R. Delaunay, Circular Forms (c) Solomon R. Guggenheim Museum

Exploring top events with fine-grained probes @CMS

P. Ferreira da Silva (CERN) *for the CMS Collaboration*

LHCtopWG public meeting 16th May 2018

Motivation

- **High statistics top sample in Run 2 as a unique opportunity to**
  - search for rare processes in phase spaces where tt is less well modelled - e.g. 4 tops, s-channel,…
  - refine and improve precision measurements ($d\sigma_{tt}/dX$, α_S, m_t, Γ_t, …)
- **Usage of NLO + Parton Shower to calibrate analyses is ubiquitous**
  - overall good agreement in rate and shape but some challenges - e.g. simultaneous $p_T(t)$ and M(tt)

p-val for $d\sigma_{parton}/dX$	$p_T(t_h)$	M(tt)
Powheg+PY8	0.02 (0.2)	0.31 (0.66)
aMC@NLO+PY8	0.53	0.28
Powheg+HW++	0.96	0.94
NNLO QCD + NLO EW	0.95	<0.01

arXiv:1805.01428

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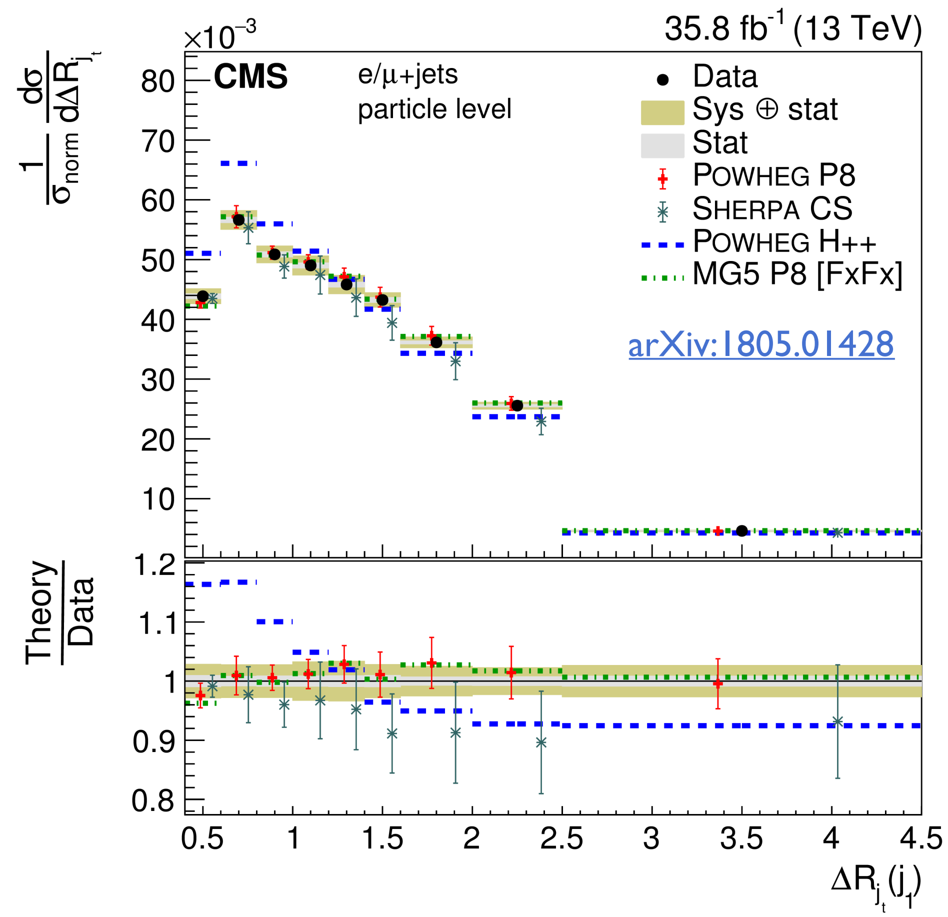

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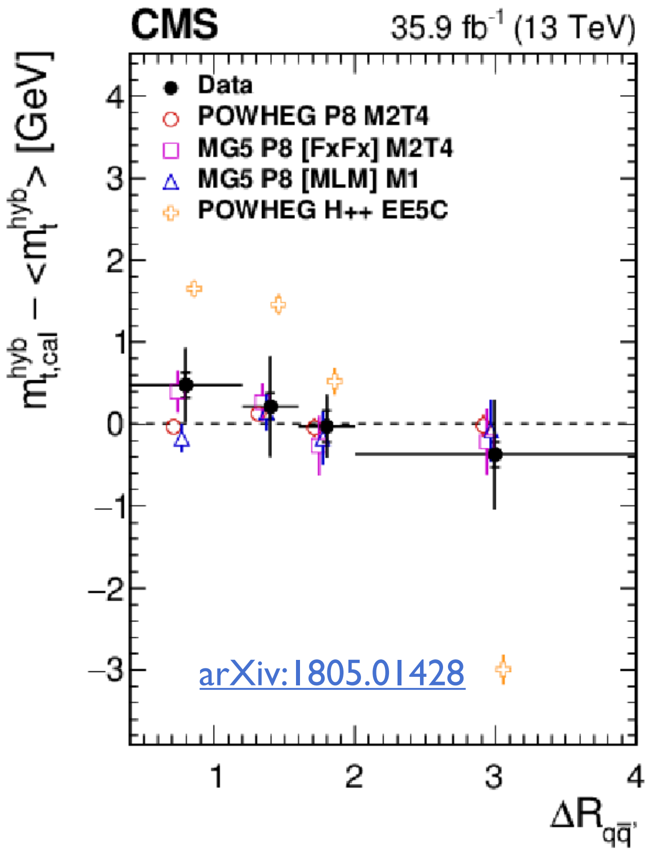
  - ISR/FSR and non perturbative-effects are often limiting factors already - e.g. ttHbb, m_t

	Model	$\delta m_t / m_t$ [%]	δm_t /Total unc.[%]
Run I arXiv:1805.01428	CR{on,off} Pythia6	<0.01	2%
Run II arXiv:1509.04044	{QCD, gluon,MPI}-based Pythia8	0.18	50%



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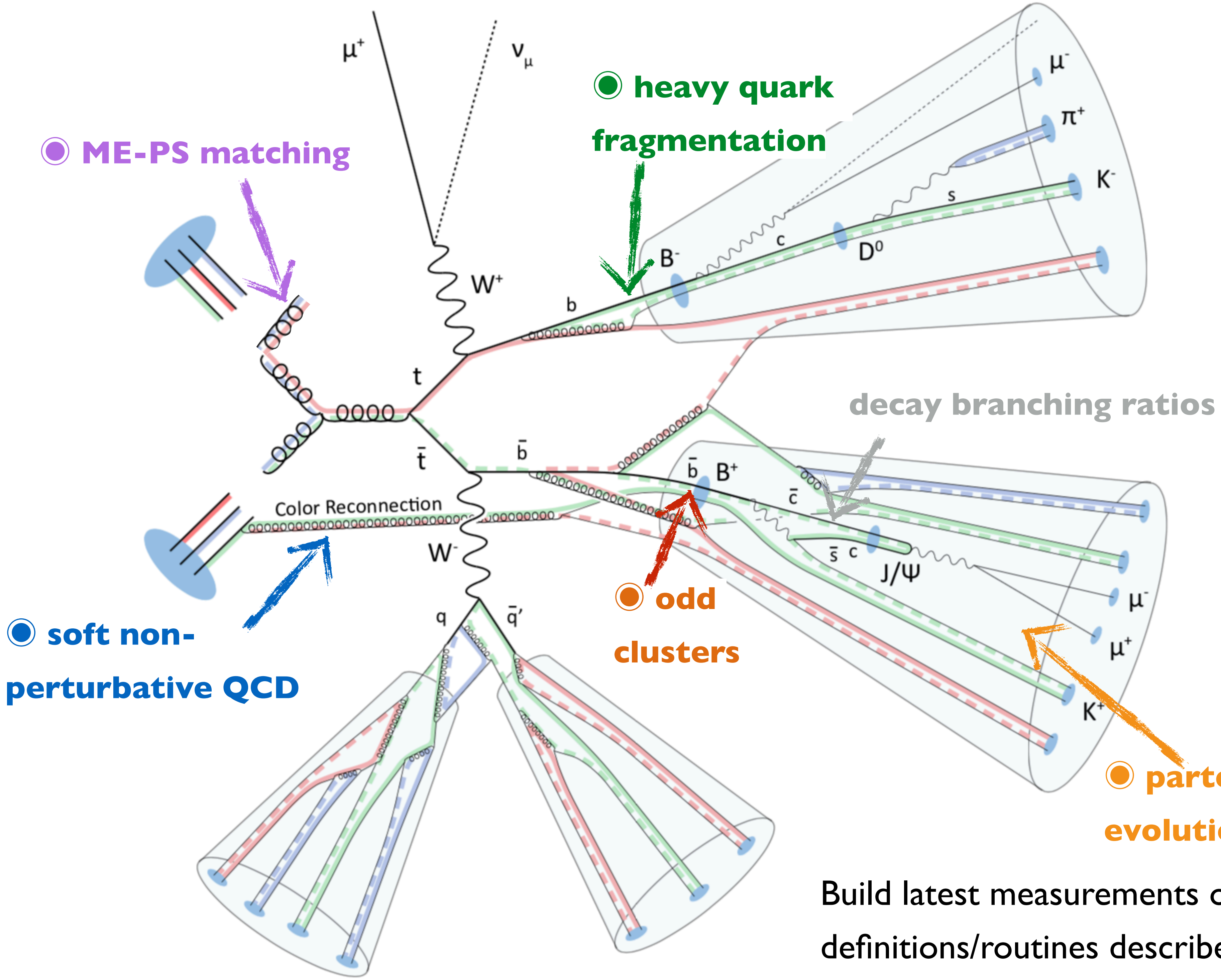
- **Improvements with respect to where we stand are possible**
  - delegate to in-situ constraints, tune from ancillary measurements…
  - in both cases: is our prescription for systematic assessment providing the correct coverage?

Strategy to improve top modelling at CMS

- Each stage of the event modelled by multi-purpose generators/specialised tools
- Specific measurements target improving these tools for improved measurements

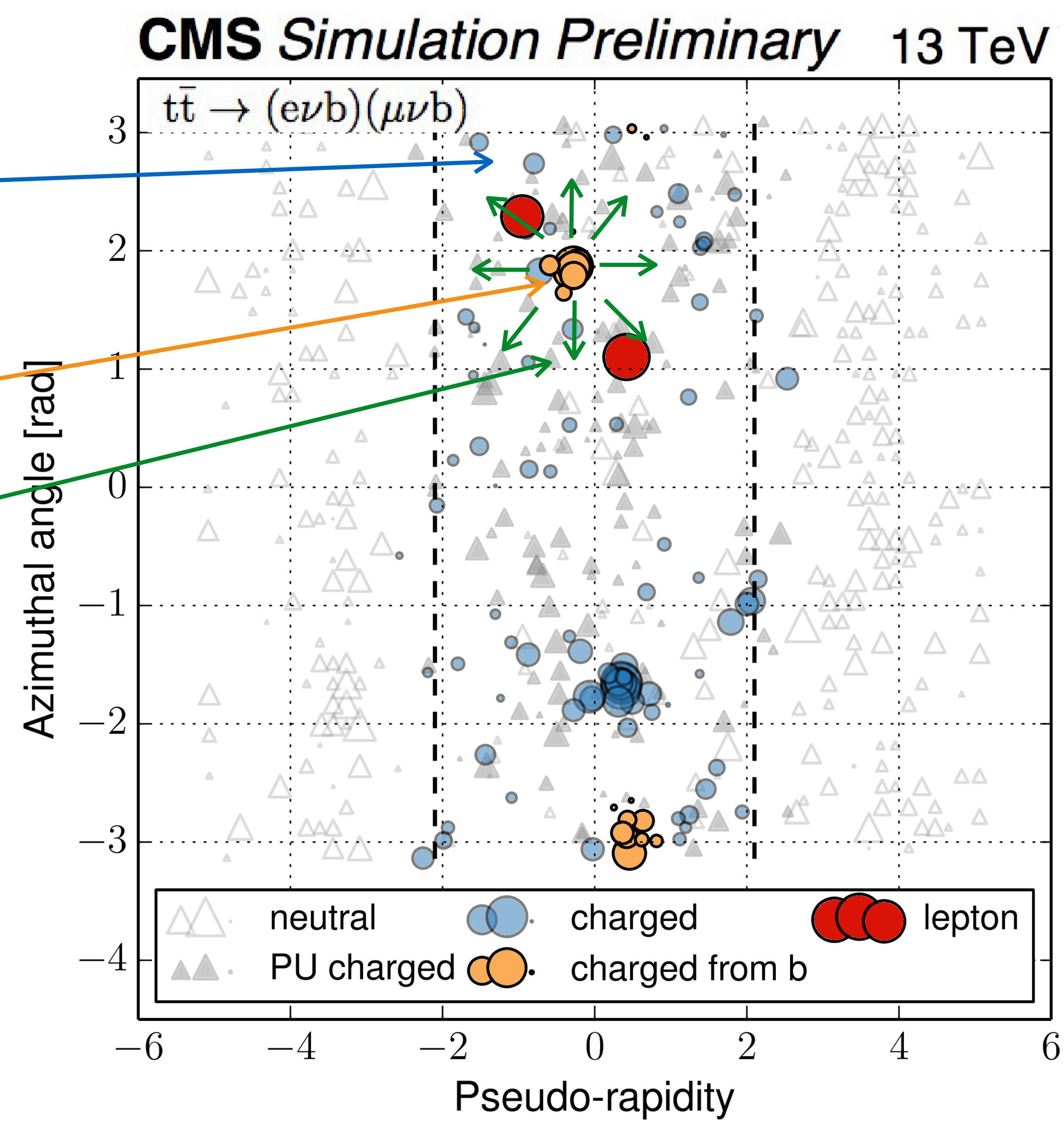


arXiv:1603.06536	heavy quark fragmentation
TOP-15-017	soft non-perturbative QCD, odd clusters
TOP-13-007	soft non-perturbative QCD, odd clusters
→ TOP-17-015	soft non-perturbative QCD, odd clusters
TOP-15-021	ME-PS matching
TOP-16-021	parton shower evolution
arXiv:1510.03072	parton shower evolution, heavy quark fragmentation
arXiv:1705.10141	parton shower evolution, heavy quark fragmentation
arXiv:1805.01428	parton shower evolution
arXiv:1803.03991	parton shower evolution
→ TOP-17-013	parton shower evolution

Build latest measurements on top of RIVET-based particle-level definitions/routines described in CMS-NOTE-TOP-2017-004

Charged particle-based analyses

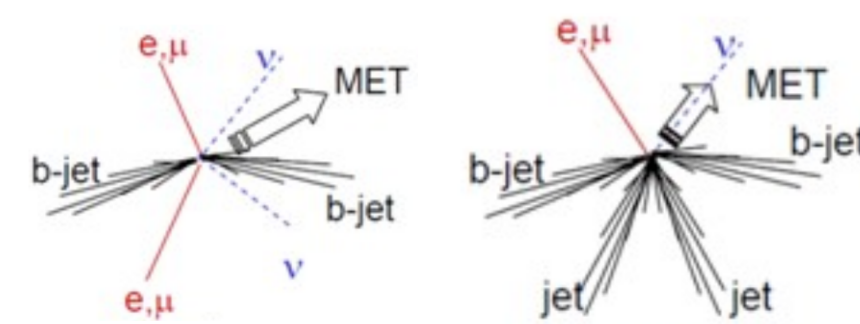
- Fine-grained probes for
  - what's produced in association with tops (underlying event, extra jets, hadronization)
  - the constituents of top quark hadronic decays (fragmentation/hadronization)
  - how do the two relate to each other (e.g. colour reconnection)



- Pileup in Run 2 is the main challenge
  - vertex association easy with geometric cuts (Δz proximity) for tracks (=charged particles)
  - neutrals are harder to associate (dilute significantly resolutions)

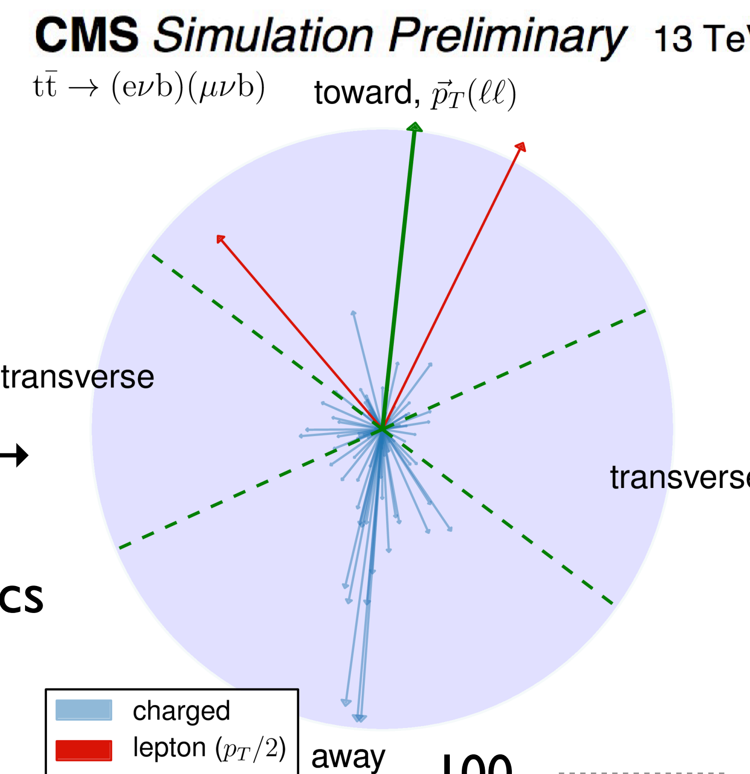
Experimental strategy

- **Use the dilepton and single lepton channels**
  - ≧2 b-tagged (ε_b~68%) jets in both cases
  - >90% purity (main background being tW in both cases)
  - use particle flow to associate charged particles to objects in the event

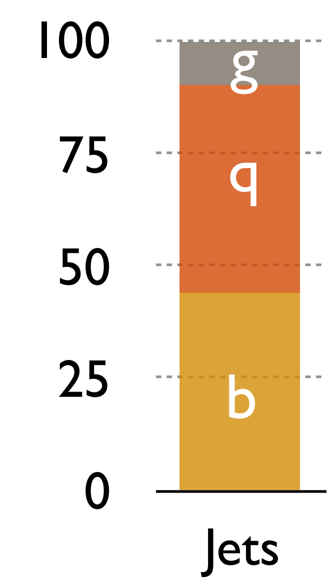


- **Dilepton channel is used for the UE studies (TOP-17-015)**
  - define UE as all charged particles not associated to b jets and leptons →
  - probe UE evolution as function of jet multiplicity and dilepton kinematics

    $p_T(\ell\ell) \propto p_T(tt)$ $m(\ell\ell) \propto Q^2$



- **Single lepton channel is used for the study of jet shapes (TOP-17-013)**
  - use probe the different jet flavour modelling with sub-structure variables
  - use b-tagging ($|M_W-M_{jj}|$<15 GeV) to define b- (quark-) enriched regions →

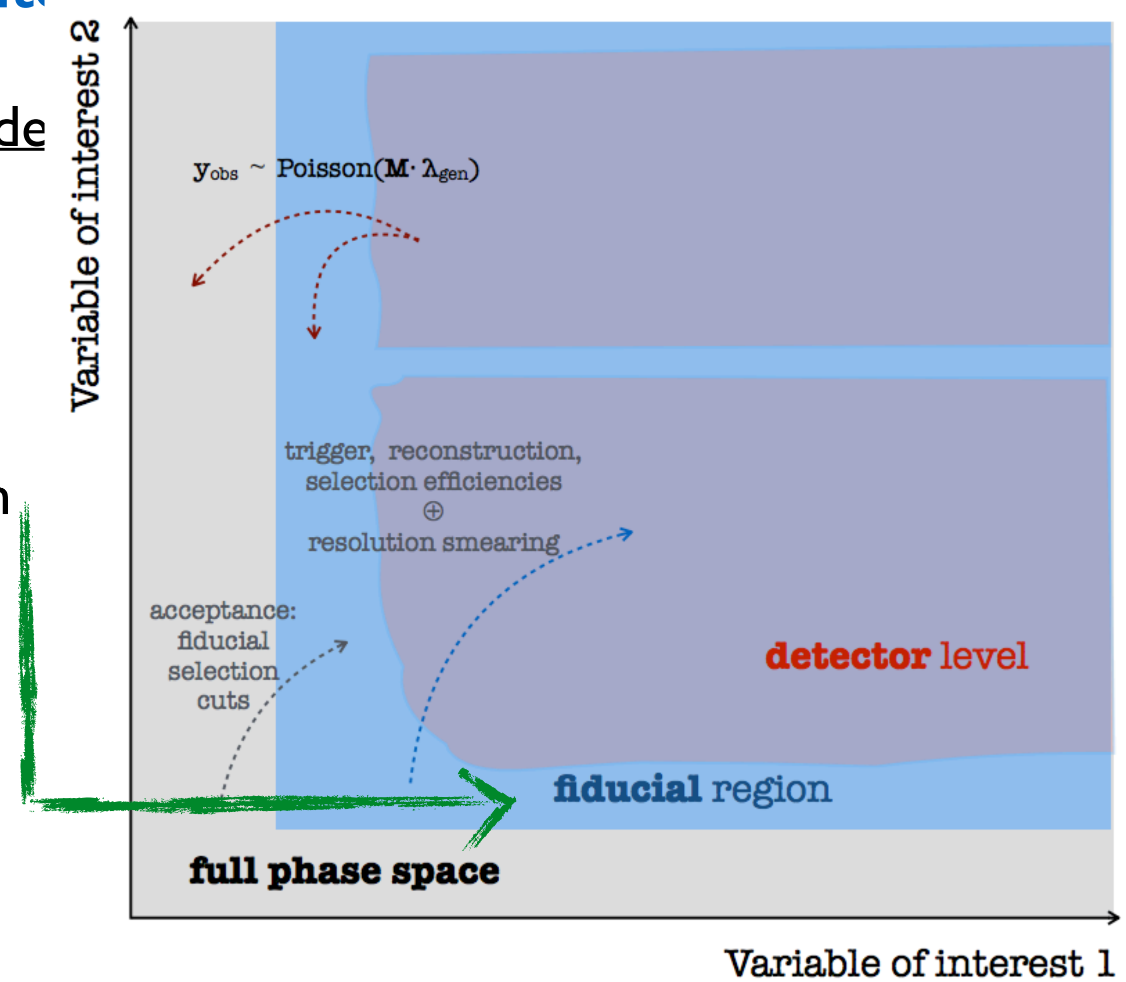


Particle level definitions

- **Both analyses measure normalised differential cross sections at particle level**
  - No access to quarks and gluons, only hadrons and leptons
  - "Dressed" leptons: cluster lepton with surrounding FSR photons
  - "Ghost" tagging for bottom quark jets

- **Definitions and routines based on RIVET code (integrated in CMS software)**
  - following CMS-NOTE-TOP-2017-004 (see also M. Seide

- **Unfolding procedure**
  - use fiducial region definitions close to offline selection
  - ensure high purity/stability in migration matrices
  - very mild (Thikonov) or no regularisation used at all



Monte-Carlo simulations

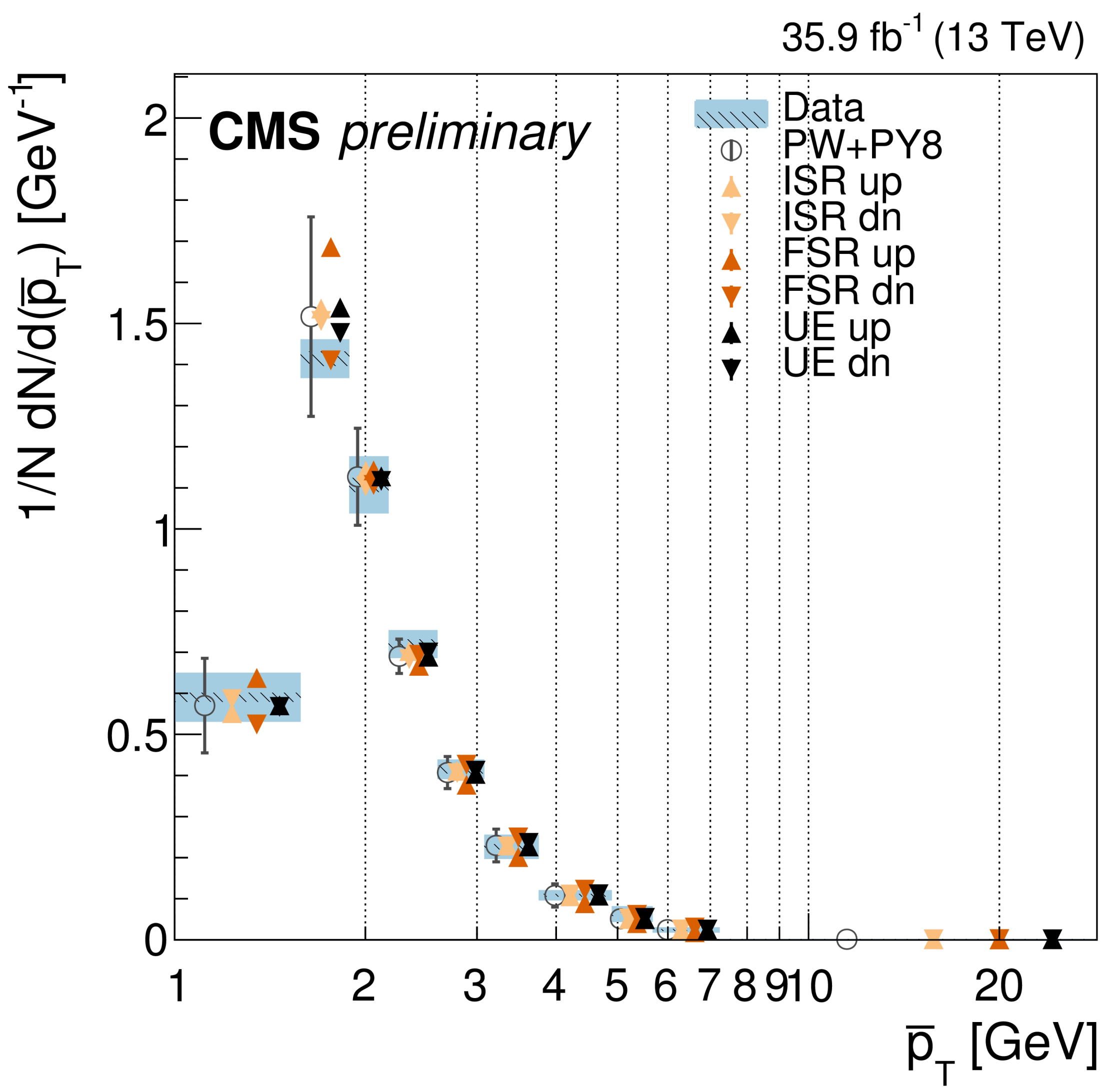
- **Extensive test of different simulations**
  - different matrix element generators (MG5_aMC@NLO, Sherpa)
  - different parton showers (HW++, HW7, Sherpa, DIRE NLO)
  - several variations of the baseline Powheg+Pythia8 (ISR, FSR, Colour Reconnection, MPI - see backup)

Event generator	**POWHEG (v2)**	**MG5_aMC@NLO**	**SHERPA 2.2.4**
		Matrix element characteristics	
Mode	hvq	FxFx Merging	OPENLOOPS
QCD scales (μ_R,μ_F)	m_T^t	$\sum_{t,\bar{t}} m_T/2$	
α_S	0.118	0.118	0.118
PDF	NNPDF3.0 NLO	NNPDF3.0 NLO	NNPDF3.0 NNLO
pQCD accuracy	$t\bar{t}$ [NLO] 1 jet [LO]	$t\bar{t}$ +0,1,2 jets [NLO] 3 jets [LO]	$t\bar{t}$ [NLO]
		Parton shower	
Setup designation	PW+PY8	aMC@NLO+PY8	SHERPA
PS	PYTHIA 8.219	PYTHIA 8.219	CS
Tune(s)	CUETP8M2T4	CUETP8M2T4	default
PDF	NNPDF2.3 LO	NNPDF2.3 LO	NNPDF3.0 NNLO
(α_S^{ISR}, α_S^{FSR})	(0.1108,0.1365)	(0.1108,0.1365)	(0.118,0.118)
ME Corrections	on	on	n/a
Setup designation	PW+HW++	PW+HW7	
PS	HERWIG++	HERWIG 7	
Tune(s)	EE5C	Default	
PDF	CTEQ6L1	MMHT2014lo68cl	
(α_S^{ISR}, α_S^{FSR})	(0.1262,0.1262)	(0.1262,0.1262)	
ME Corrections	off	on	

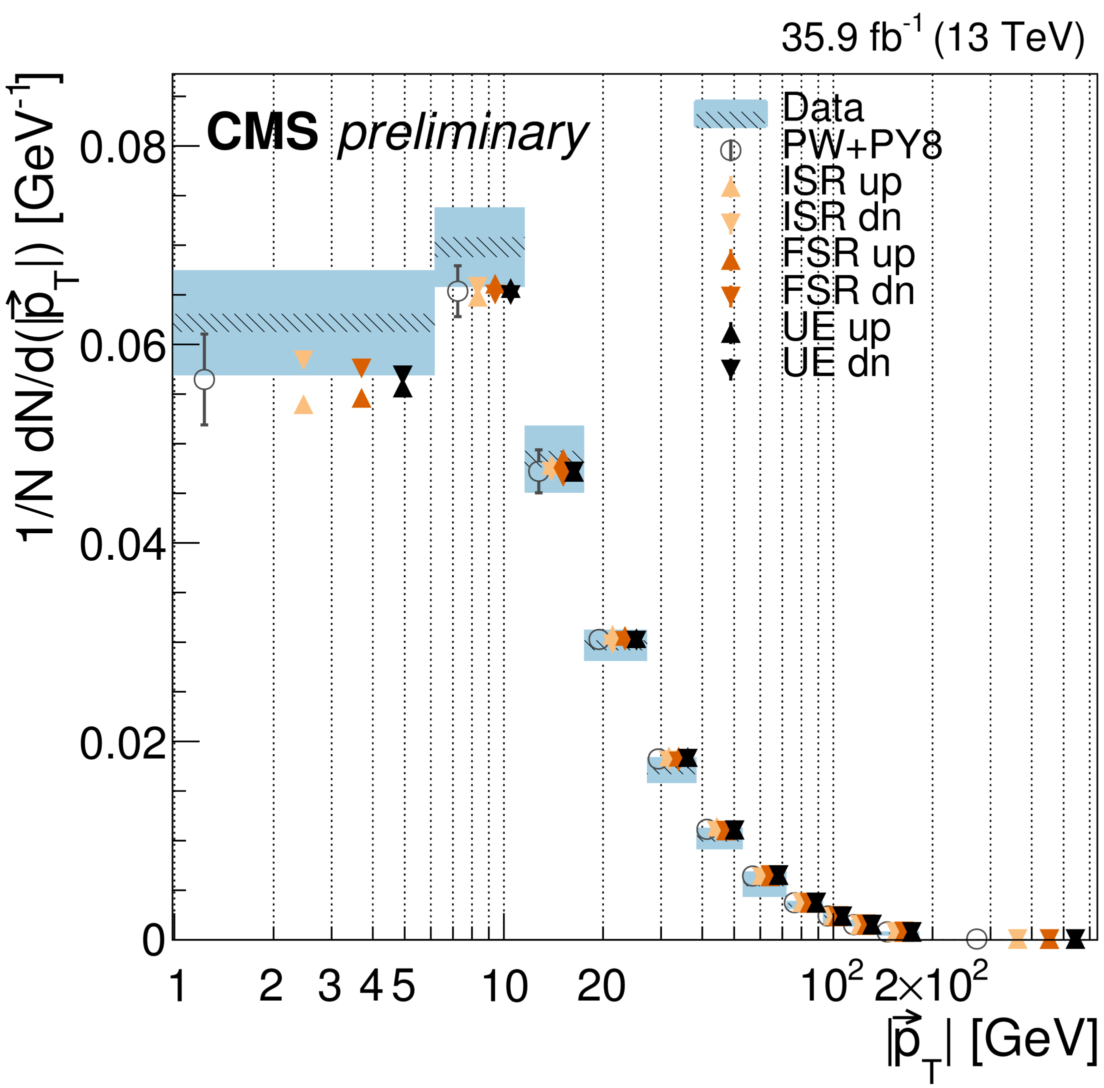
Characterisation of the recoil of the tt system I TOP-17-015

- **We count additional particles with respect to the tt decay products**
  - typically ~20 particles per event with <p_T>~1.5-2.0 GeV and <p_Z>~2.5-3.0 GeV
  - charged component of the tt recoil has typically $|p_T|$~10 GeV

<p_T> has sensitivity to α_S(FSR)
data prefers lower α_S(FSR)



$|p_T|$ is robust against different variations
(expected from momentum conservation)



Characterisation of the recoil of the tt system II

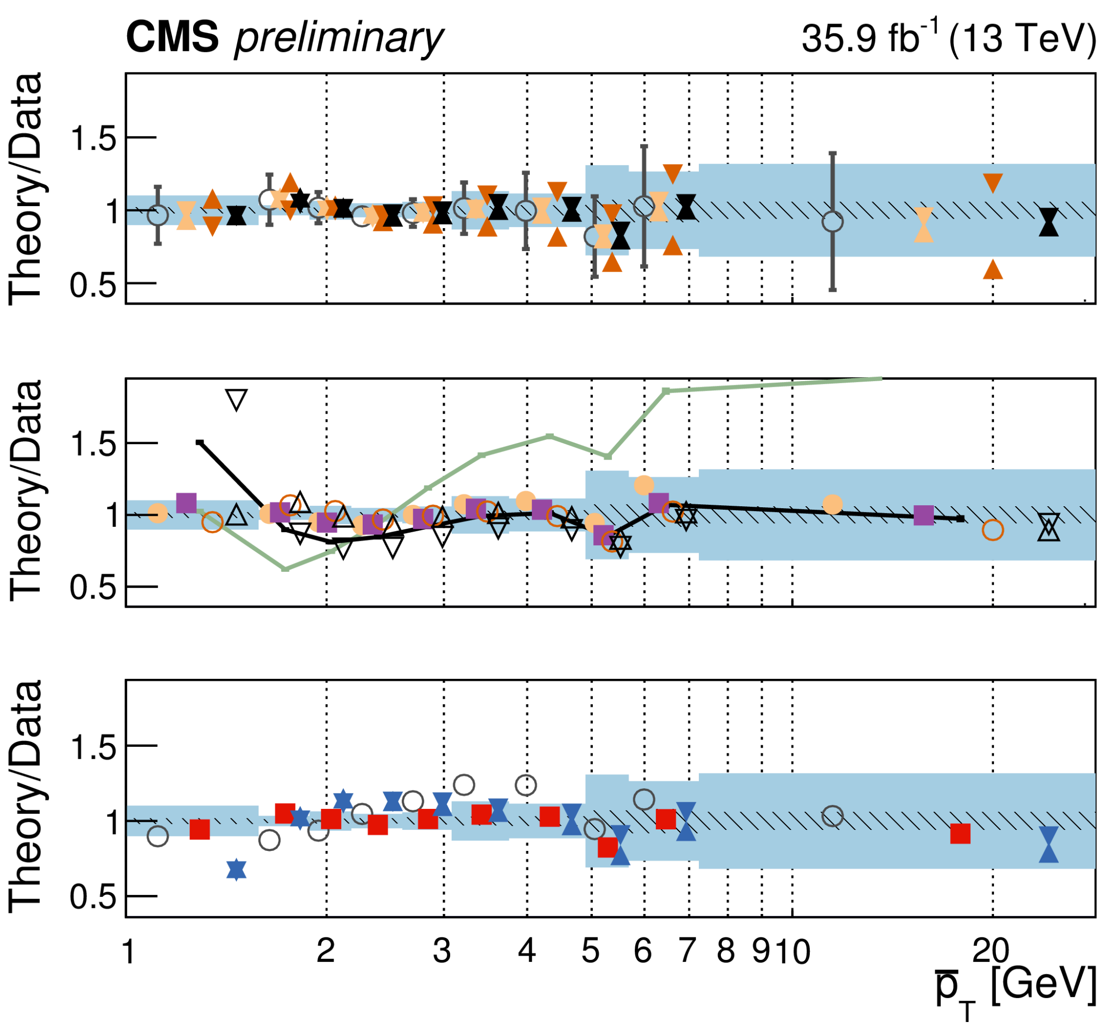
- **Agreement with baseline Powheg+Pythia8**
  - Powheg ↔ MG5_aMC@NLO has small impact
  - disagreement with Sherpa or PW+HW++/HW7

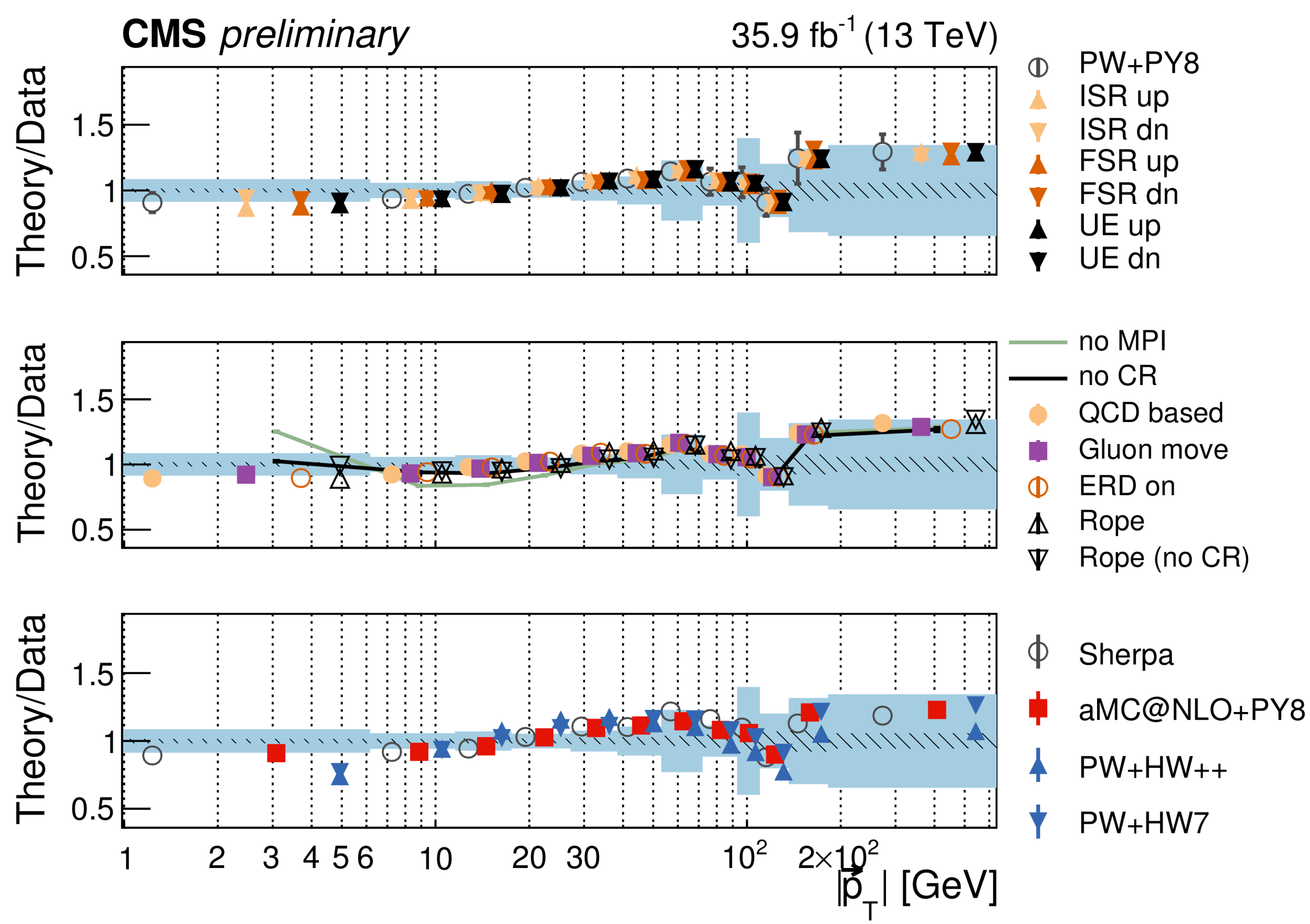
MC setup χ^2/dof

	PW PY8	MG5_aMC@NLO PY8	PW HW++	PW HW7	Sherpa
$\langle p_T \rangle$	12/9 (1/9)	6/9	40/9	56/9	38/9
$\lvert p_T \rvert$	17/11 (7/11)	20/11	102/11	49/11	33/11

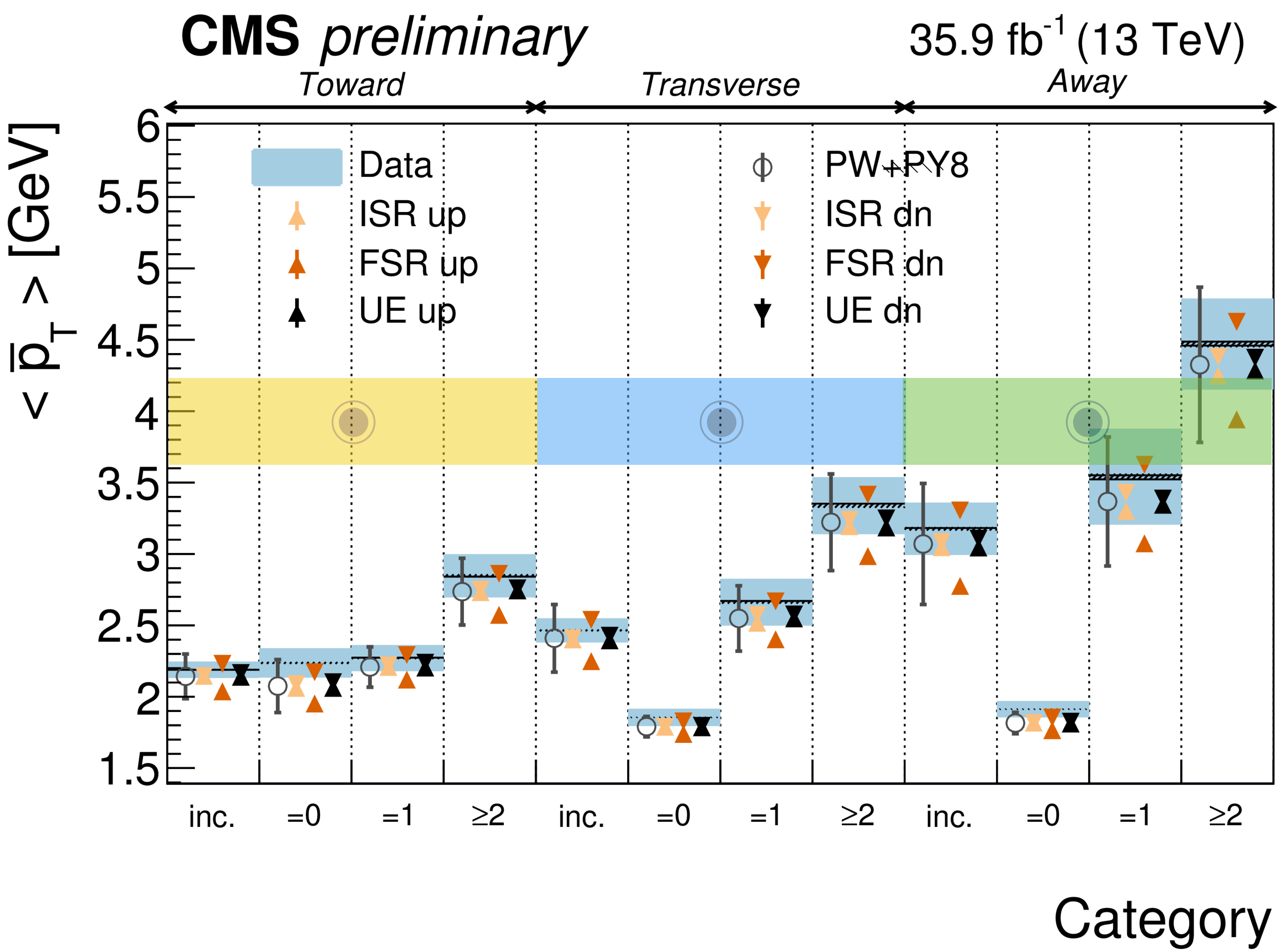
$\langle p_T \rangle$ has sensitivity to α_S(FSR), MPI and CR
data prefers lower α_S(FSR) and needs MPI+CR

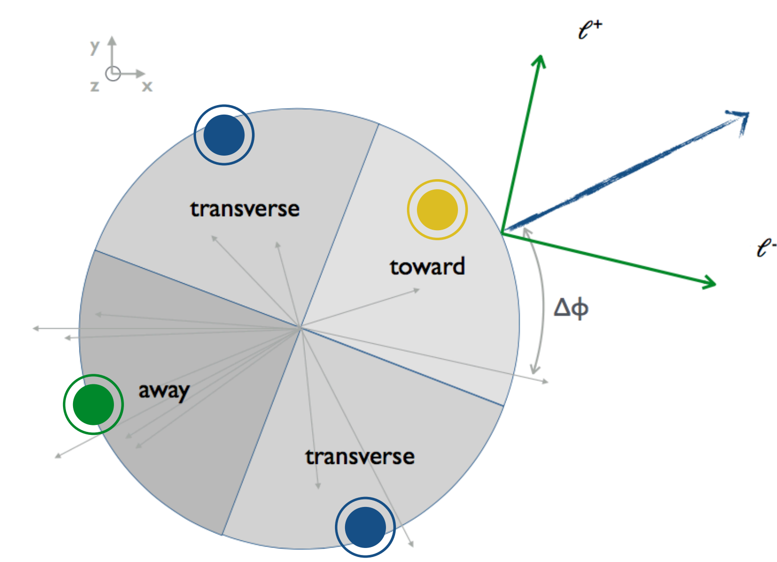
$\lvert p_T \rvert$ is robust against different variations
(expected from momentum conservation)





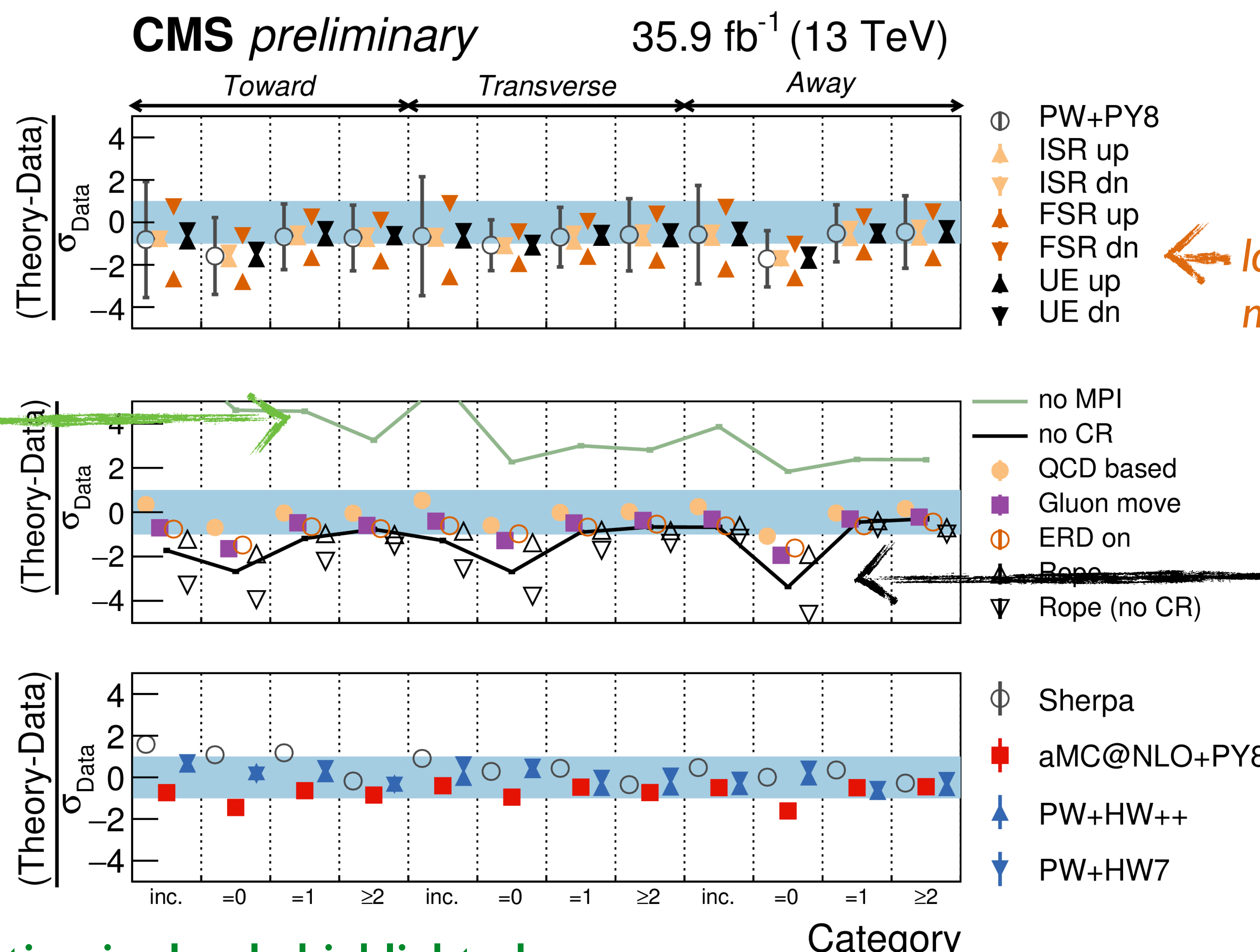
Evolution of the recoil I





- **Additional jet multiplicity clearly boosting particles in the UE in all regions**
    - total uncertainty in Powheg+Pythia8 always covers (residual) difference to data
- **Little or no dependency as function of pT($\ell\ell$) and m($\ell\ell$)**

Evolution of the recoil II

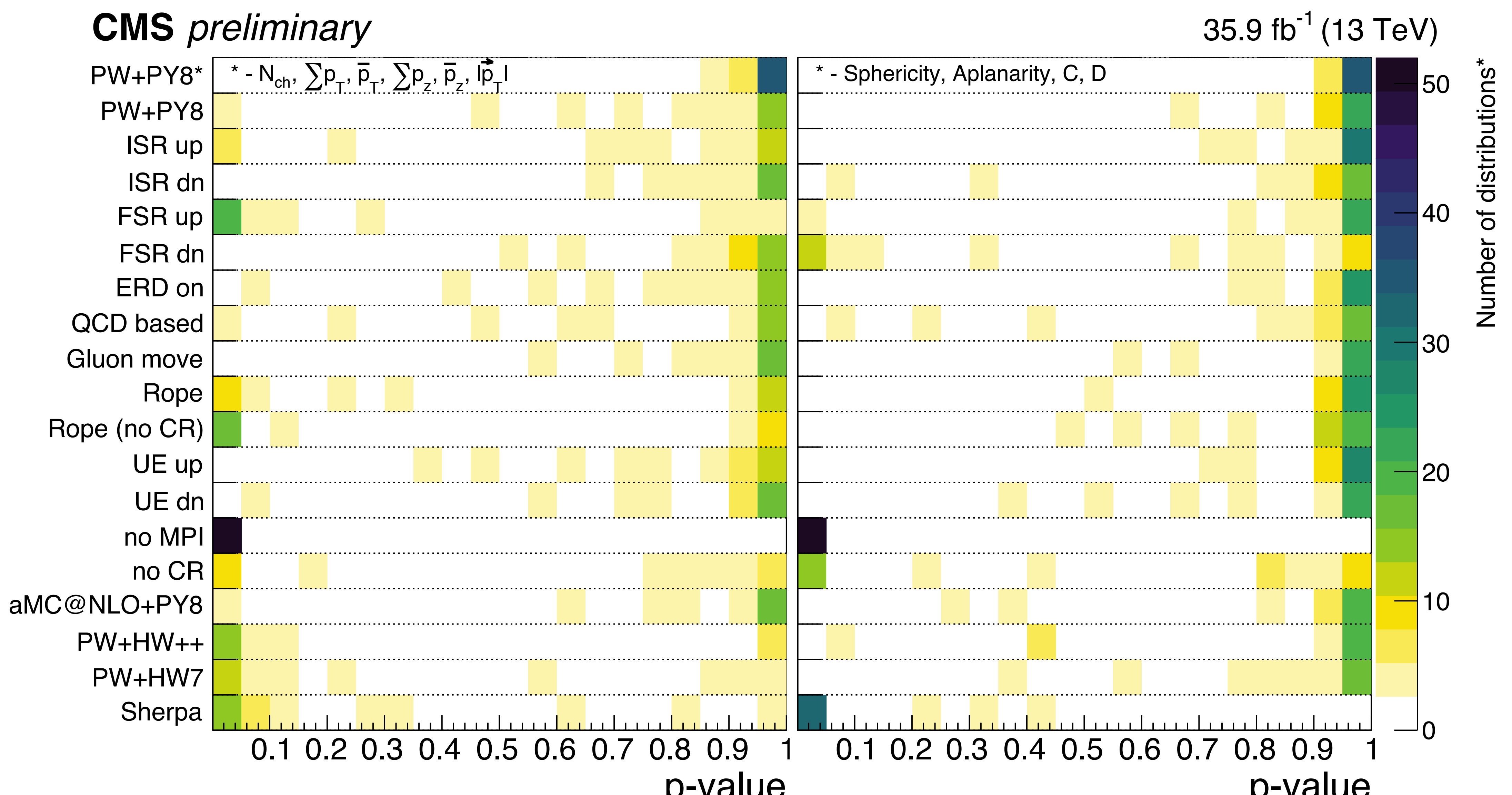


lower α_S(FSR) needed in all categories

- **MPI contribution is clearly highlighted**
  - expected as smaller scale distances probed in tt wrt to min. bias or Drell-Yan
- **Colour reconnection is crucial in events with no addition jet (p_T>30 GeV)**
  - small but visible differences between QCD, gluon move and rope models

Grand-summary

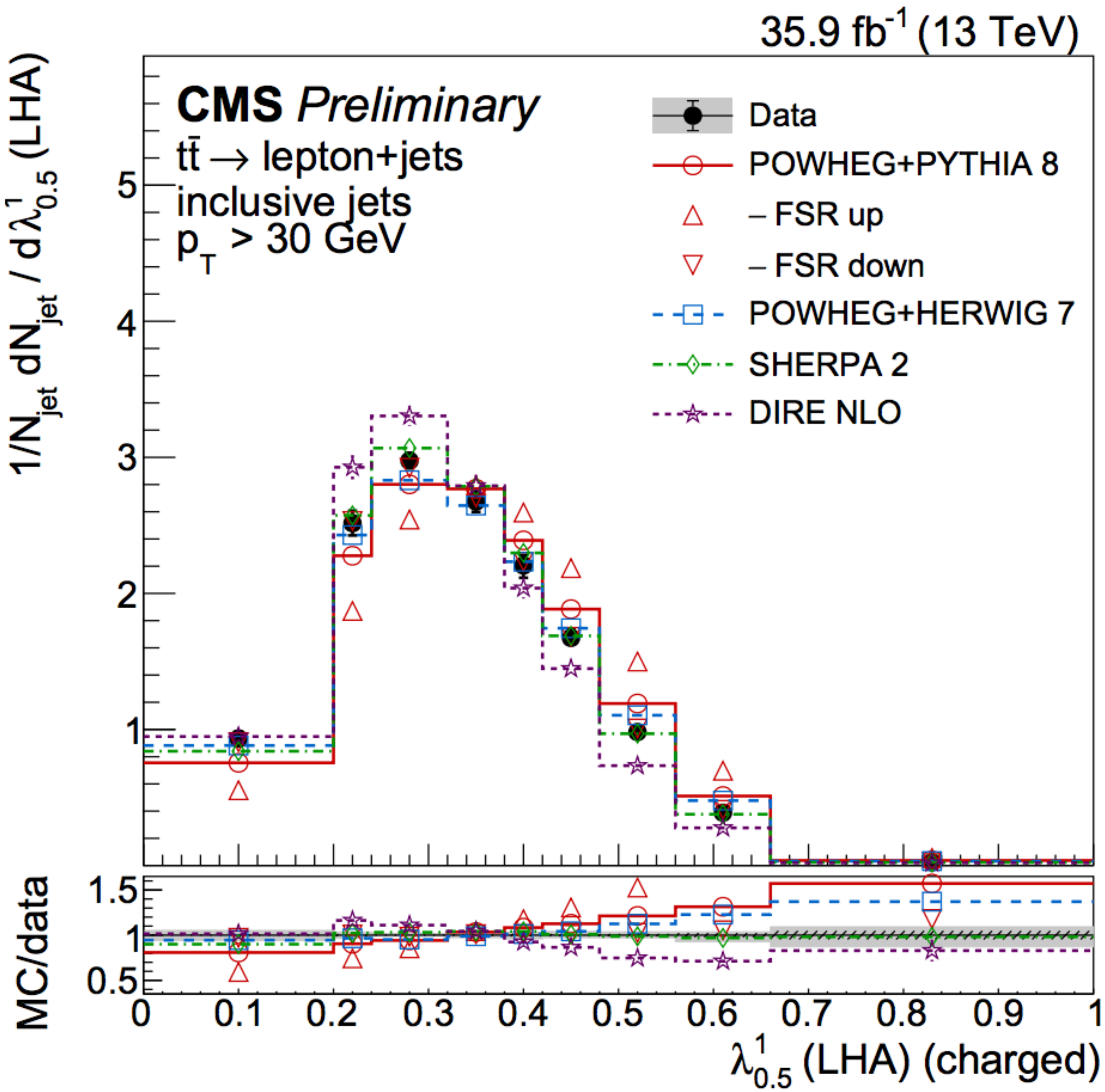
- **>200 distributions analysed in different categories**
  - general good agreement for baseline Powheg+Pythia8 with systematics p-val>0.8 for all
    ⇒ conservative uncertainty prescription? space to improve (see slide 17)
  - Herwig disagrees in flux-related variables / Sherpa disagrees in both flux and event shapes



Generalised jet shape angularities

- **In general sensitive to jet flavour, FSR**
  - but also npQCD effects and parton shower model

    (in general k≠1 are IRC-unsafe, e.g. λ^0_0=multiplicity)

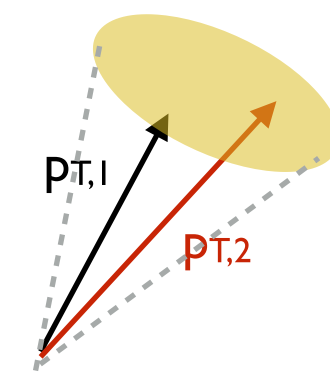


arXiv:1408.3122

$$\lambda^{\kappa}_{\beta} = \sum_i z_i^{\kappa} \left(\frac{\Delta R\,(i, \hat{n}_r)}{R} \right)^{\beta}$$

momentum fraction — *winner-take-all scheme*

$z_i = p^i_{\mathrm{T}} / \sum_i p^i_{\mathrm{T}}$



$p_{Tr} = p_{T1} + p_{T2}$

$\hat{n}_r = \begin{cases} \hat{n}_1 & \text{if } p_{T1} > p_{T2} \\ \hat{n}_2 & \text{if } p_{T2} > p_{T1} \end{cases}$

- **$\lambda^1_{0.5}$ = Les Houches Angularity**
  - potential for q/g discrimination
  - favour lower scale for α_S^{FSR} and Herwig7
  - DIRE NLO prediction in disagreement…

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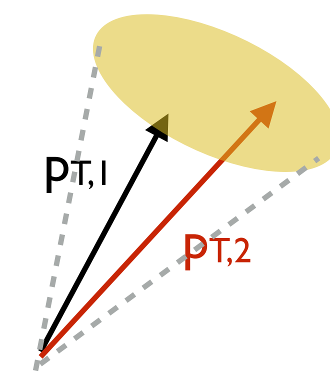

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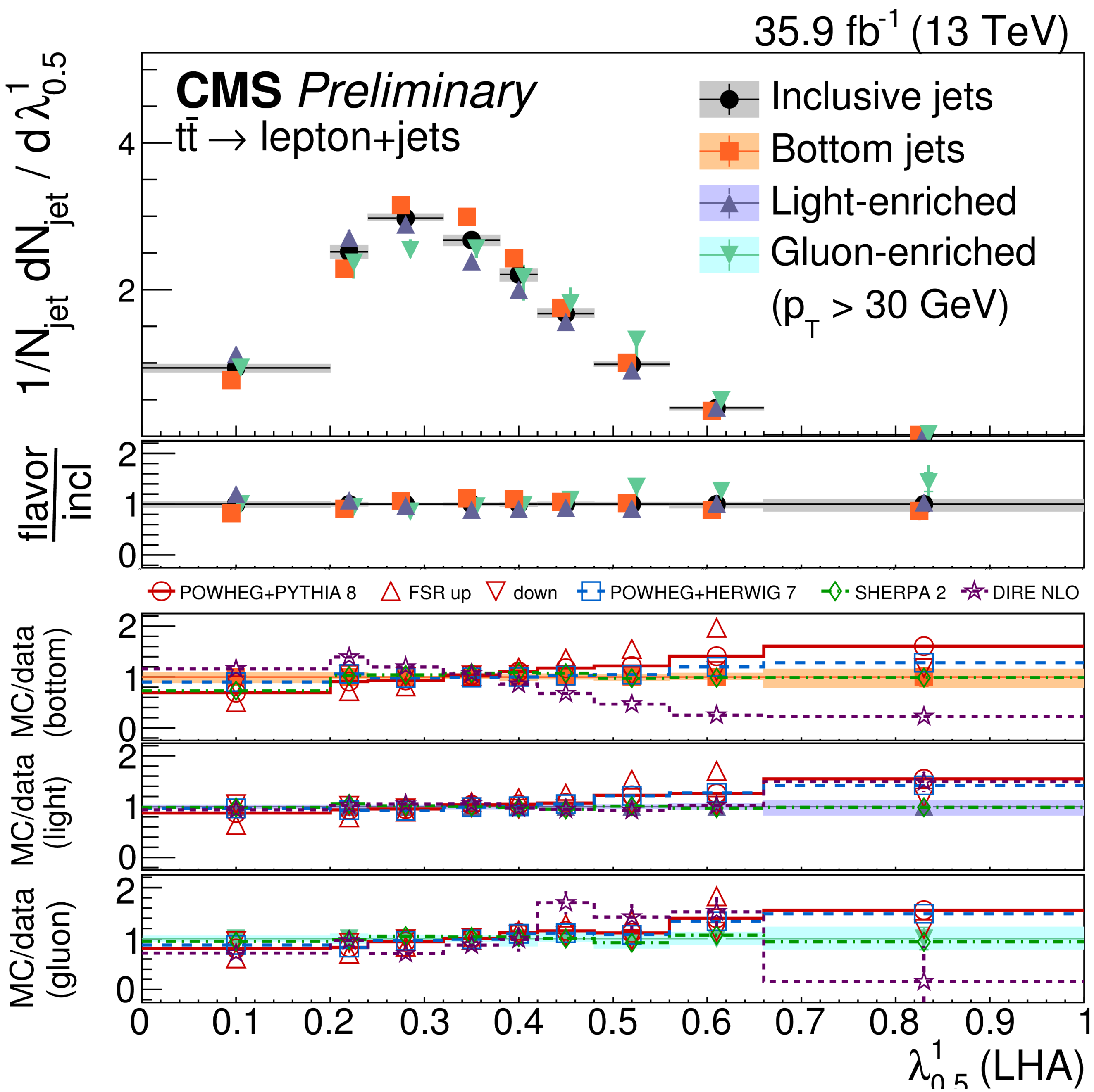

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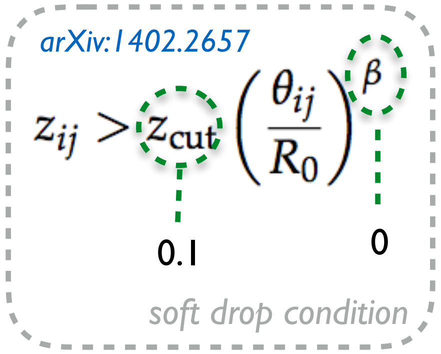
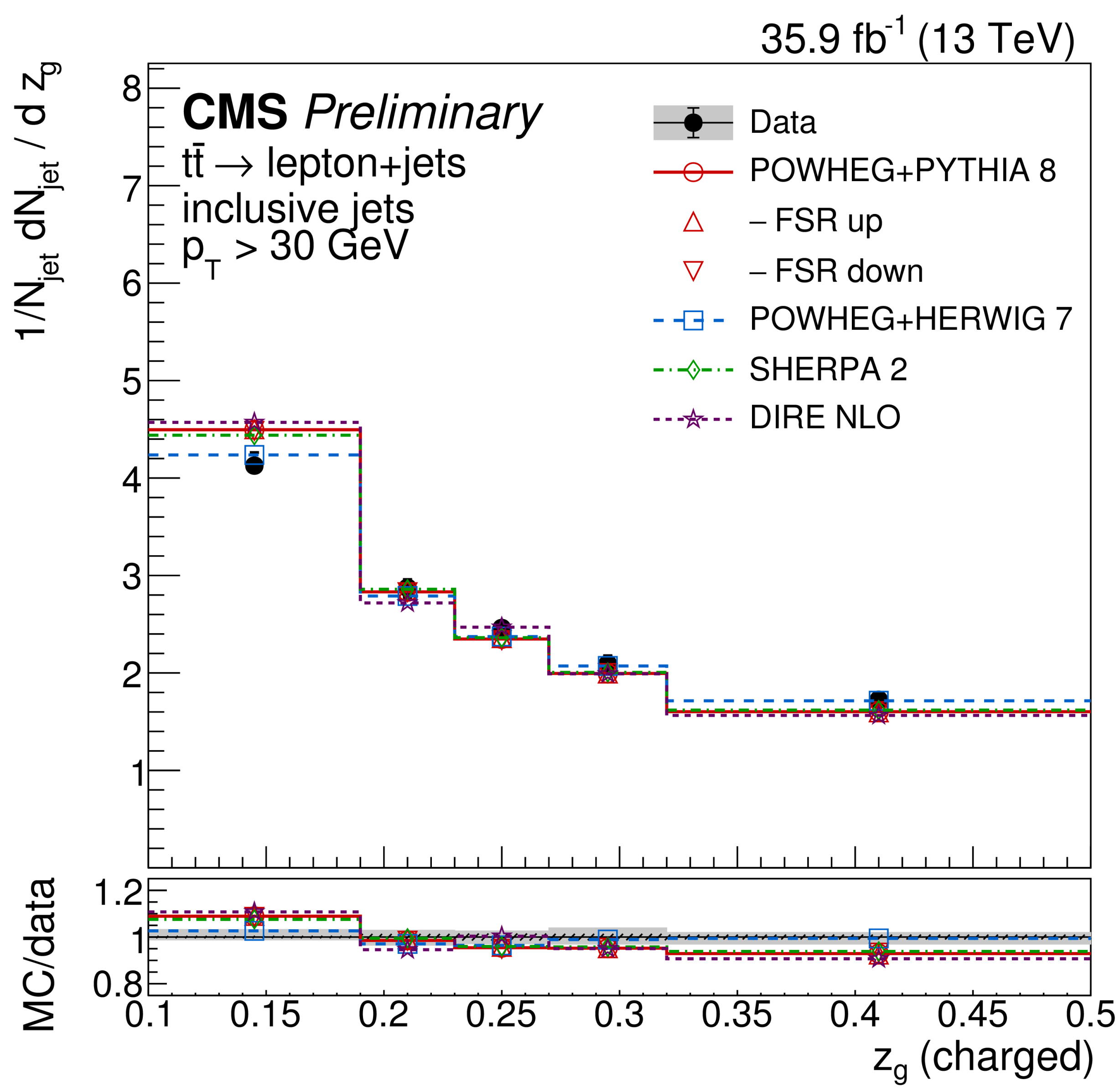
    … v2.001 missing splitting functions

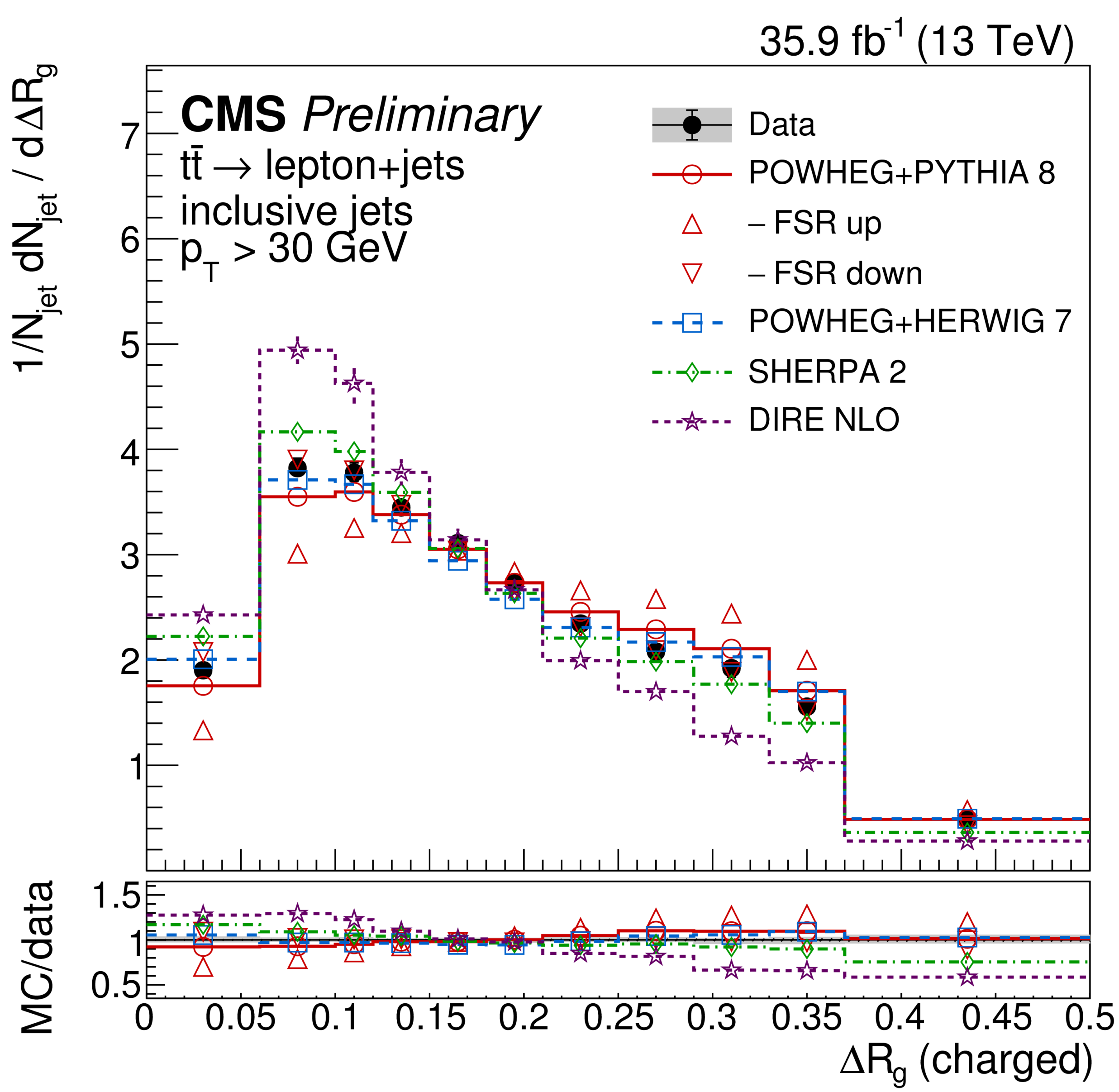
    to cover full b→bg structure

Soft drop observables



- **Use last de-clustering iteration: $j_0 \rightarrow j_1 + j_2$ as a proxy to the hardest splitting**
  - groomed momentum fraction $z_g = p_{T,2}/p_{T,0}$ is insensitive to α_S^{FSR}
  - angular separation of two sub-jets (ΔR_g) - better described by lower α_S^{FSR} and Herwig7





Energy correlation functions

- **Different behaviour expected for quarks and gluons**
- **However data differs significantly from predictions**
  - flavour-dependent improvements seem needed to tune MC

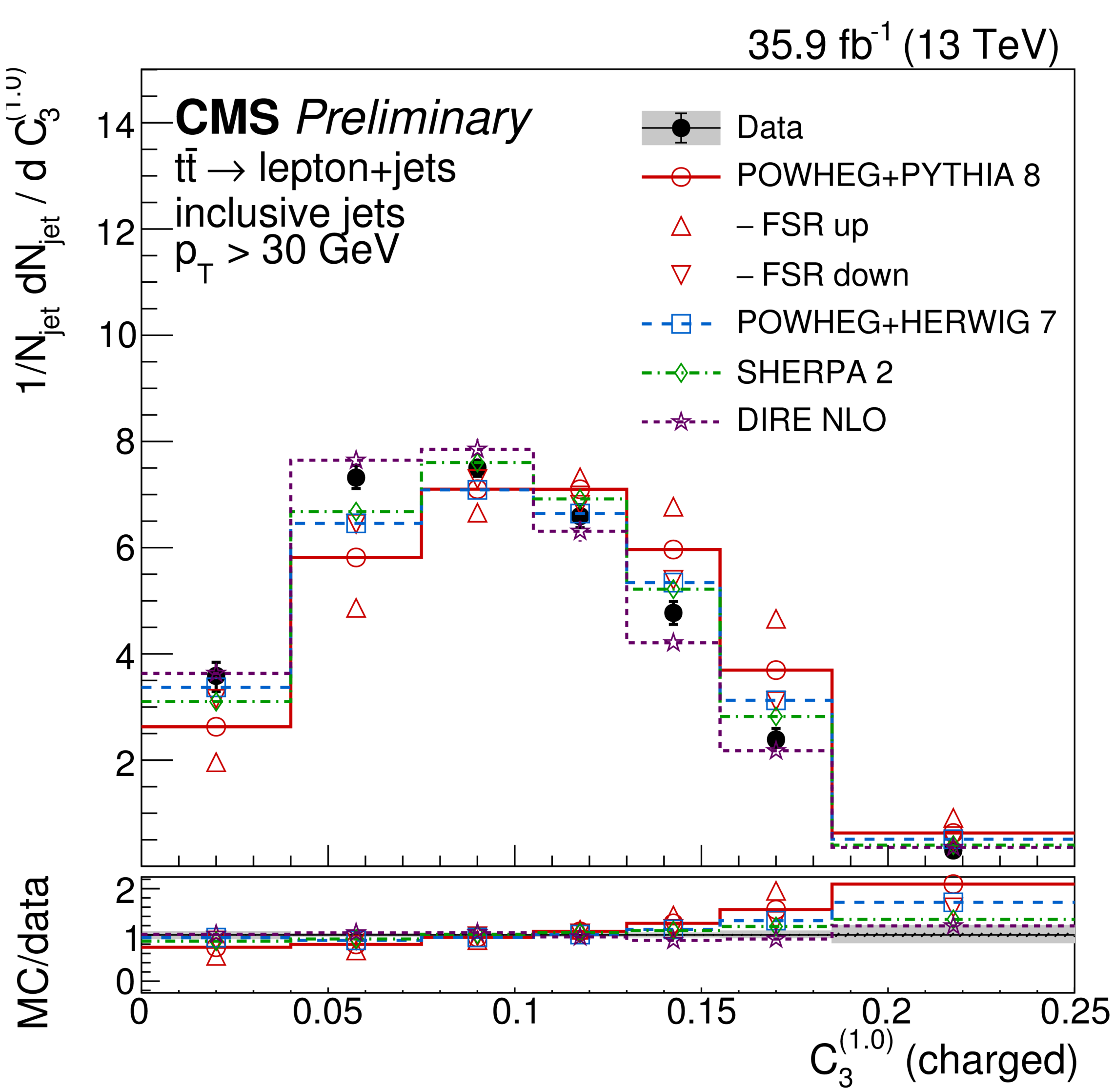
arXiv:1305.0007

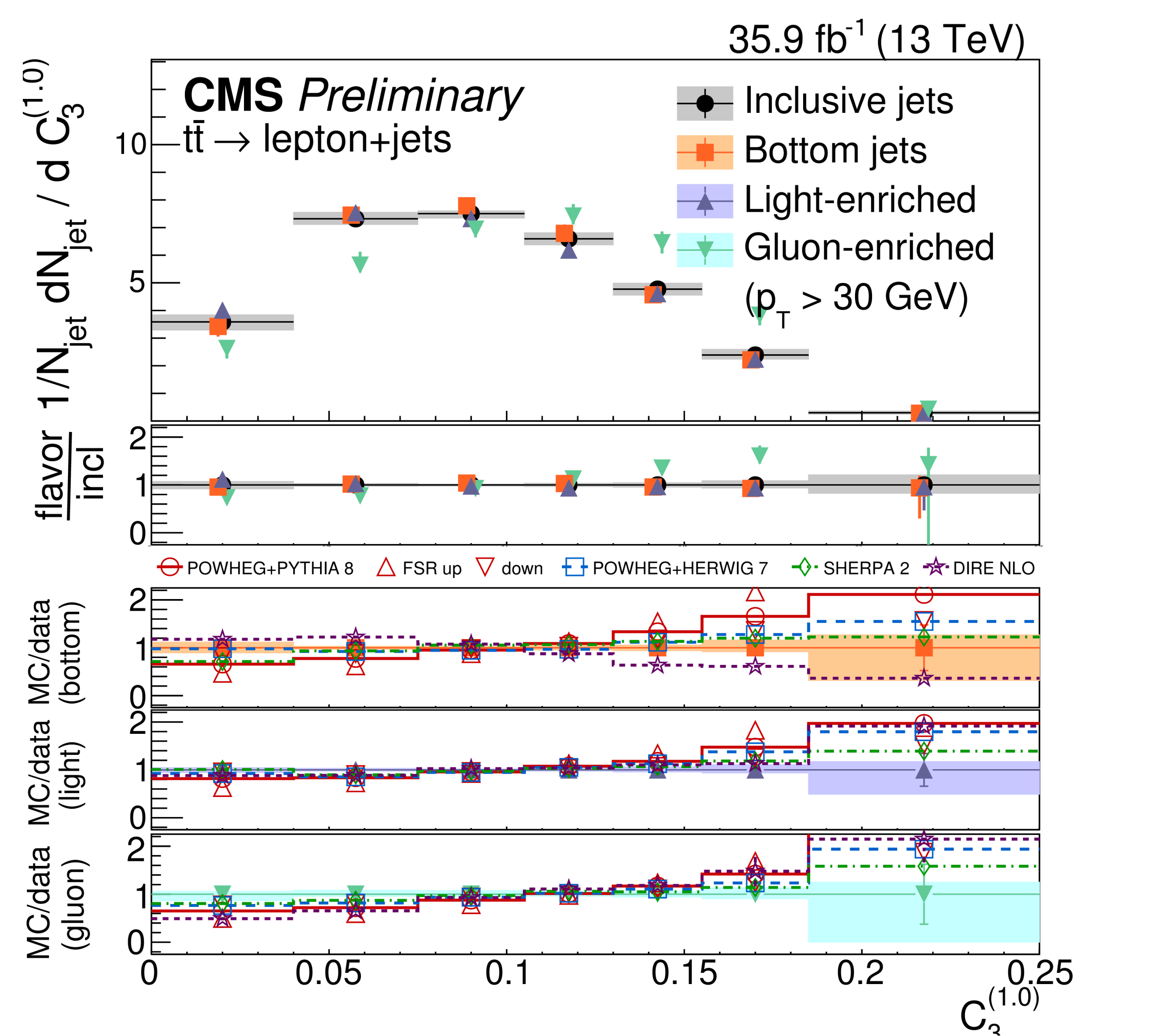
$$C_N^{(\beta)} = \frac{\mathrm{ECF}(N+1,\beta)\,\mathrm{ECF}(N-1,\beta)}{\mathrm{ECF}(N,\beta)^2}$$

$$\mathrm{ECF}(N,\beta) = \sum_{i_1<i_2<\ldots<i_N} \left(\prod_{a=1}^{N} p_{T\,i_a}\right) \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^{N} \Delta R_{i_b i_c}\right)^{\beta}$$

N particles p_T

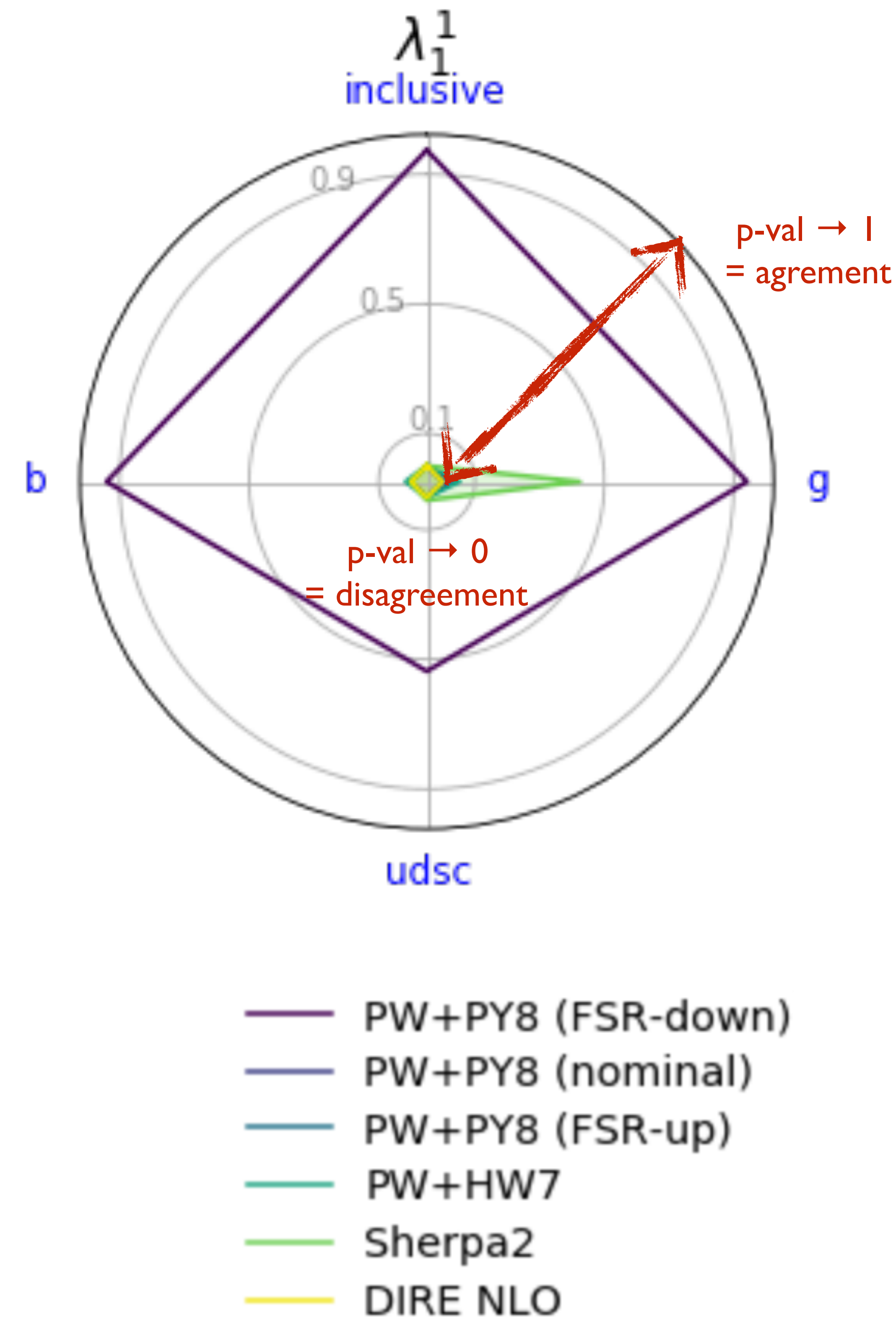
$\binom{N}{2}$ *2-particle angular distance*





Summary

- **Cherry-picking four sensitive variables**
  - width (λ_1^1), eccentricity (ε), z_g, t_{43}
  - small correlation (<25%)
- **p-values per flavour for different models λ_1^1**
  - lower α_S^{FSR} enhances the agreement across the board
  - other generators have low compatibility with data



a free interpretation of Table 1 in TOP-17-013 by the speaker

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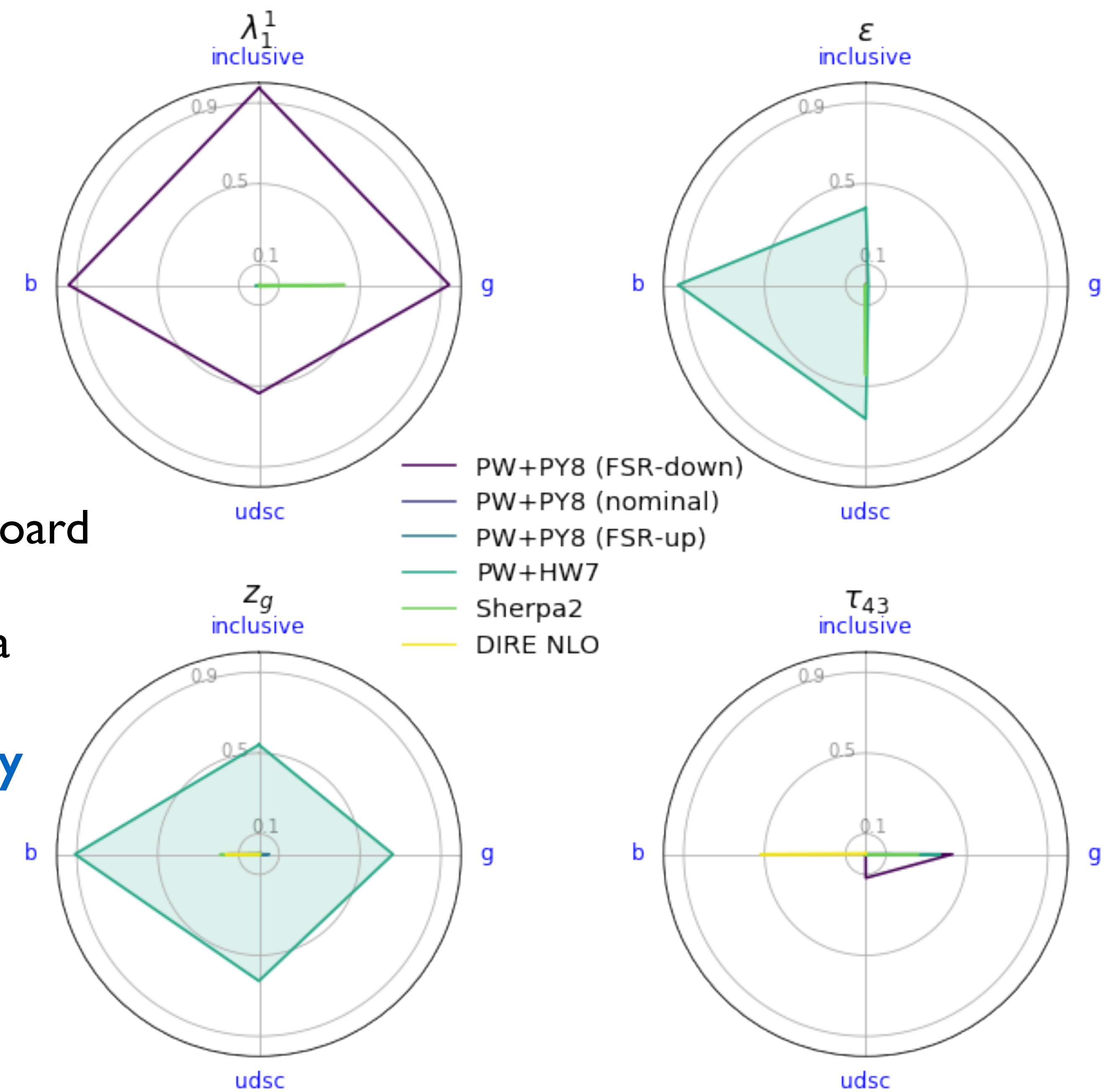
- **p-values per flavour for different models λ_1^1**
  - lower α_S^{FSR} enhances the agreement across the board
  - other generators have low compatibility with data
- **Other variables harder to describe completely**
  - Herwig7 describing better ε and z_g
  - most predictions disagree with τ_{43}
  - results seem to point in addition to flavour-specific dependencies



a free interpretation of Table 1 in TOP-17-013 by the speaker

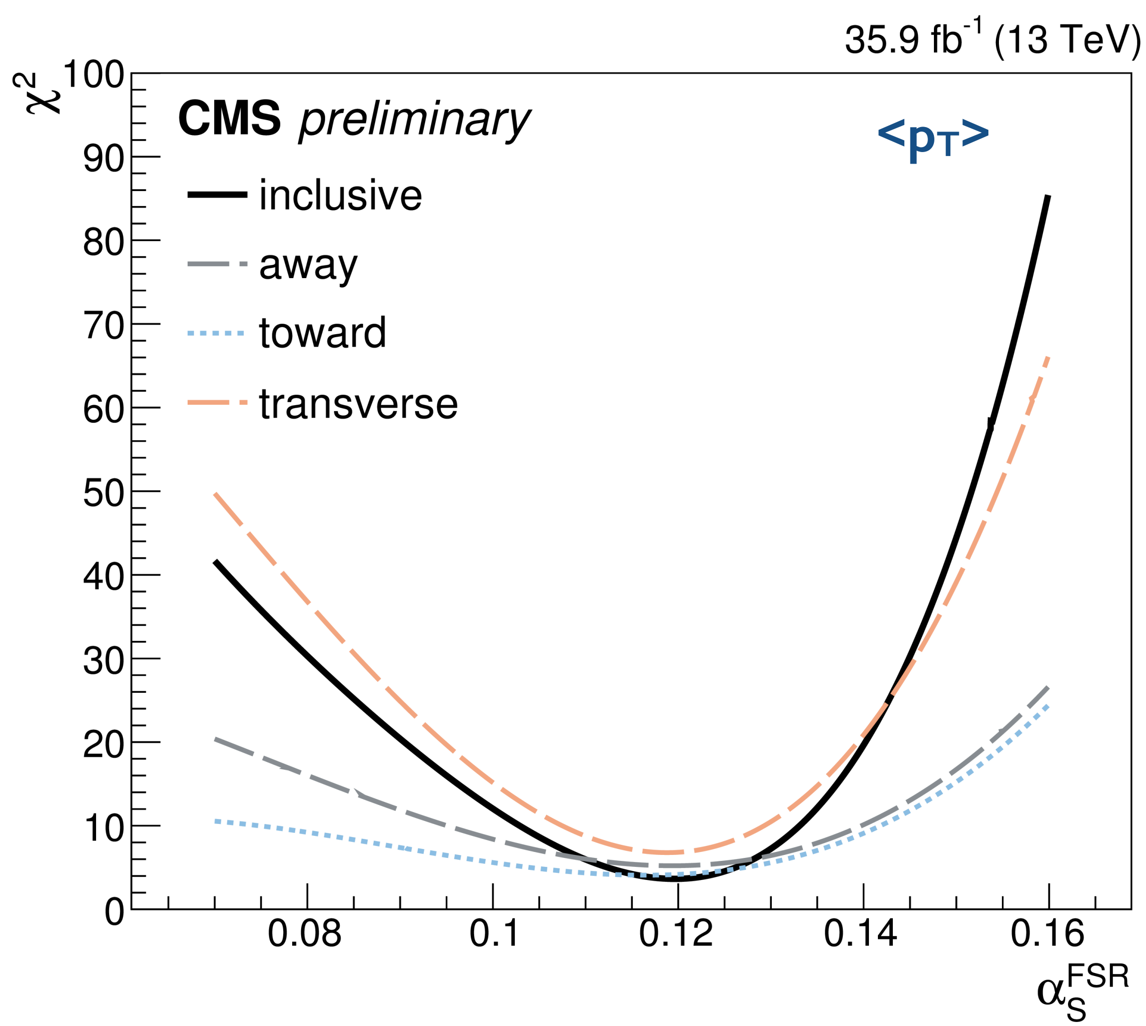
Sensitivity to α_S^{FSR}

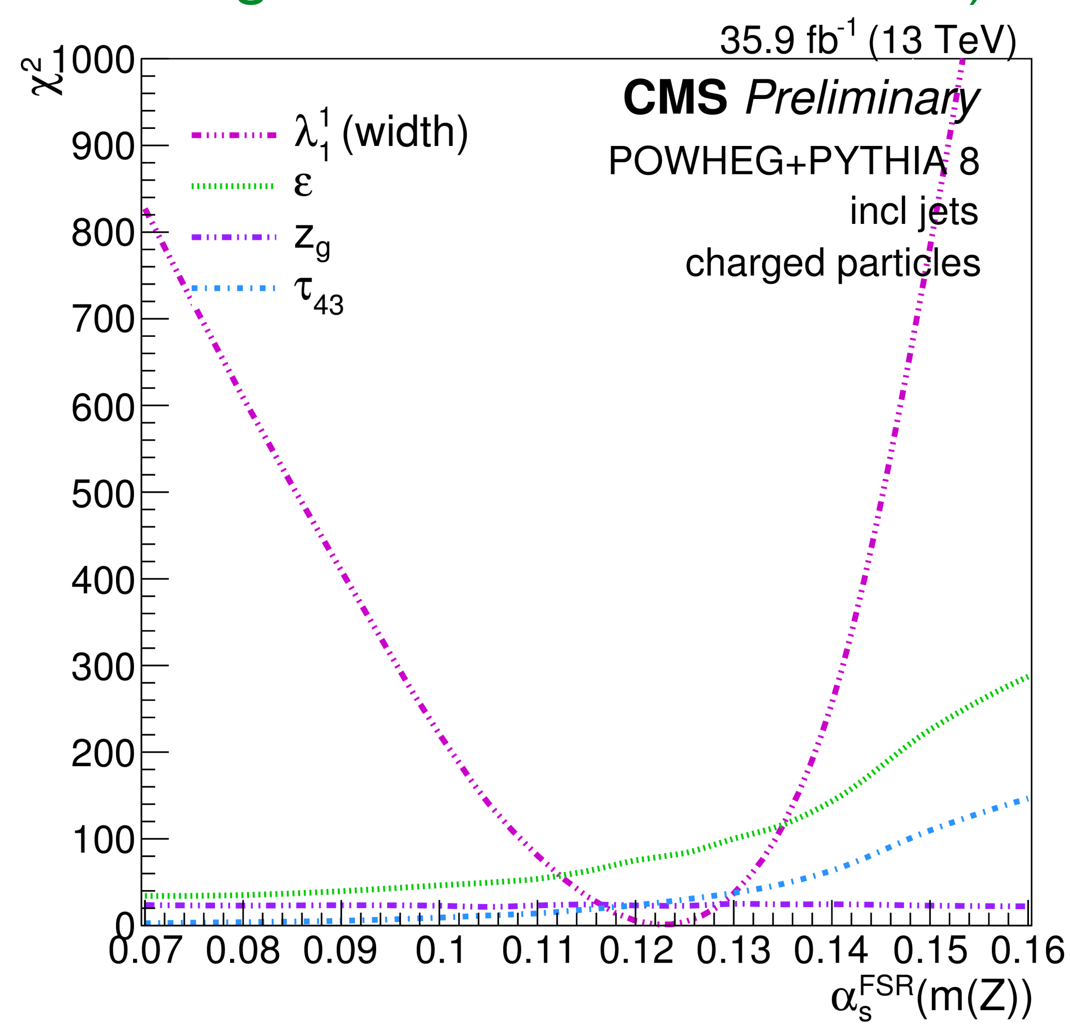
- **Scan $\alpha_S^{FSR}(M_Z)$ in underlying event and jet shapes**
  - good agreement between the two analyses
  - baseline (2,1/2) scale variation reduce-able to ≈($\sqrt{2}$,1/$\sqrt{2}$) →
  - a complete tune needed to improve agreement in other variables

Fit	$\alpha_S^{FSR}(M_Z)$
Monash	0.1365
$\langle p_T \rangle$	0.120 ± 0.006
λ_1^1(width)	0.123 ± 0.001

- **Jet shapes: surpass LO precision! if CMW is used to which order can we claim it?**

☞ looking forward for D. Kim's talk :)





Conclusions

- **Plethora of new particle-level measurements using 2016 data**
  - jet substructure for different jet flavours
  - underlying event observables
- **Probing different aspects of tt modelling**
  - different phase space regions probing ISR, FSR, CR, MPI, parton shower
  - different CR models tested yield valid data description (unlike CR off in Run I)

    ⇒ closer to describe a "true" uncertainty for m_t determinations?
  - flavour-dependent tunings seem to be needed in some variables
  - jet shapes: interesting potential to measure α_S (to which order can it be claimed?)
- **All will be available in Rivet/HepData soon**
  - expect to improve current MC generators and future precision measurements

Backup

Powheg+Pythia8 variations

Parameter	PW+PY8 simulation setups									
	CUETP8M2T4	Extreme variations		Fine grain variations						
				MPI/CR	Parton shower scale		CR including $t\bar{t}$			
		no MPI	no CR	UE up/down	ISR up/down	FSR up/down	ERD on	QCD based [32]	Gluon move [4]	Rope (no CR) [33, 34]
PartonLevel										
MPI	on	off								
SpaceShower										
renormMultFac	1.0				4/0.25					
alphaSvalue	0.1108									
TimeShower										
renormMultFac	1.0					4/0.25				
alphaSvalue	0.1365									
MultipartonInteractions										
pT0Ref	2.2			2.20/2.128				2.174	2.3	
ecmPow	0.2521							0.2521		
expPow	1.6			1.711/1.562				1.312	1.35	
ColorReconnection										
reconnect	on		off							(off)
range	6.59			6.5/8.7						
mode	0							1	2	
junctionCorrection								0.1222		
timeDilationPar								15.86		
m0								1.204		
flipMode									0	
m2Lambda									1.89	
fracGluon									1	
dLambdaCut									0	
PartonVertex										
setVertex										on
Ropewalk										
RopeHadronization										on
doShoving										on
doFlavour										on
PartonLevel										
earlyResDec	off						on	on	on	on

Jet shapes summary per tested model