University of Zurich[UZH]

Physics Institute

Parton showers and event generators studies and modeling

Weijie Jin

QCD@LHC 2024

Underlying event, proton structure and particle production

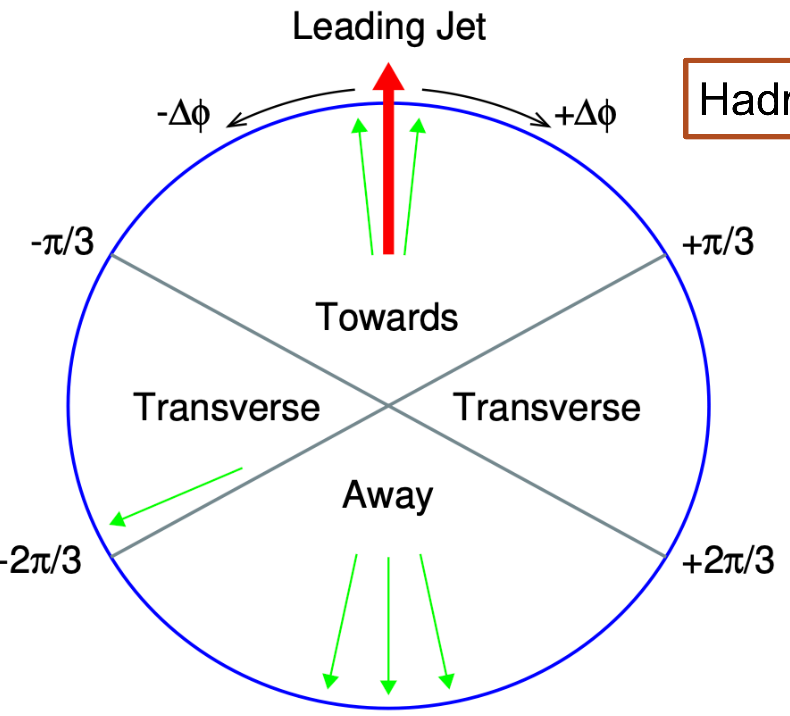
Underlying-event studies with strange hadrons in pp collisions at √s = 13 TeV with the ATLAS detector
axiv:2405.05048

Study of Z boson plus jets events using variables sensitive to double-parton scattering in pp collisions at √s = 13 TeV (CMS)
arxiv:2105.14511

Energy scaling behavior of intrinsic transverse momentum parameters in Drell-Yan simulation (CMS)
arxiv:2409.17770

Strange hadron production in underlying events (UE)

https://arxiv.org/abs/2405.05048



Hadronization & multiple-parton interaction (MPI) models

affects the MC

The data can be used to tune

Strange hadron production in UE

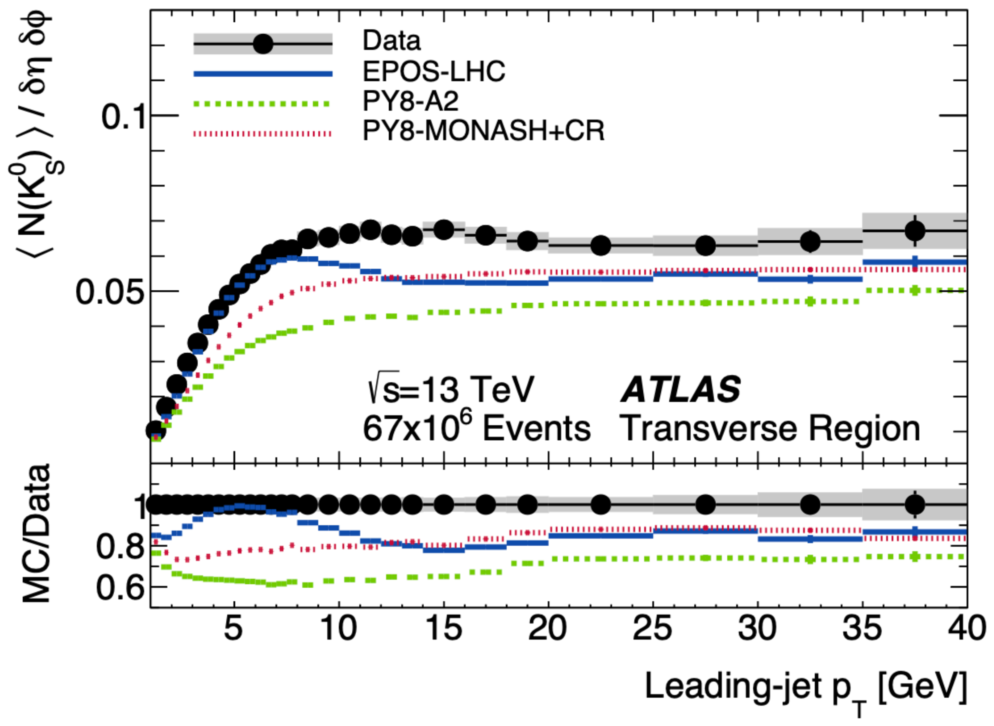
Measure them

$K_S^0 \to \pi^+\pi^-, \Lambda \to \pi^- p, \bar{\Lambda} \to \pi^+\bar{p}$

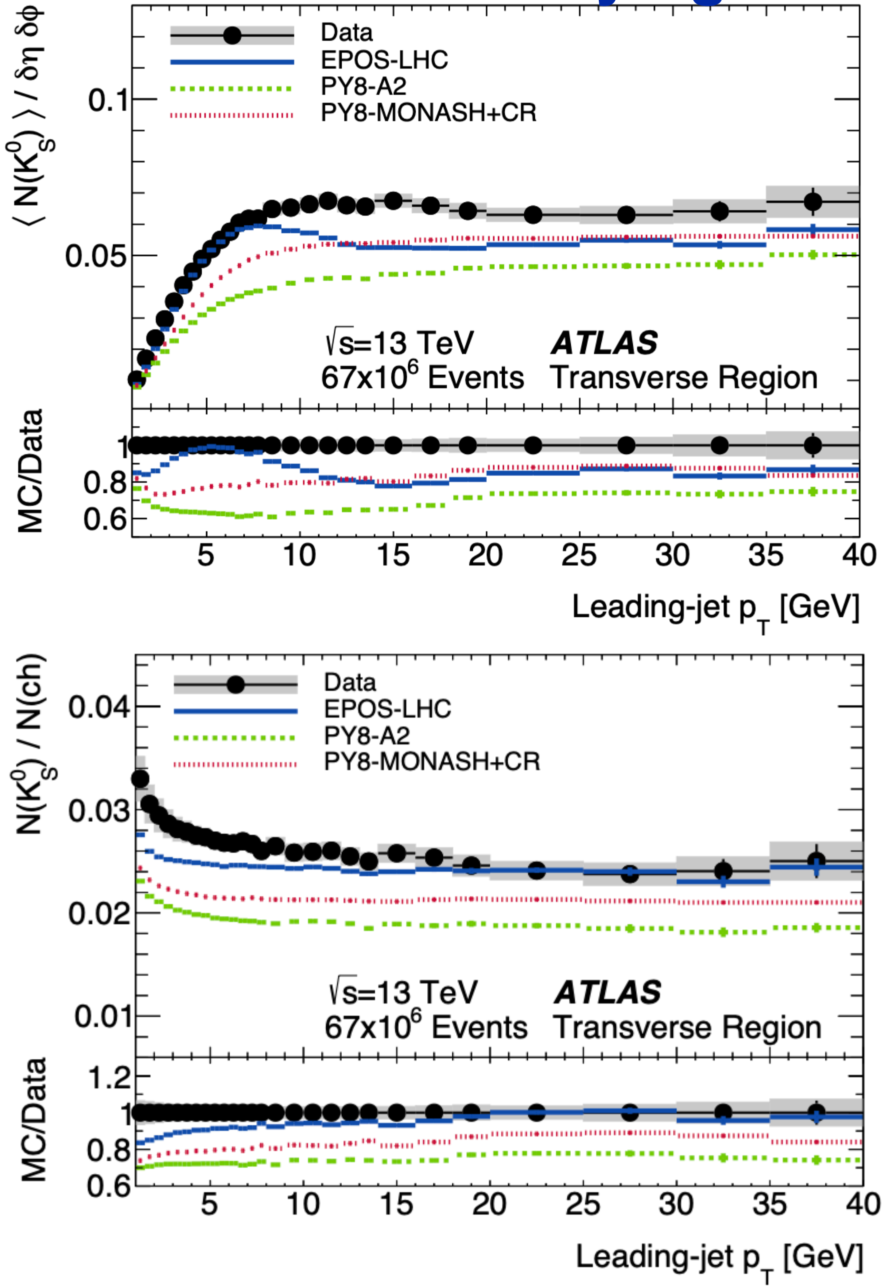
→ use displaced two-particle vertices to reconstruct them

Measure:

- Strange hadron density or fraction
- In Towards, Transverse or Away regions
- In bins of leading jet p_T



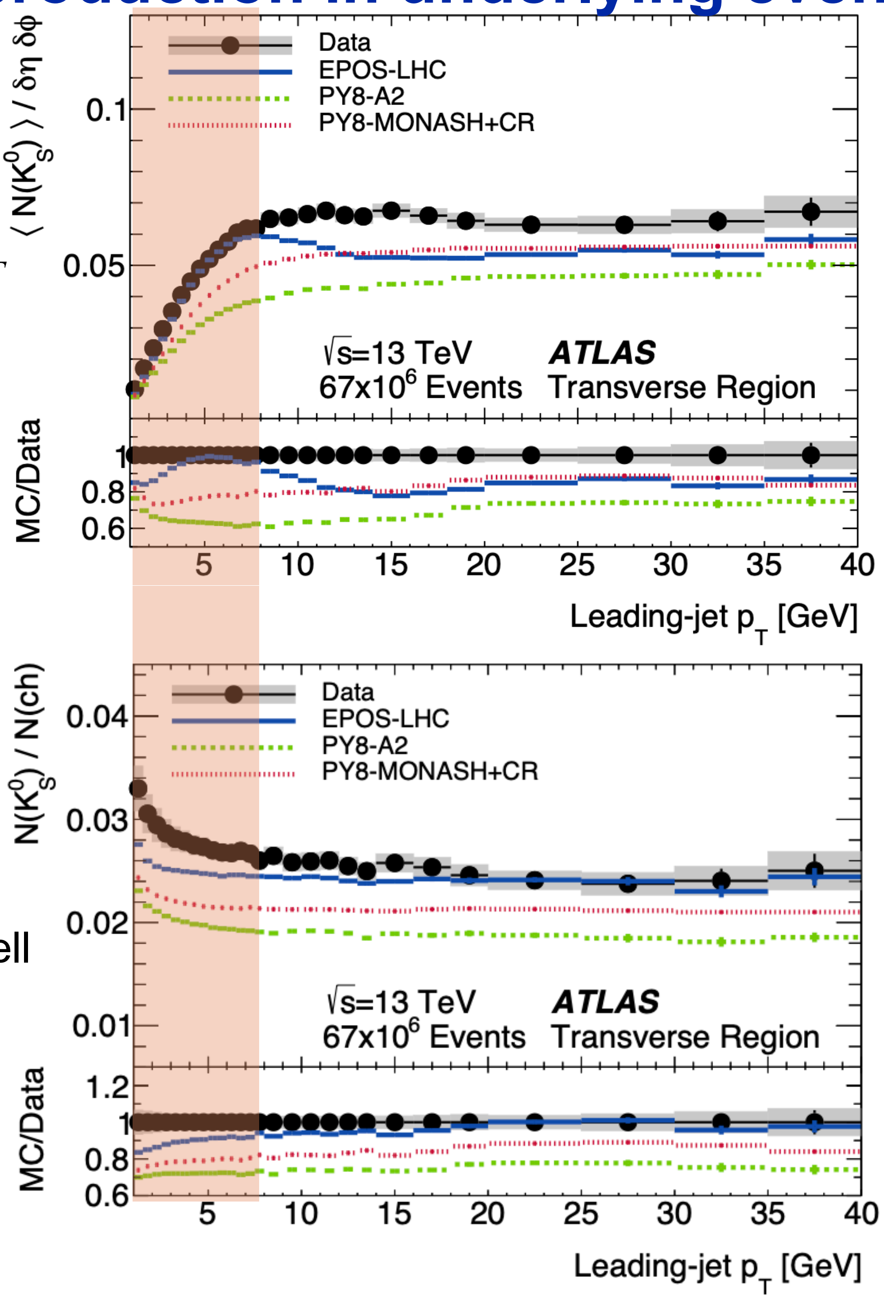
Strange hadron production in underlying events (UE)



Strange hadron production in underlying events (UE)

Low leading jet p_T
~ soft scattering region

- Increase of K_S^0 density versus jet p_T
- EPOS-LHC describes the data
  → different pp collision model (hydrodynamic) from Pythia
- Pythia A2 & color-reconnection tune under-estimates
- Color-reconnection tune performs better the A2 tune



- None of the generators describe well the K_S^0 / Nch(prompt)

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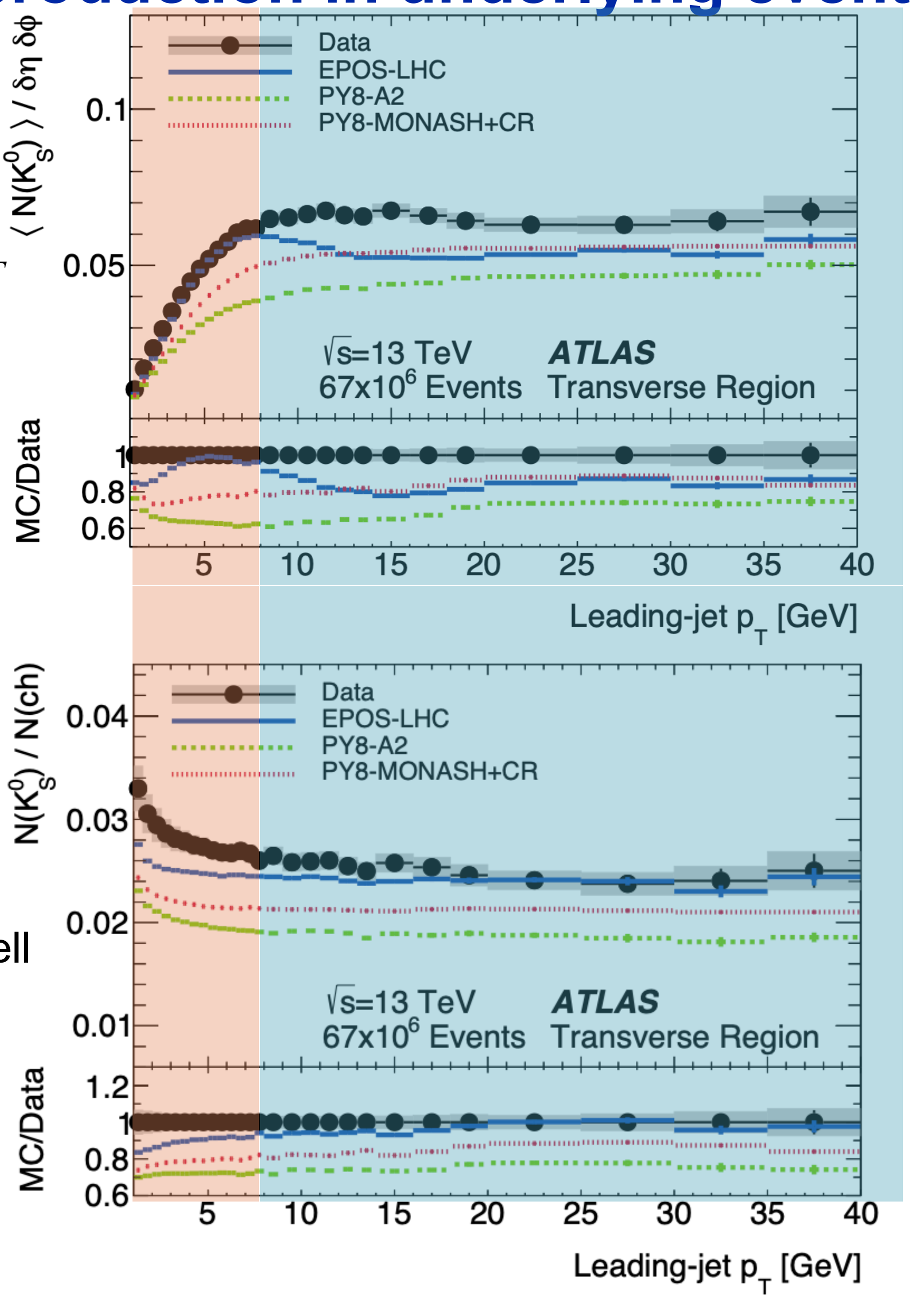
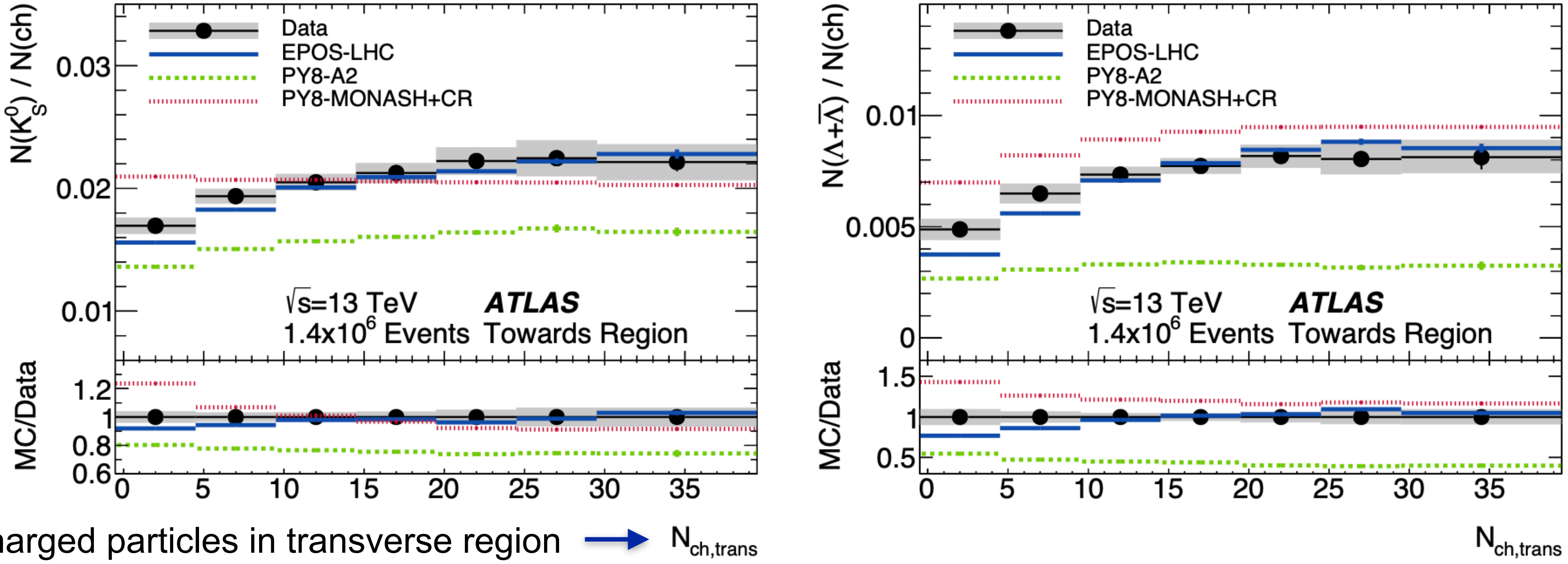


High leading jet p_T
~ hard scattering region

- Weak dependence on jet p_T
  - Dominated by non-diffractive hard collisions
  → the measured K_S^0 dominated by MPI
  → especially in region transverse to leading jet
- EPOS-LHC mismodeling
  - not monotonic & underestimates the data
  → probably because of lack of hard scattering model
- Pythia tunes predicts the shape well but under estimates the yield overall

Strange hadron production in underlying events (UE)



charged particles in transverse region → $N_{ch,trans}$
~ # MPI

Enhancement of K_S^0 and $\Lambda + \bar{\Lambda}$ / Nch (prompt) in towards region of leading jet
→ the feature is captured by **EPOS-LHC**

Summary

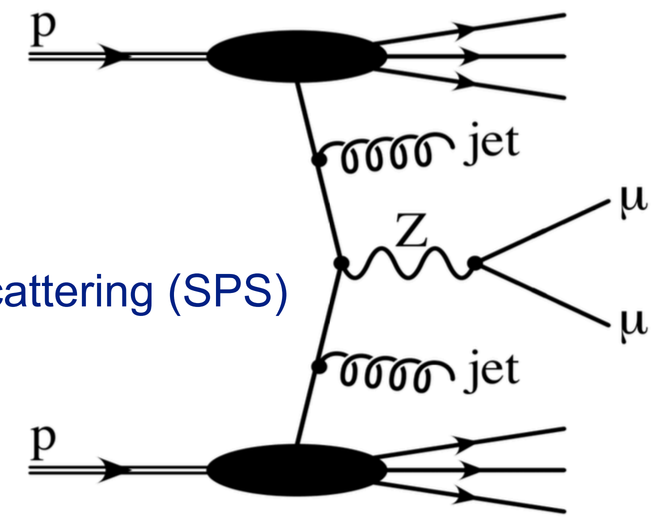
- These strangeness observables are sensitive to hadronization models (e.g. color reconnection)
  → inputs for generator tuning
- They reflect non-perturbative effects in pp collisions (difference between EPOS & Pythia)
  → useful for investigating non-perturbative phenomena e.g. quark-gluon plasma

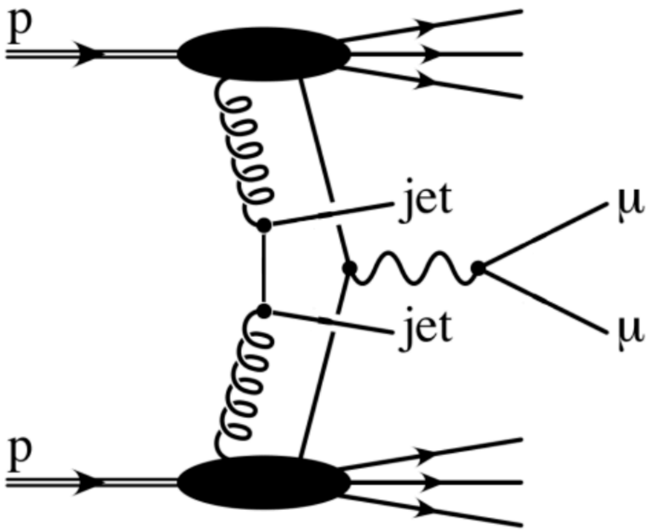
Double parton scattering (DPS) in Z+jets events

arxiv:2105.14511

Z → μμ production is experimentally clean and theoretically well understood
→ use it to explore the simultaneously occurred scatterings — presence of MPI, typically DPS

Z+jets from
single parton scattering (SPS)





Z+jets from
double parton scattering (DPS)

The kinematics of jets tend to be **correlated** with Z
& **balance** the Z momentum

The jets are **less likely to balance each other**

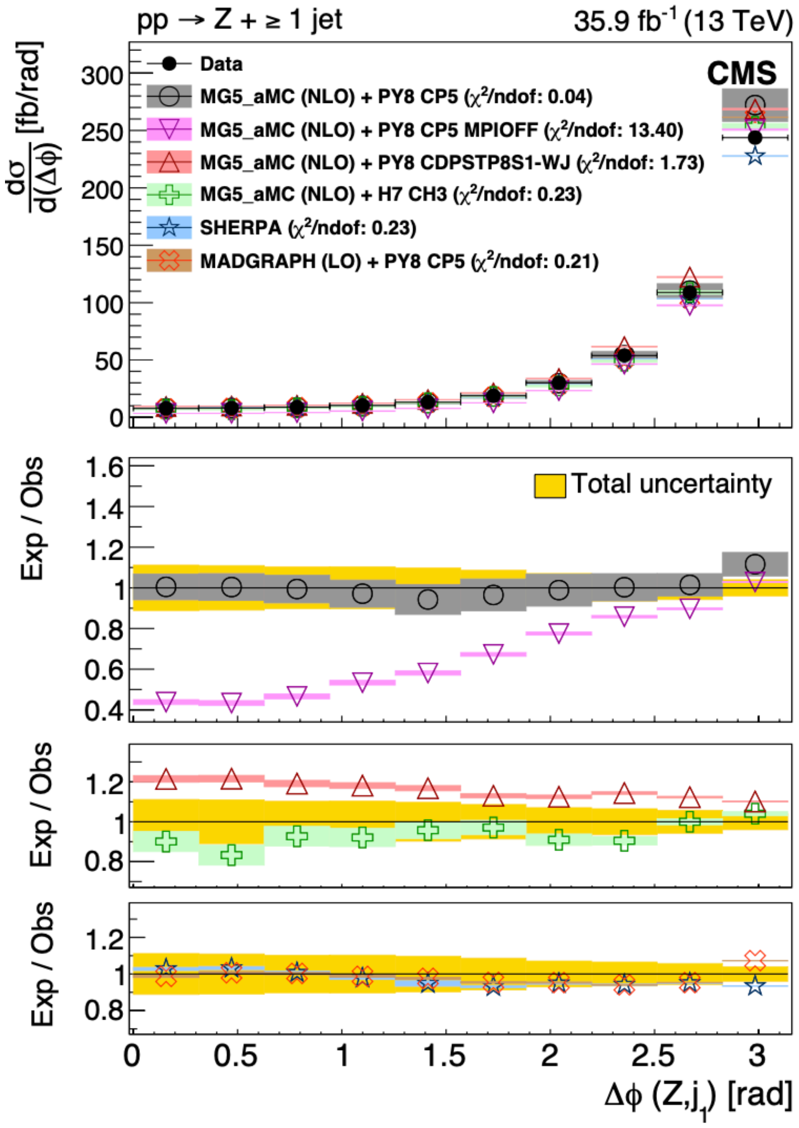
Two separate scatters
→ the kinematics of jets are **less correlated** with Z
→ the jets are **less likely to balance the Z momentum**

The jets **more likely to balance each other**

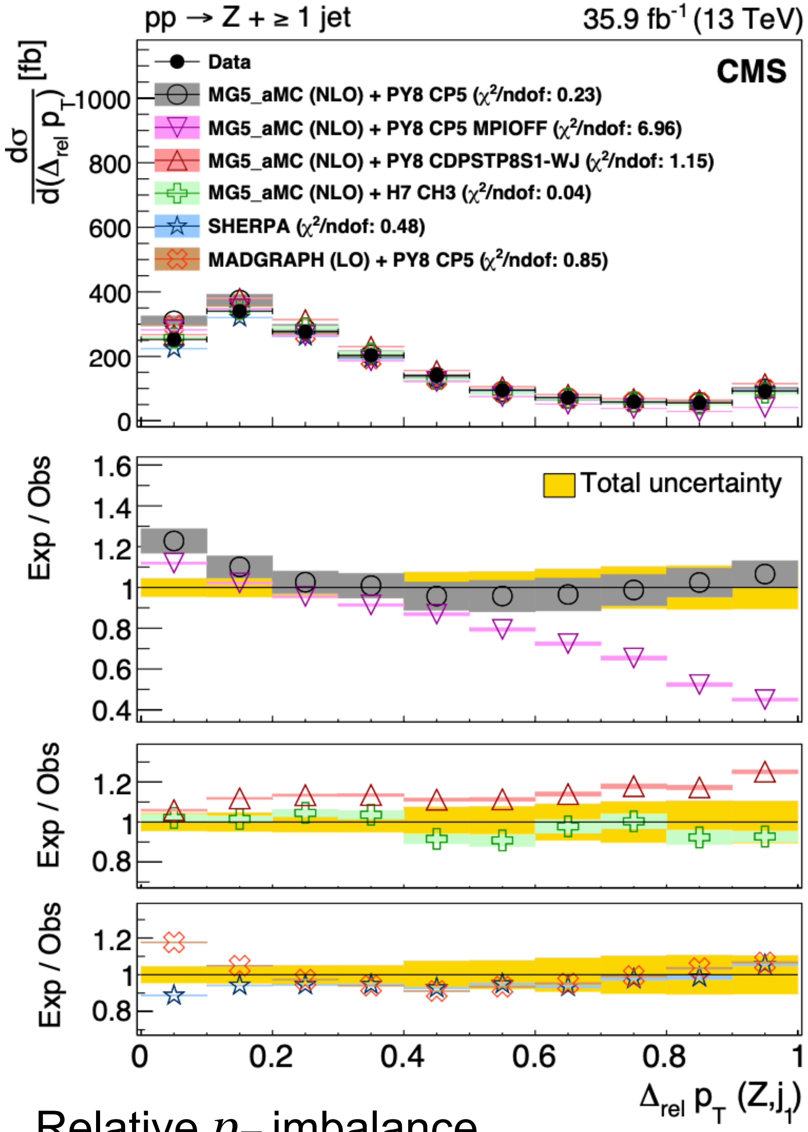
Design variables about **Z&jet**, **Z&dijet**, and **two jets** relations
- sensitive to **momentum correlation**
- sensitive to **momentum balance**

⇨ The measurements reflect DPS modeling

Double parton scattering (DPS) in Z+jets events



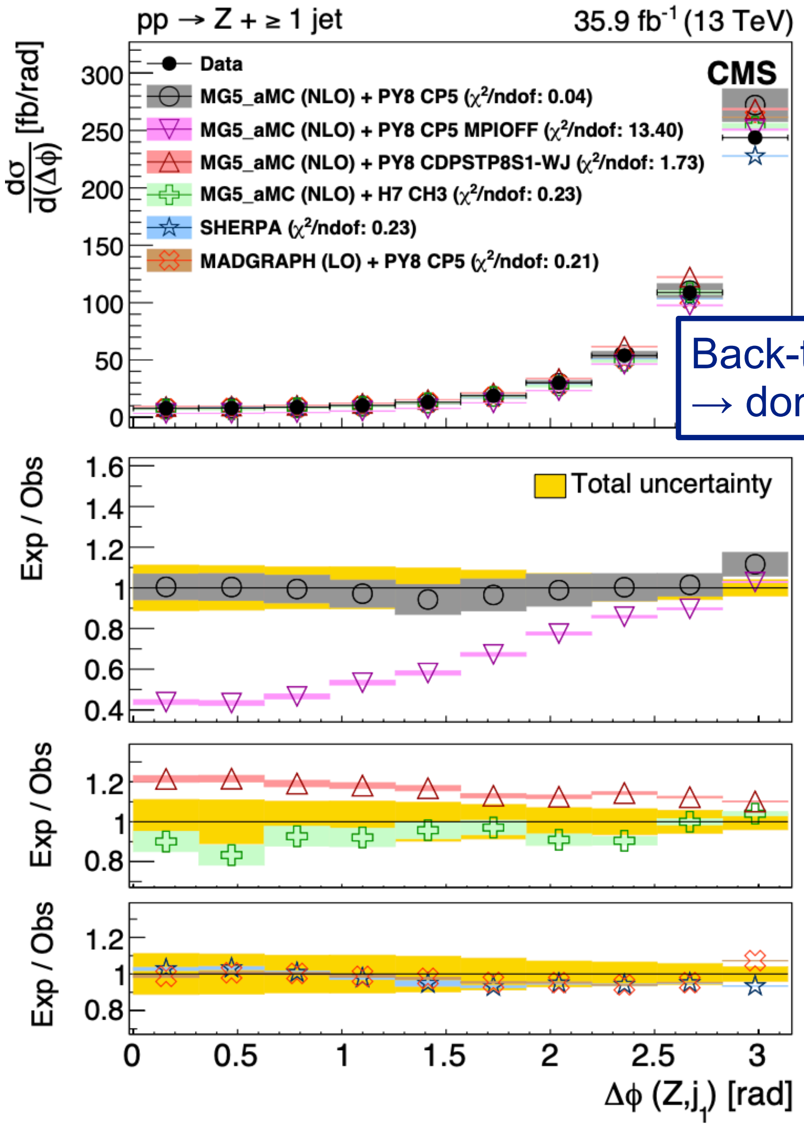
Azimuthal angle between Z and leading jet



Relative p_T imbalance

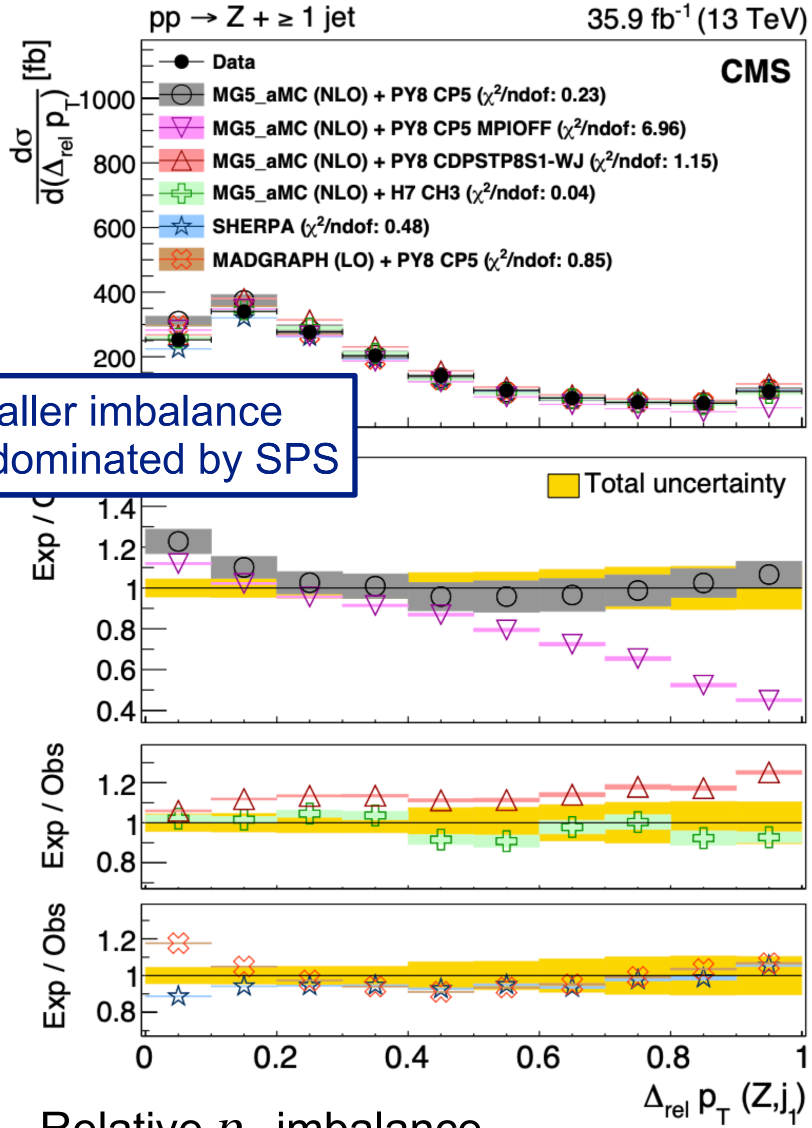
$$\Delta_{\text{rel}} p_{\text{T}}(Z, j_1) = \frac{|\vec{p_{\text{T}}}(Z) + \vec{p_{\text{T}}}(j_1)|}{|\vec{p_{\text{T}}}(Z)| + |\vec{p_{\text{T}}}(j_1)|}$$

Double parton scattering (DPS) in Z+jets events



Back-to-back
→ dominated by SPS

Azimuthal angle between Z and leading jet

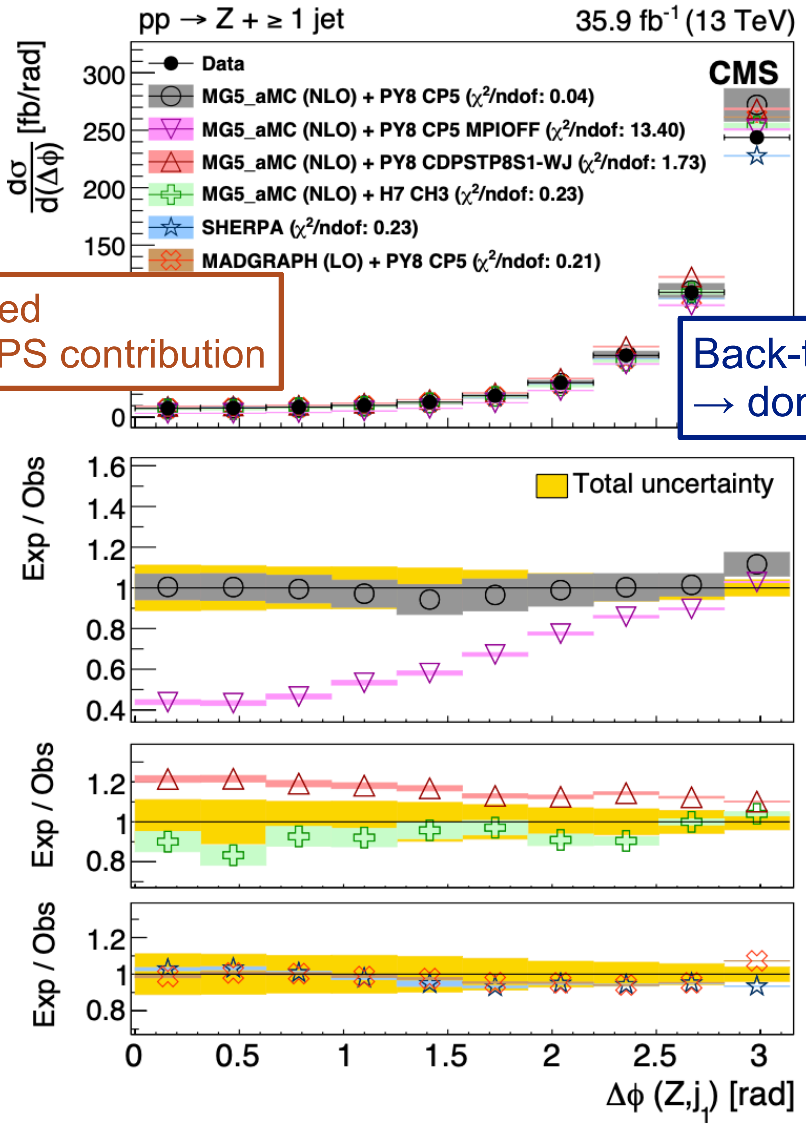


Smaller imbalance
→ dominated by SPS

Relative p_T imbalance

$$\Delta_{\text{rel}} p_{\text{T}}(Z, j_1) = \frac{|\vec{p_{\text{T}}}(Z) + \vec{p_{\text{T}}}(j_1)|}{|\vec{p_{\text{T}}}(Z)| + |\vec{p_{\text{T}}}(j_1)|}$$

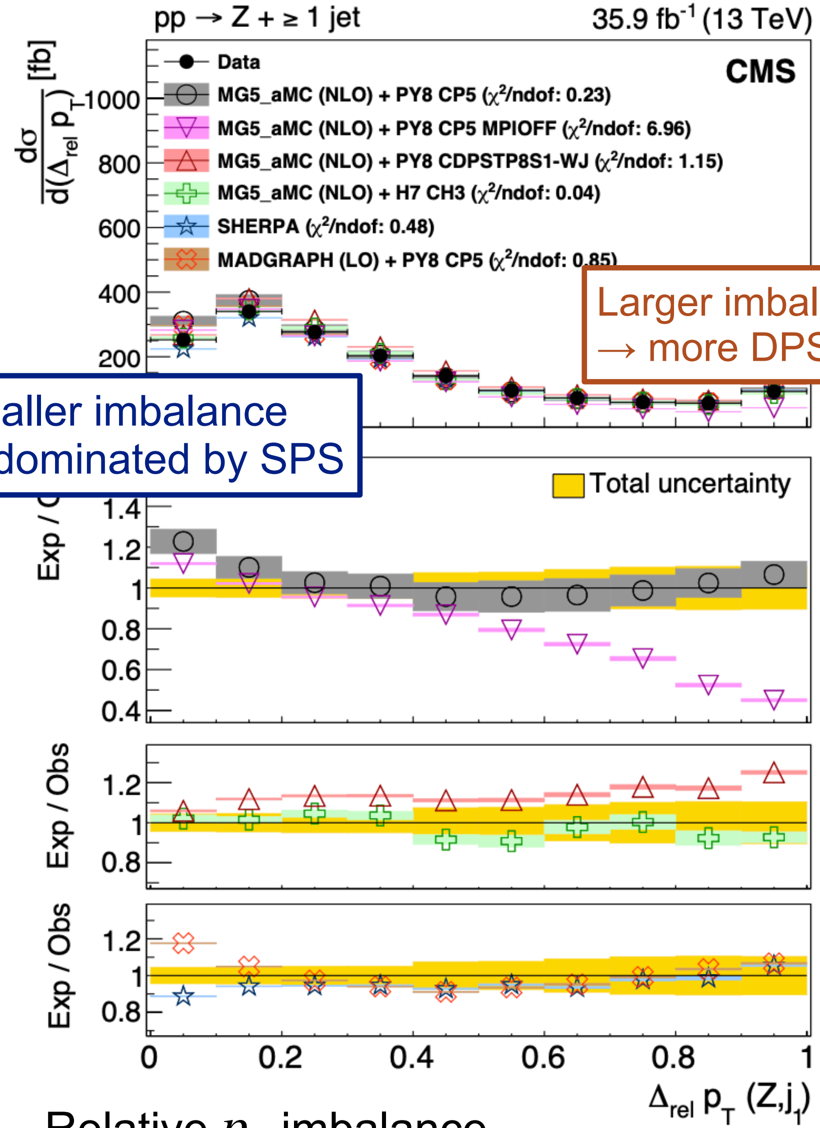
Double parton scattering (DPS) in Z+jets events



Uncorrelated
→ more DPS contribution

Back-to-back
→ dominated by SPS

Azimuthal angle between Z and leading jet



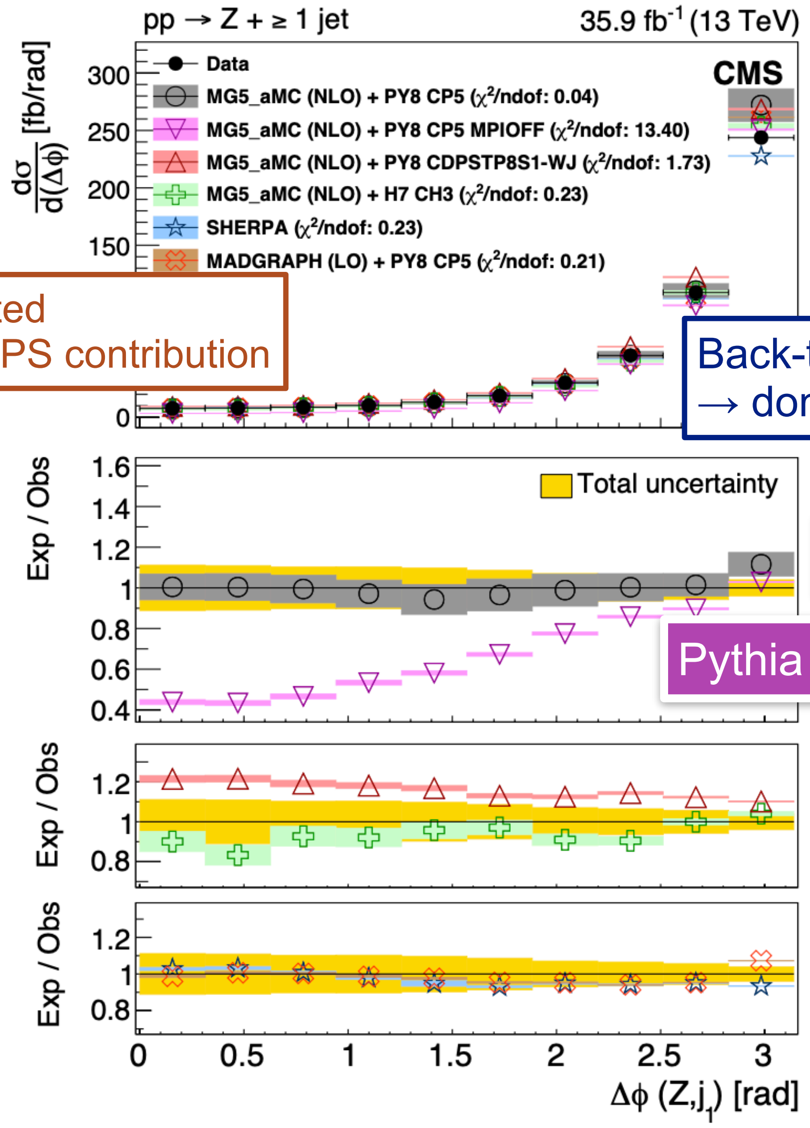
Larger imbalance
→ more DPS contribution

Smaller imbalance
→ dominated by SPS

Relative p_T imbalance

$$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(Z, j_1) = \frac{|\vec{p_{\mathrm{T}}}(Z) + \vec{p_{\mathrm{T}}}(j_1)|}{|\vec{p_{\mathrm{T}}}(Z)| + |\vec{p_{\mathrm{T}}}(j_1)|}$$

Double parton scattering (DPS) in Z+jets events



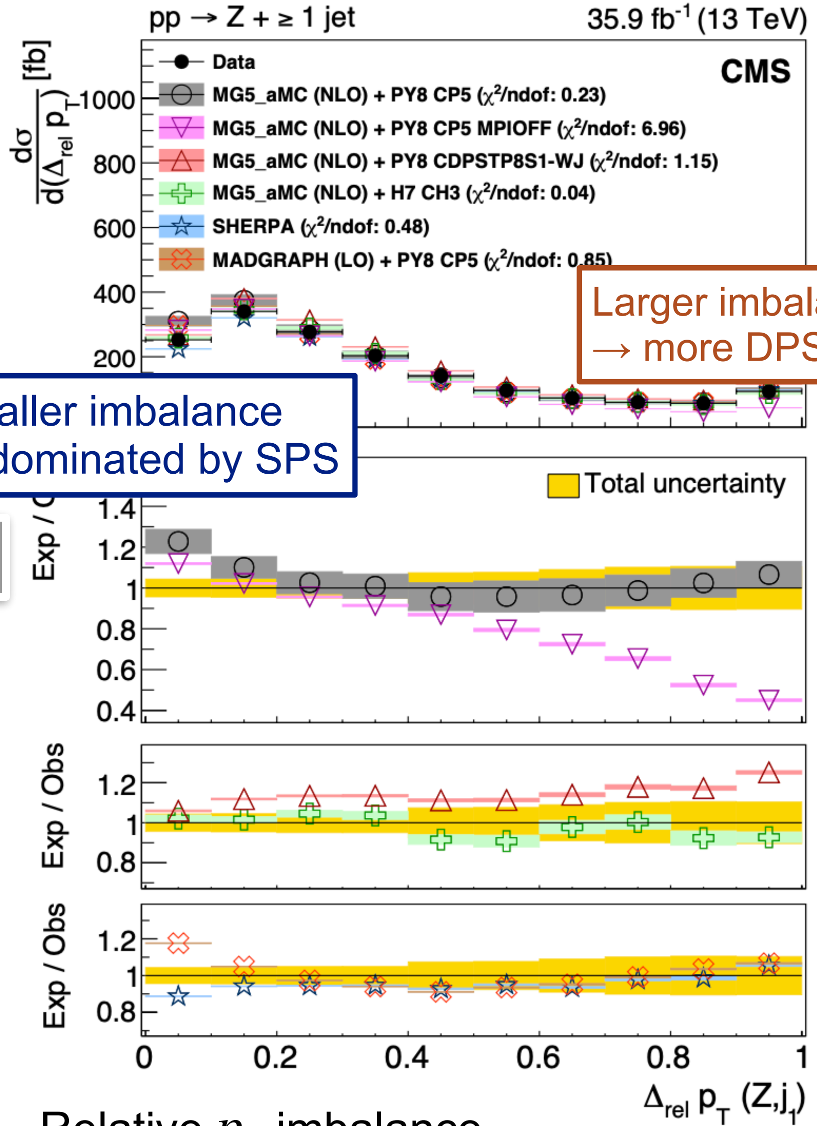
Uncorrelated → more DPS contribution

Back-to-back → dominated by SPS

Pythia CP5 with MPI

Pythia CP5 no MPI

Azimuthal angle between Z and leading jet



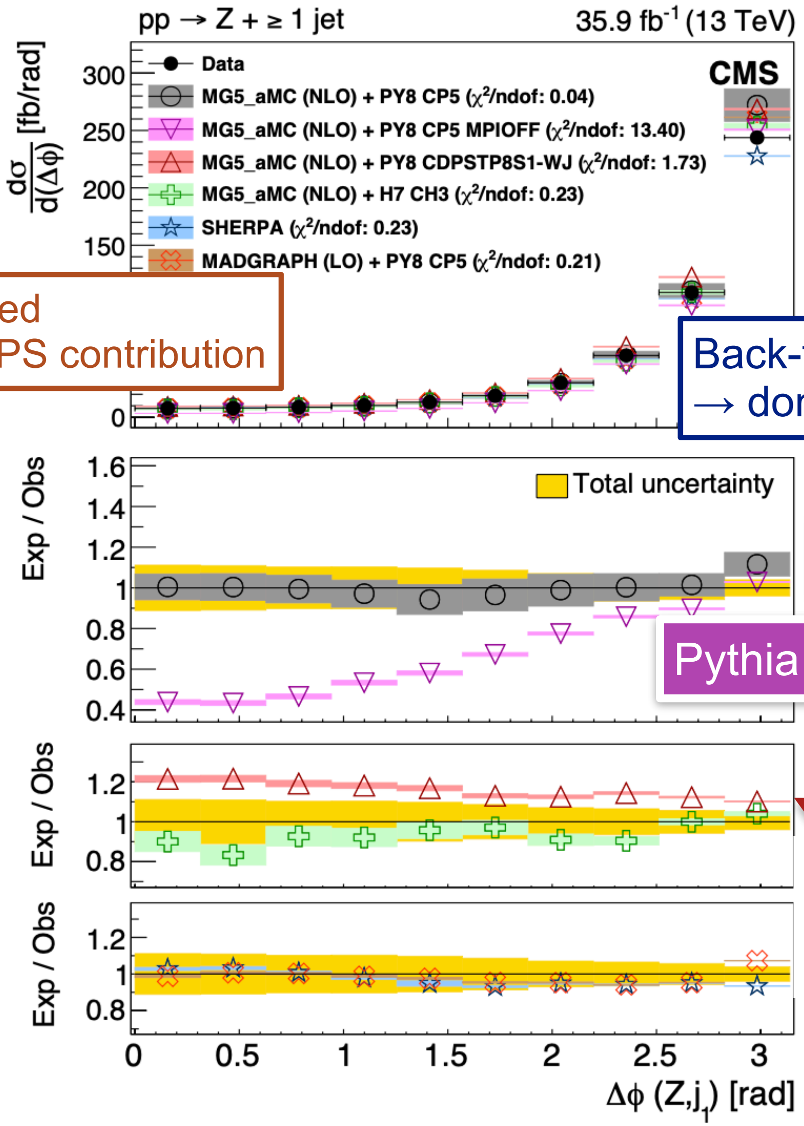
Smaller imbalance → dominated by SPS

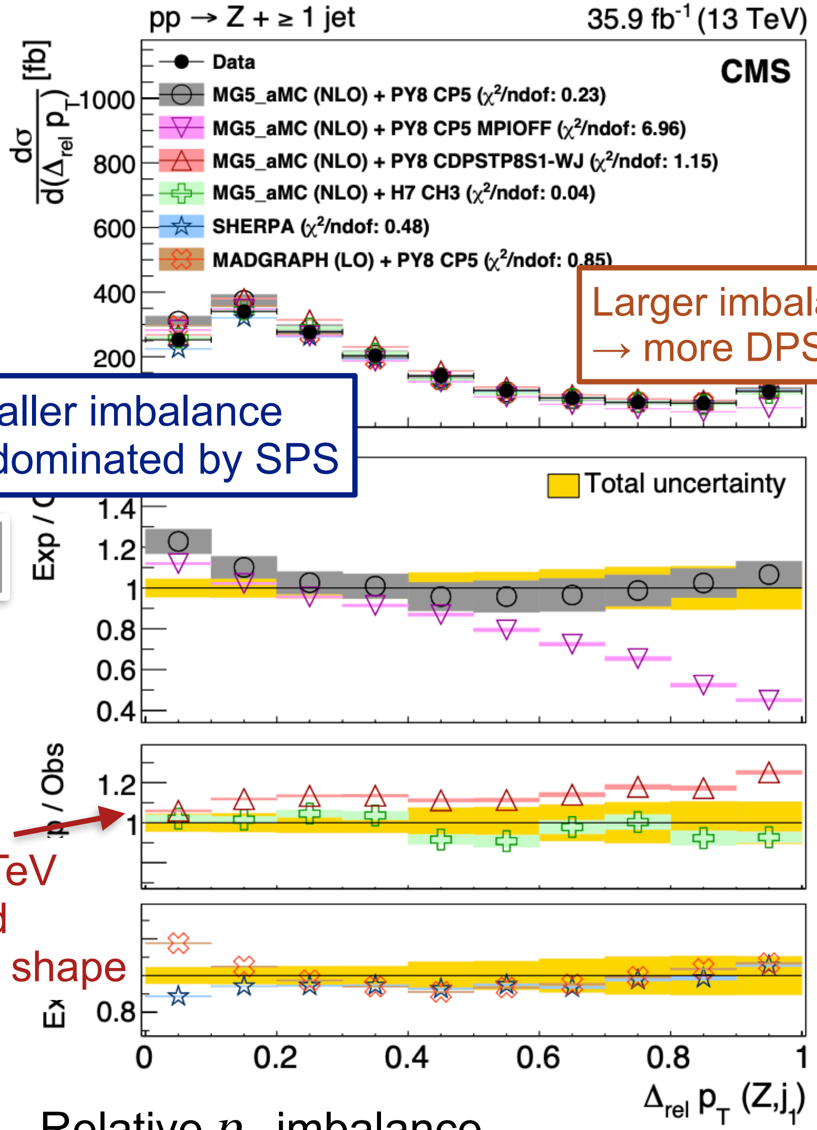
Larger imbalance → more DPS contribution

Relative p_T imbalance

$$\Delta_{\rm rel} p_{\rm T}(Z, j_1) = \frac{|\vec{p_{\rm T}}(Z) + \vec{p_{\rm T}}(j_1)|}{|\vec{p_{\rm T}}(Z)| + |\vec{p_{\rm T}}(j_1)|}$$

Double parton scattering (DPS) in Z+jets events





Uncorrelated
→ more DPS contribution

Back-to-back
→ dominated by SPS

Smaller imbalance
→ dominated by SPS

Larger imbalance
→ more DPS contribution

Pythia CP5 with MPI

Pythia CP5 no MPI

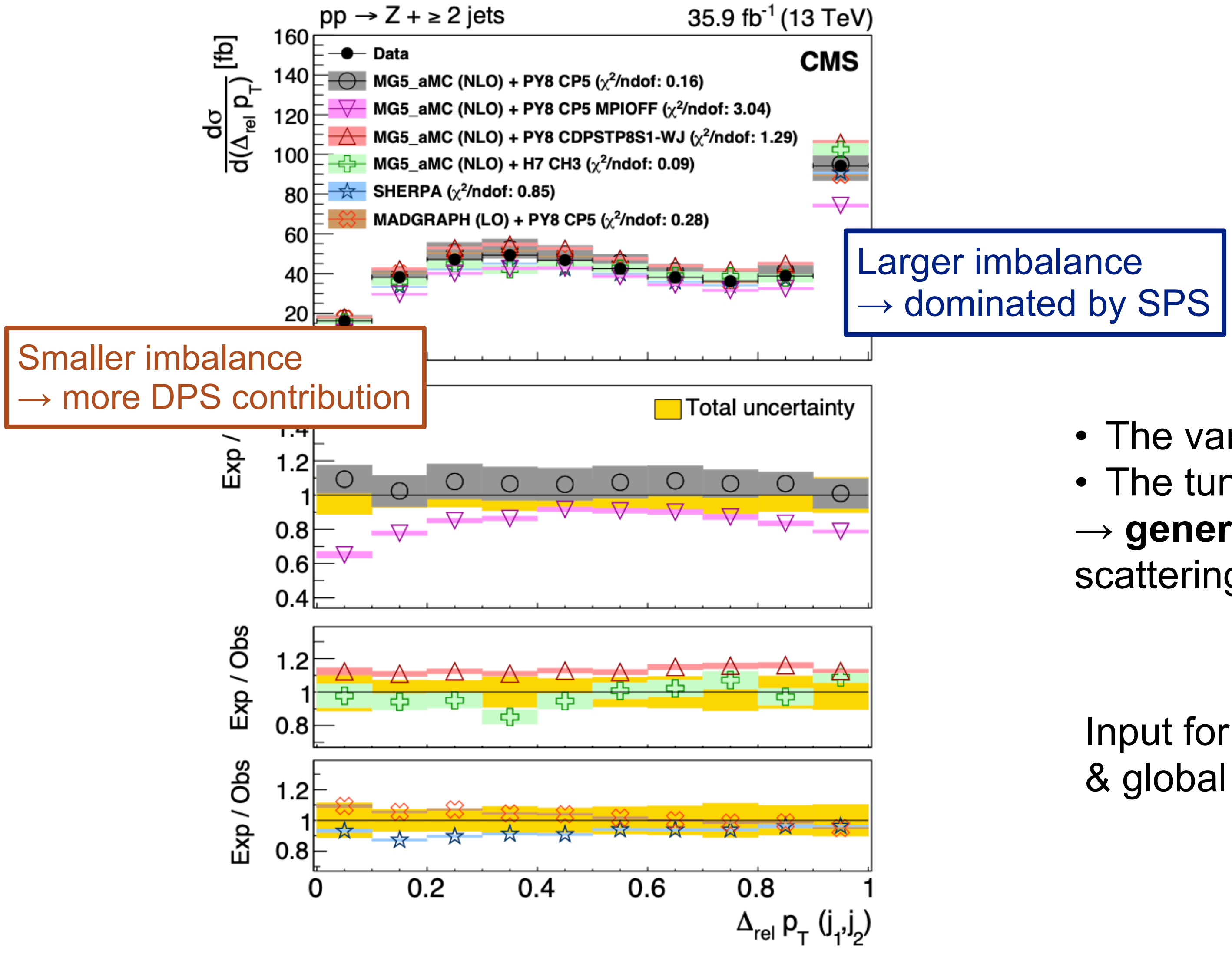
DPS-specific tune at 7 TeV
- Overestimate the yield
- Correctly describe the shape

Azimuthal angle between Z and leading jet

Relative p_T imbalance

$$\Delta_{\mathrm{rel}} p_{\mathrm{T}}(\mathrm{Z}, j_1) = \frac{|\vec{p_{\mathrm{T}}}(\mathrm{Z}) + \vec{p_{\mathrm{T}}}(j_1)|}{|\vec{p_{\mathrm{T}}}(\mathrm{Z})| + |\vec{p_{\mathrm{T}}}(j_1)|}$$

Double parton scattering (DPS) in Z+jets events



- The variables show **high sensitivity to DPS**
- The tunes were **fit** to data from **soft QCD process**

→ **generally describes well** these variables from hard scattering process (Z production)

Input for DPS-specific tunes
& global tunes with other soft QCD measurements

Relative p_T imbalance

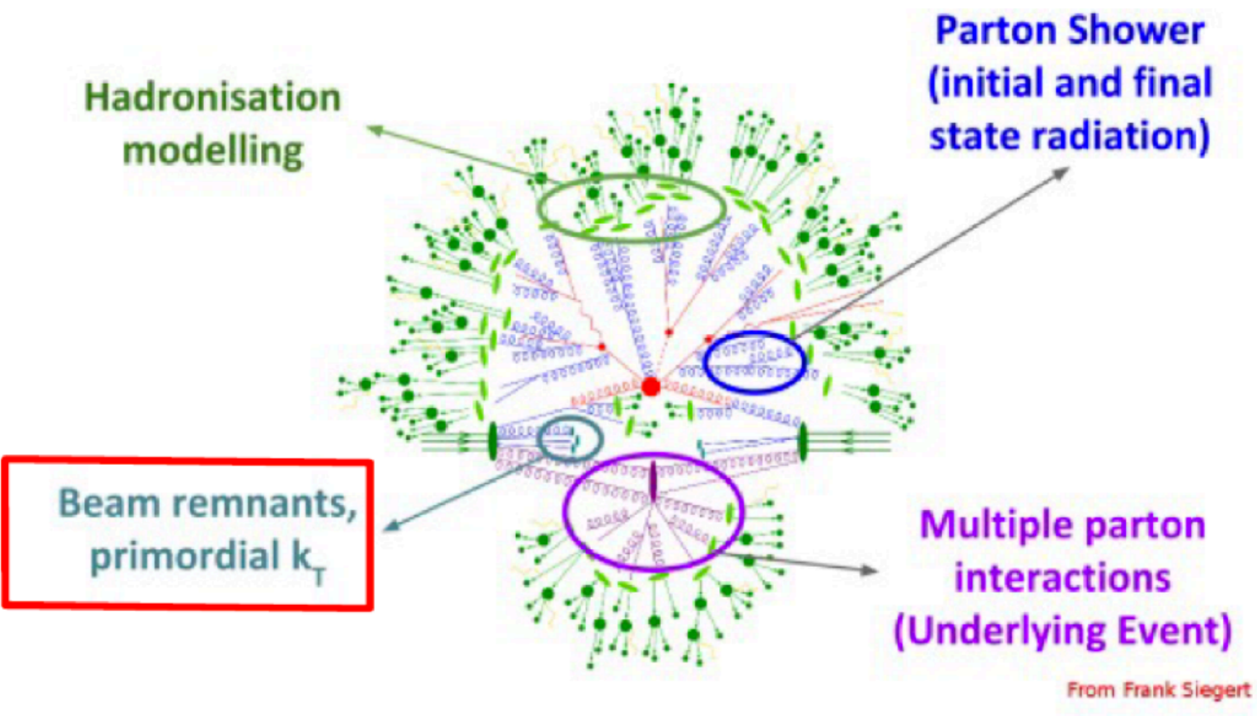
$$\Delta_{\rm rel} p_{\rm T}(j_1, j_2) = \frac{|\vec{p_{\rm T}}(j_1) + \vec{p_{\rm T}}(j_2)|}{|\vec{p_{\rm T}}(j_1)| + |\vec{p_{\rm T}}(j_2)|}.$$

Intrinsic k_T in generators probed by Drell-Yan p_T

arxiv:2409.17770

Intrinsic k_T:

The **transverse momenta** of the partons in the incoming colliding hadrons
→ **Not calculable** in perturbative QCD
→ Described by **phenomenological models**



Use **Drell-Yan** p_T to **probe the intrinsic** k_T

- DY $p_T(l^+l^-)$ measured from **precisely reconstructed** l^+l^-
- DY $p_T(l^+l^-)$ reflects the **intrinsic** k_T **from incoming partons**

→ especially the **low** $p_T(l^+l^-)$ **region**

Generator models of intrinsic k_T:

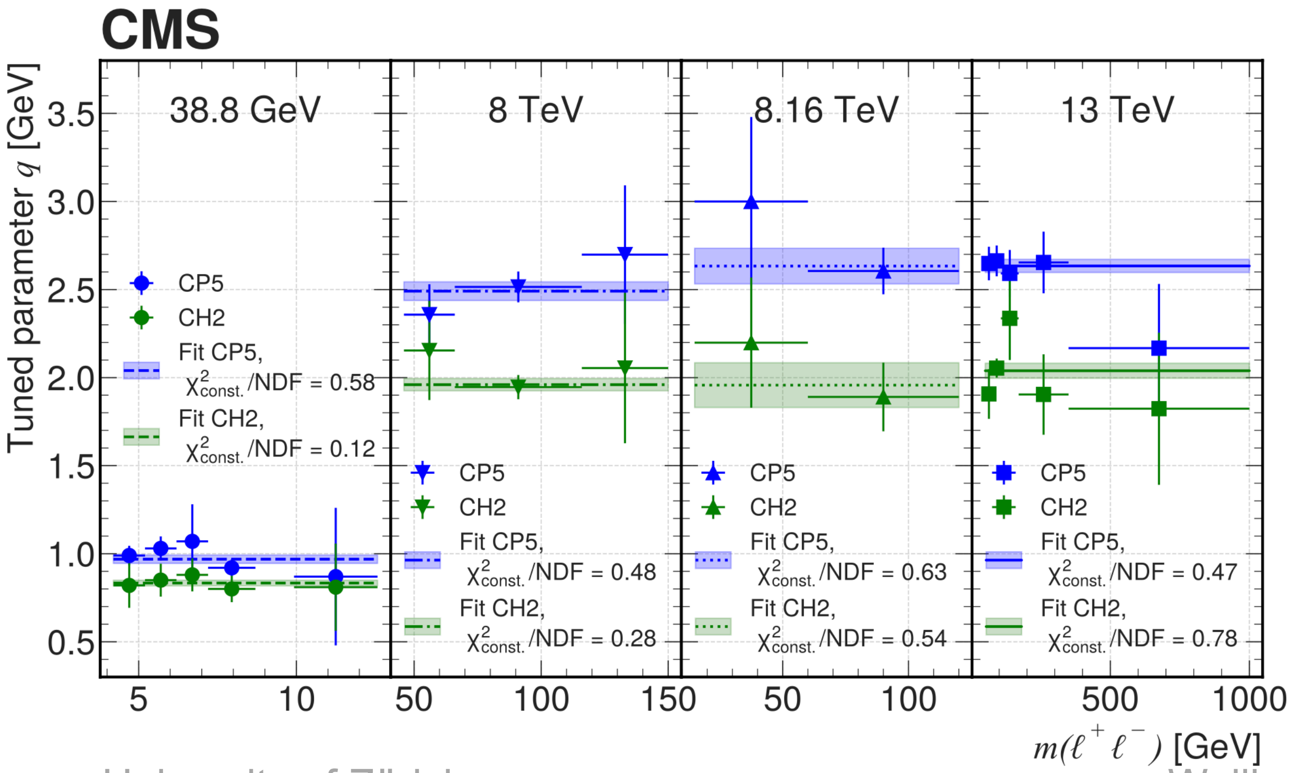
- **Fermi motion** of partons **(non-perturbative)**
- **Soft parton emissions** not included by the parton shower in initial state radiation (ISR) (**perturbative** + **non-perturbative**)

Intrinsic k_T in generators probed by Drell-Yan p_T

Intrinsic k_T parameter is tuned to DY differential XS at low $p_T(l^+l^-)$
→ Tune results gives hints on **parton Fermi motions** and **soft ISR**, **non-perturbative** and **perturbative**

Tune both **Pythia** and **Herwig** with a few underlying-event (UE) tunes + NLO DY matrix elemens
→ Study the impact of **parton shower** and **UE** model

Tune to data from experiments of various √s and hadron types
- NuSea, R209, PHENIX, D0, CDF, CMS, ATLAS, LHCb
- **√s: 38.8 GeV— 13 TeV, $m(l^+l^-)$ 5 GeV—1 TeV**



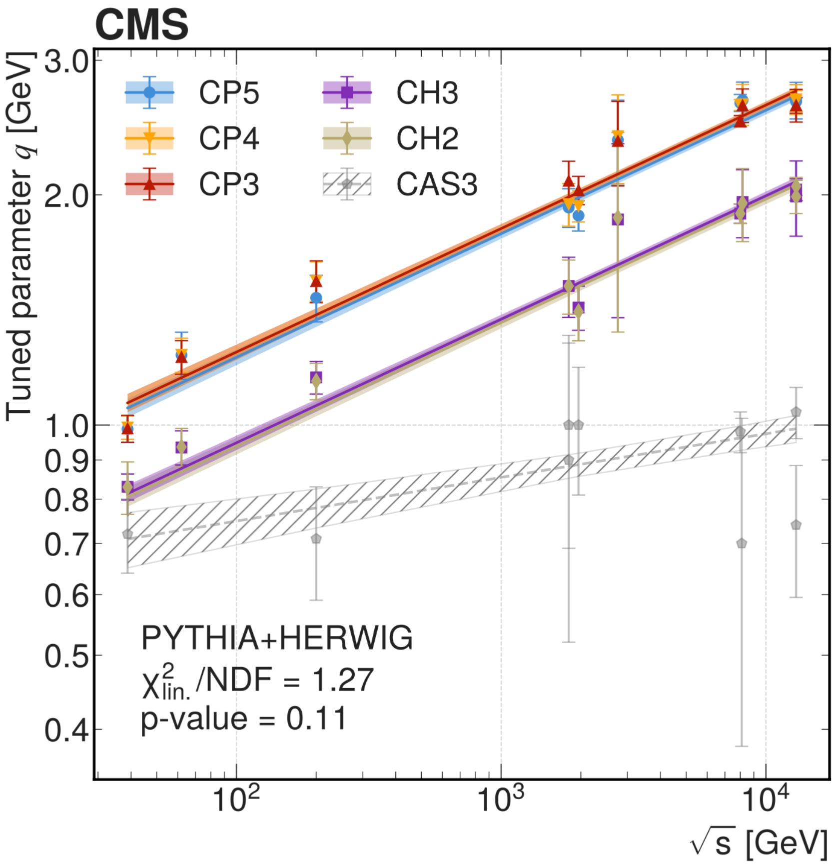
For each √s, tune intrinsic k_T separately for **various** $m(l^+l^-)$ **~ hard scattering scale**

→ **Stable** tune results versus $m(l^+l^-) \sim x_1 x_2 \sqrt{s}$ **under fixed √s**
→ **Weak/no dependence** on **parton momentum fraction** x_1, x_2

Intrinsic k_T in generators probed by Drell-Yan p_T

Tune intrinsic k_T under various √s
- Tune results **increase with √s**
- **Power-law scaling behaviour log(intrinsic k_T) ∝ log(√s)**

⇨ Parton Fermi motion cannot depend on √s
→ the behaviour comes from **missing ISR in parton shower**



The trend is similar for Pythia & Herwig
→ The scaling behaviour is **robust versus parton shower model** (p_T-ordered or angular-ordered)

Tuning result with CASCADE (arxiv:2312.08655) shows a **weaker dependence on √s**

CASCADE simulation uses **parton-branching** method to **describe transverse momentum dependent PDF**
→ Different from the Pythia and Herwig **parton shower and collinear PDF**
→ Includes more non-perturbative soft gluon emissions

The **intrinsic k_T — √s scaling** behaviour in Pythia & Herwig probably related non-perturbative gluon emissions

Jets and jet substructure

Dependence of the Jet Energy Scale on the Particle Content of Hadronic Jets in the ATLAS Detector

ATL-PHY-PUB-2022-021

Measurement of energy correlators inside jets and determination of the strong coupling $\alpha_S(m_Z)$ (backup)

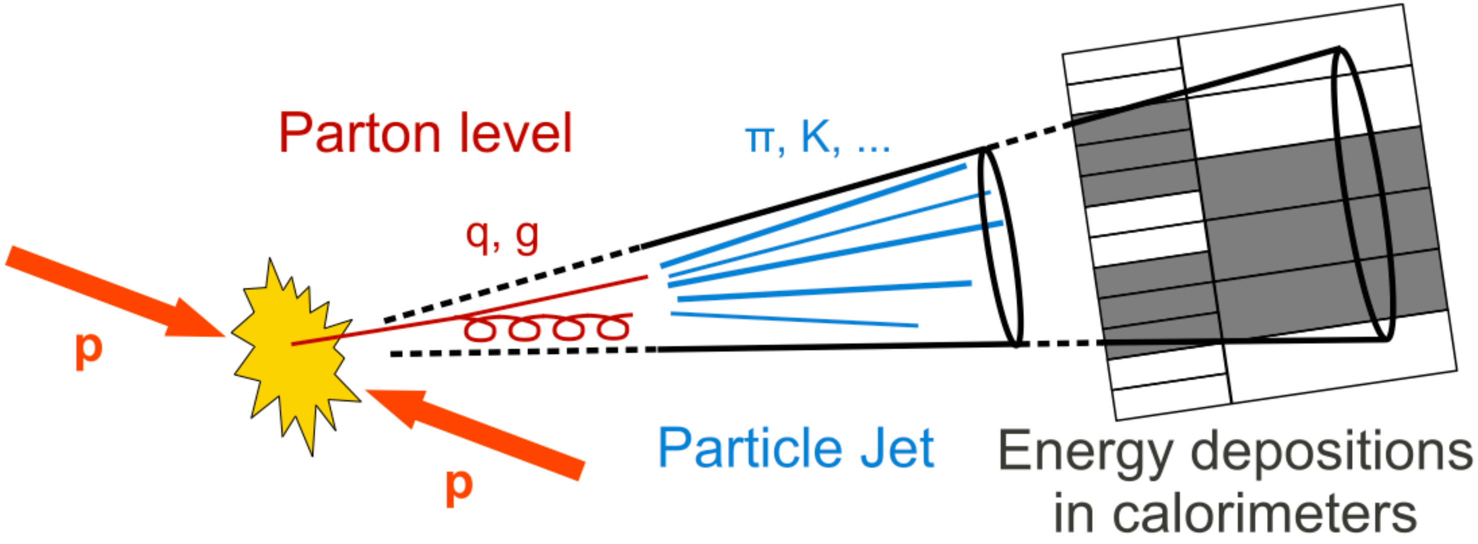
covered by Oleg Kuprash

arxiv:2402.13864

Calibration of jets depending on simulation models

ATL-PHY-PUB-2022-021

Jets as collimated sprays of hadrons from **partons** ⇨ **Detector response**



Reconstructed jet energy does not exactly equal to the truth

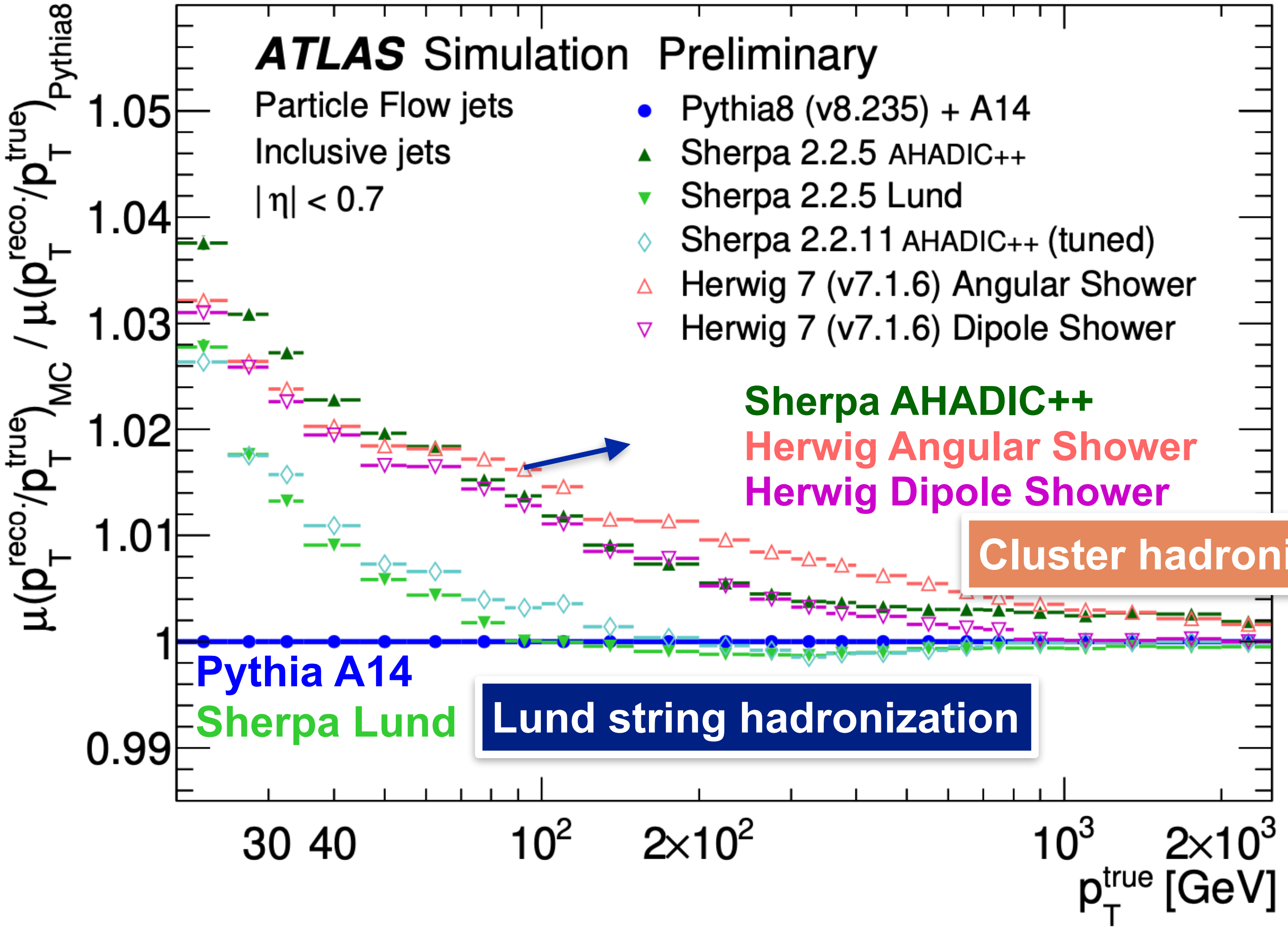
→ **calibration** (jet energy scale) needed based on **MC models of jets** and **detector simulation**

- **Electromagnetic shower** can be correctly reconstructed $\langle E_{reco}/E_{true}\rangle = 1$ 😃
- Energy deposit of **hadronic shower** is **not fully reconstructed** 😖 (non-compensation hadronic calorimeter)
  - Averagely under-calibrated $\langle E_{reco}/E_{true}\rangle < 1$
  - $\langle E_{reco}/E_{true}\rangle$ depends on energy/type of hadrons

E_{reco} depends on **MC models of jet**
— **hadron contents & kinematics**
→ **Jet models** affects the **calibration**

Calibration of jets depending on simulation models

Ratio of Simulated jet response (p_T^{reco}/p_T^{true}) to Pythia response

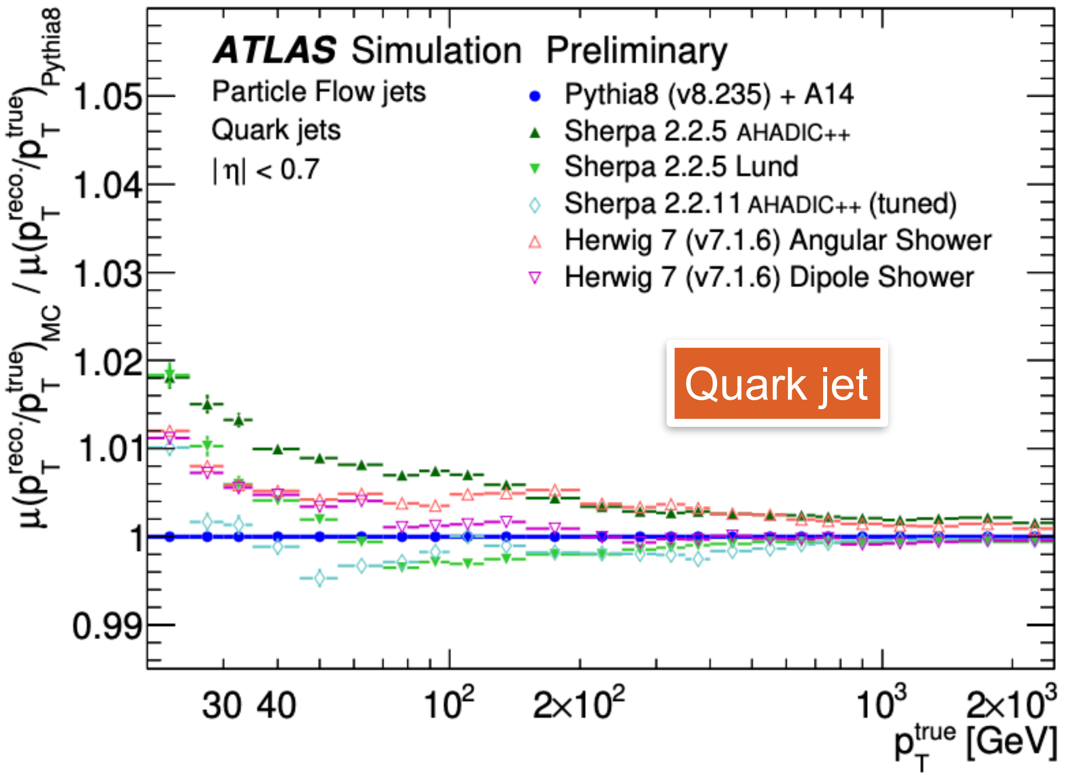


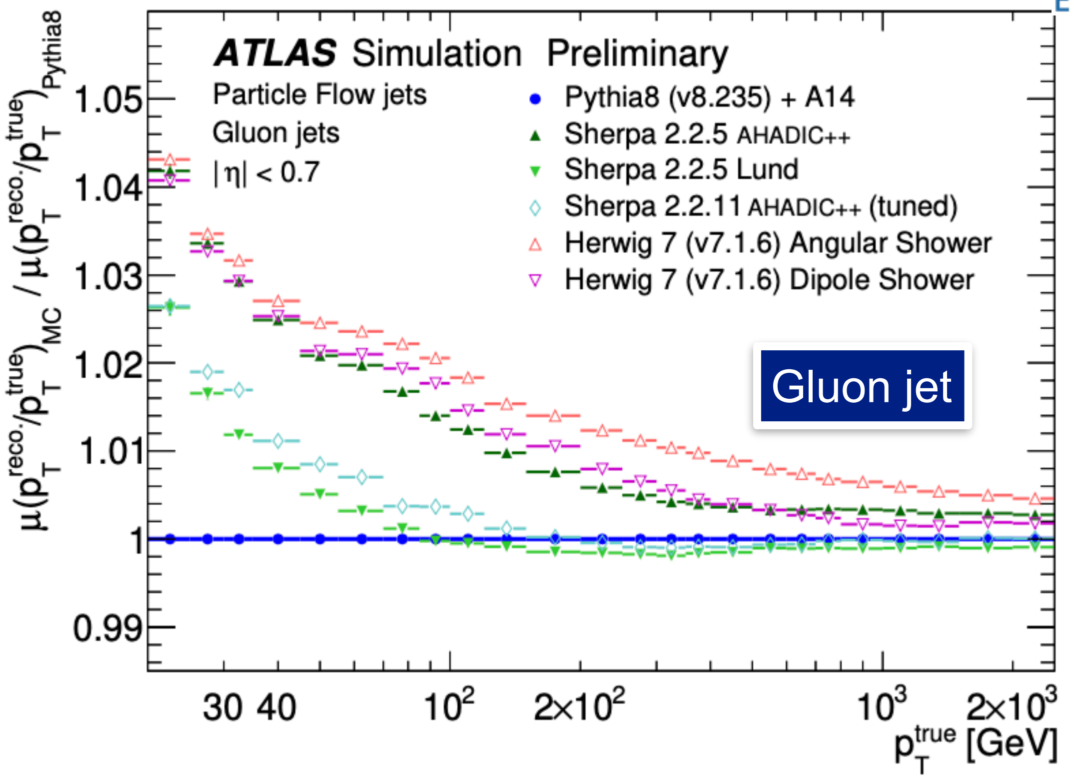
The jet response clearly groups by **hadronization model**

Sherpa AHADIC(tuned):
Tuning Sherpa hadronization model
→ re-tuned baryon fraction
→ performance is **very different** from **Sherpa AHADIC++**
→ similar to **Pythia A14** and **Sherpa Lund**

Hadronization model induces **majority of response difference**

Calibration of jets depending on simulation models

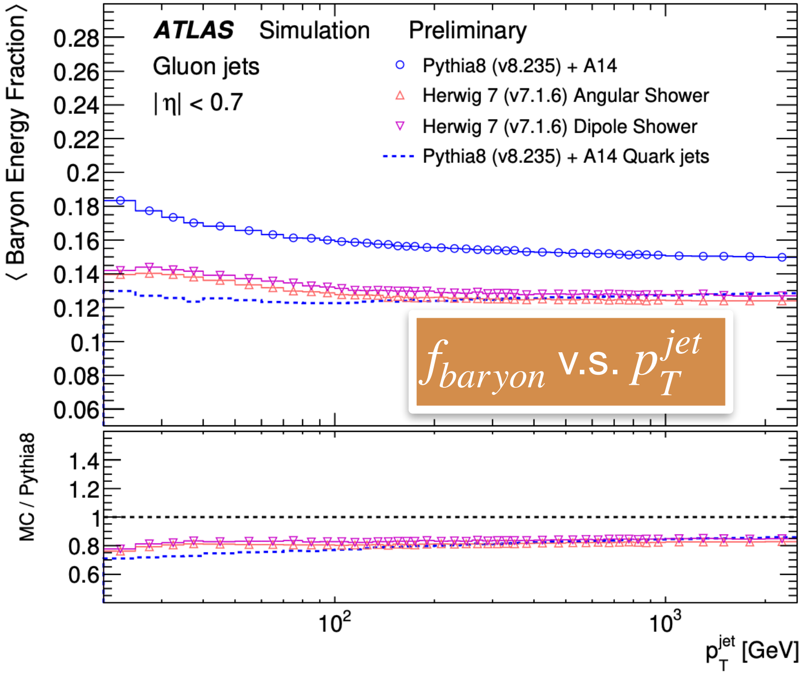


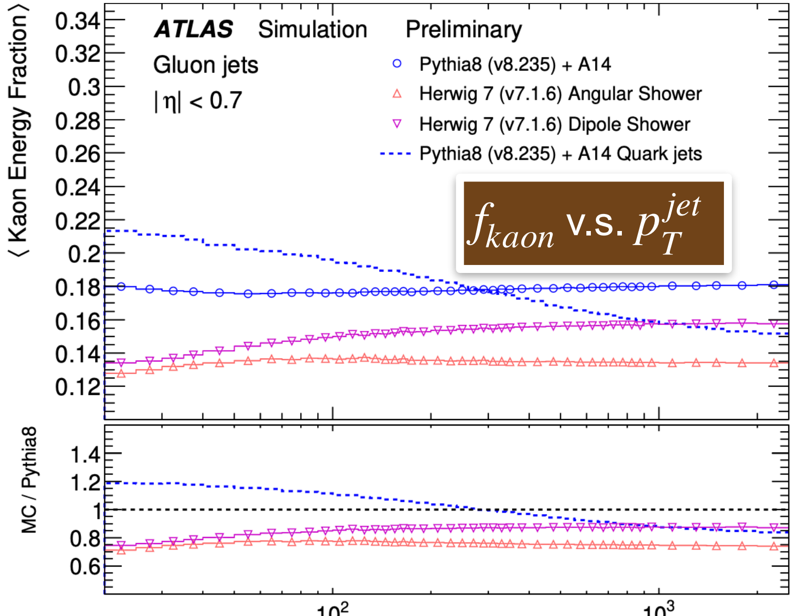


Quark jets and **gluon jets** have different jet response
→ different **fragmentation pattern** → hadron momentum spectrum
→ different **hadron contents** e.g. fraction of baryons & kaons

Important to model the **jet fragmentation pattern** and **hadron contents**

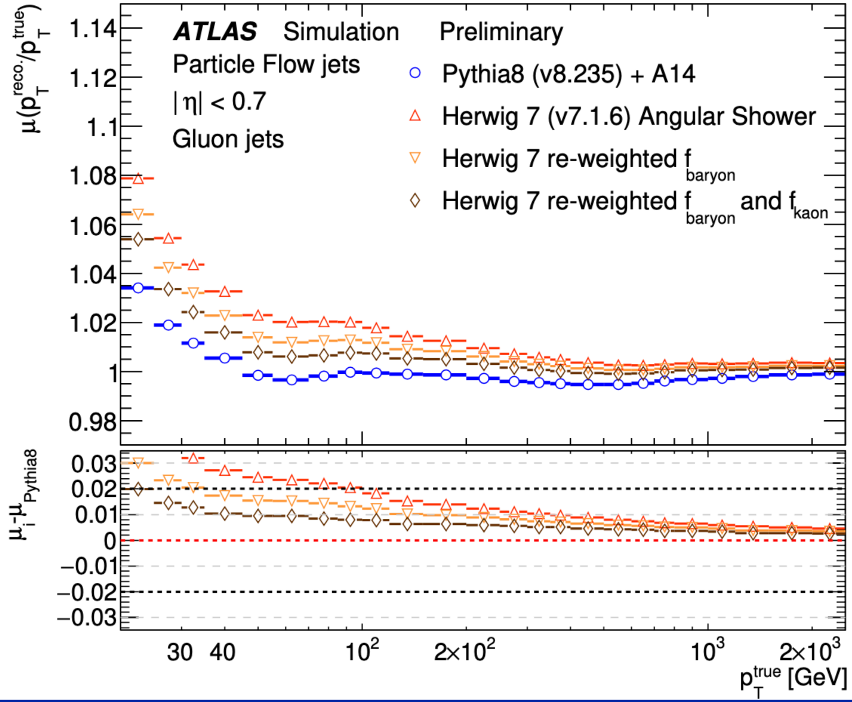
Calibration of jets depending on simulation models





The modeling differences of hadron contents are investigated by **Baryon Energy Fraction** f_{baryon} & **Kaon Energy Fraction** f_{kaon}

Reweighting **Herwig** to **Pythia** by f_{baryon} and f_{kaon} versus p_T^{jet}
→ **closer jet response !**



First quantitive estimate of the **effects of hadron contents** on **jet reconstruction**
→ encourages **improvement on hadronization models** for **jet calibration** & **precision measurements**

Modeling of Top processes

Simulation of on- and off-shell $t\bar{t}$ production with the Monte Carlo generator b_bbar_4l at CMS
CMS-NOTE-2023-015

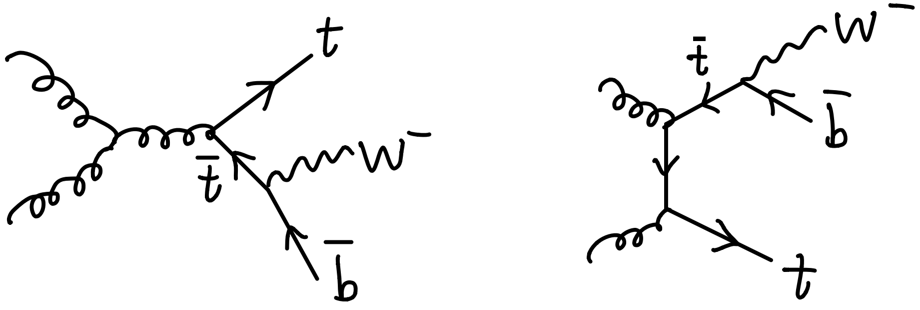
Study of matrix element correction in $t\bar{t}$ events using MG5_aMC@NLO+Pythia8
ATL-PHYS-PUB-2024-002

Studies on the improvement of the matching uncertainty definition in top-quark processes simulated with Powheg+Pythia 8
ATL-PHYS-PUB-2023-029

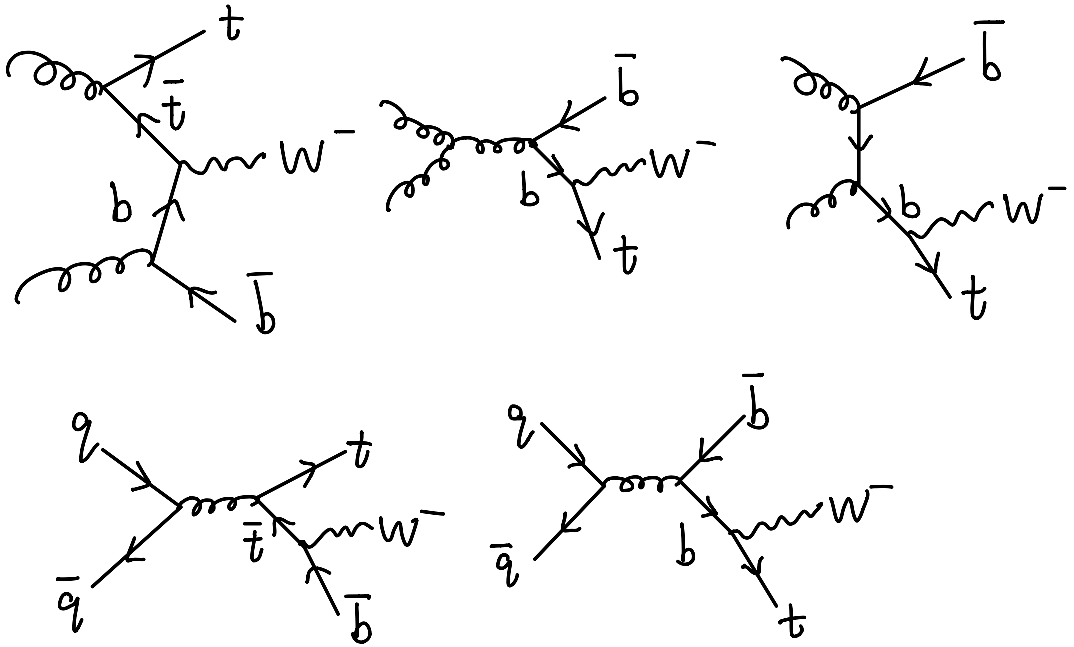
State-of-the-art MC simulation of $t\bar{t}$ at NLO

CMS-NOTE-2023-015

Sketch of $t\bar{t}$ processes



One of the top quarks goes off-shell
→ Large interference with tW processes



For precise modeling of $t\bar{t}$ kinematics
→ **Full NLO calculation** of $pp \to b\bar{b}l^{+}l^{-}\nu\bar{\nu}$ needed
(assume leptonic final states)

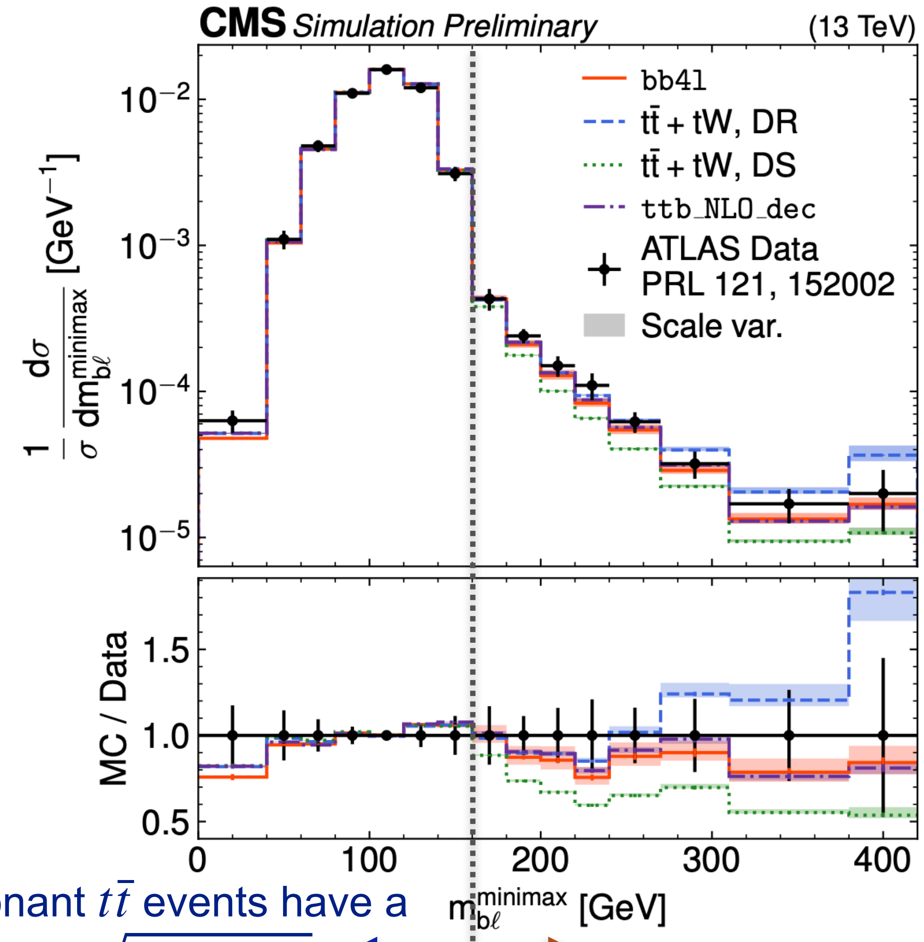
→ CMS simulation on board

`b_bbar_4l (bb4l)` generator in POWEG BOX RES package + matched PYTHIA shower (CP5 tune)

State-of-the-art MC simulation of $t\bar{t}$ at NLO

MC tests on a variable sensitive to $t\bar{t}$, tW interference

$$m_{b\ell}^{\text{minimax}} = \min\left[\max\left(m_{b_1\ell_1}, m_{b_2\ell_2}\right), \max\left(m_{b_1\ell_2}, m_{b_2\ell_1}\right)\right]$$



Double-resonant $t\bar{t}$ events have a kinematic cutoff $\sqrt{m_t^2 - m_W^2}$

Off-shell $t\bar{t}$ and interference

Lower accuracy MC samples assuming stable top:
NLO $t\bar{t}$ production in narrow width approximation (NWA)
NLO tW production in NWA
+ interference treatment to prevent double counting
- diagram removal (DR) scheme → $\mathbf{t\bar{t} + tW, DR}$
- diagram subtraction (DS) scheme → $\mathbf{t\bar{t} + tW, DS}$

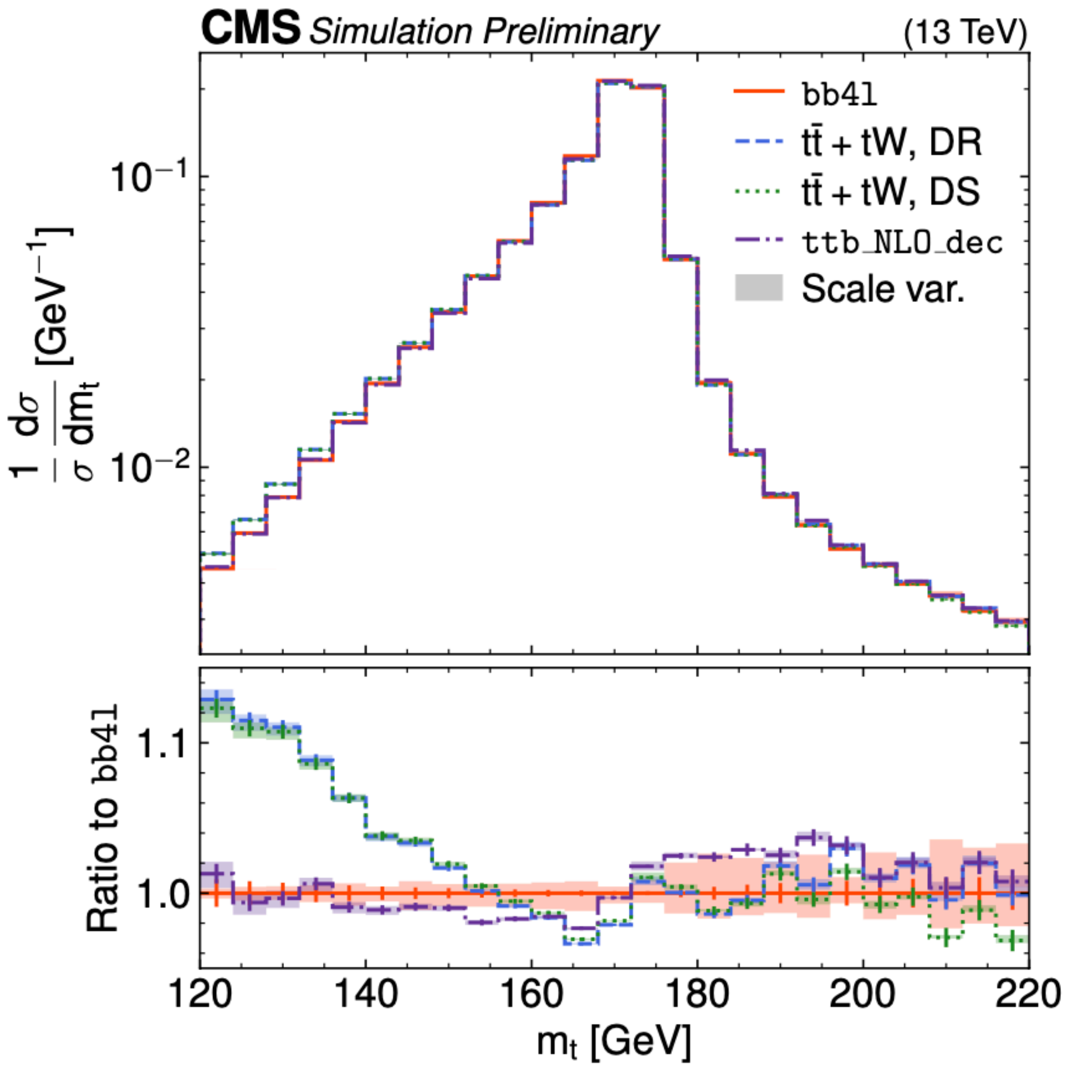
+ LO top quark decay

bb4l describes data better than $\mathbf{t\bar{t} + tW, DR}$, $\mathbf{t\bar{t} + tW, DS}$ in regions sensitive to off-shell $t\bar{t}$ and interference

NLO $t\bar{t}$ production and NLO top quark decay
+ LO treatment of $t\bar{t}$, tW interference
→ **ttb_NLO_dec**

ttb_NLO_dec and **bb4l** matches data similarly

State-of-the-art MC simulation of $t\bar{t}$ at NLO



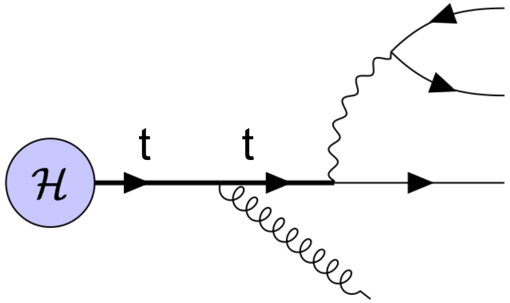
Prediction of top quark mass spectrum is significantly different for **bb4l** and $\mathbf{t\bar{t} + tW, DR}$, $\mathbf{t\bar{t} + tW, DS}$
→ indicates the effects of off-shell top production and NLO top decay
→ expect to give **bb4l** to give a more accurate prediction

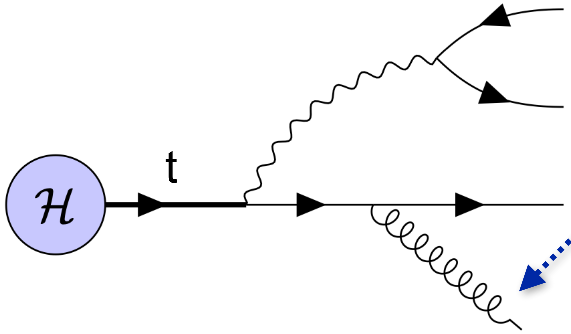
Studies of matrix element correction (MEC) in $t\bar{t}$ events using MG5_aMC@NLO+Pythia8

ATL-PHYS-PUB-2024-002

$t\bar{t}$ **production at NLO** by MG5_aMC@NLO (narrow width approximation)
+ Pythia shower of $t\bar{t}$

Already including NLO corrections in top production





MEC added in Pythia shower for hard recoils (new recommendation for Pythia*)

- Higher order corrections to top decays
- More precise than NL parton shower

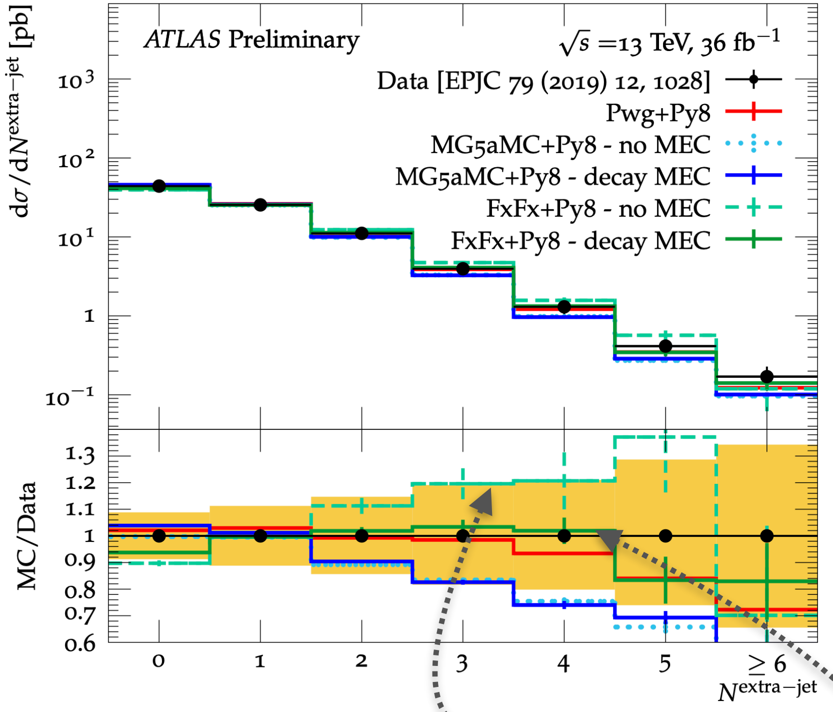
* Frixione, S., Amoroso, S., & Mrenna, S. (2023). Matrix element corrections in the Pythia8 parton shower in the context of matched simulations at next-to-leading order. *The European Physical Journal C*, *83*(10), 970.

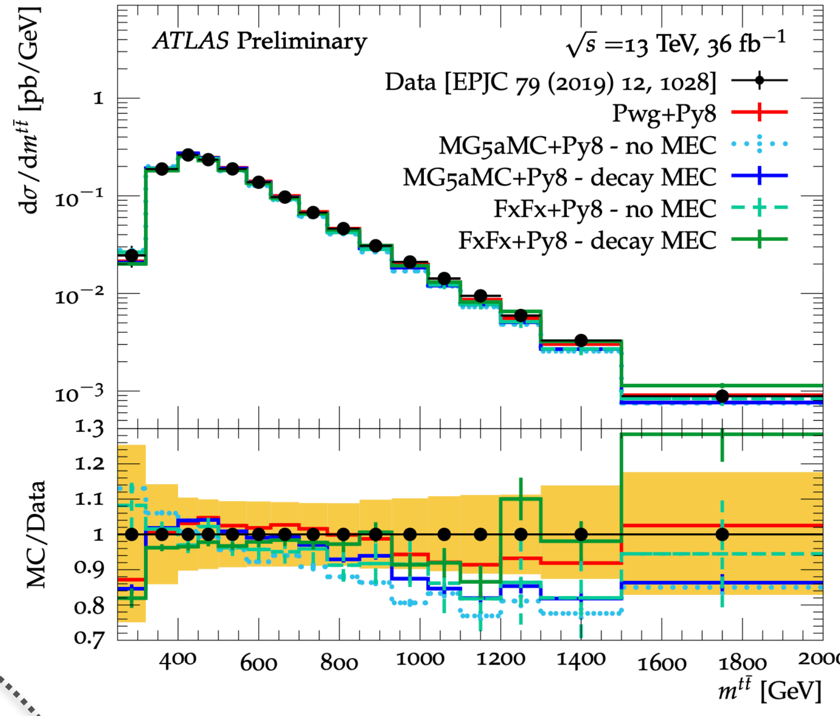
Studies of matrix element correction (MEC) in $t\bar{t}$ events using MG5_aMC@NLO+Pythia8

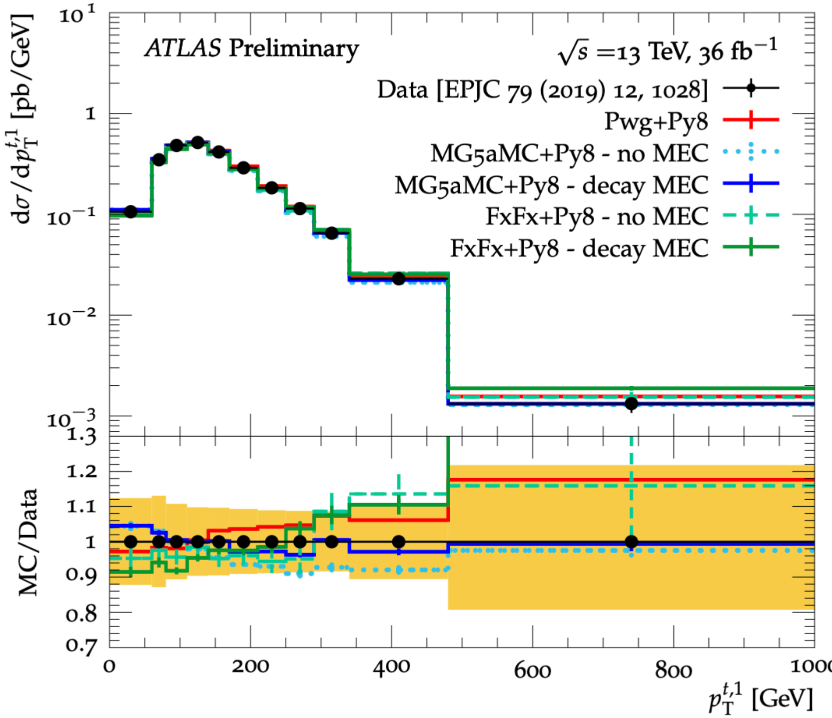
MC test for MG5_aMC@NLO

- Inclusive $t\bar{t}$ production (**MG5aMC**)
- $t\bar{t}$ production + FxFx merging up to two partons at the Born level (**FxFx**)

+ Pythia shower with/without MEC







MEC effects are visible for the **FxFx** sample for **#extra jet** and $\mathbf{m_{t\bar{t}}}$ distribution
Small impacts for the **MG5aMC** sample

MEC affects $p_T^{t,1} < 200$ GeV region for **FxFx**
$p_T^{t,1} > 200$ GeV region for **MG5aMC**

New matching uncertainty estimation strategy for top process simulation

ATL-PHYS-PUB-2023-029

Matrix element (ME) calculation of the hard scatter ·························· Parton shower

Match

Double counting or holes in the phase space
→ Matching uncertainty

Previous uncertainty estimation
— Difference between **PowhegBox+Pythia** and **MG5_aMC@NLO+Pythia**
→ includes **multiple effects**: shower adjustments to ME generator, top-decay settings
→ **Over-coverage** for matching uncertainty

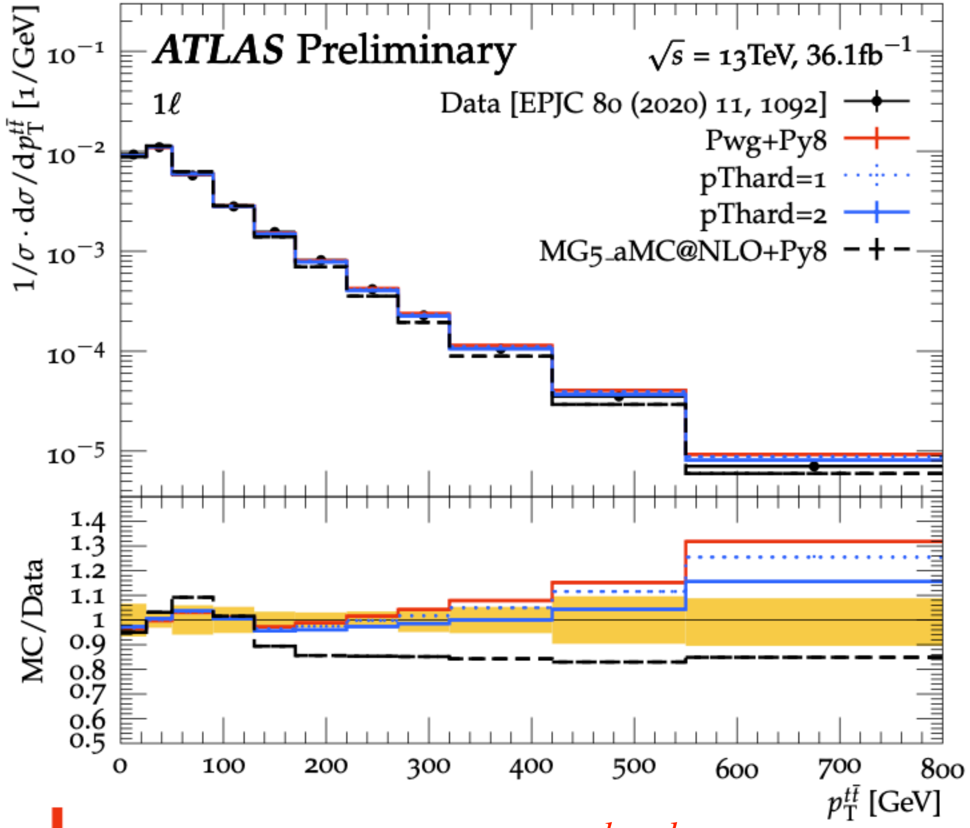
New prescription for the matching uncertainty:

- Both Powheg and Pythia have emissions based a p_T **based variable "hardness"**
- Pythia vetos the emission above the "hardness" to avoid double counting

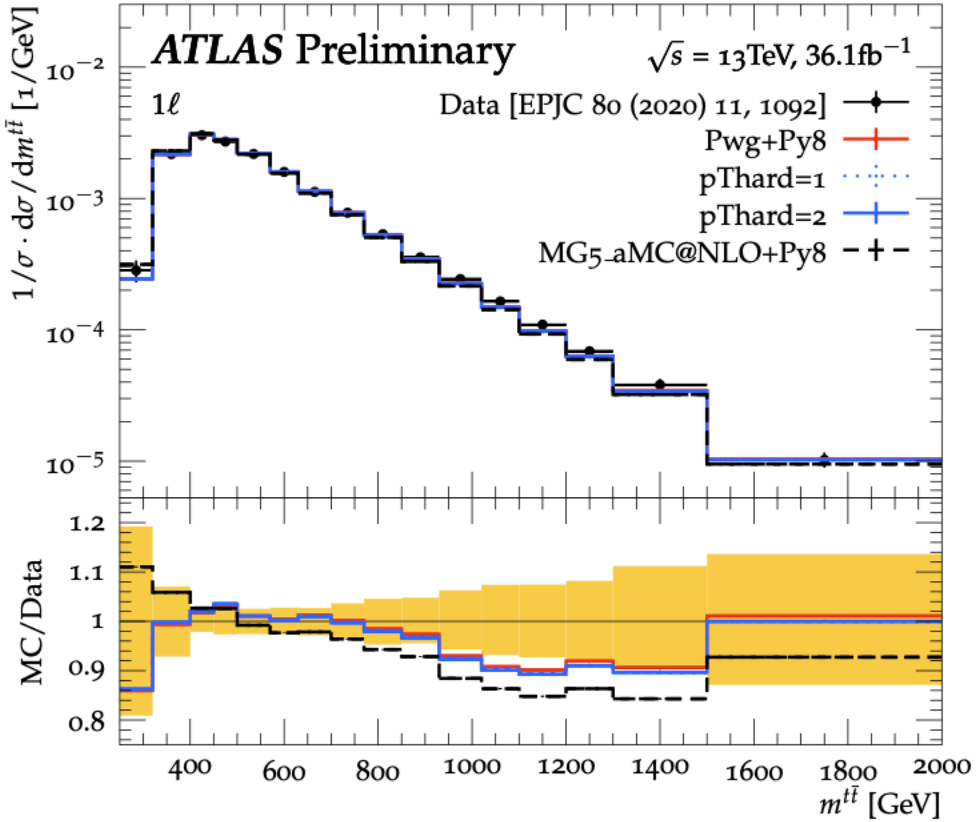
→ Use **various choices of "hardness" (p_T^{hard})** definition to estimate the uncertainty

New matching uncertainty estimation strategy for top process simulation

Example of variable sensitive to matching: $p_T^{t\bar{t}}$



Example of variable insensitive to matching: $m^{t\bar{t}}$



Powheg+Pythia p_T^{hard} = 0 (default) "hardness" in Pythia as the SCALEUP parameter given by Powheg

Powheg+Pythia p_T^{hard} = 1 "hardness" as the p_T of the Powheg gluon emission in top production

Powheg+Pythia p_T^{hard} = 2 "hardness" as the minimal p_T of all the Powheg final-state partons

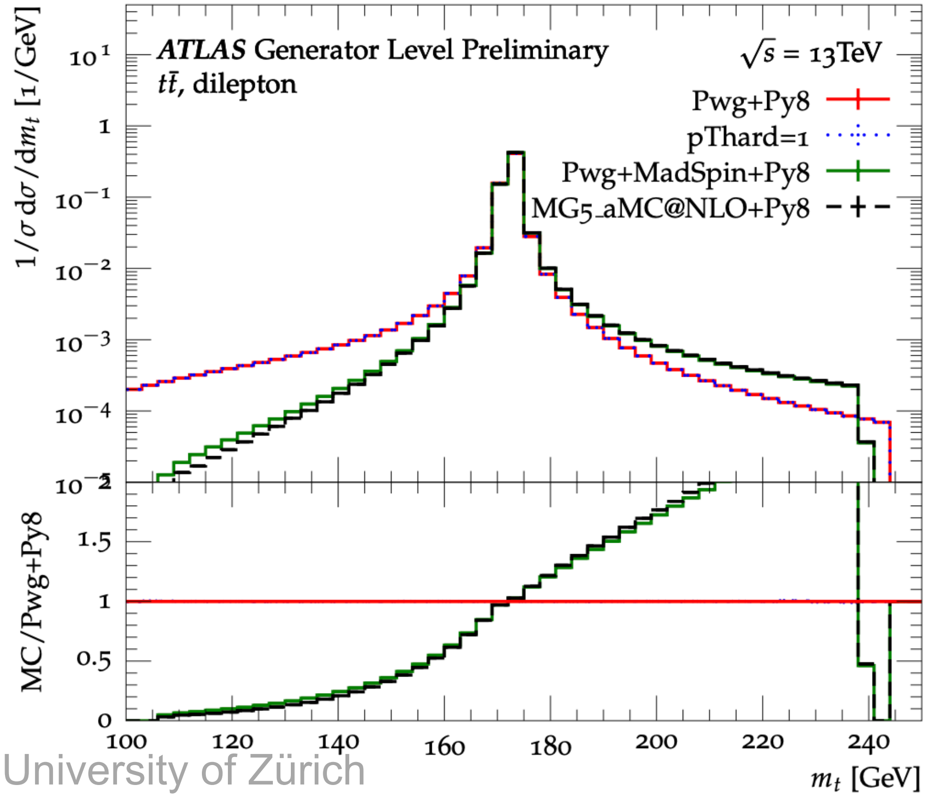
New matching uncertainty estimation strategy for top process simulation

Some effects previously covered by **PowhegBox** and **MG5_aMC@NLO** differences are not included

- Modeling of **top decay lineshape**
- Modeling of **top p_T spectrum**

→ corresponding new prescriptions for them

Similar approach in **PowhegBox** and **MG5_aMC@NLO** for top production and decay
— narrow width approximation for top production
+ smear mass by Breit-Wigner distribution
+ reshuffle momenta of other particles for energy-momentum conservation



model difference for the two generators
— **top decay lineshape** difference
→ **isolate this effect:** replace the reshuffling method of **PowhegBox** with the **MG5_aMC@NLO one (MadSpin)**

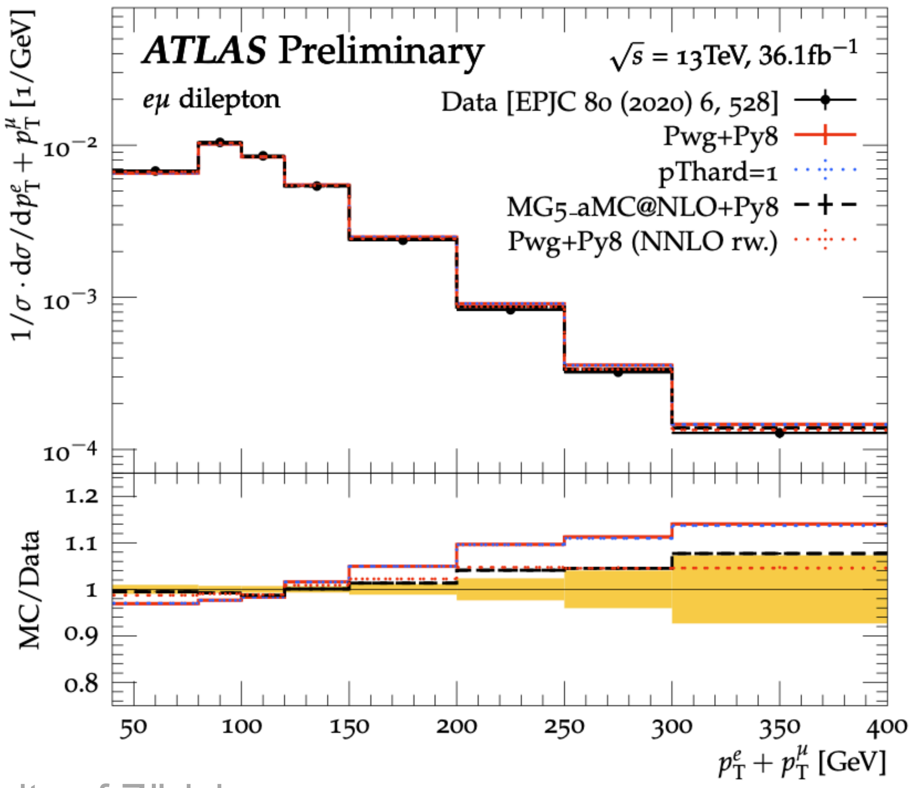
top decay lineshape difference is approximated by the **PowhegBox** and **PowhegMadSpin** difference

New matching uncertainty estimation strategy for top process simulation

Some effects previously covered by **PowhegBox** and **MG5_aMC@NLO** differences are not included

- Modeling of **top decay lineshape**
- Modeling of **top p_T spectrum**

Several **NLO+PS** generator shows **a similar trend of mismodeling**
→ Mismodeling comes from **NNLO contribution**



Solution: reweight **PowhegBox+Pythia** to NNLO calculation by $m^{t\bar{t}}$ and $p_T^{t\bar{t}}$

reweighted sample

Description to data is improved by reweighting

Summary

Non-perturbative QCD effects & modeling in pp collisions

- **Underlying event** study: **strange** hadron measurement in UE
- **Double parton scattering**: use Drell-Yan process as a standard candle to measure the extra scatter
- **Intrinsic k_T in generators:** how the parameter scales with √s and hard-scattering scale

Jets as a probe for generator models

- How the **hadron** content modeling of jets affect the **jet calibration**
- Use **jet substructure** to extract the **strong coupling constant** $\alpha_S(m_Z)$

Development of top process models

- Full **NLO simulation** of on-shell and off-shell $t\bar{t}$ at the CMS
- Adding **matrix element corrections** to improve $t\bar{t}$ simulation with MG5_aMC@NLO at the ATLAS
- Improved **matching uncertainty estimation** subscription in top processes from Powheg at the ATLAS

Studies not discussed in the talk

- Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell--Yan production in proton-proton collisions at √s = 13 TeV (CMS-SMP-20-003)
- Measurement of double-parton scattering in inclusive production of four jets with low tranverse momentum in proton-proton collisions at √s = 13 TeV (CMS-SMP-20-007)
- Study of quark and glon jet substructure in Z+jet and dijet events from pp collisions (CMS-SMP-20-010)
- Measurement of jet multiplicity and jet transverse momentum in multijet events in proton-protn collisions at √s = 13 TeV (CMS-SMP-21-006)
- Measurement of inclusive and differential cross sections for single top quark production in association with a W boson (CMS-TOP-21-010)
- Measurement of differential cross sections for the production of top quark pairs and of additional jets (CMS-TOP-20-006)
- Measurement of the top quark pole mass using pair produced top quarks (CMS-TOP-21-008)
- Measurement of the inclusive and differential ttɣ cross section (CMS-TOP-21-004)
- Measurement of the shape of the b quark fragmentation function using charmed mesons produced inside b jets from (CMS-TOP-18-012)
- Studies of Monte Carlo predictions for the $t\bar{t}b\bar{b}$ process (ATL-PHYS-PUB-2022-006)
- Measurements of observables sensitive to colour reconnection in $t\bar{t}$ events with the ATLAS detector at √s = 13 TeV (TOPQ-2019-01)
- Modelling and computational improvements to the simulation of single vector-boson plus jet processes for the ATLAS experiment (PMGR-2021-01)

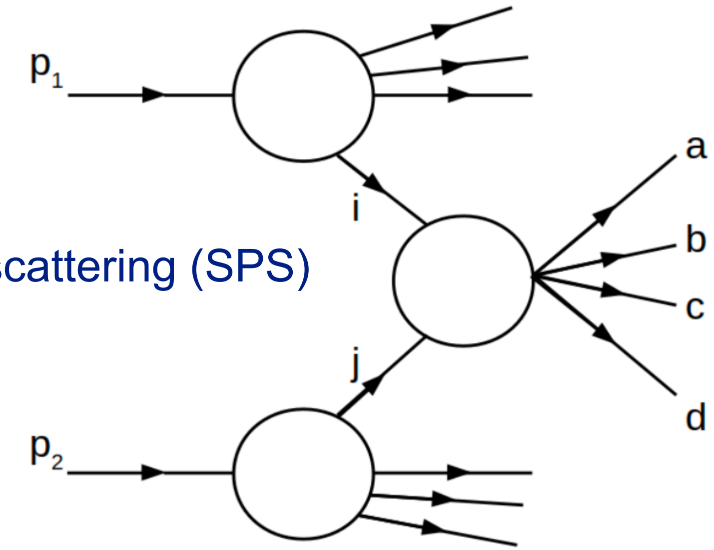
Backup

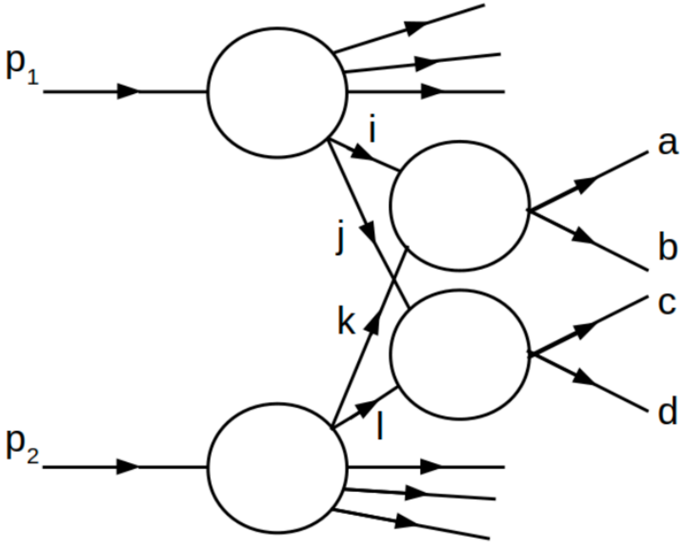
Double parton scattering in 4-jet events with low p_T

CMS-SMP-20-007

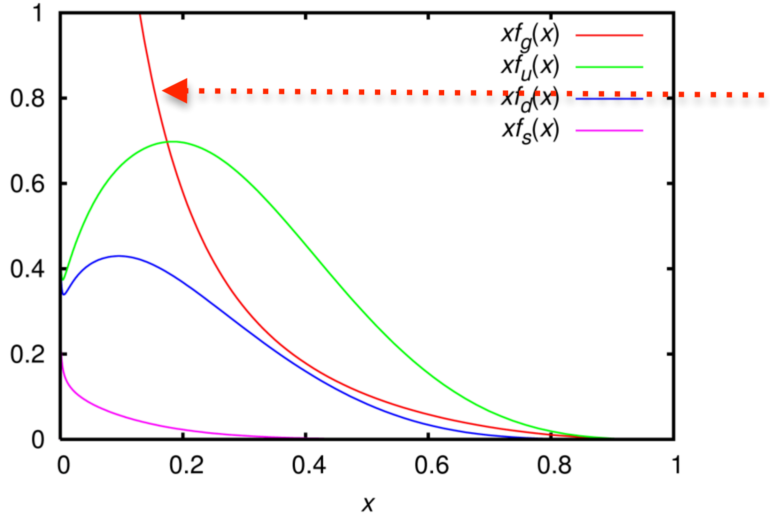
Multijet is the background for many measurements
→ important to improve the theoretical models of multijet

Single parton scattering (SPS)
→ 4 jets





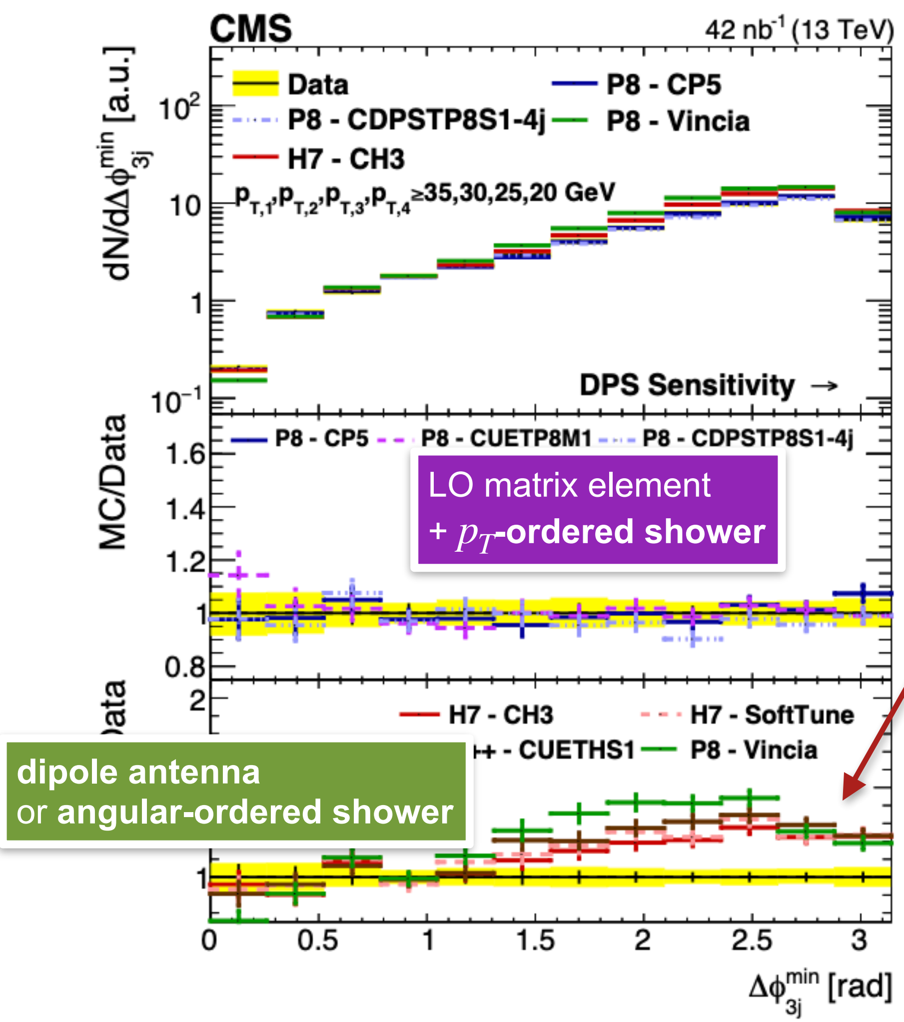
Double parton scattering (DPS)
→ 4 jets



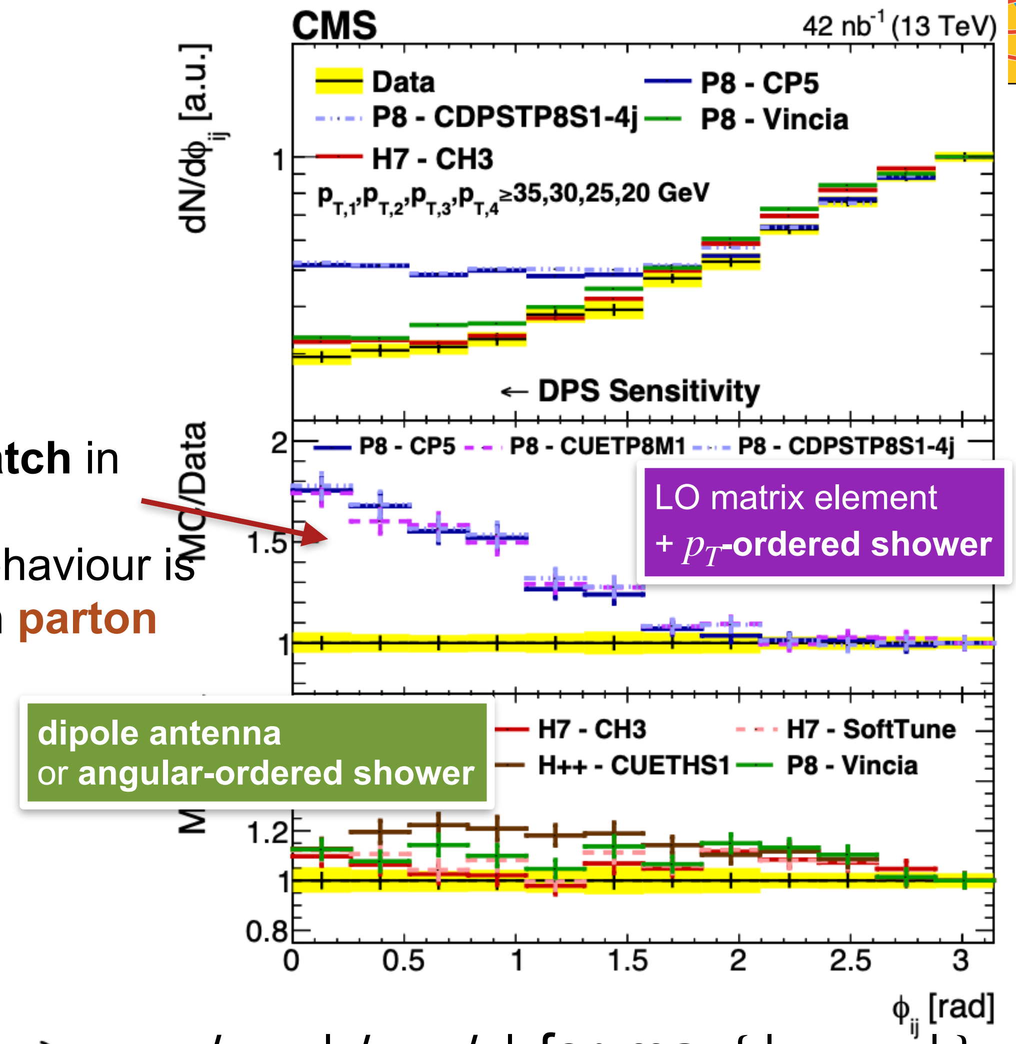
Low p_T jets probes **small momentum fraction** x of partons
→ **higher gluon density** and **higher probability of DPS**

Choose 4-jet final states with low p_T cut (35, 30, 25, 20 GeV)
→ Measure correlations of the 4 leading jet kinematics
(azimuthal angle ϕ, pseudorapidity η, transverse momentum $\vec{p}_T$)

Double parton scattering in 4-jet events with low p_T



Large MC-data mismatch in **DPS-sensitive** regions
→ However, the MC behaviour is **largely correlated** with **parton shower models**



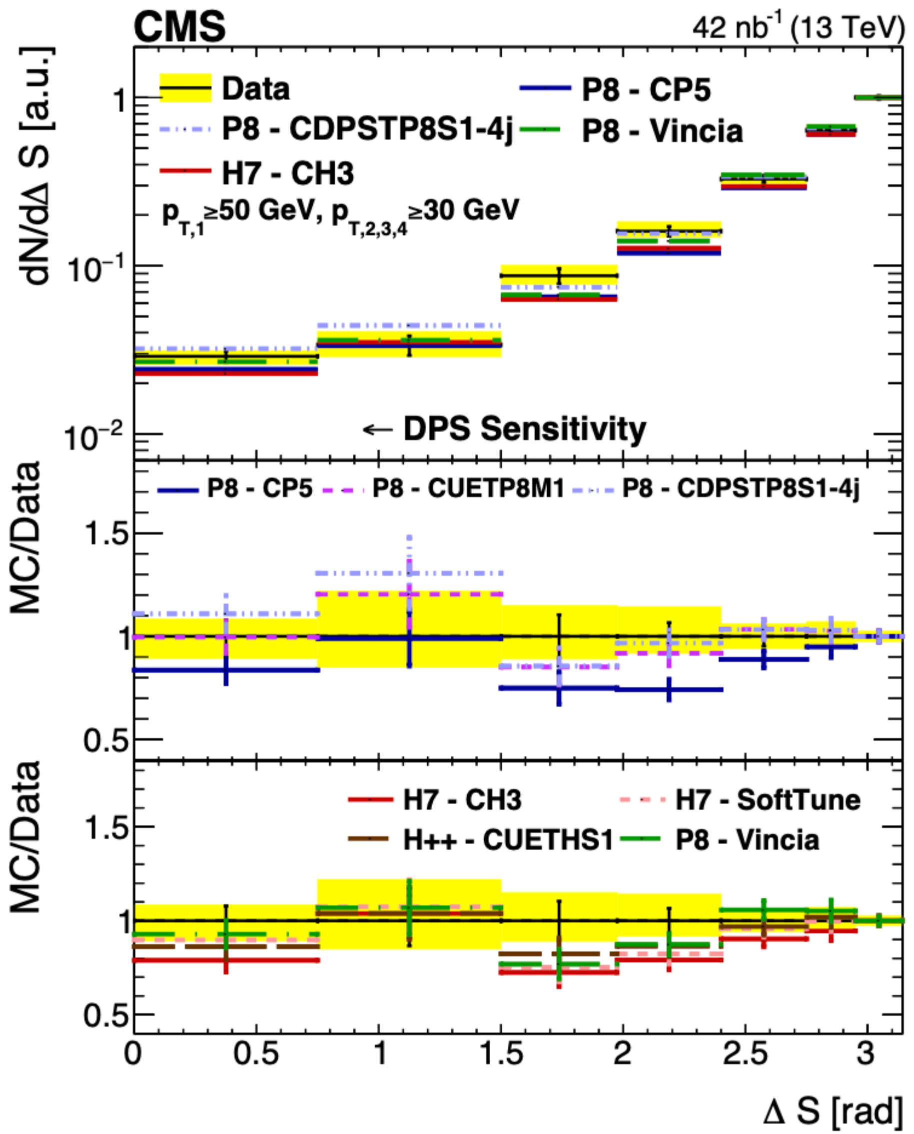
$$\Delta\phi_{3j}^{\min} = \min\left\{|\phi_i - \phi_j| + |\phi_j - \phi_k| \,\middle|\, i,j,k \in [1,2,3,4], i \neq j \neq k\right\}$$

$$\phi_{ij} = |\phi_i - \phi_j| \text{ for } \max\{|\eta_i - \eta_j|\}$$

Azimuthal angle between the jet pair with the maximum pseudorapidity separation

Normalised to DPS insensitive bins
(first 4 bins in $\Delta\phi_{3j}^{min}$ or the last bins of ϕ_{ij})

Double parton scattering in 4-jet events with low p_T



Azimuthal angular difference between the hard and soft jet pairs

$$\Delta S = \arccos\left(\frac{(\vec{p}_{T,1}+\vec{p}_{T,2})\cdot(\vec{p}_{T,3}+\vec{p}_{T,4})}{|\vec{p}_{T,1}+\vec{p}_{T,2}|\,|\vec{p}_{T,3}+\vec{p}_{T,4}|}\right)$$

← More robust MC behaviours under various shower models

Suitable for extracting the **DPS** contribution and DPS-specific tunes

Energy correlators in jets & extraction of $\alpha_S(m_Z)$

arxiv:2402.13864

Cross section of jet production

$$E2C(x_L) = \sum_{i,j} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j})$$

indices of all the hadrons

$$\Delta R_{i,j} = \sqrt{\Delta\eta_{i,j}^2 + \Delta\phi_{i,j}^2}$$

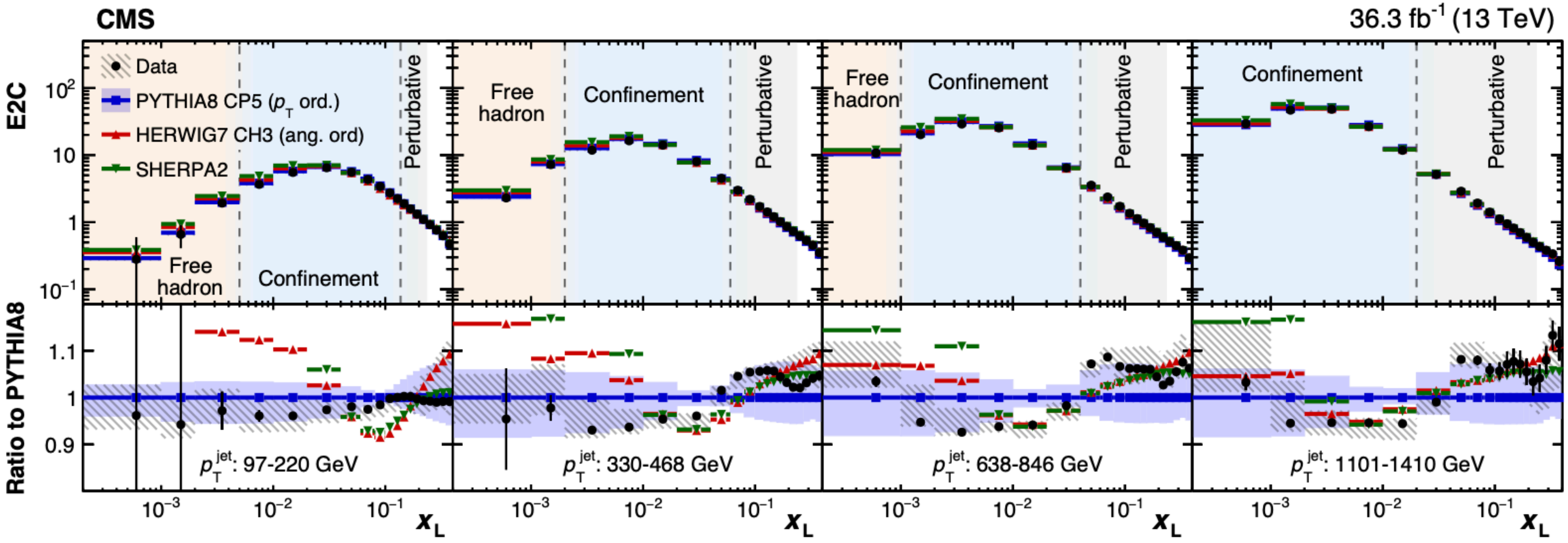
$$E3C(x_L) = \sum_{i,j,k} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k}))$$

Compute E2C and E3C for each jet

→ **Sum up for all the jets and get $E2C(x_L)$ & $E3C(x_L)$**

Weighting by energy fraction

→ **suppress impacts of soft radiaions**

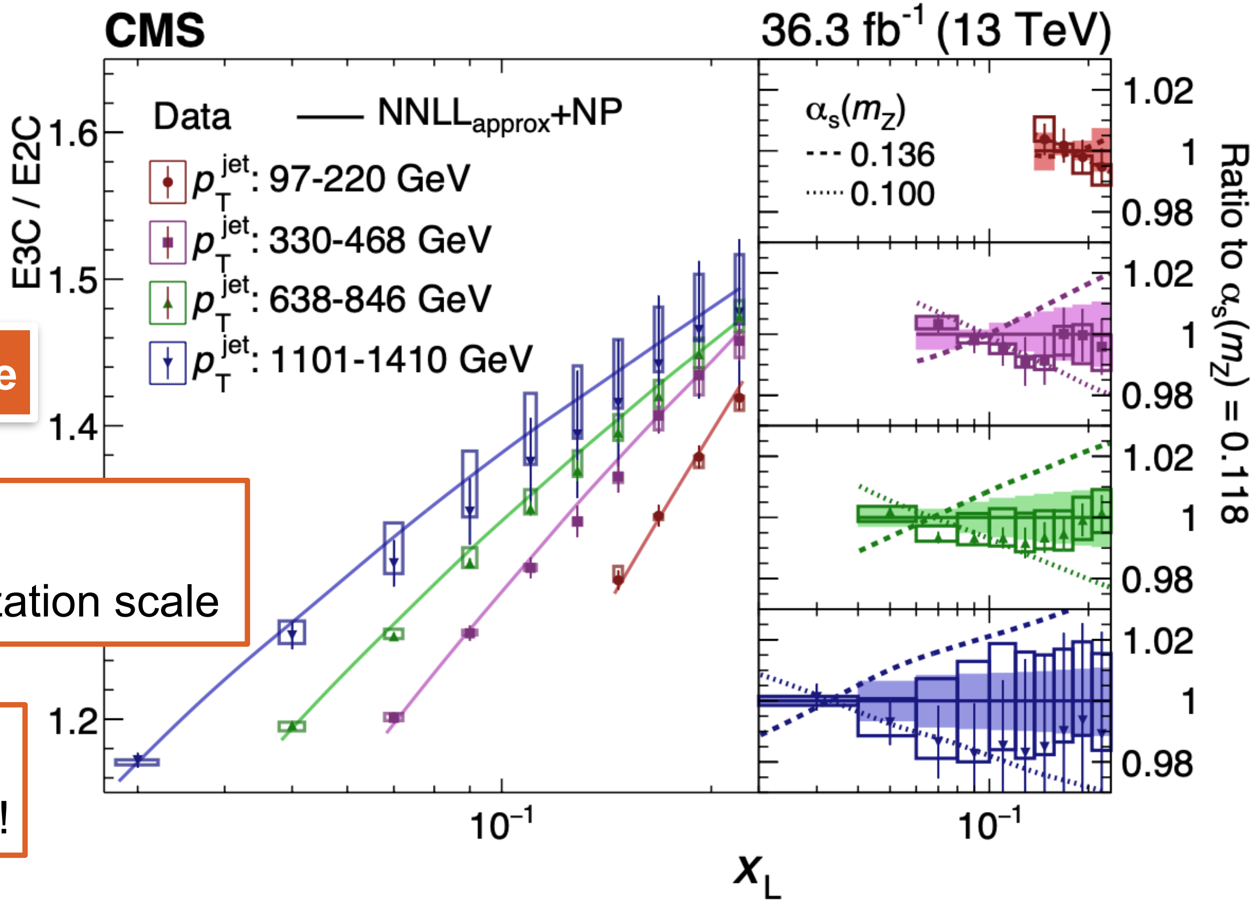


Energy correlators in jets & extraction of $\alpha_S(m_Z)$

Take $E3C/E2C(x_L)$ ratio
→ non-perturbative effects are suppressed

Theoretical prediction
$E3C/E2C \simeq \alpha_S ln x_L$

α_S is approximately the **slope**



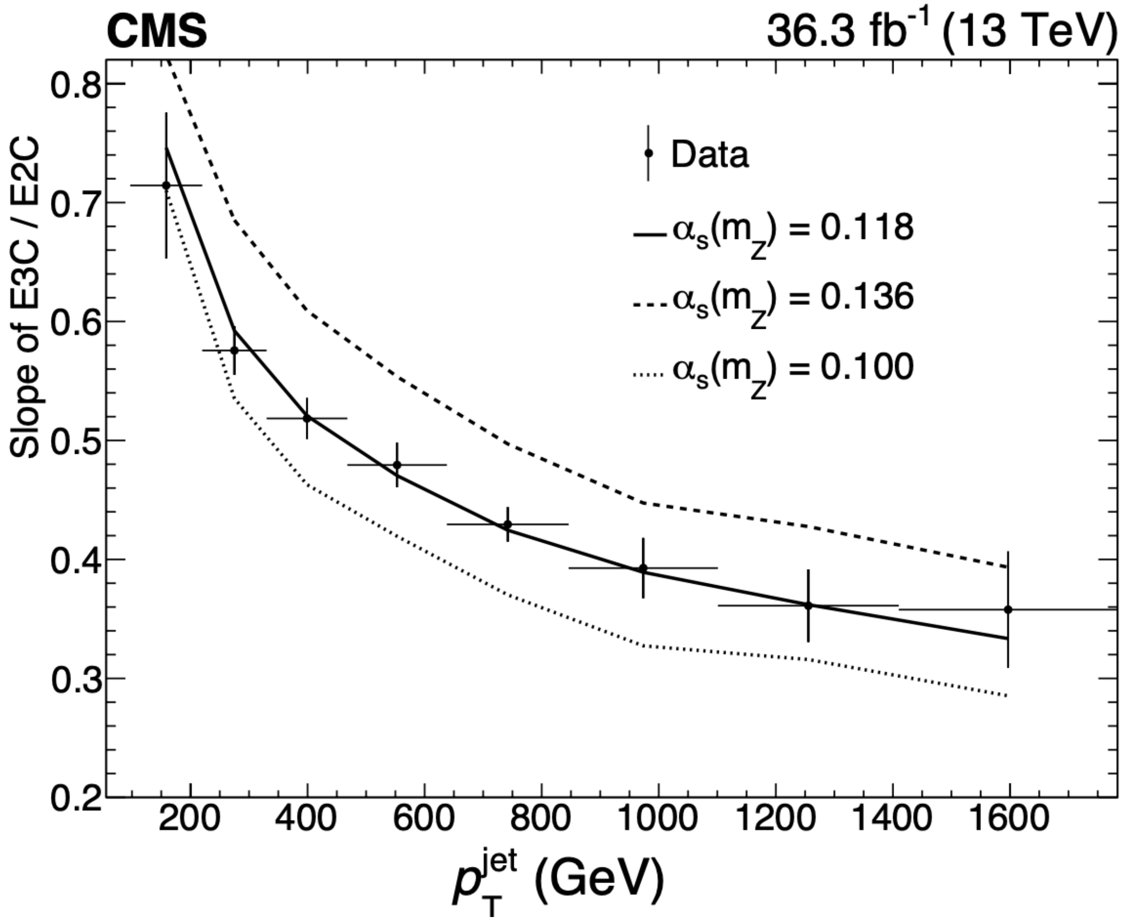
MC/data
with different $\alpha_S(m_Z)$
assumptions

Template fit to extract $\alpha_S(m_Z)$

Slope variation versus p_T^{jet}
→ running α_S with renormalization scale

Smaller slope for larger p_T^{jet}
→ QCD asymptotic freedom!

Energy correlators in jets & extraction of $\alpha_S(m_Z)$



Measure the E3C/E2C versus x_L slope at various p_T^{jet}

Generate MC predictions from various $\alpha_S(m_Z)$
→ Interpolate

Fit MC templates to data
→ measured $\alpha_S(m_Z)$

$$0.1229^{+0.0014}_{-0.0012}\,(\text{stat})^{+0.0030}_{-0.0033}\,(\text{theo})^{+0.0023}_{-0.0036}\,(\text{exp})$$

Most precise $\alpha_S(m_Z)$ from jet substructures