_1x_2\sqrt{s}$
(x1, x2 are the momentum fractions of colliding partons in protons)

Intrinsic k_T tunes not affected by x_1, x_2 of partons

Interpretation of the tuning results





$$\sigma(intrinsic\ k_T) = a\sqrt{s}^{\,b}$$

a=0.82 GeV (CP5)
a=0.45 GeV (CH2) ⇨ <p_T> when √s = M_{proton}

b=0.16 ⇨ √s dependence

- provides a tune model for both Pythia & Herwig
- valid for 3(2) orders of magnitude in √s (Q)

Summary

Energy dependent intrinsic kT tune from 38.8 GeV to 13 TeV

- **Similar energy scaling behavior** of int-kT width for Pythia (CP3, CP4, CP5) and Herwig (CH2,CH3)
- **Linear relation log(int-kT) — log(√s)** → a model for future measurement
- **Identical slopes** for all the setups
- Further theoretical interpretation → potential non-perturbative features in the energy-scaling behaviour

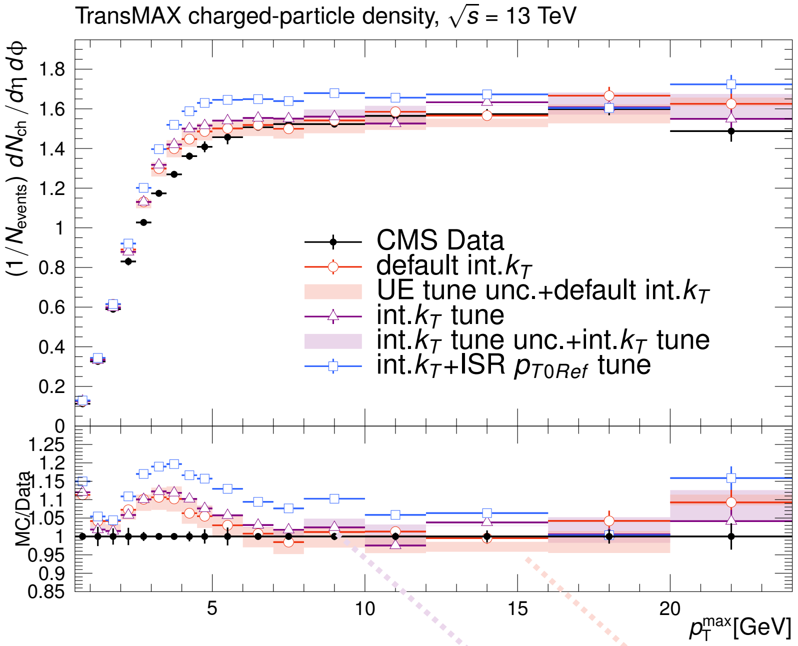
  - Motivates the implementation of energy-dependent intrinsic k_T parametrization in generators
  - The model can be extrapolated to higher energy (e.g. 13.6 TeV)

Impact of the hard scattering scale on intrinsic k_T

- **Identical int-kT tune in different M(l+l-) ranges** at the same √s
- **Weak/no dependence** of int-kT on the **hard scattering scale**

Backup

Decouple the underlying-event tune & intrinsic kT tune

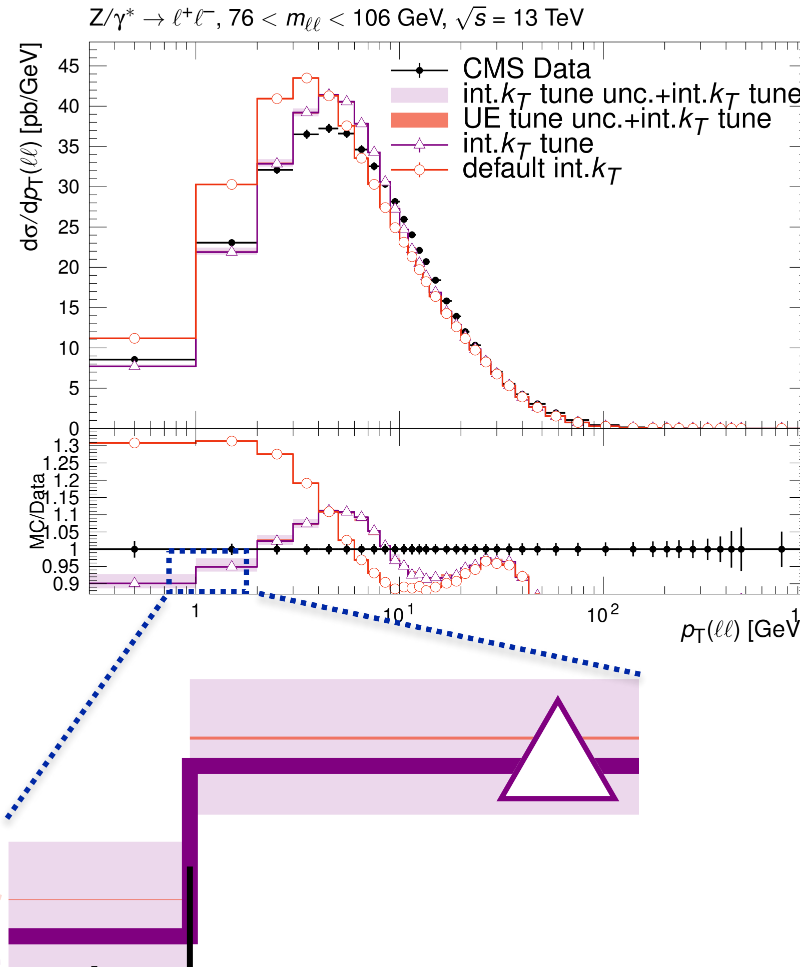


Intrinsic kT has little impact on UE obs

UE parameters have little impact on pT(Z)

Two parts can be factorised

Intrinsic kT can be tuned on top of CP5 without destroying UE description



— CP5+default int.kT

— CP5+int.kT tune

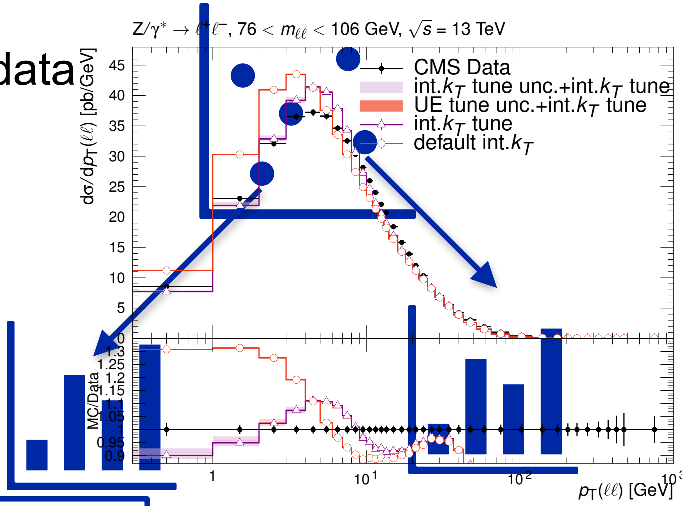
Improves the DY pT description
Keeps the UE agreement to data

▨ Uncertainty of UE tune
→ small impact on DY pT

▨ Uncertainty of int.kT tune
→ small impact on UE obs.

Tuning procedure

We use Professor 2 (https://arxiv.org/abs/0907.2973) to fit the model parameters to data



Random sample in the tuning parameter space

Generate **MC events** for **each sample** and get MC **histograms**

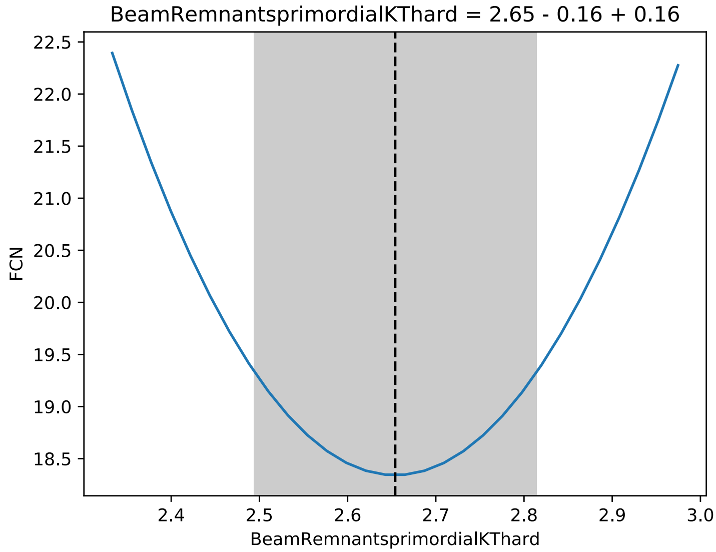
Interpolate the **MC response** in each bin as a **polynomial** of the **tuning parameters**

MC response uncertainty **another polynomial**

goodness of fit

$$\chi^2(p) = \sum_{bin} \frac{(MC_{bin}(p) - data_{bin})^2}{\sigma^2_{data_{bin}} + \sigma^2_{MC_{bin}(p)}}$$

Calculate the goodness of fit χ²(p) using **data** histogram and **interpolated MC**
Find the minimum of χ²(p) numerically and get the **tuning result for p**.



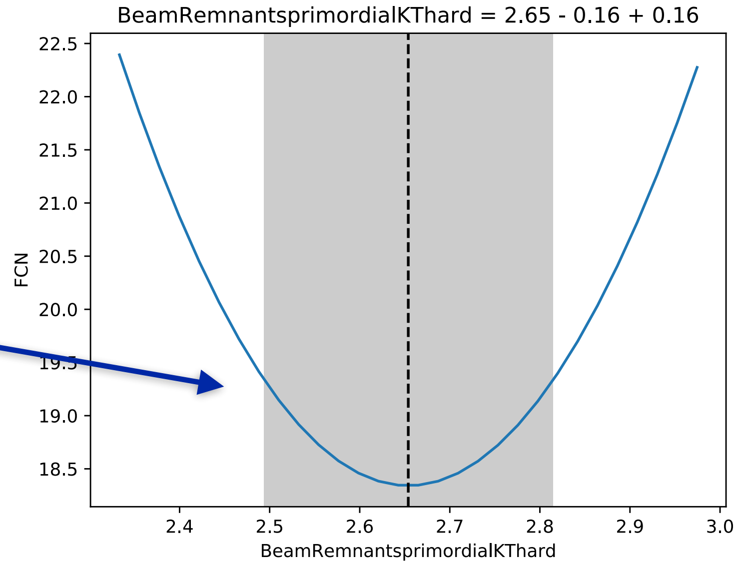
Tune uncertainties:

- MC statistics
- Data uncertainty
- Choice of tuning range
- Functional form of interpolation

Uncertainty sources

The tuning results come from minimisation of the goodness of fit:

$$\chi^2(p) = \sum_{bin} \frac{(MC_{bin}(p) - data_{bin})^2}{\sigma^2_{data_{bin}} + \sigma^2_{MC_{bin}(p)}}$$


BeamRemnantsprimordialKThard = 2.65 - 0.16 + 0.16

- Uncertainty from the **data uncertainty** and **MC statistics**
  → Estimated from the parameter range corresponding to minimum χ²+1

$$\chi^2(p) = \sum_{bin} \frac{(MC_{bin}(p) - data_{bin})^2}{\sigma^2_{data_{bin}}}$$

range for minimum χ²+1

Uncertainty from data

$$\chi^2(p) = \sum_{bin} \frac{(MC_{bin}(p) - data_{bin})^2}{\sigma^2_{MC_{bin}(p)}}$$

range for minimum χ²+1

Uncertainty from MC stat.

More accurate estimation:

- generate **toy data** to mimic the measurement fluctuations according to the data unc.
- **tune** to **multiple toys** of the data
- estimate the **covariance matrix** and **uncertainty** from **variations of the toy tunes**

Uncertainty sources

The tuning results come from minimization of the goodness of fit:

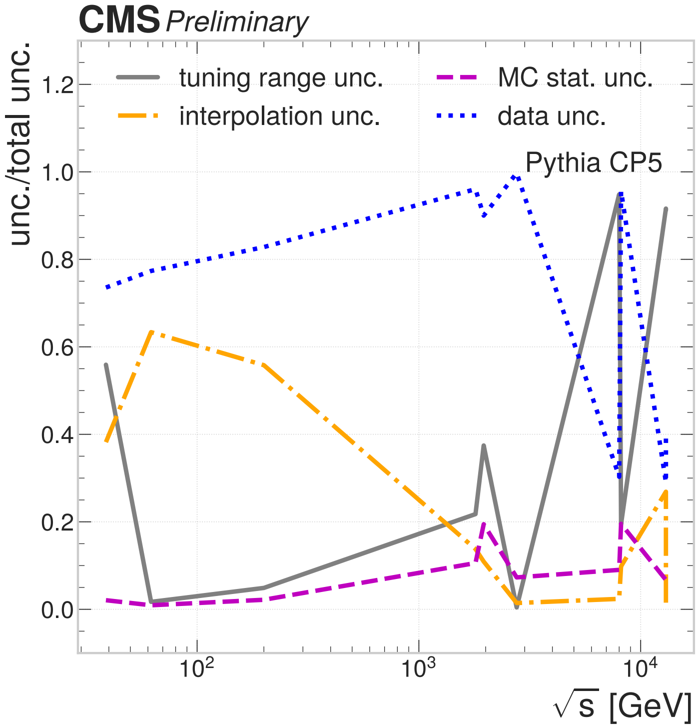
$$\chi^2(p) = \sum_{bin} \frac{(MC_{bin}(p) - data_{bin})^2}{\sigma^2_{data_{bin}} + \sigma^2_{MC_{bin}(p)}}$$

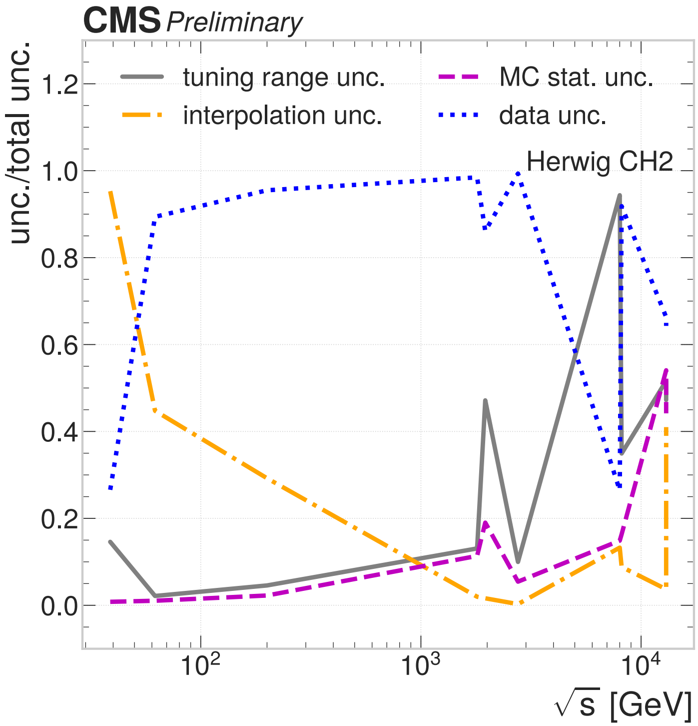
- Uncertainty from the **data uncertainty** and **MC statistics**
  → Estimated from the parameter range corresponding to minimum χ^2+1

- Uncertainty from the **interpolation of the MC response and its uncertainty**
  → Estimated by the tune difference of using order-3 & order-5 polynomials

- Uncertainty from the **choice of the pT range for tuning** ← The low pT (a few GeV) distribution is sensitive to intrinsic kT
  → Estimated by the difference of tuning to pT 0 - 10 GeV & 0 - 15 GeV for √s > 1 TeV
  0 - max pT in data & 0 - (max pT - 2) in data for √s < 1 TeV

Uncertainty decomposition





The tuning uncertainty is dominated by the **data uncertainty**

The 5 setups were tuned to the same measurements
→ the uncertainty from the **data** is **highly correlated** for tunes at the same energy
→ the correlation estimated from toy experiments

- The contribution from **MC stat.** is **uncorrelated**
- We assume the contribution from **tuning range** and **interpolation** to be **uncorrelated**

Intrinsic kT tune results

Validate the intrinsic kT tunes:

- Generate **DY events** with the **tuned parameters**
- Generate events with **up & down variations**
- Compare the **pT predictions** with **data**
  - **Tune unc.** from the difference between **up & down**

MC/data ratio after the tune
DY pT **0 -10 TeV**
Agreement with data is verified