TOP Differential Cross Sections

Top Workshop, Saint-Malo, 23 Sep 2024

Olaf Behnke, DESY

on behalf of the ATLAS and CMS Collaborations

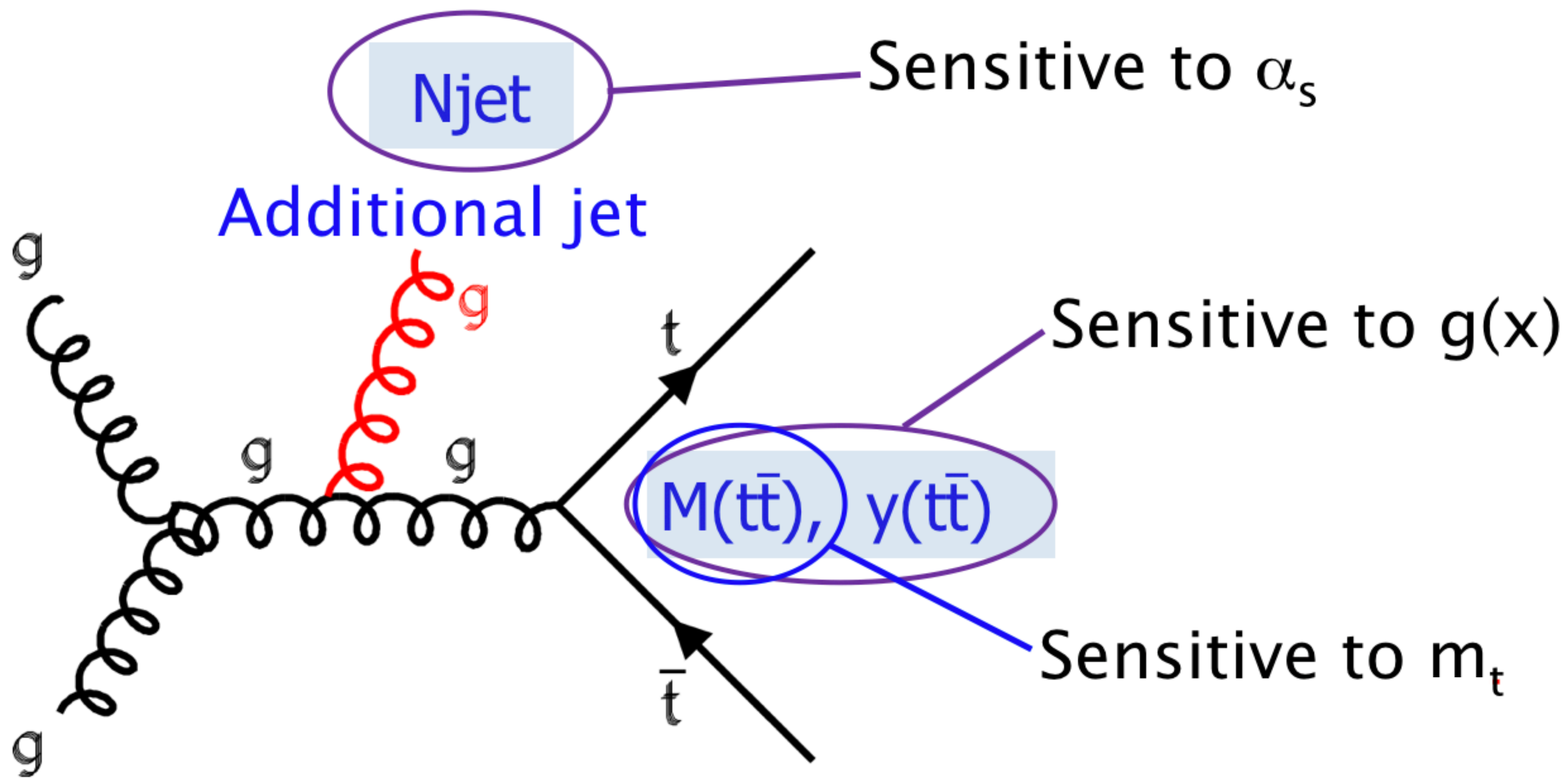
Will focus on top pair production, single top differential results are covered in talk by Javier Del Riego Badas

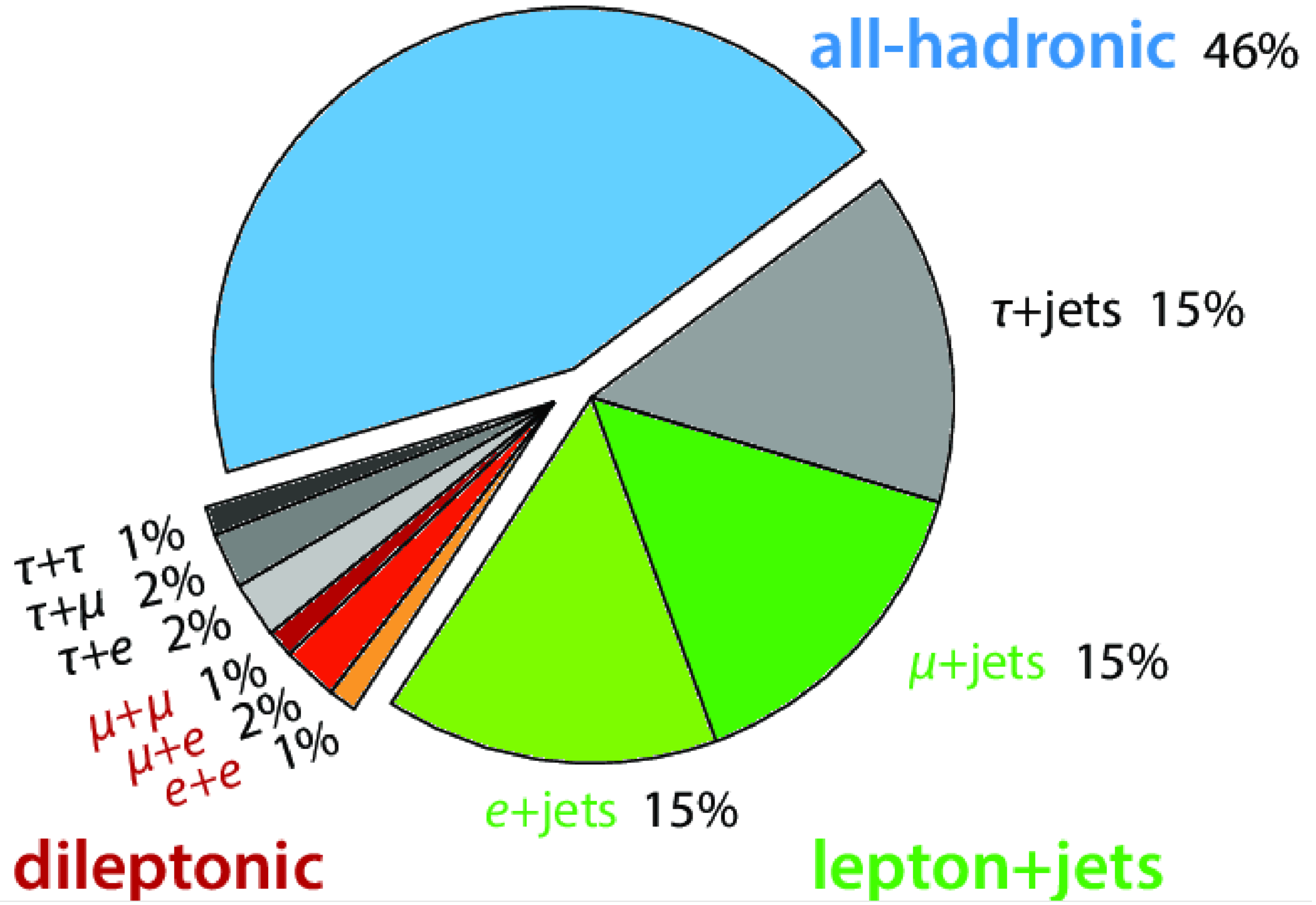
Differential $t\bar{t}$ production at the LHC

→ study kinematical & topological distributions:
✓ QCD+EW Test
✓ Sensitive to theory parameters

tt Events in ATLAS and CMS	
Run 2	Run 3 till now
~100M	~100M

No differential $t\bar{t}$ results yet



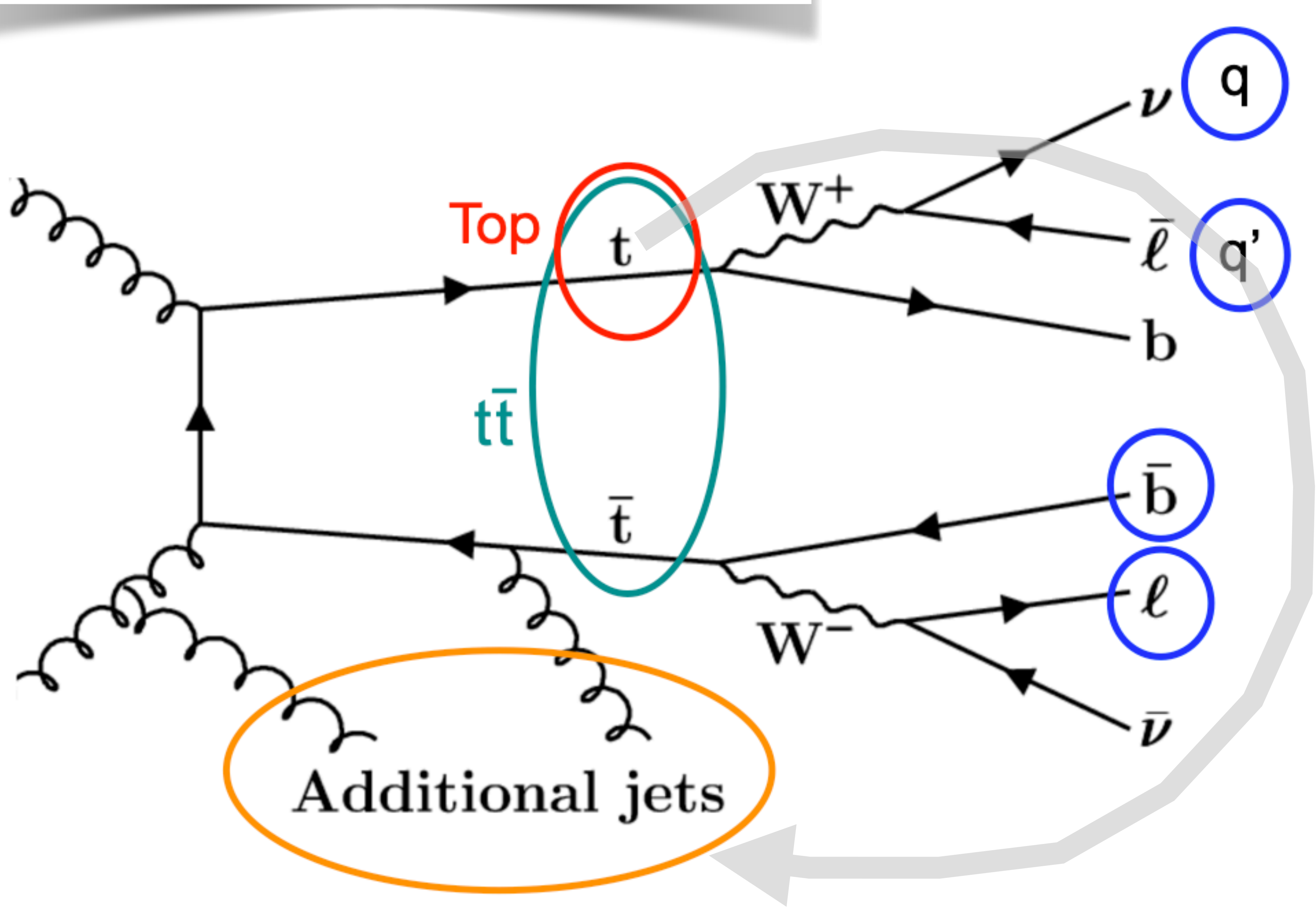


Today's Menu: review of RUN 2 results

- Make a round trip through the observable systems and kinematic distributions
- Compare most comprehensive ATLAS and CMS results with state-of-the-art predictions

Observable systems

Decay particles: l,b,q,q'



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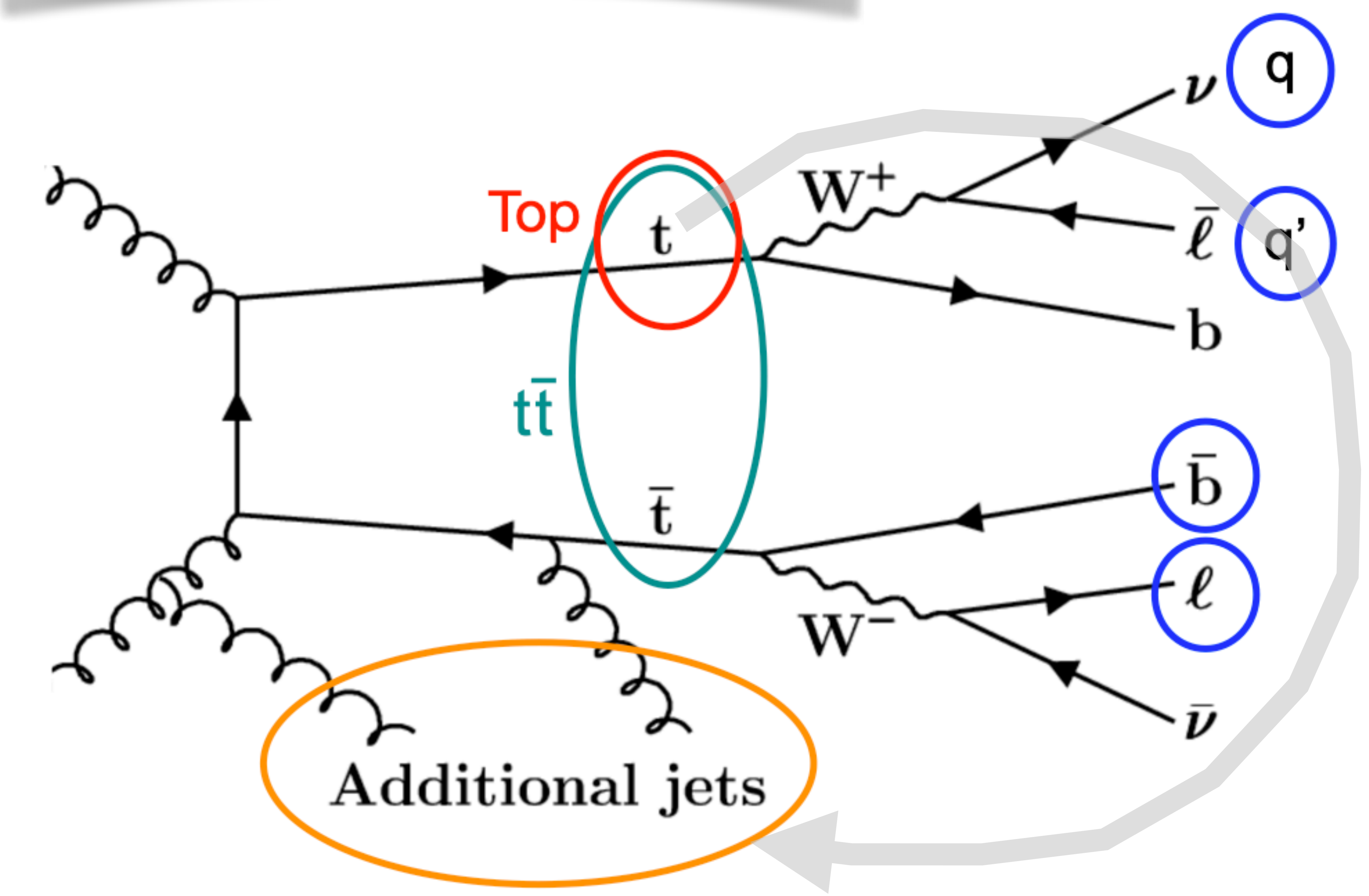

Featured Analyses

Exp.	Journal or arXiv:	Channel	Lumi fb-1	Phase space	Unfolding	Top	tt	Decay particle	Additional Jets	Largest Syst.
CMS	2402.08486	Dilepton	138	Resolved	TUnfold	✓	✓	✓	✓	JES/R
CMS	PRD 104 (2021) 092013	l+jets	137	Resolved +Boosted	MLE	✓	✓	✓	✓	JES/R
CMS	PRD 97,112003 (2018)	l+jets	36	Resolved	D'Agostini	✓	✓	✓	✓	JES/R
ATLAS	JHEP 08 (2024) 182	l+jets	140	Resolved	D'Agostini			✓	✓	JES/R
ATLAS	JHEP07 (2023) 141	emu	140	Resolved	Bin-by-bin			✓		tt - tW interf. s and b modeling
ATLAS	JHEP 04 (2023) 080	All had	139	Both tops Boosted	D'Agostini	✓	✓			Top tagging
ATLAS	JHEP 06 (2022)063	l+jets	139	Boosted	D'Agostini	✓	✓		✓	JES/R, tt modeling
ATLAS	EPJC 79 (2019) 2018	l+jets	36	Resolved +Boosted	D'Agostini	✓	✓		✓	JES/R

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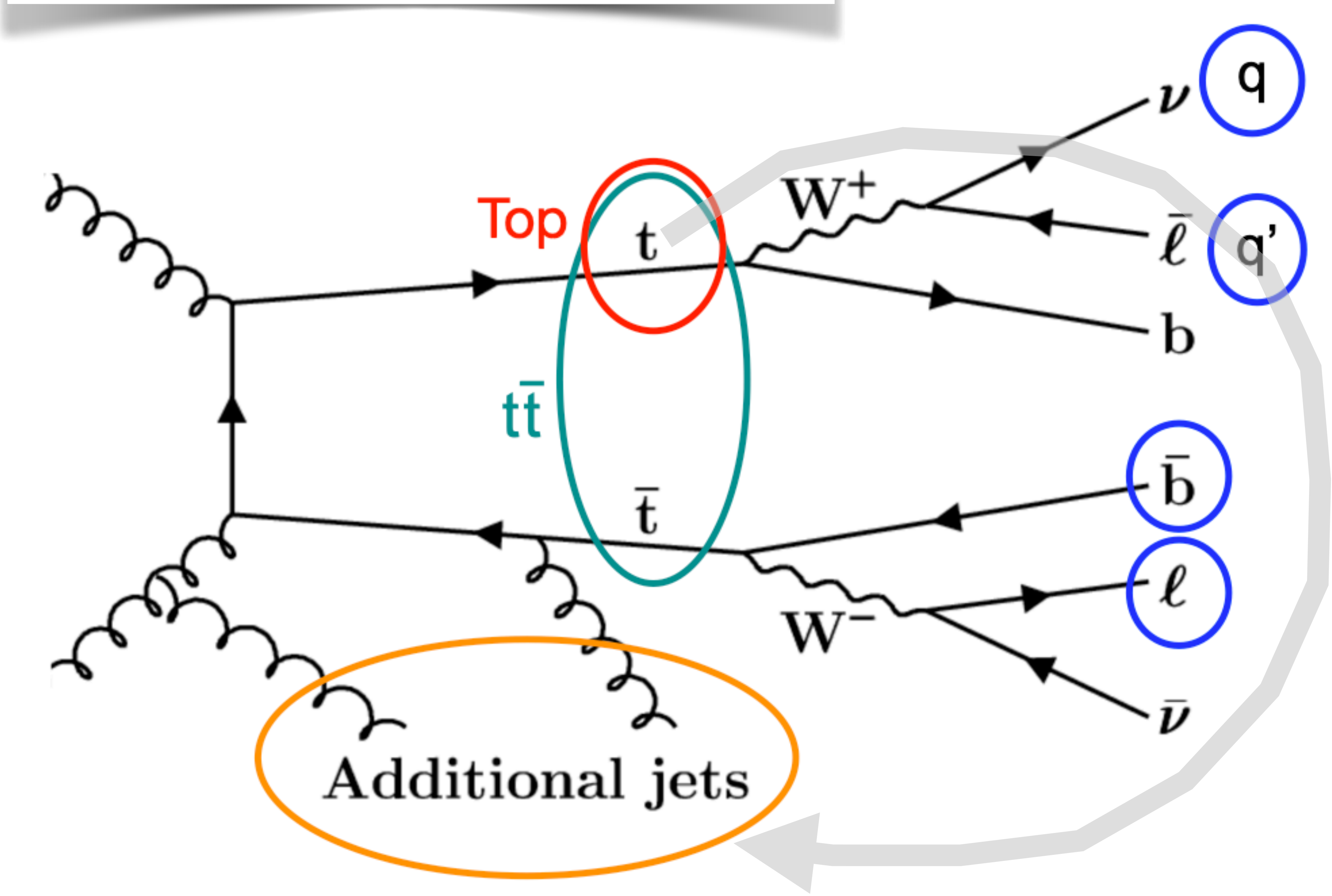

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Key questions:

- Phase space coverage, precisions, sensitivities?
- Which systems are well or not so well described by NLO+PS or NNLO?

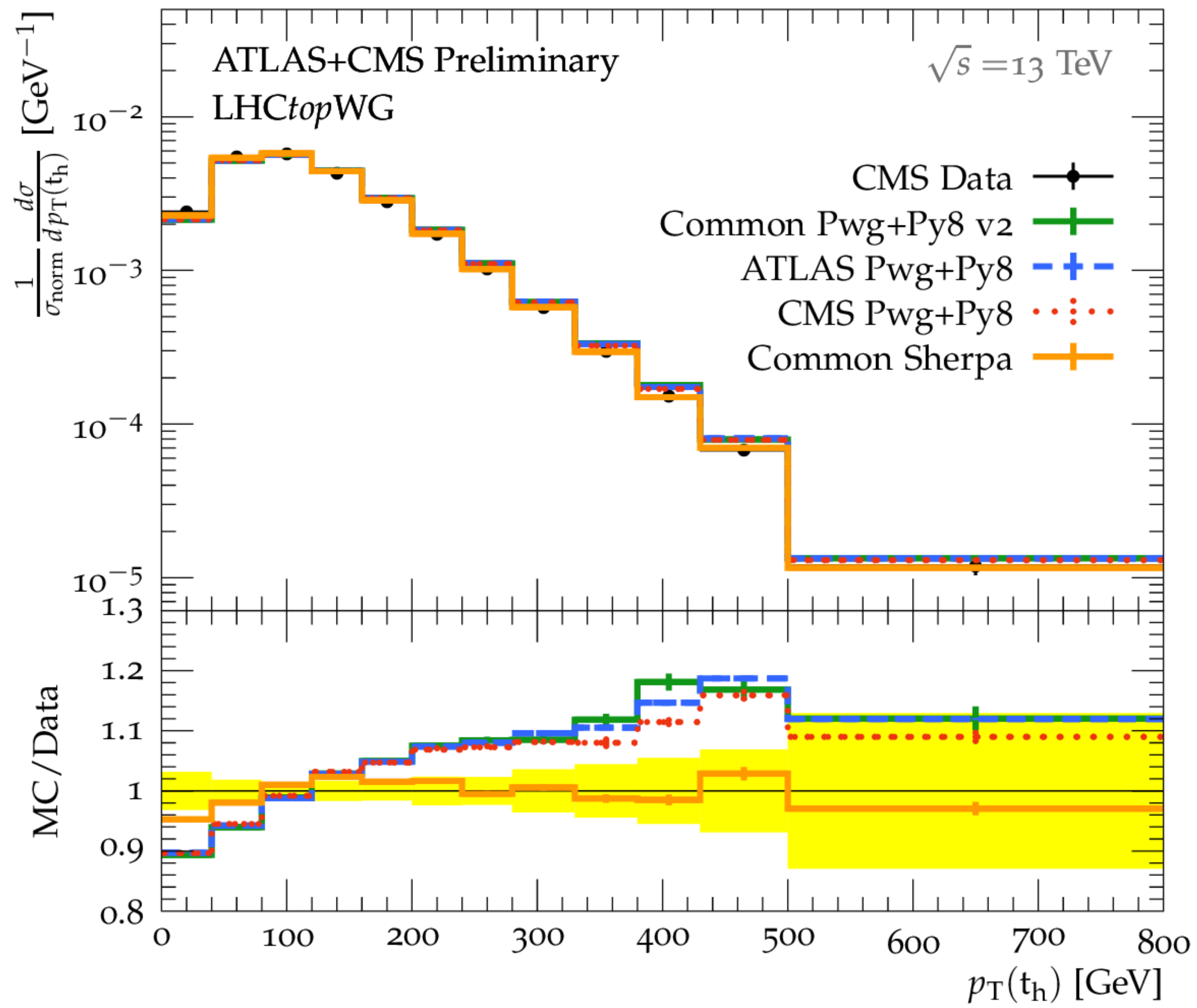
Previous Review in 2020 by M. Romano and O.B.

Models to compare to

All references provided in the ATLAS/CMS papers

- NLO+PS Reference model: POWHEG+PYTHIA (POW)
- Effort towards common ATLAS/CMS $t\bar{t}$ MC settings

ATL-PHYS-PUB-2022-052



- For results today: ATLAS and CMS POW settings different
- ATLAS **also** uses POW with P_T(t) reweighted to NNLO

- Other predictions shown today:

NLO+PS
o(α_s^3) or higher

- POWHEG+HERWIG
- MCatNLO+PYTHIA
- MCatNLO+HERWIG
- FXFX (based on MC@NLO)
- SHERPA

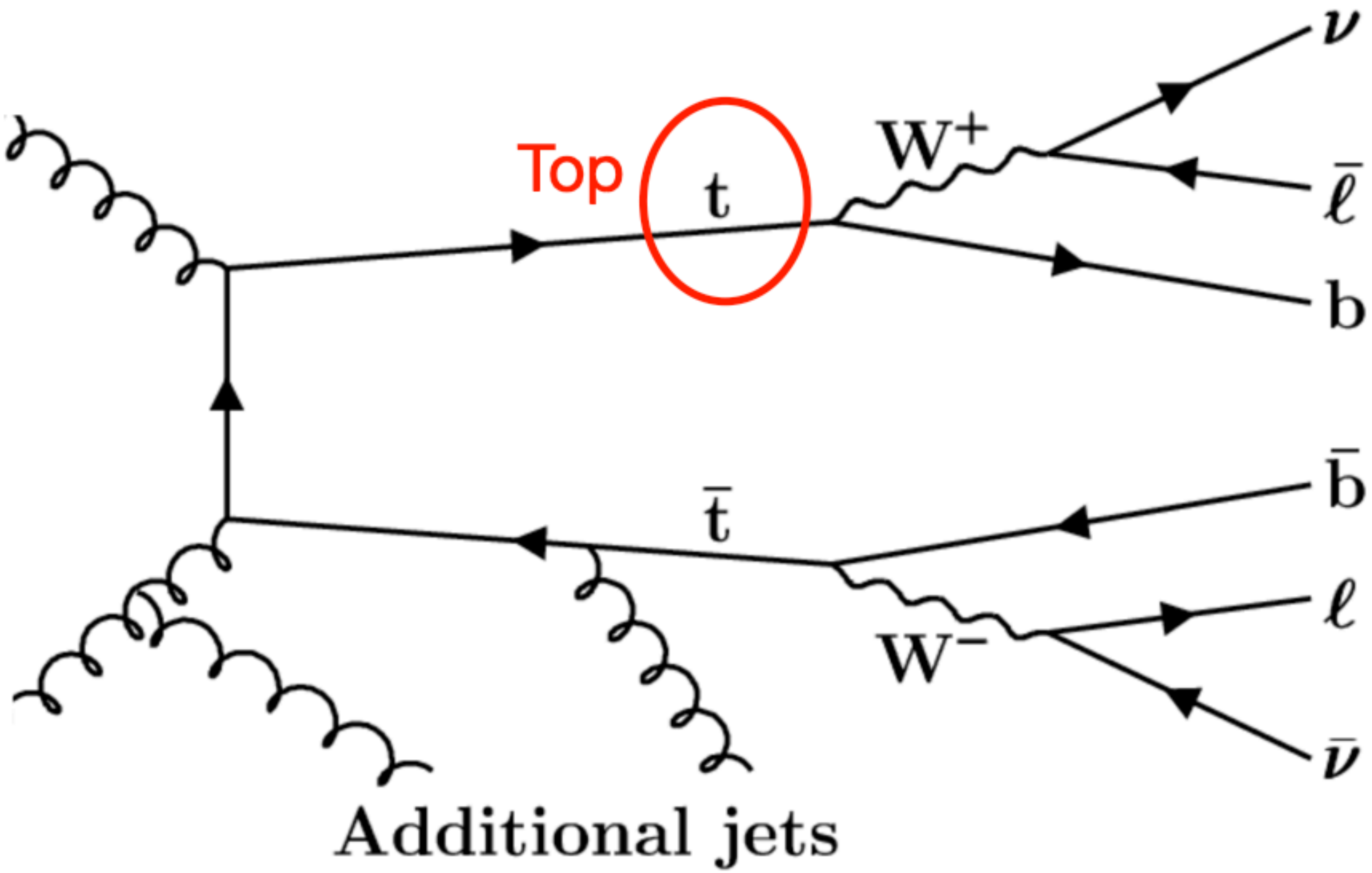
NNLO
o(α_s^4) or higher

- NNLO (Czakon et al.)
- Stripper (Czakon et al.)
- Matrix (Grazzini et al.)

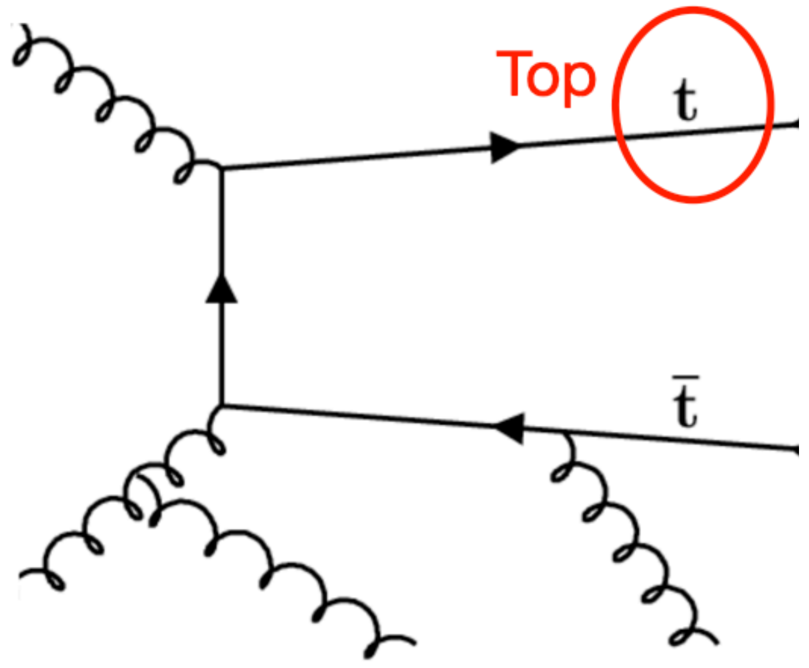
NNLO+PS
o(α_s^4) or higher

- MINNLOPS (Monni et al.)

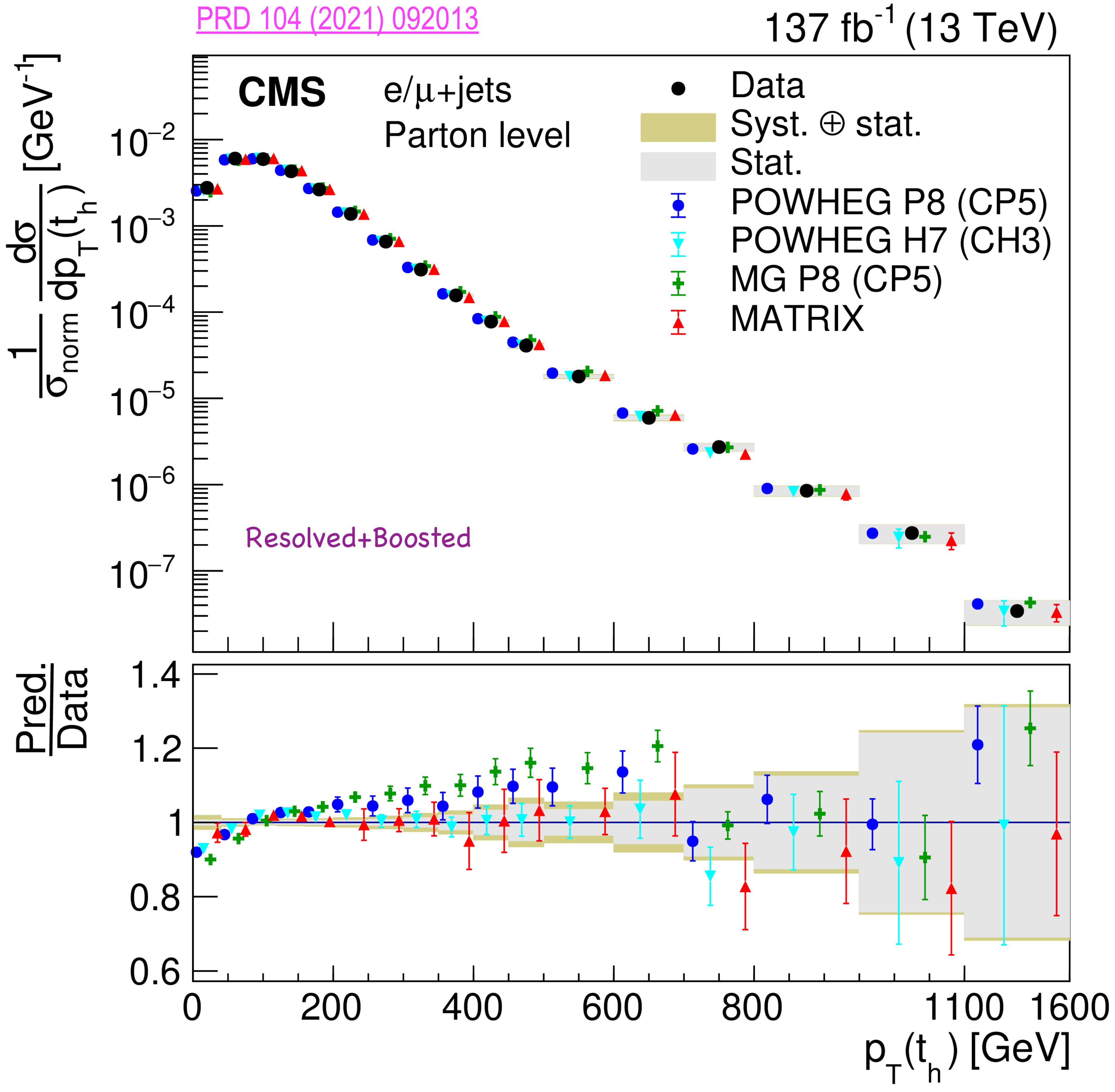
Results:

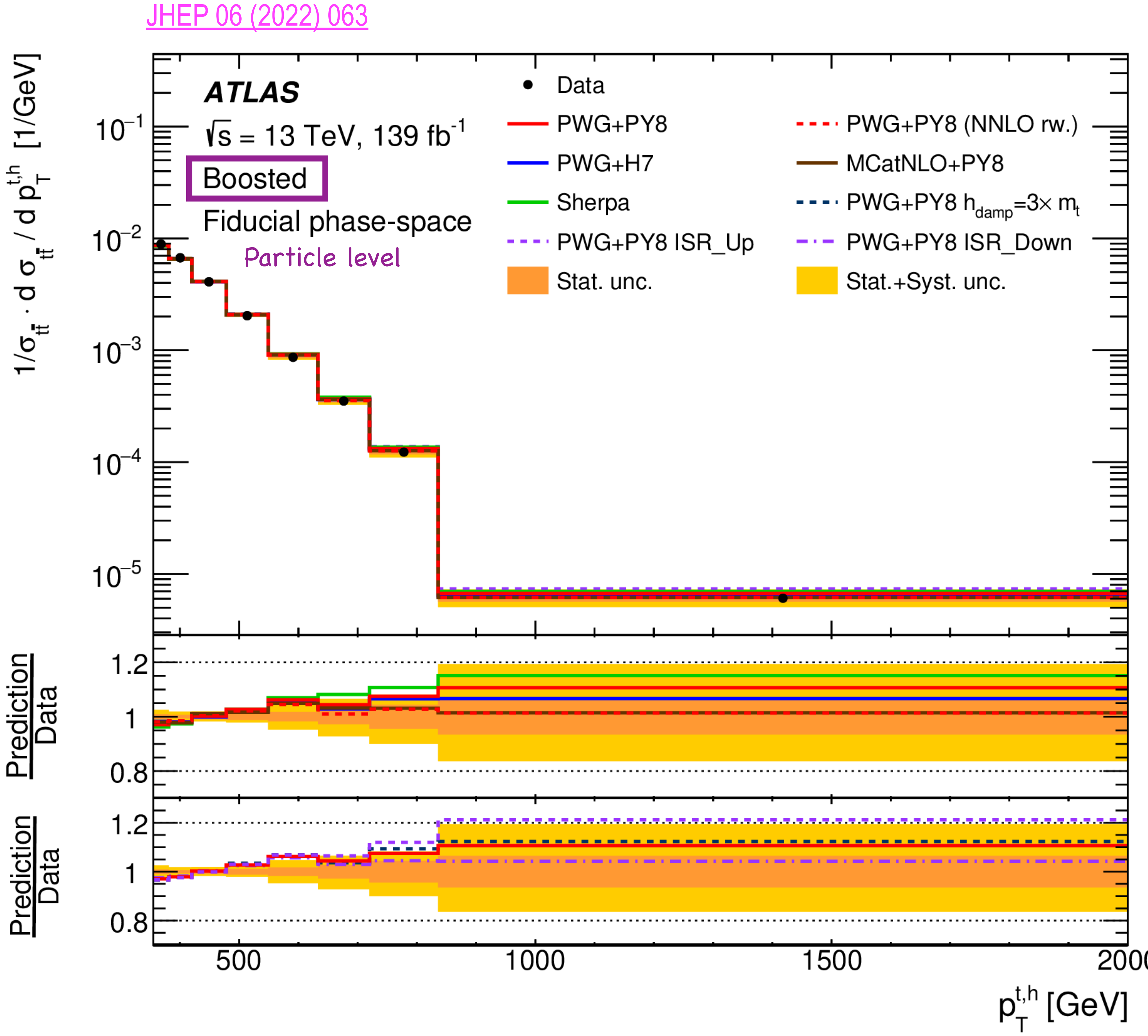


$p_T(t)$



l+jets





POW/CMS: →

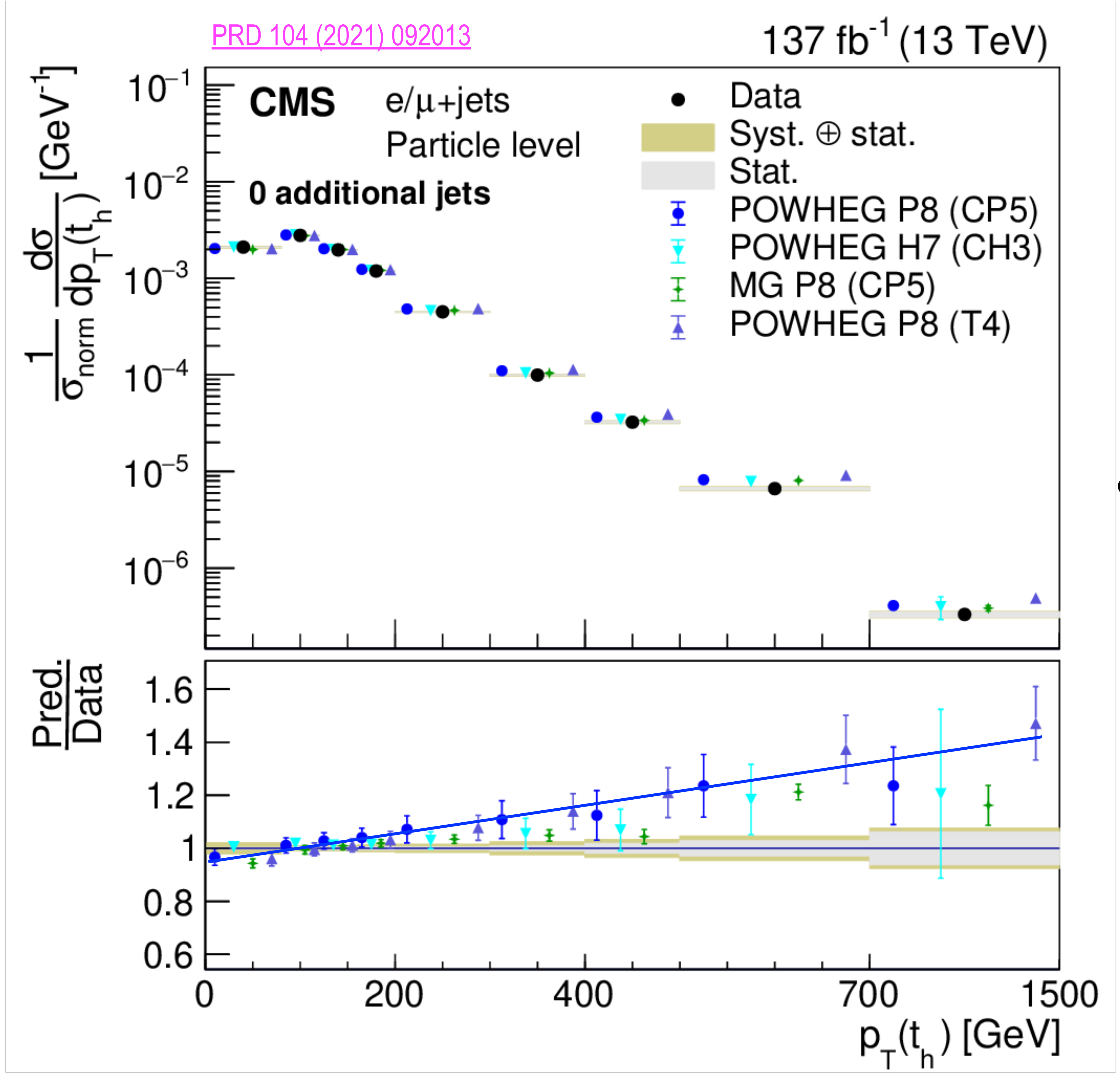
NNLO/CMS: →

POW/ATLAS: →

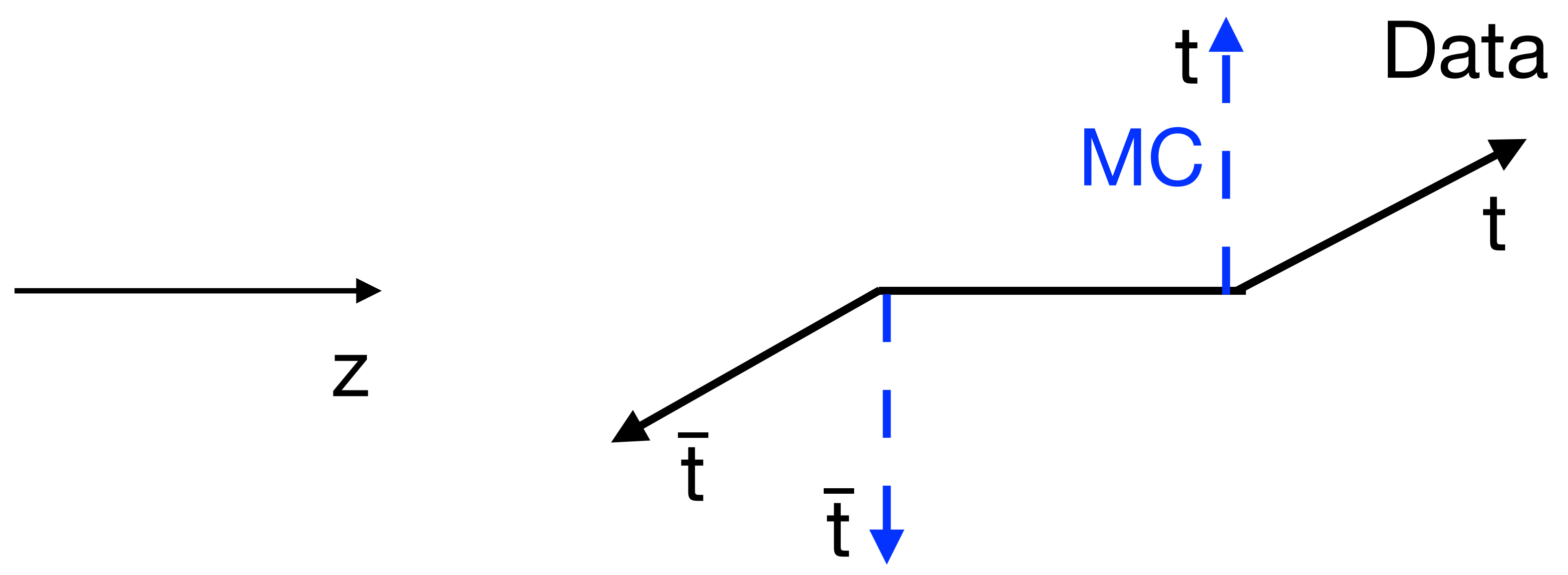
NNLO rw. POW/ATLAS: →

⇒ Known since long time: NNLO improves $p_T(t)$ prediction

"NLO+PS p_T(t) problem" - learn from multi-differential studies

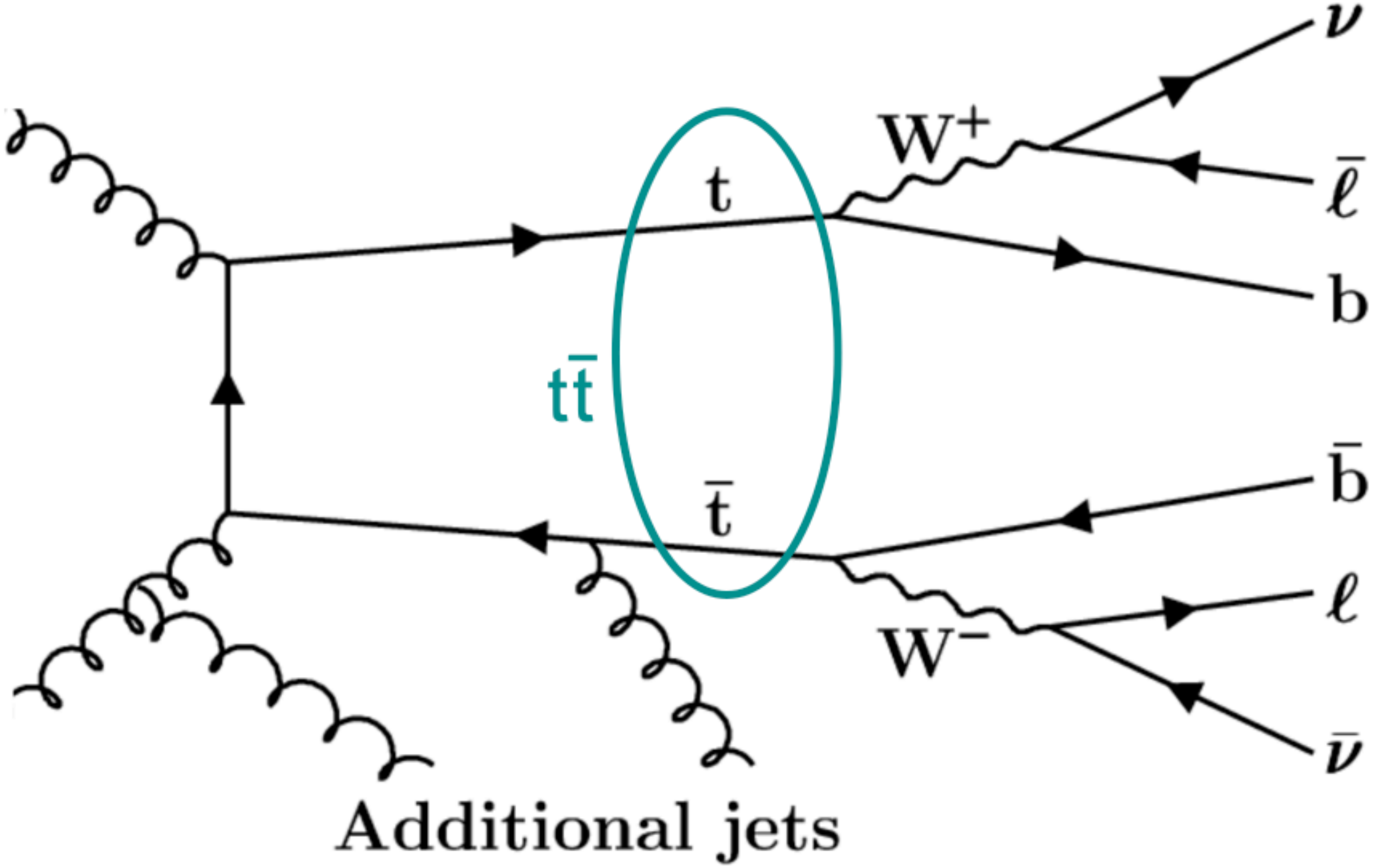


- POW/Data p_T(t) slope is
  - Mostly visible for 0 or 1 additional jets, see left Plot
  - Increases with m(tt), see Plot
  - At high m(tt): $\Delta\eta(t, \bar{t})$ larger in data than in MC, see Plot



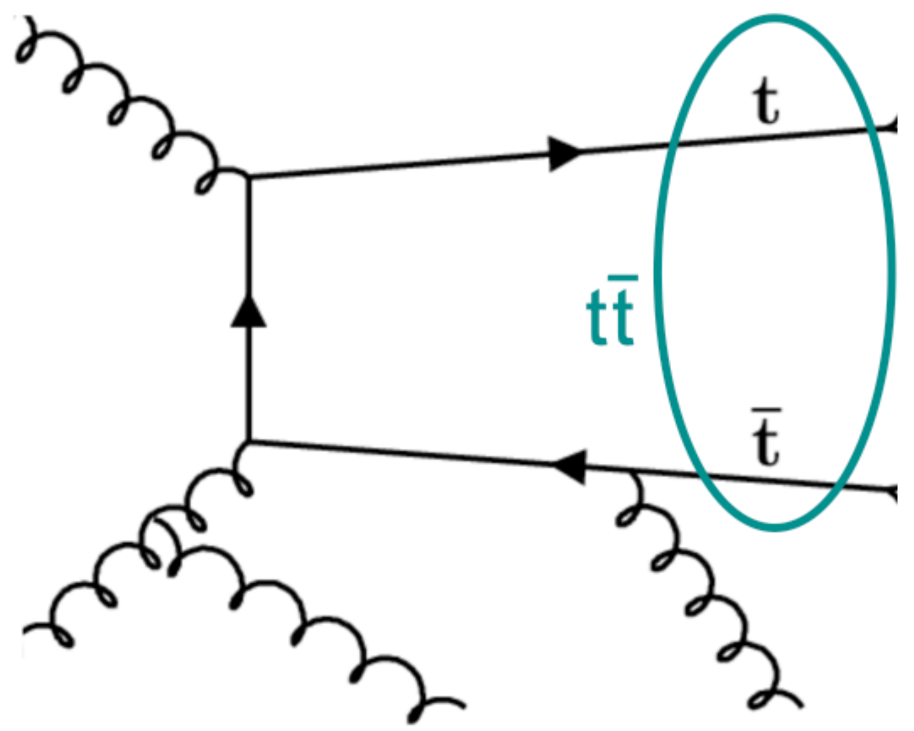
⇒ Do we need further studies?

Results:



$p_T(t\bar{t})$

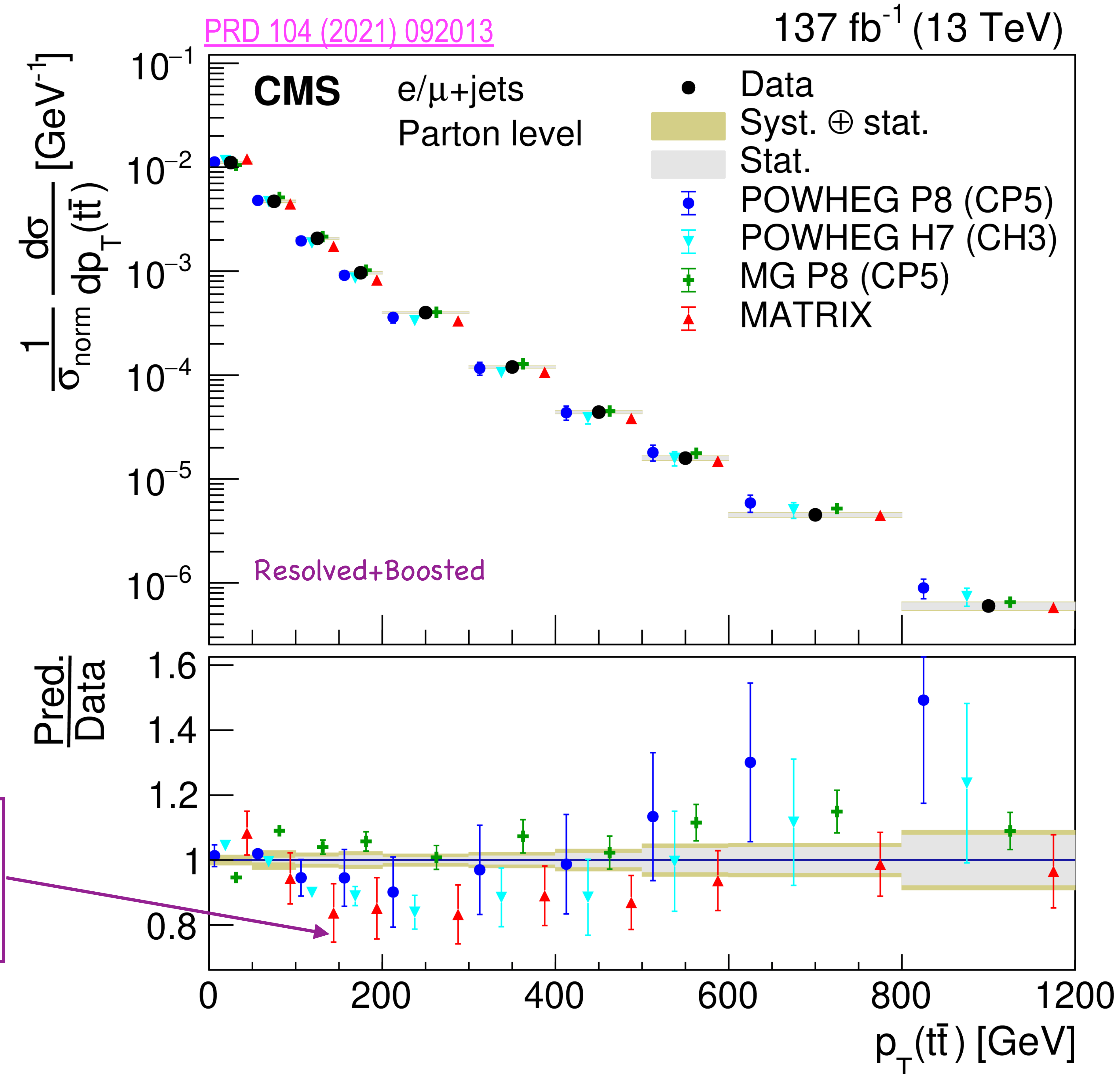
l+jets, Parton level



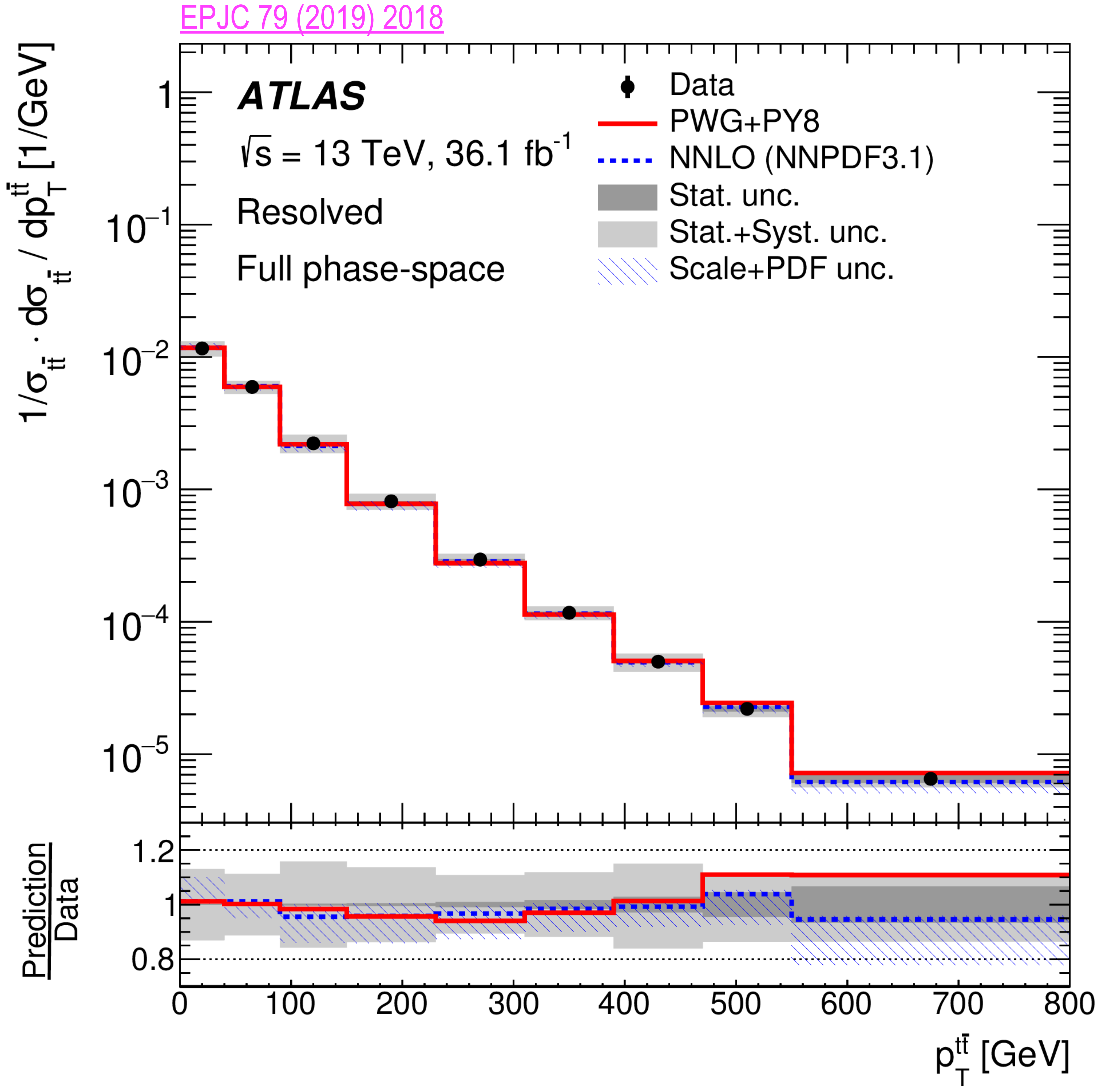
Non-zero $p_T(t\bar{t})$ directly sensitive to NLO QCD

⇒ Large theory scale Uncertainties

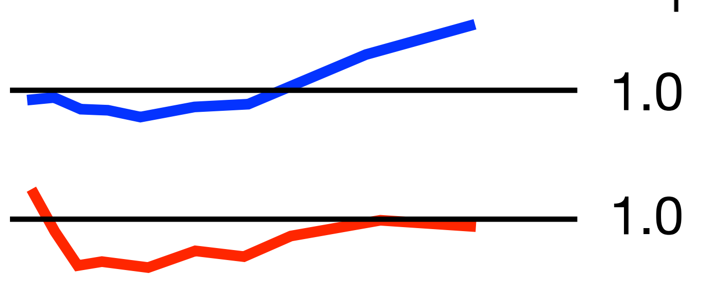
PRD 104 (2021) 092013



EPJC 79 (2019) 2018

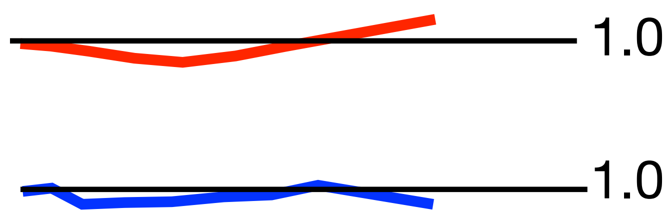


POW/CMS:



NNLO/CMS:

POW/ATLAS:

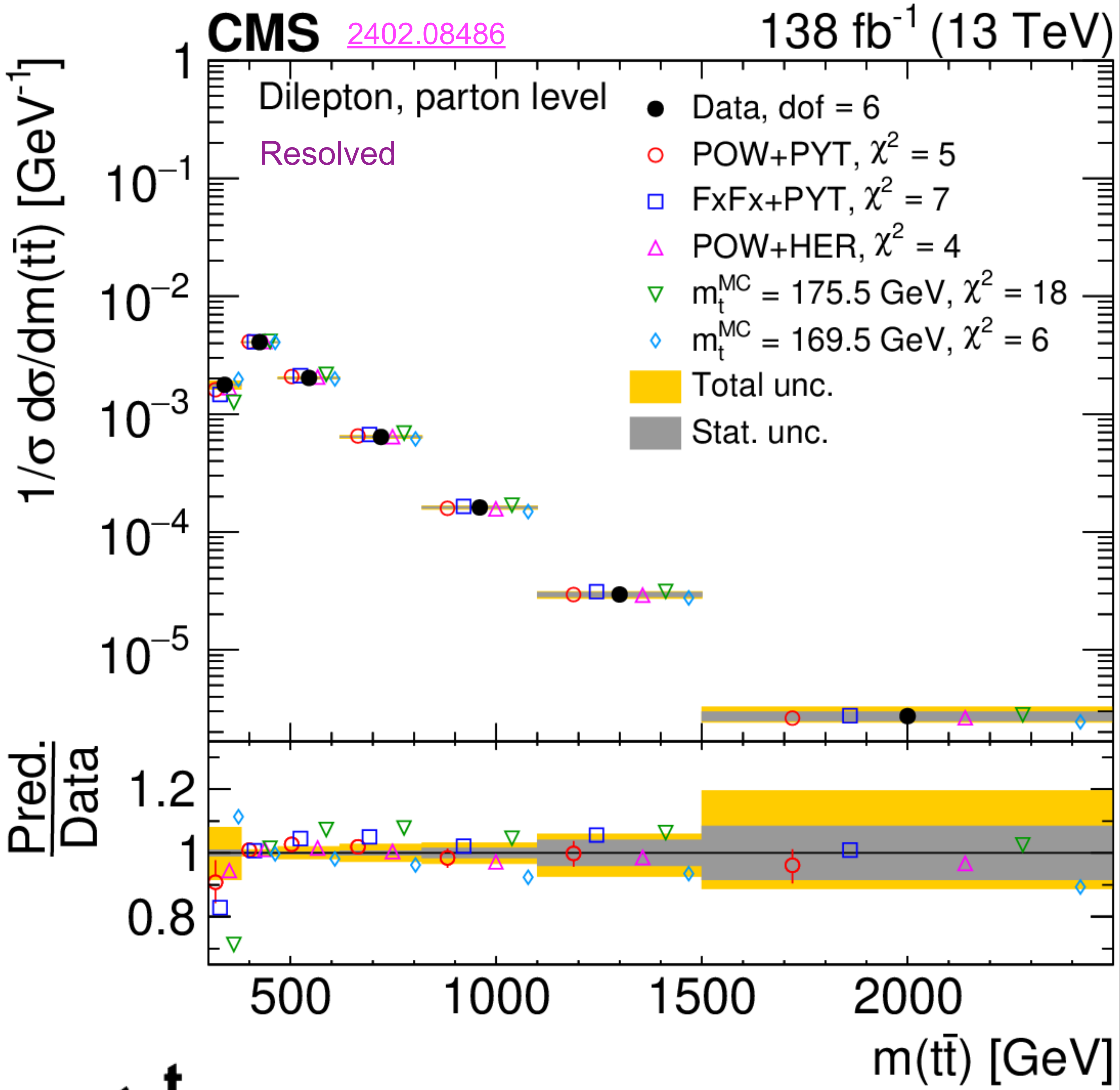


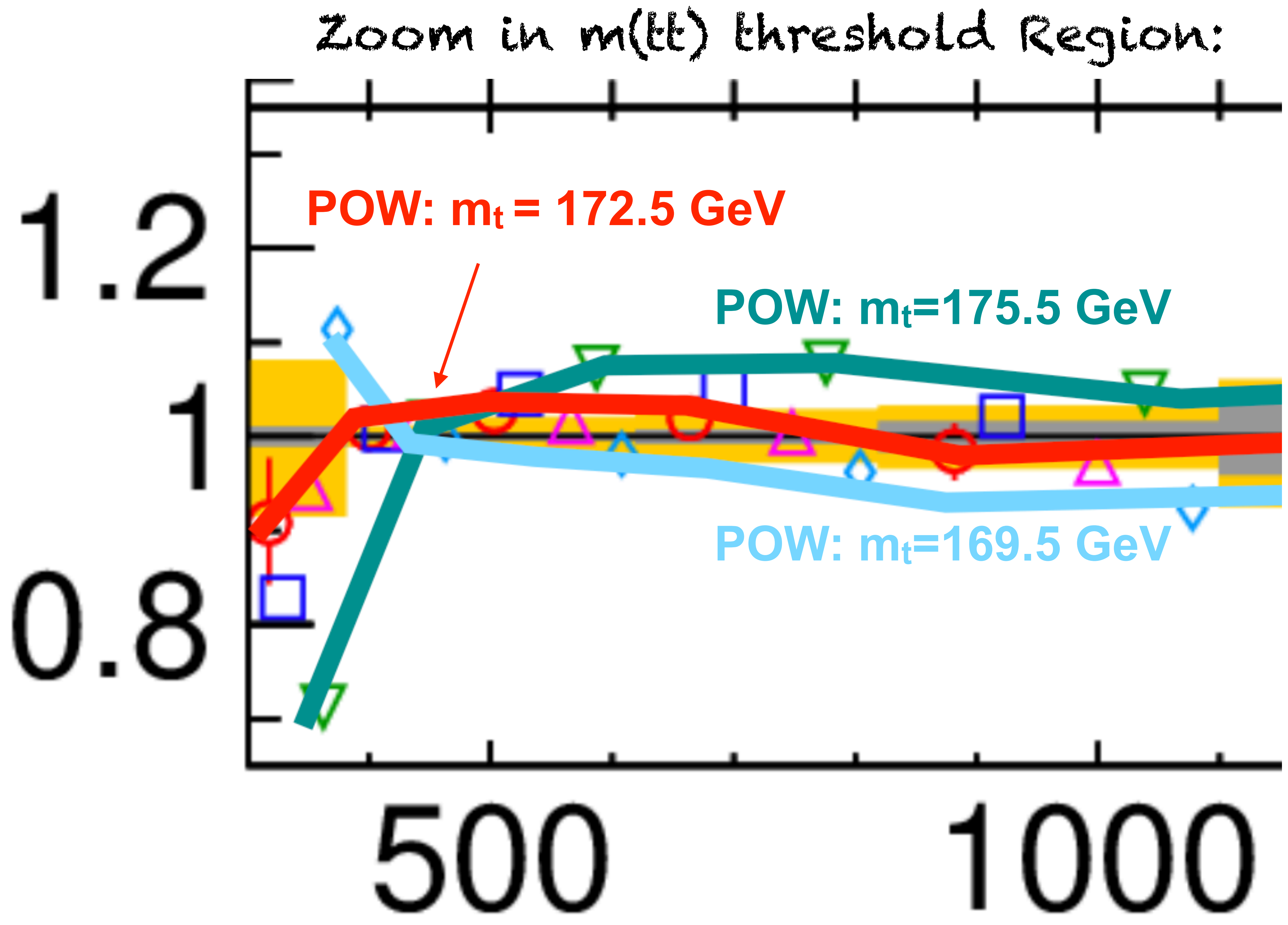
NNLO/ATLAS:

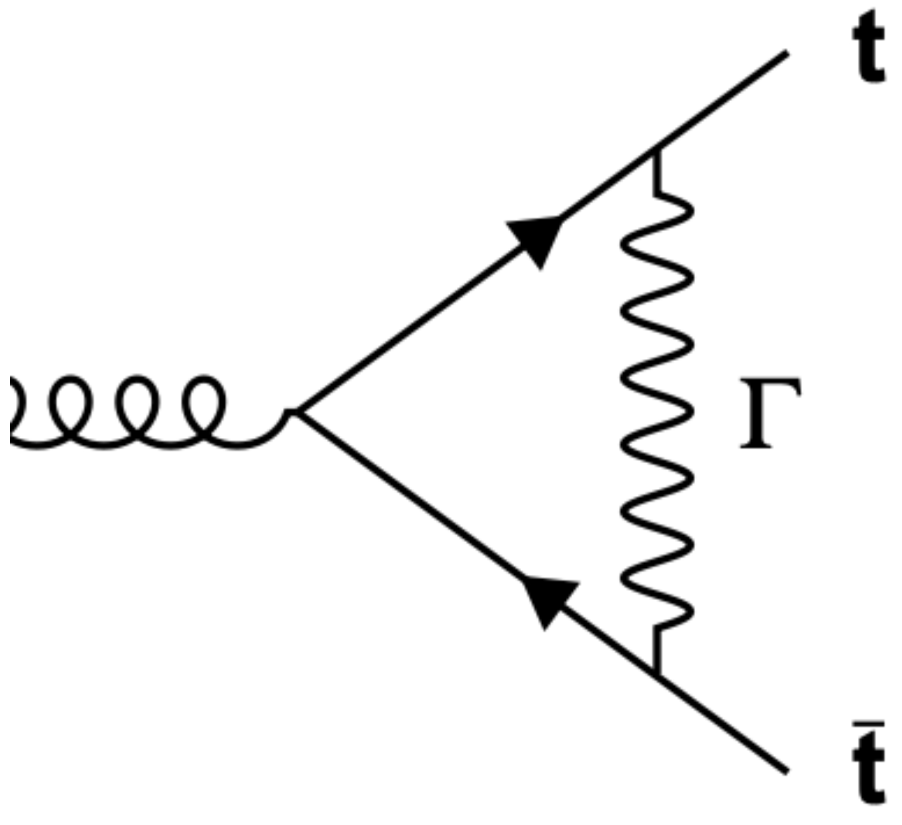
⇒ Both NNLO and POW exhibit some wiggles around the data

⇒ Need NNNLO

$m(t\bar{t})$







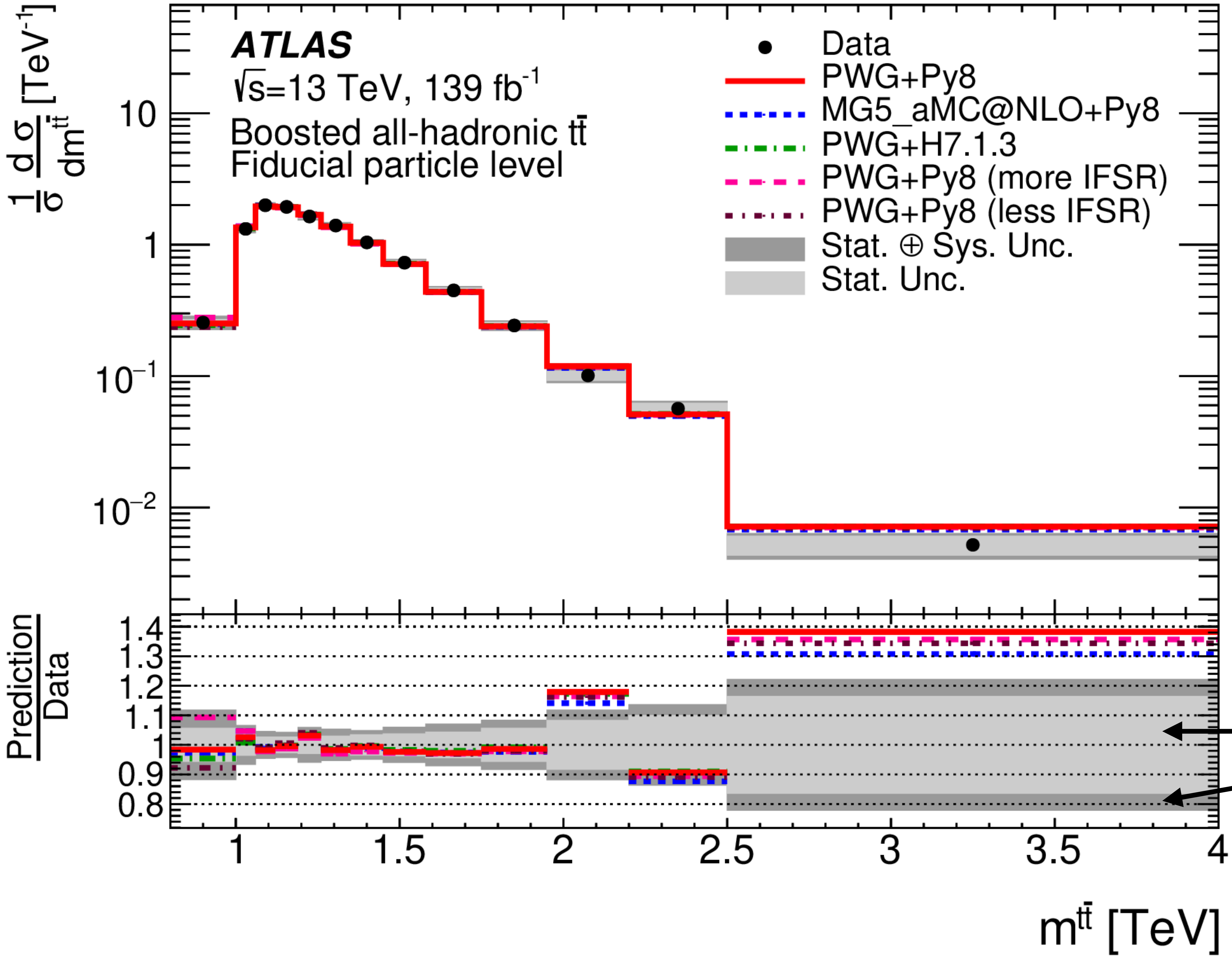
$m(t\bar{t})$ near $2 \cdot m_t$ threshold sensitive to:

- m_t ⟵ Let's focus on
- Top Yukawa coupling
- Soft/virtual gluons
- Toponium

⇒ ~o(1 GeV) sensitivity to top quark mass

See 2403.01313 for an overview of m_t measurement techniques

JHEP 04 (2023) 080

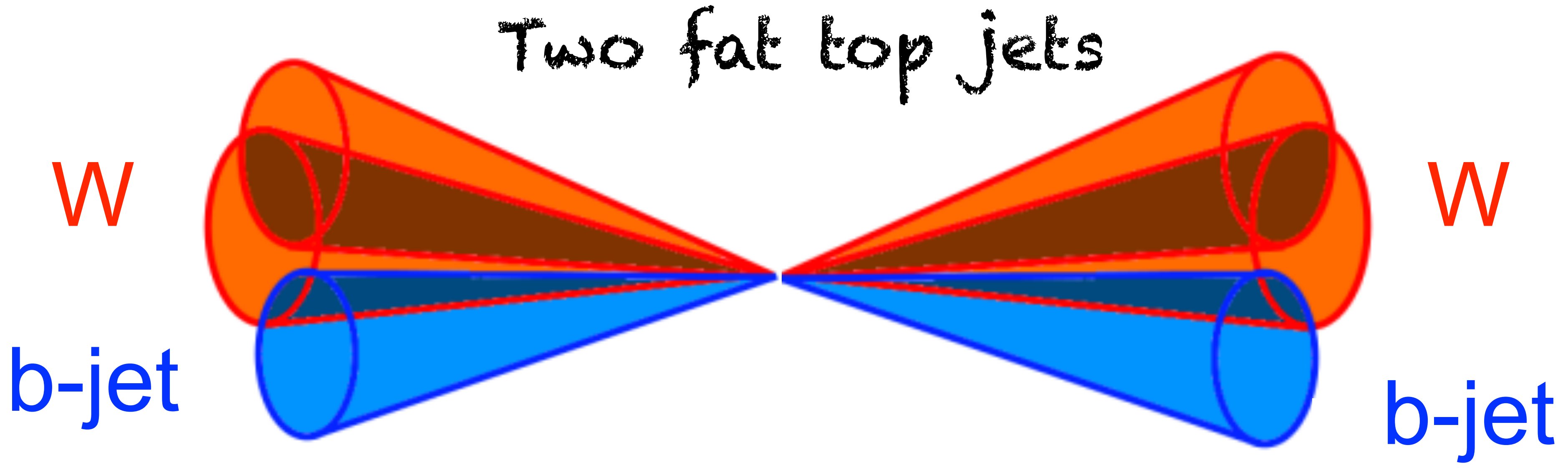


ATLAS

$m(t\bar{t})$

All had, Boosted

$P_T(t_1)>500$ GeV, $P_T(t_2)>350$ GeV



⇒ Exploring masses up to 4 TeV

⇒ Reasonable description by NLO+PS MCs

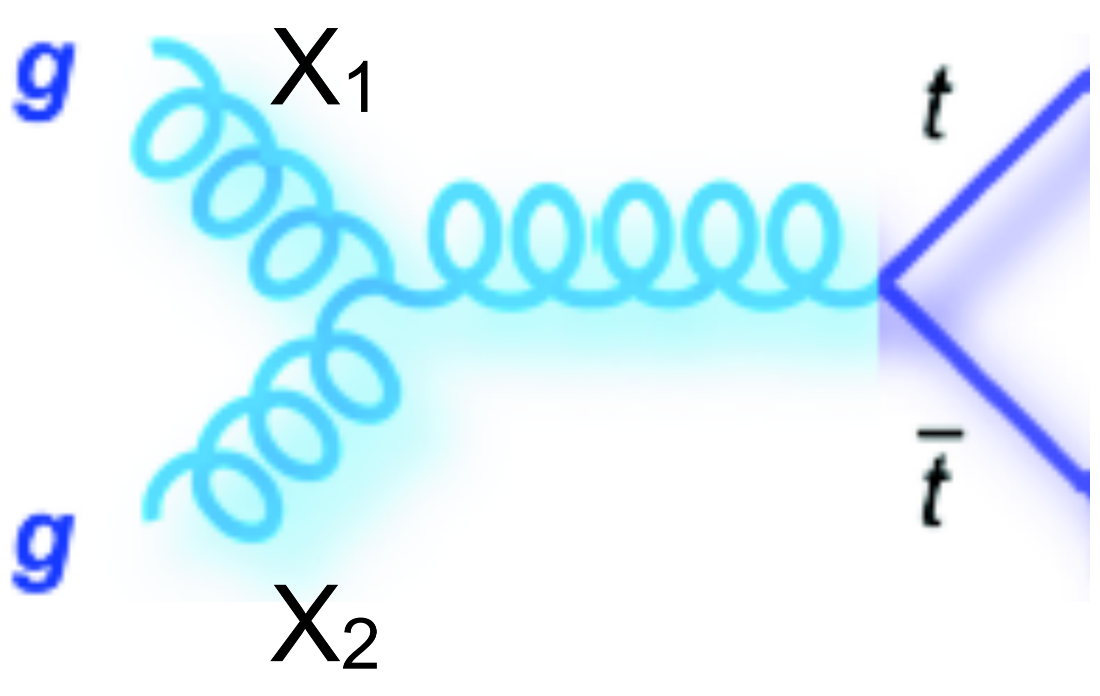
Dominant uncertainties:

- Statistical
- Boosted Top Tagger efficiencies

$y(t\bar{t})$

l+jets, Parton level

LO picture:

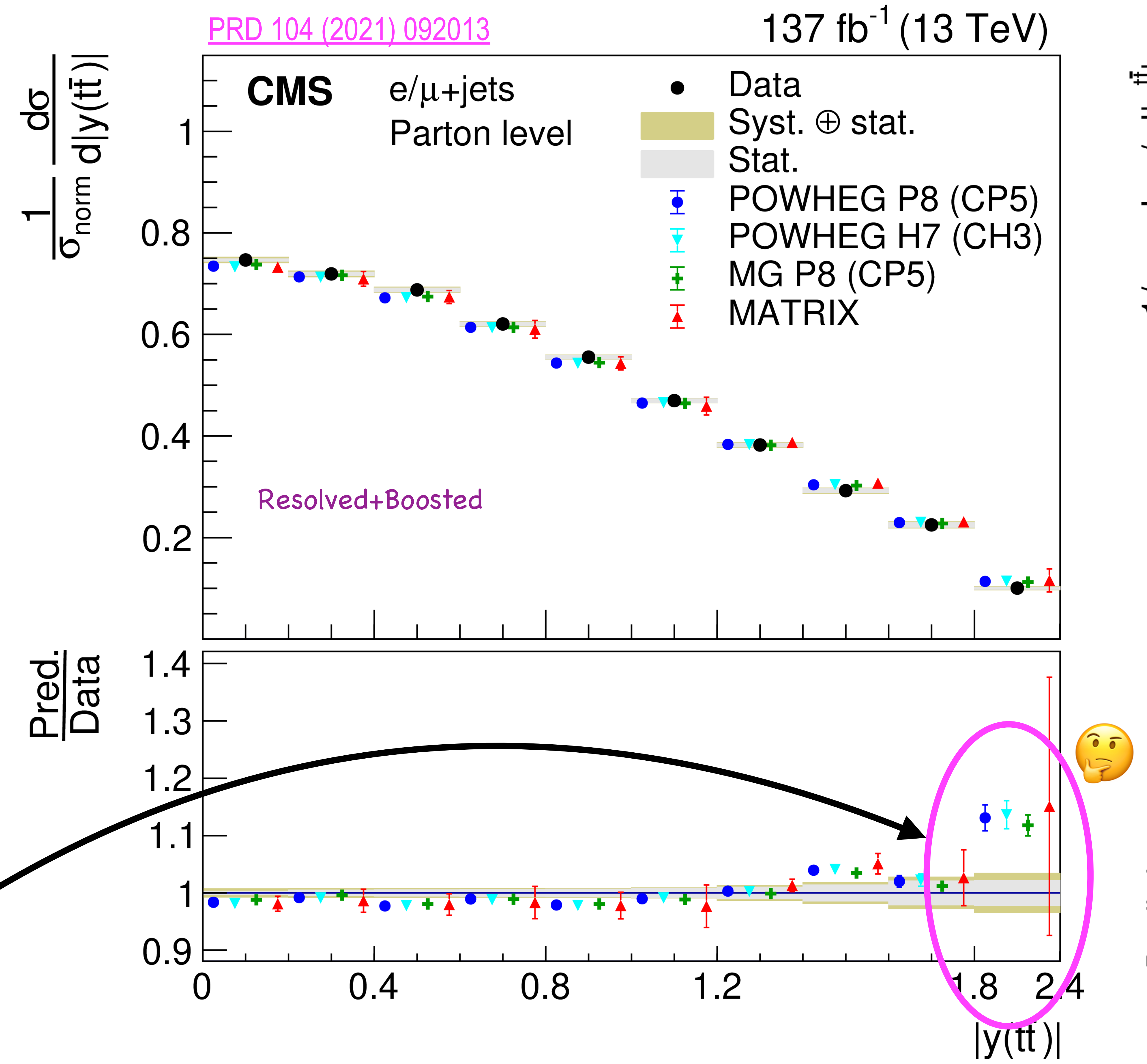


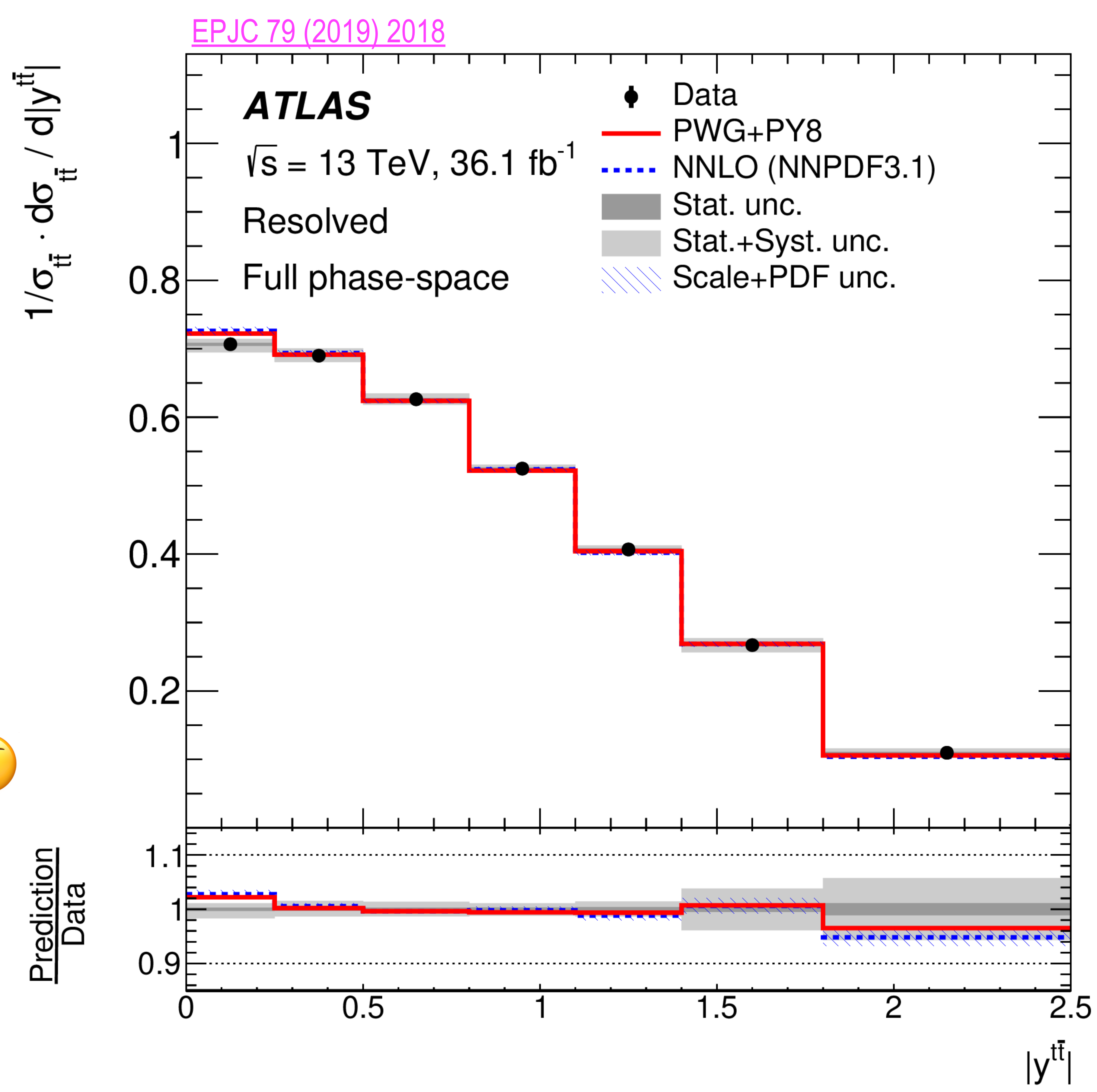
$$ln\left(\frac{x_1}{x_2}\right) = 2 \cdot y(t\bar{t})$$

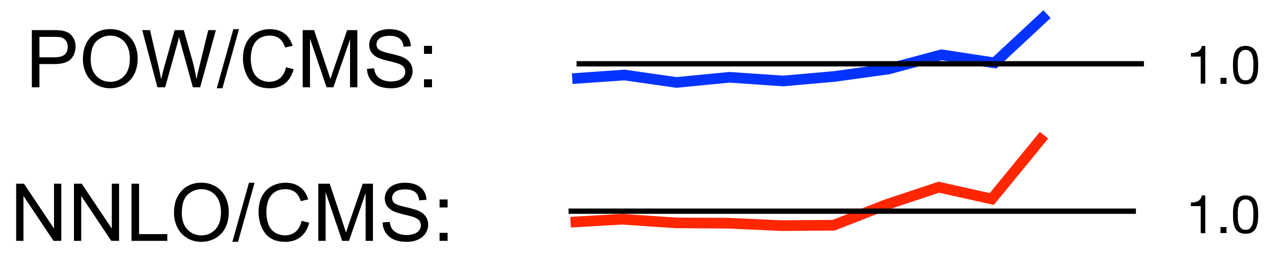
→ at high positive $y(t\bar{t})$

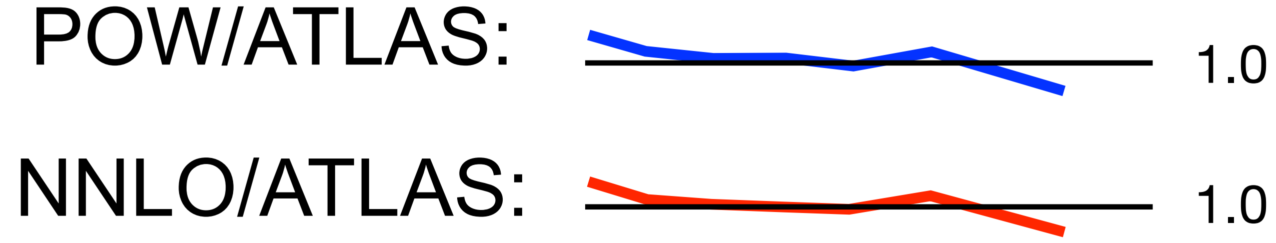
probing large x_1

⇒ sensitive to g(x)





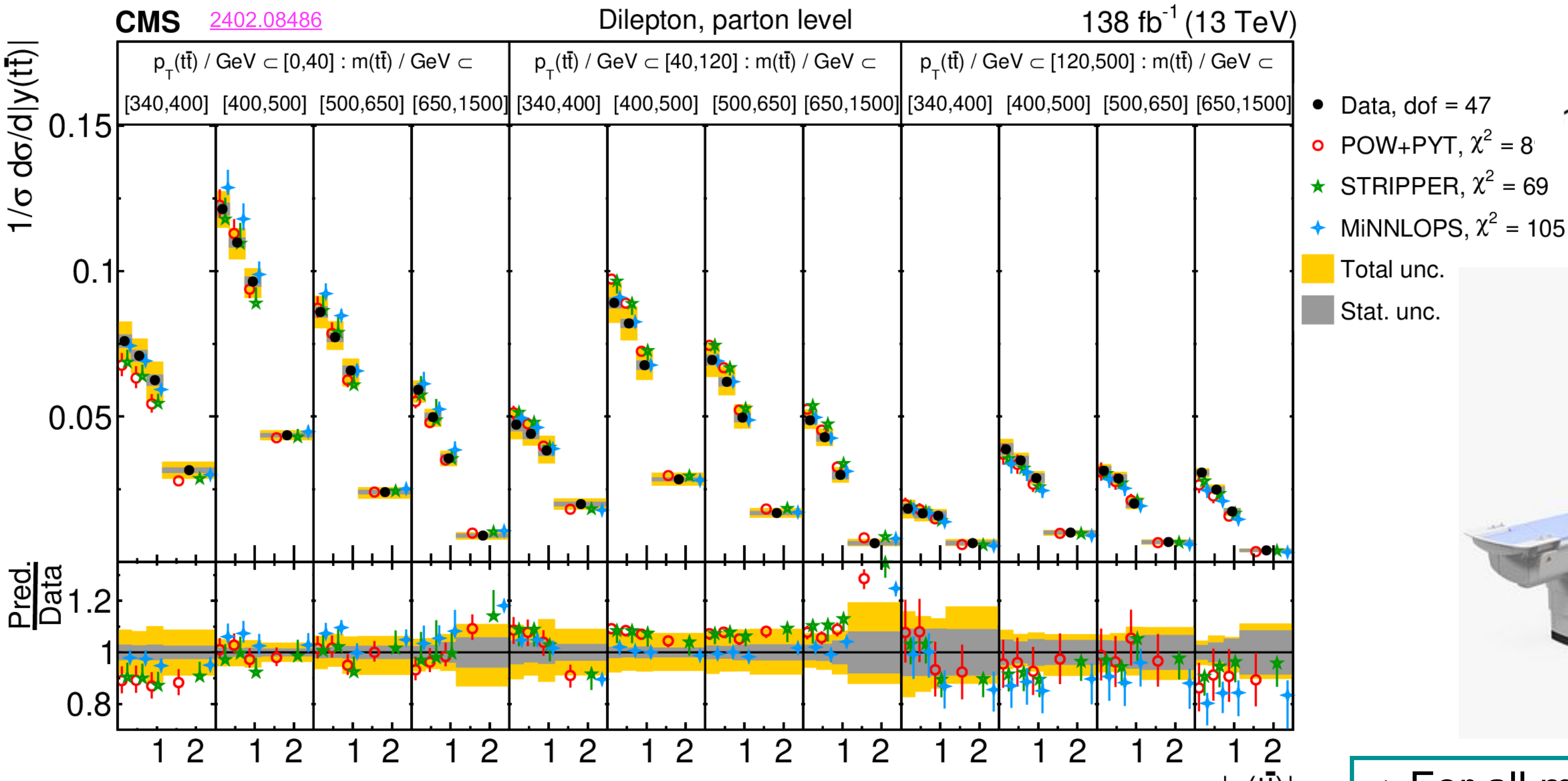


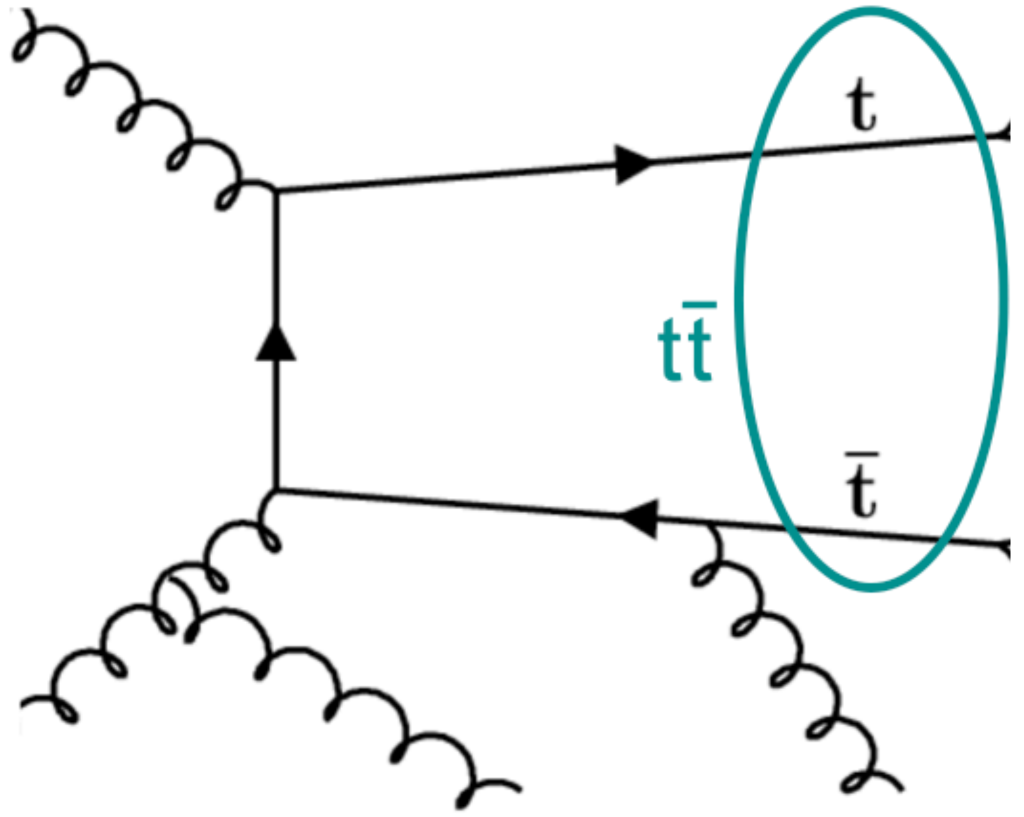


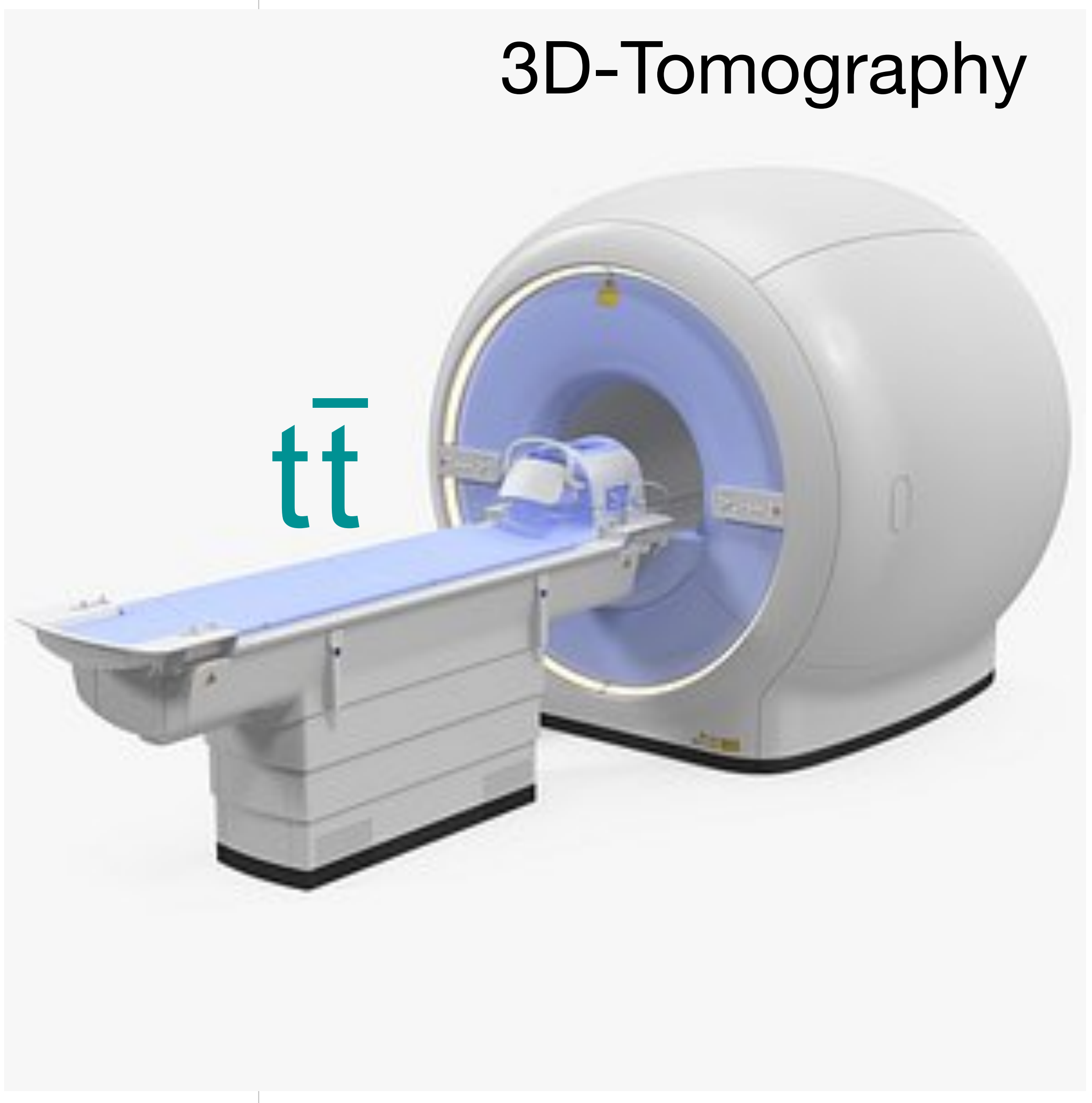
⇒ POW/NNLO describe Data mostly within 2% ⇒ Reasonable description

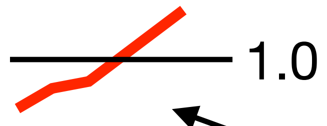
Dilepton, Parton level, Resolved

$y(t\bar{t})$ vs $m(t\bar{t})$ vs $p_T(t\bar{t})$







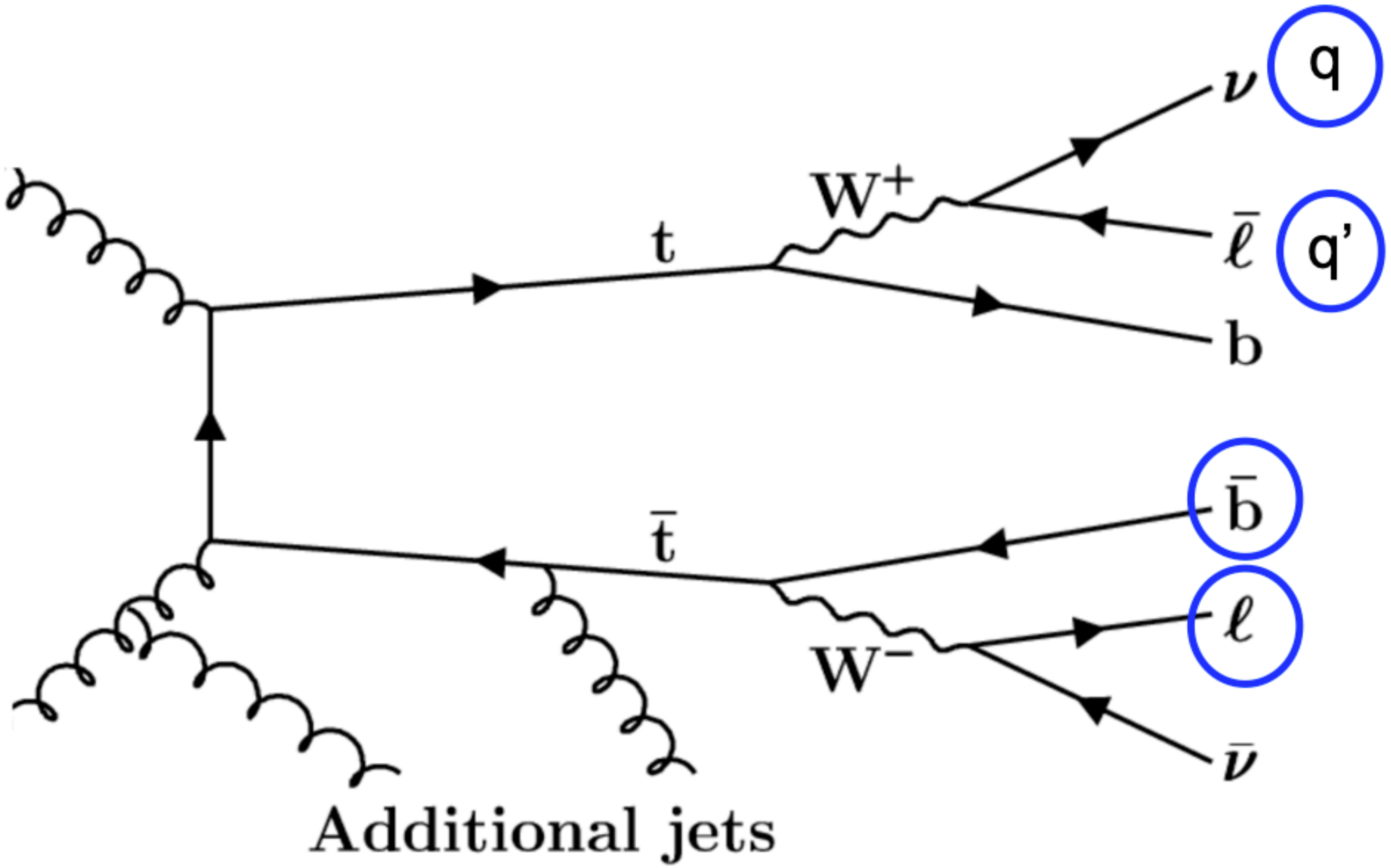


Example $y(t\bar{t})$ distribution at small $pT(t\bar{t})$, large $m(t\bar{t})$
POW/CMS positive slope

⇒ For all models: clearly some local trends visible vs Data

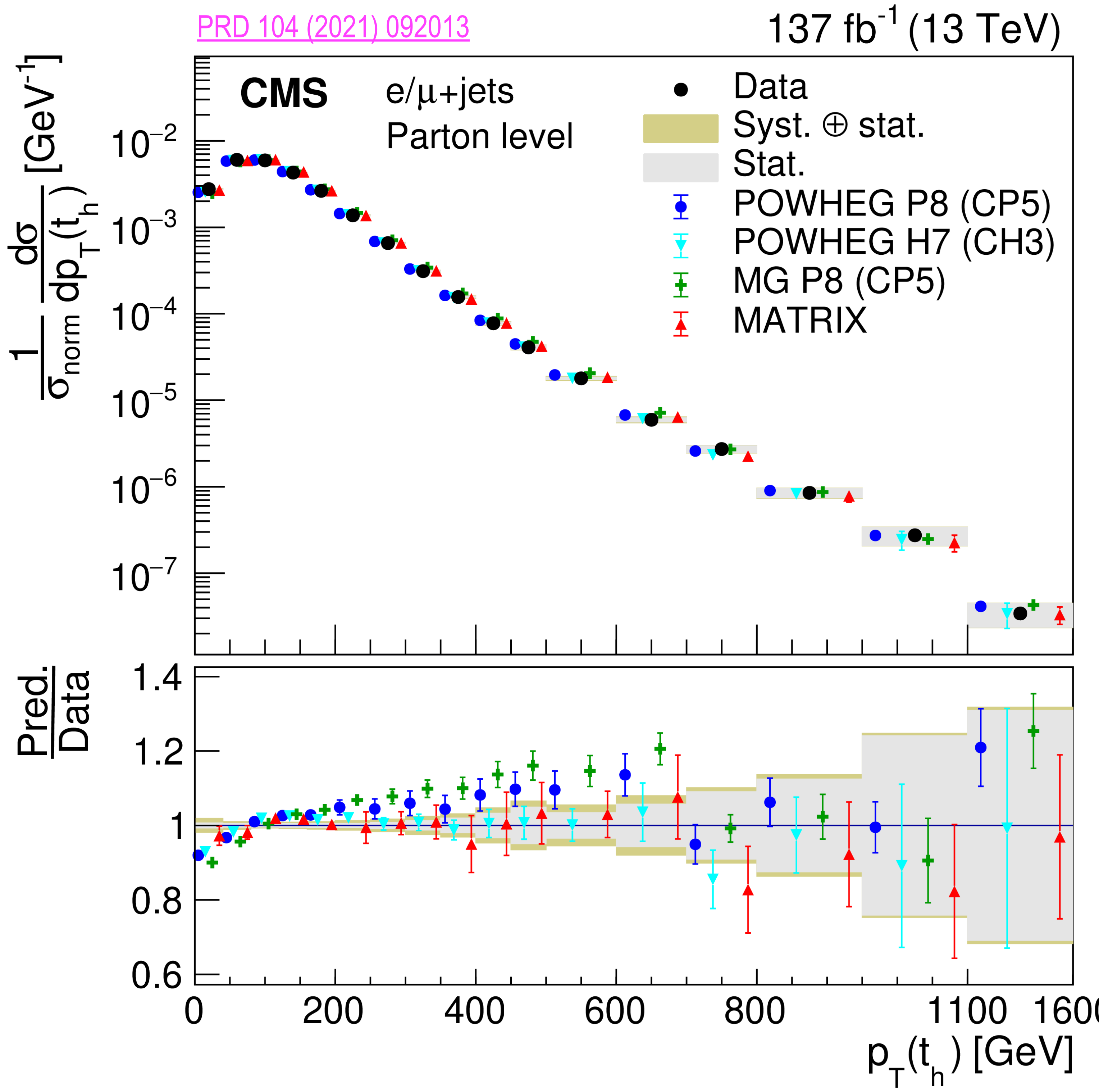
Results:

Decay particles: l,b,q,q'

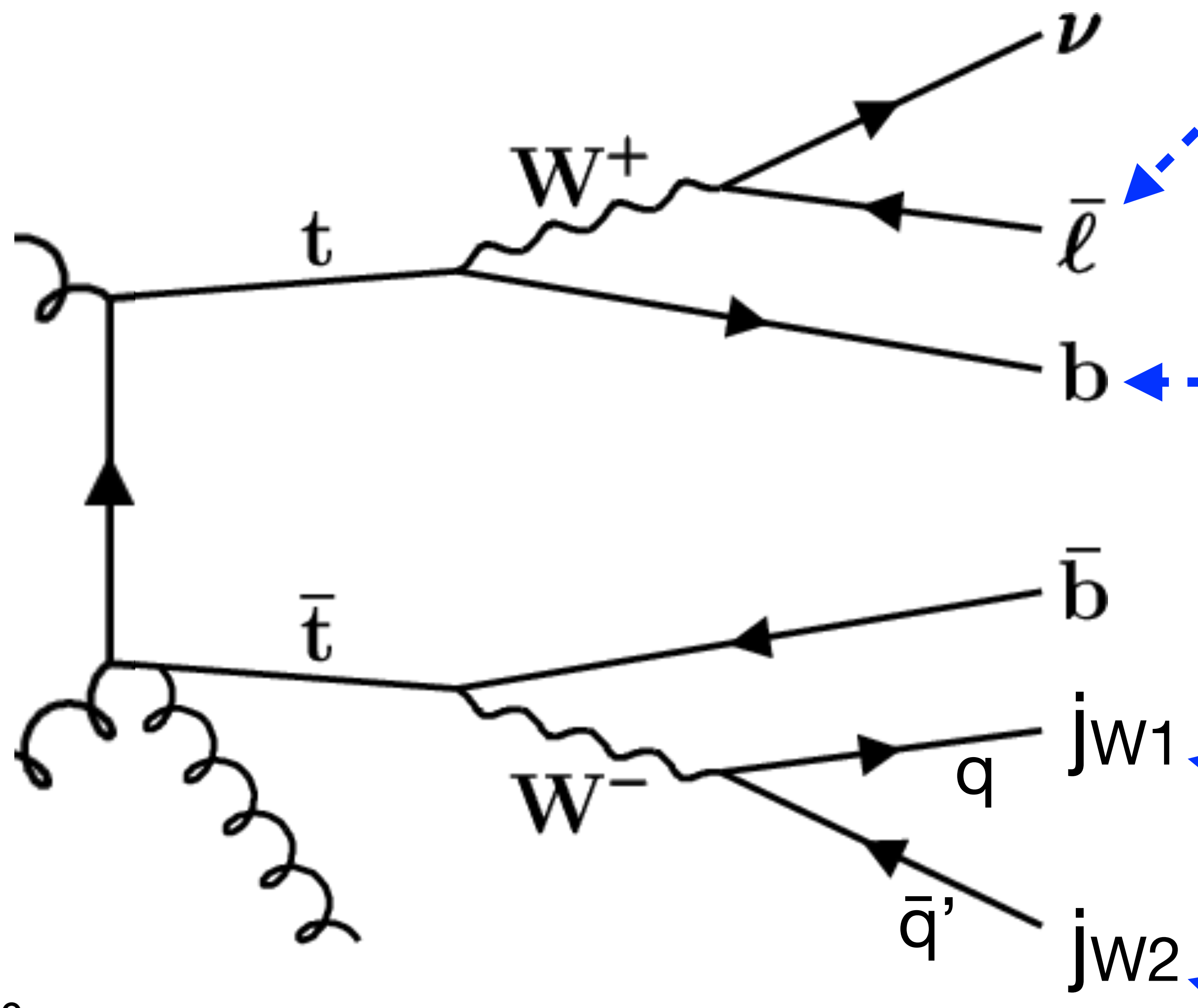


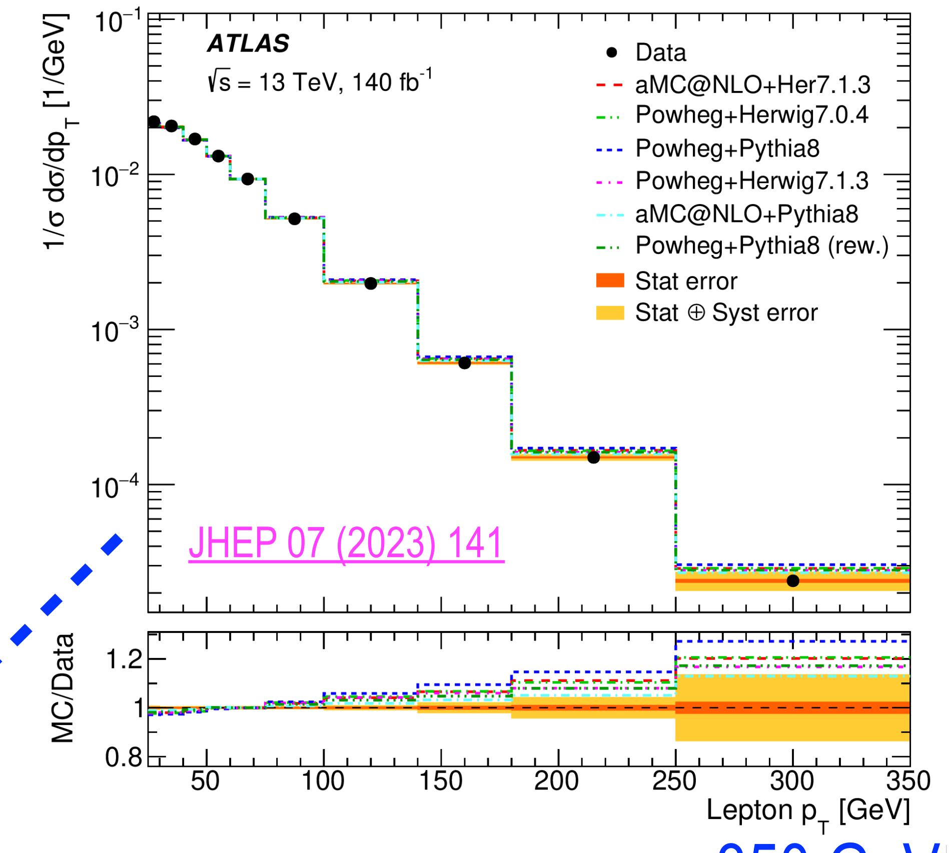
Probing dynamics of
tt̄ production ⁂ decay

p_T of top and daughter particles

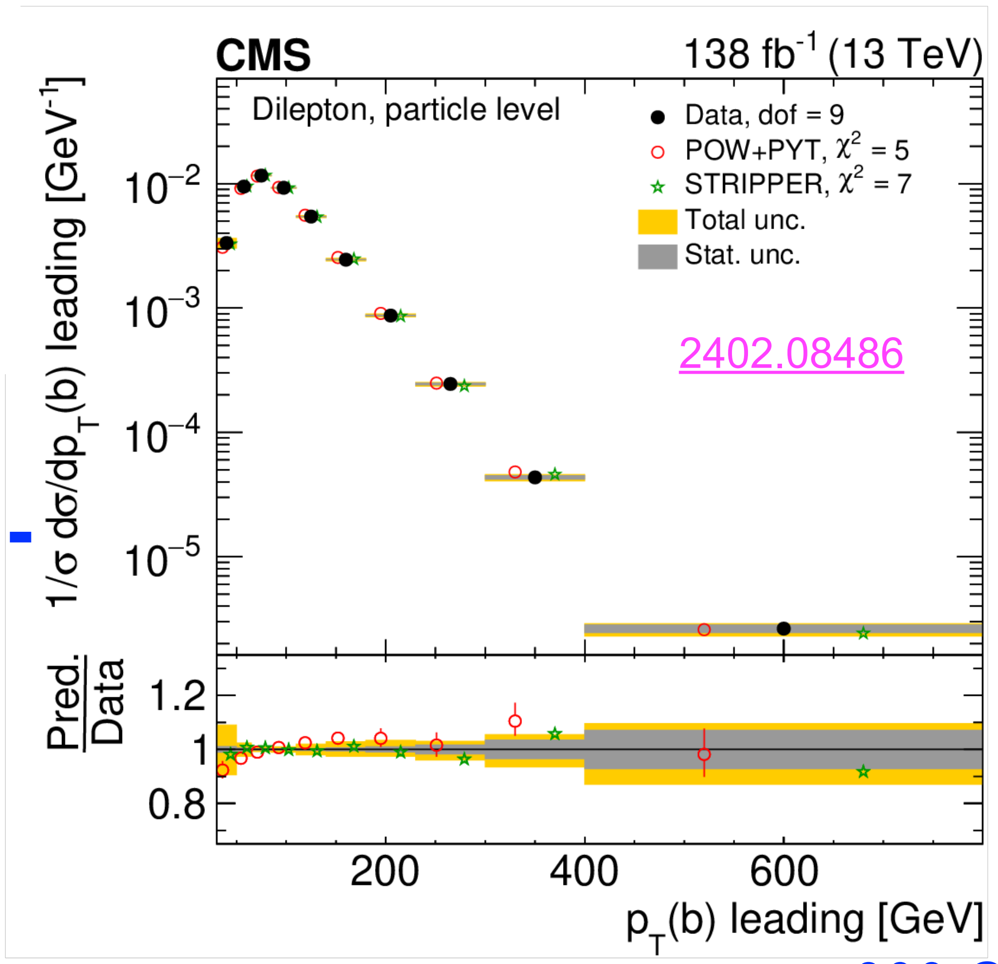


1600 GeV

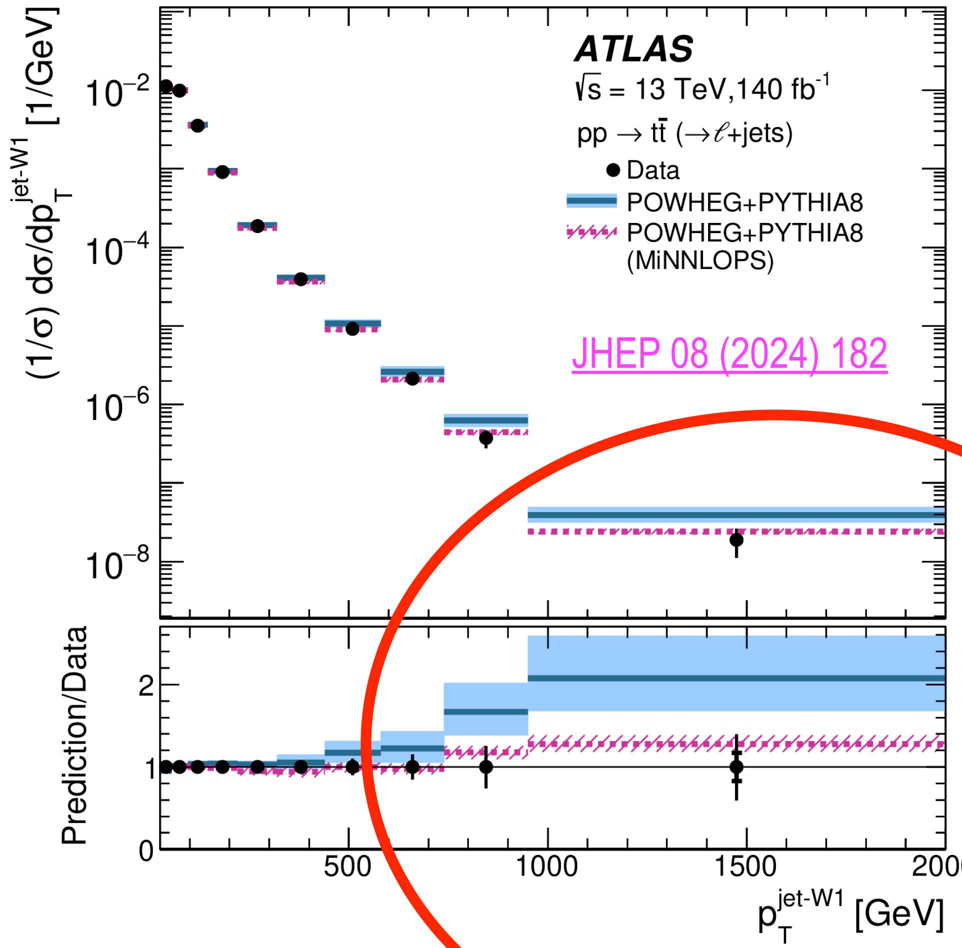




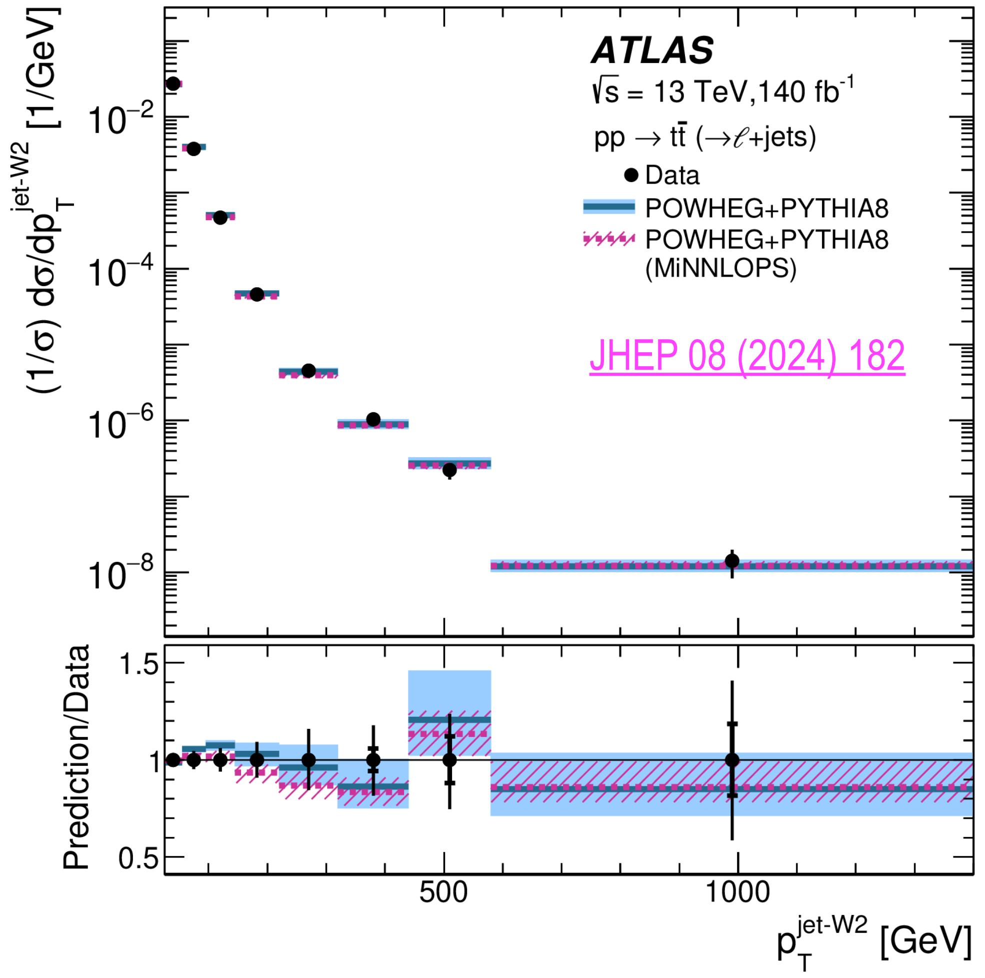
350 GeV



800 GeV



2000 GeV



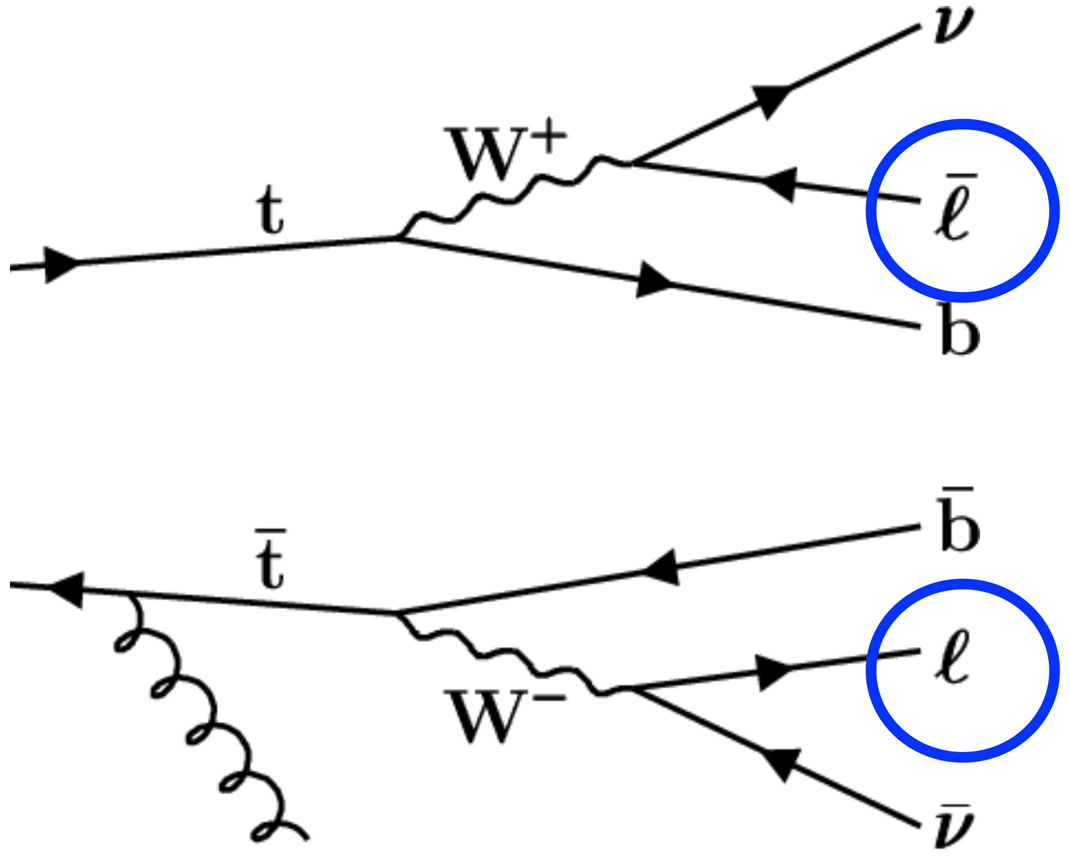
1400 GeV

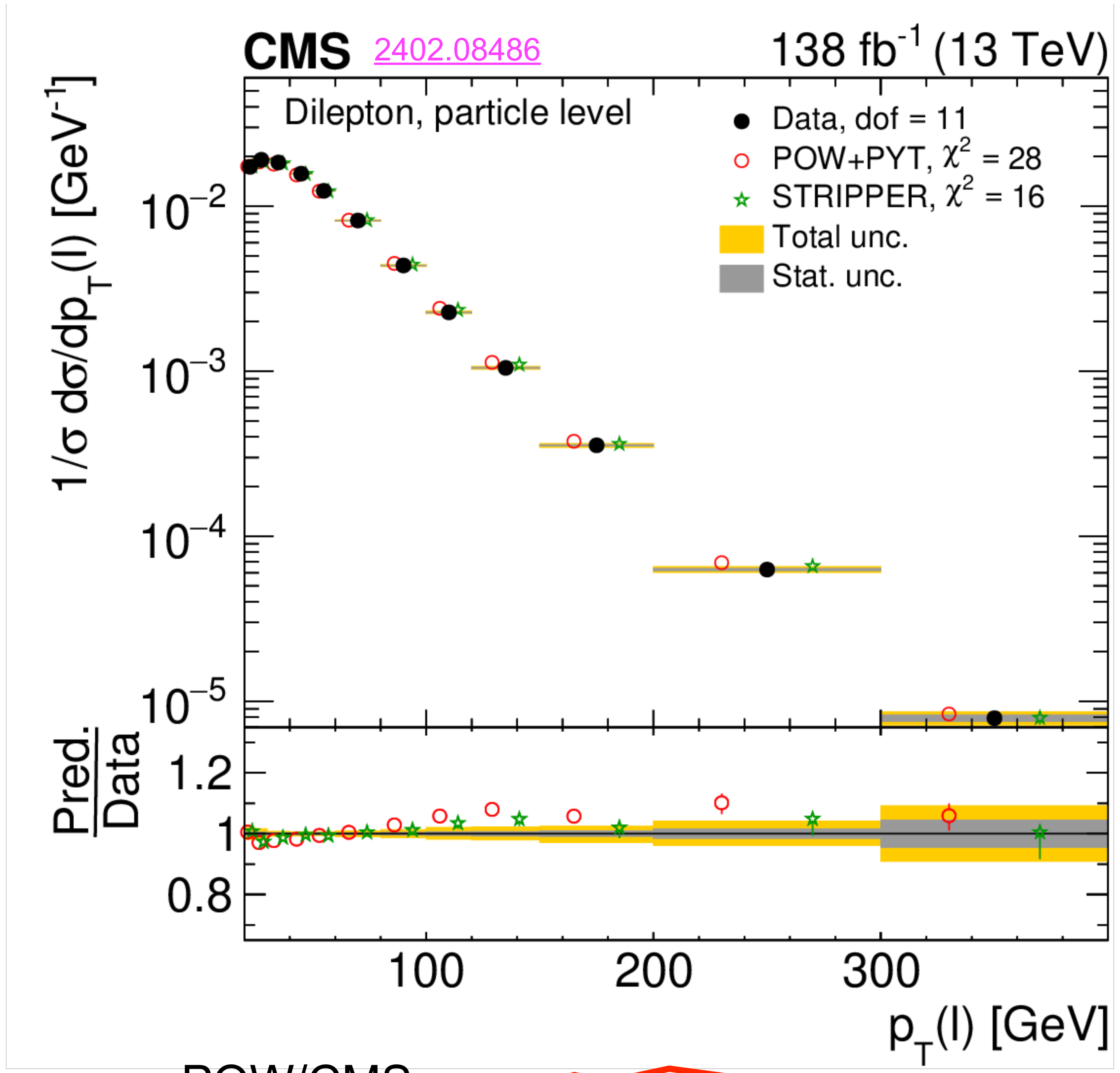
⇒ All particles inherit top positive Pow/data P_T slope except jW2

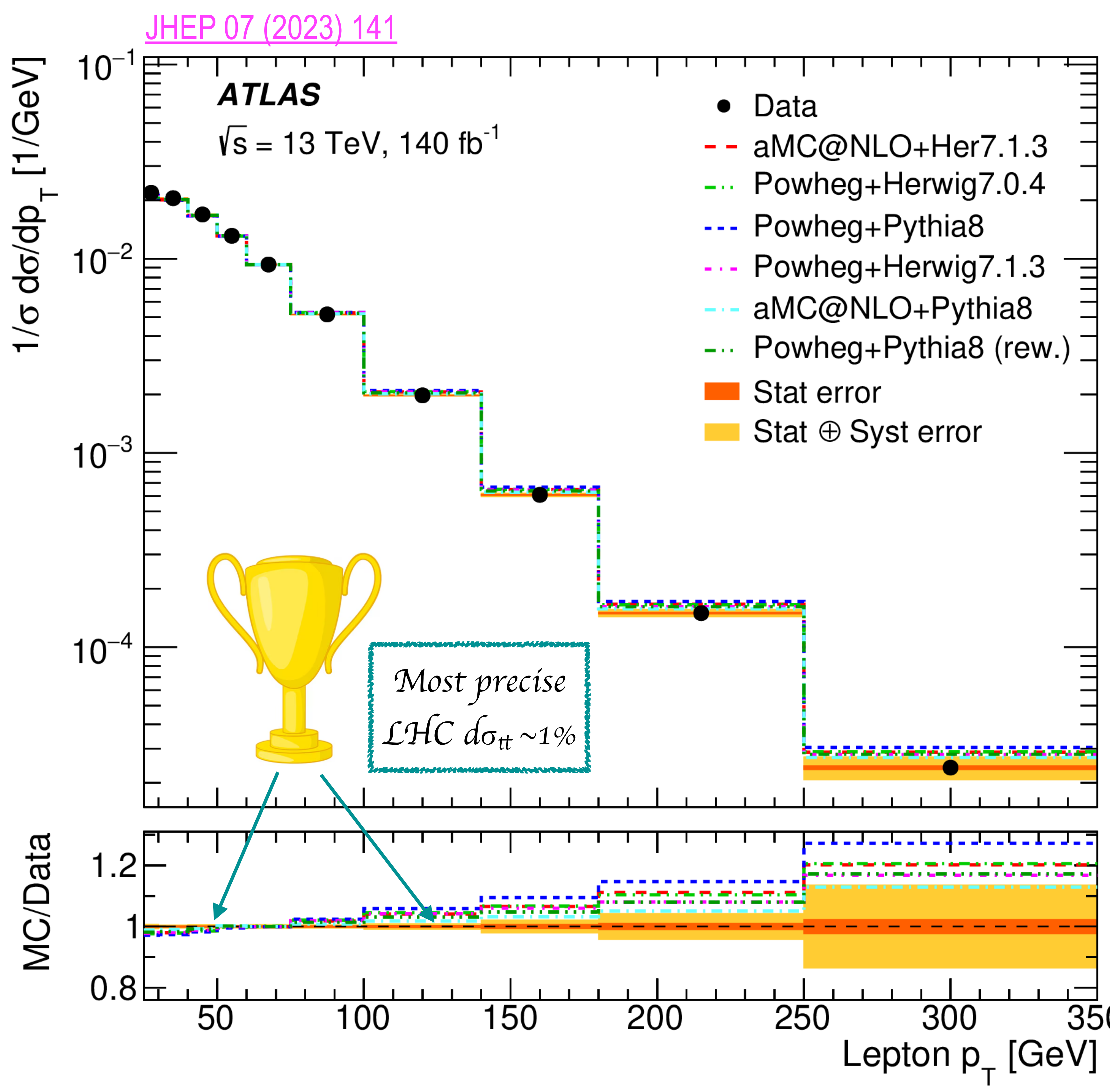
Should do more such high jet pT analyses!

$p_T(l)$

Dilepton, Particle level, Resolved

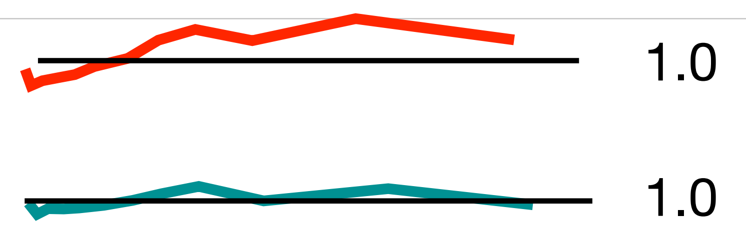






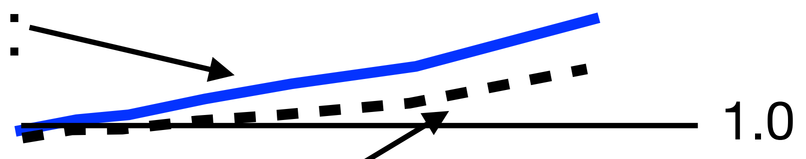
POW/CMS:

NNLO/CMS:

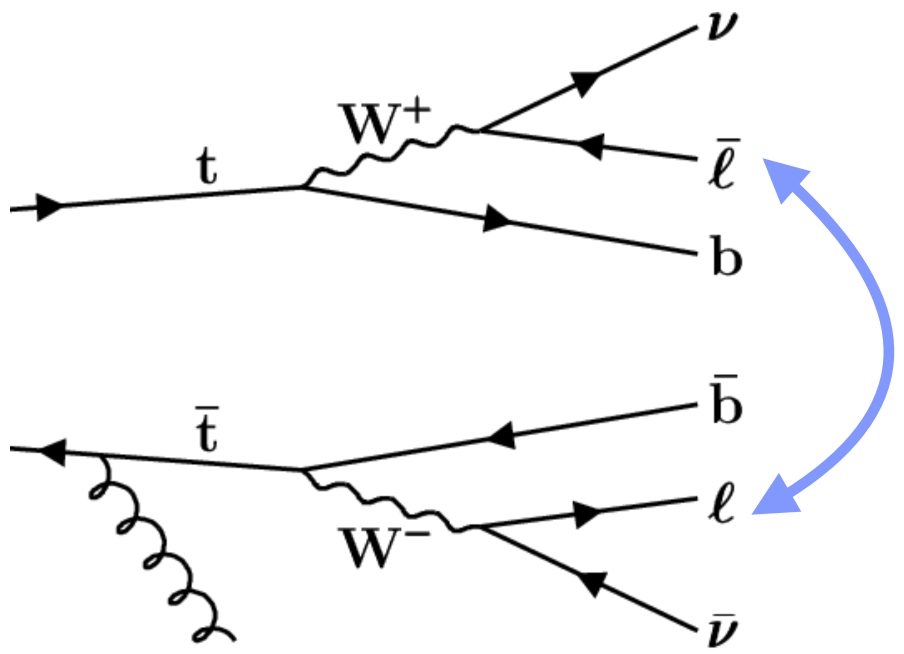


POW/ATLAS:

NNLO rw. POW/ATLAS:



⇒ NNLO seems to improve the description



$|\Delta\Phi^{e\mu}|$

Dilepton, Particle level, Resolved

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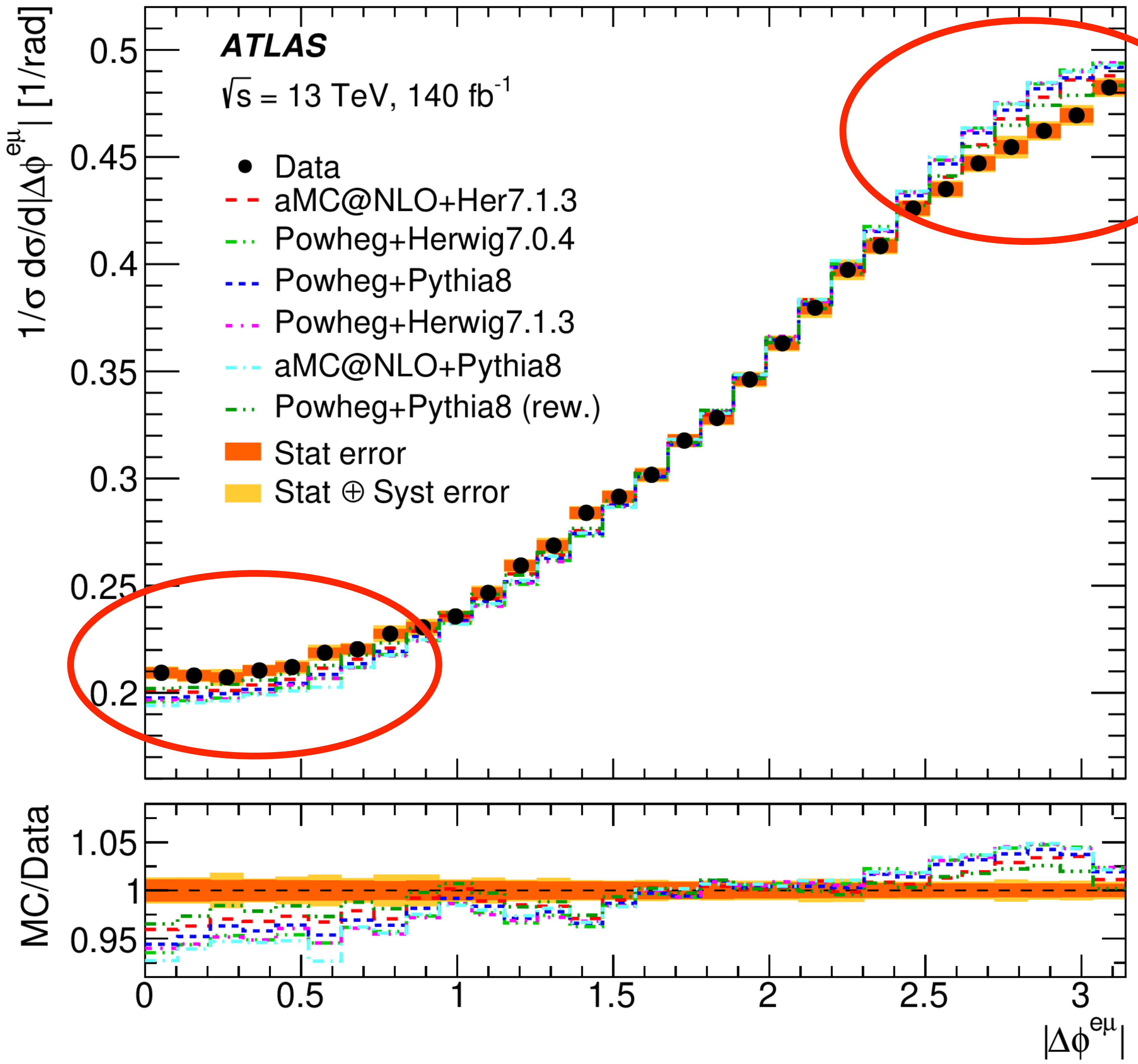
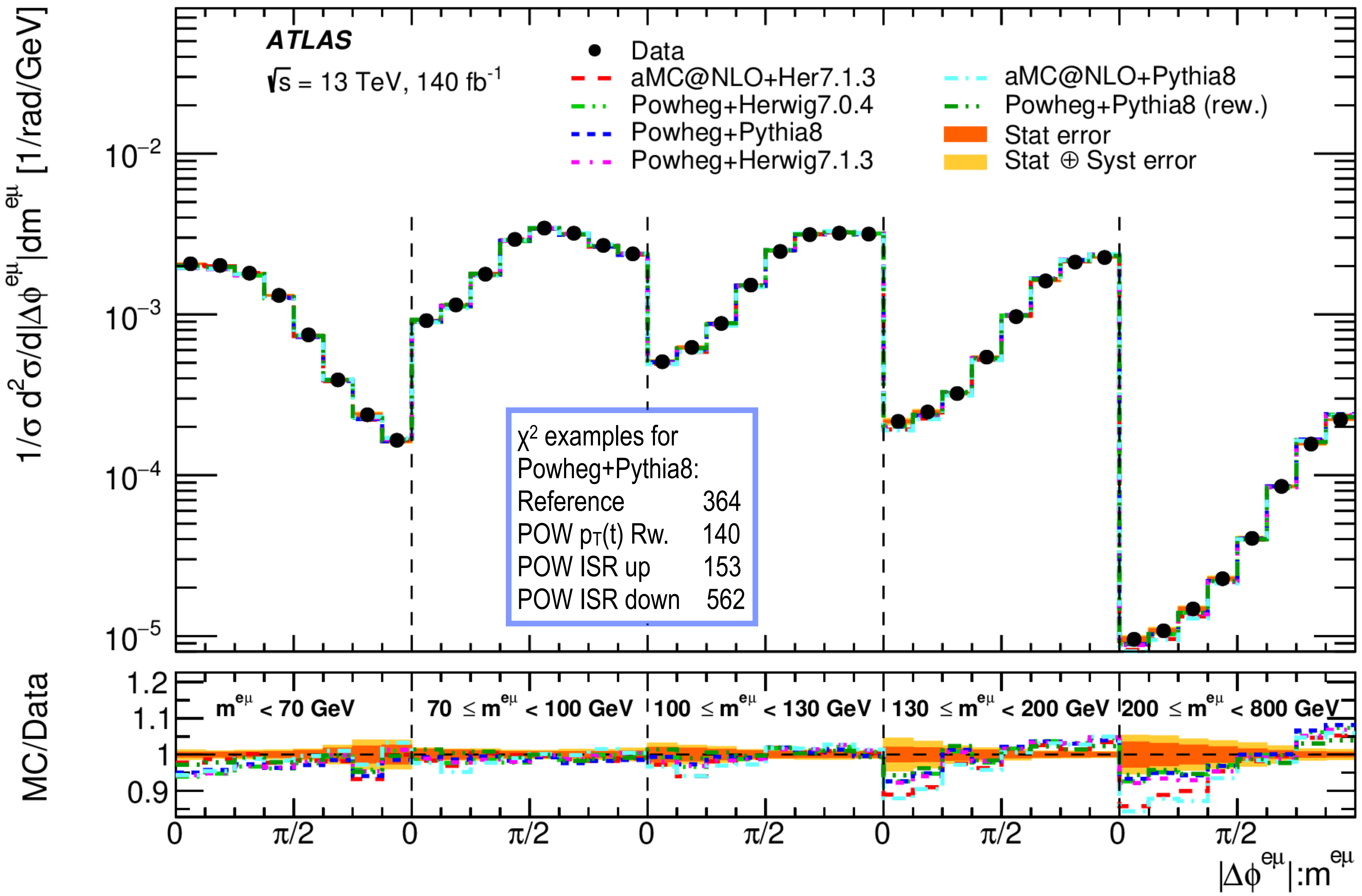
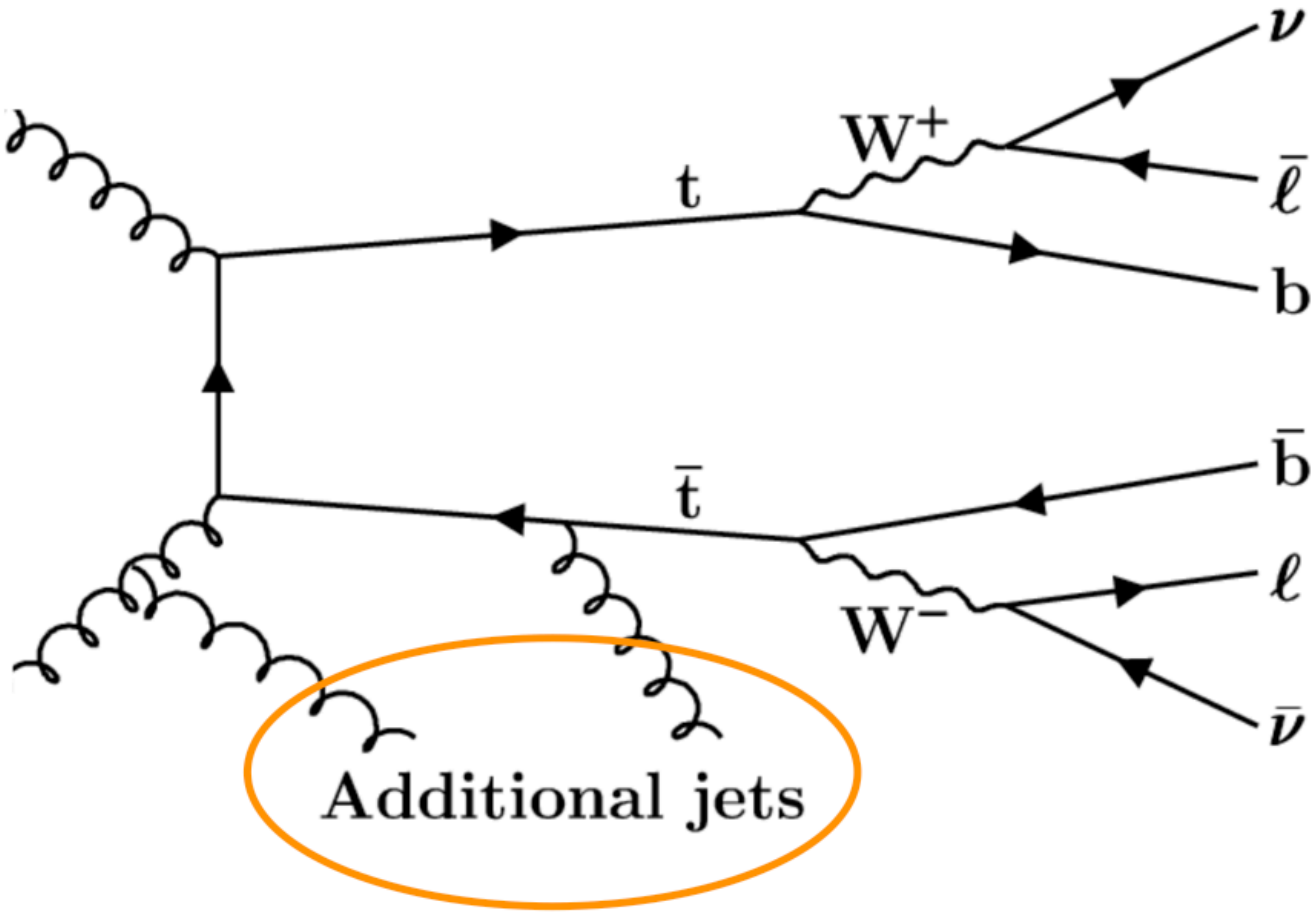




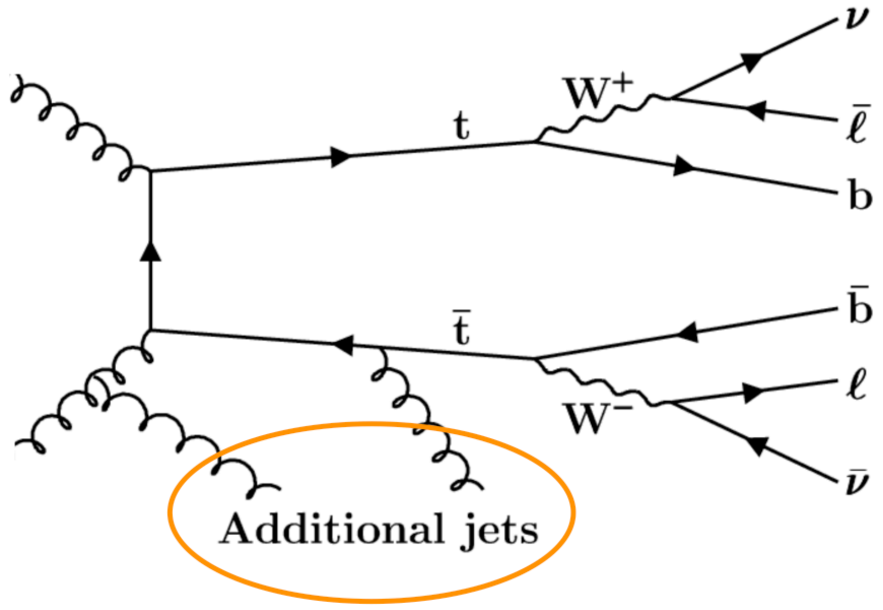
⇒ All models predict more back-to-back leptons than seen in data

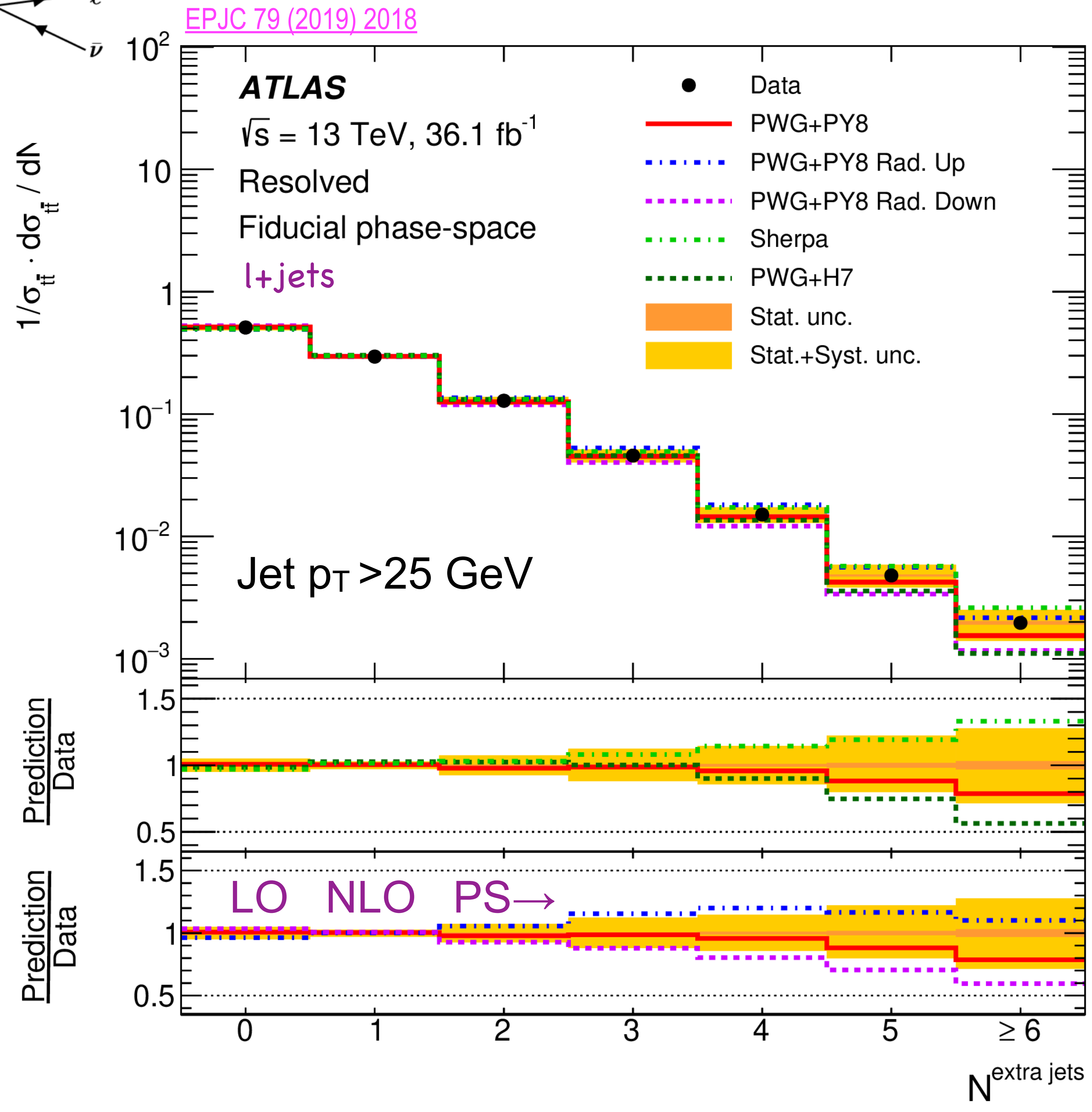
⇒ Double differential xsec $|\Delta\Phi^{e\mu}|$: $m^{e\mu}$ is among the ones described worst → MC Tuning potential!

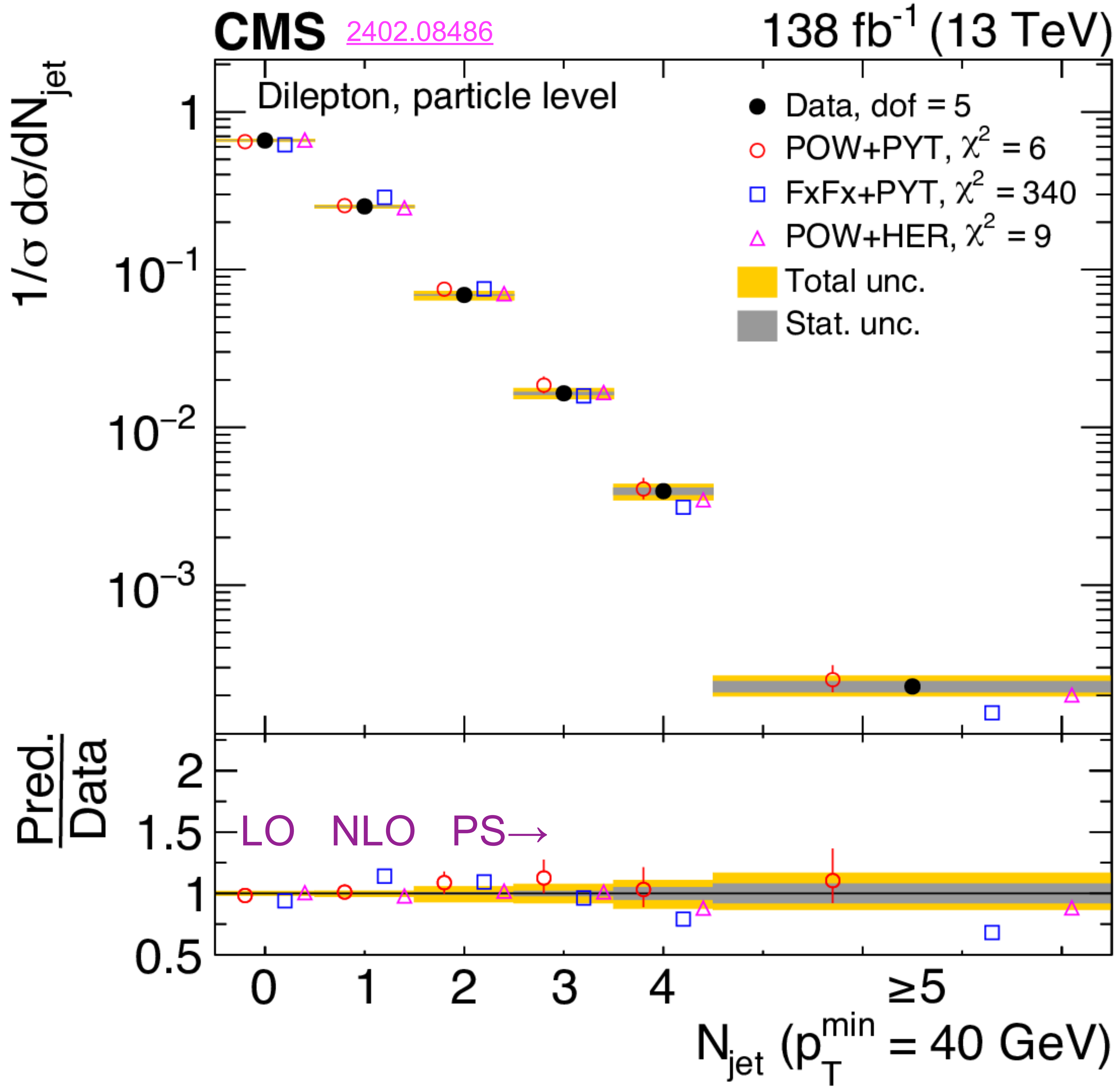
Results:



$N^{\text{extra jets}}$



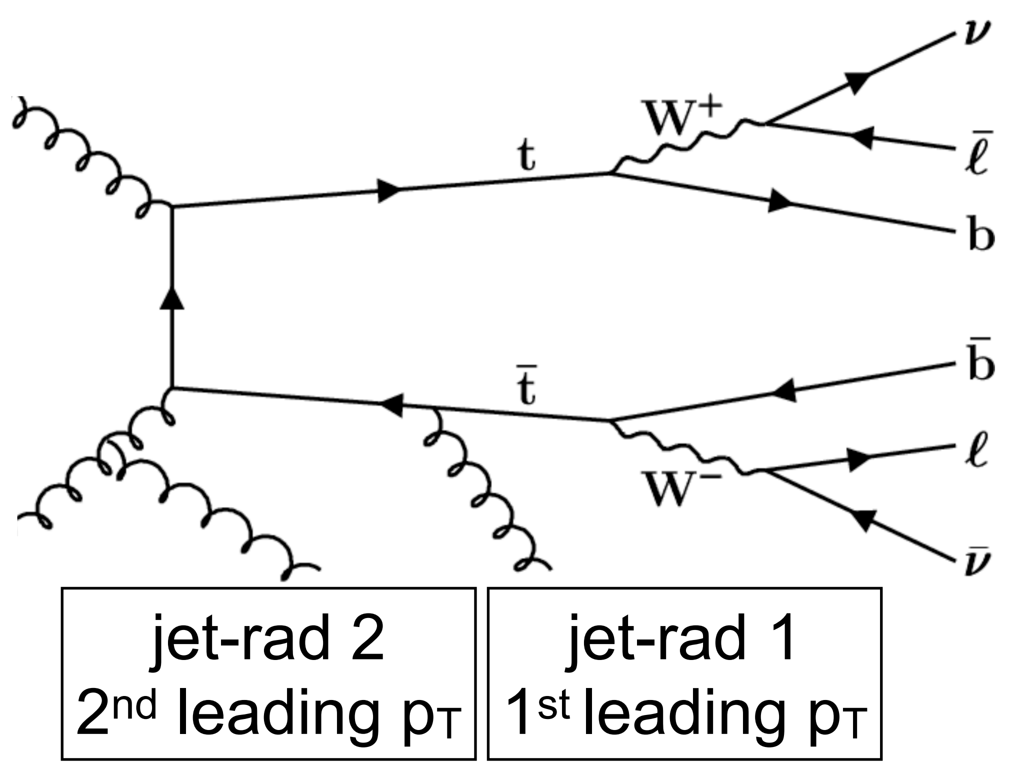


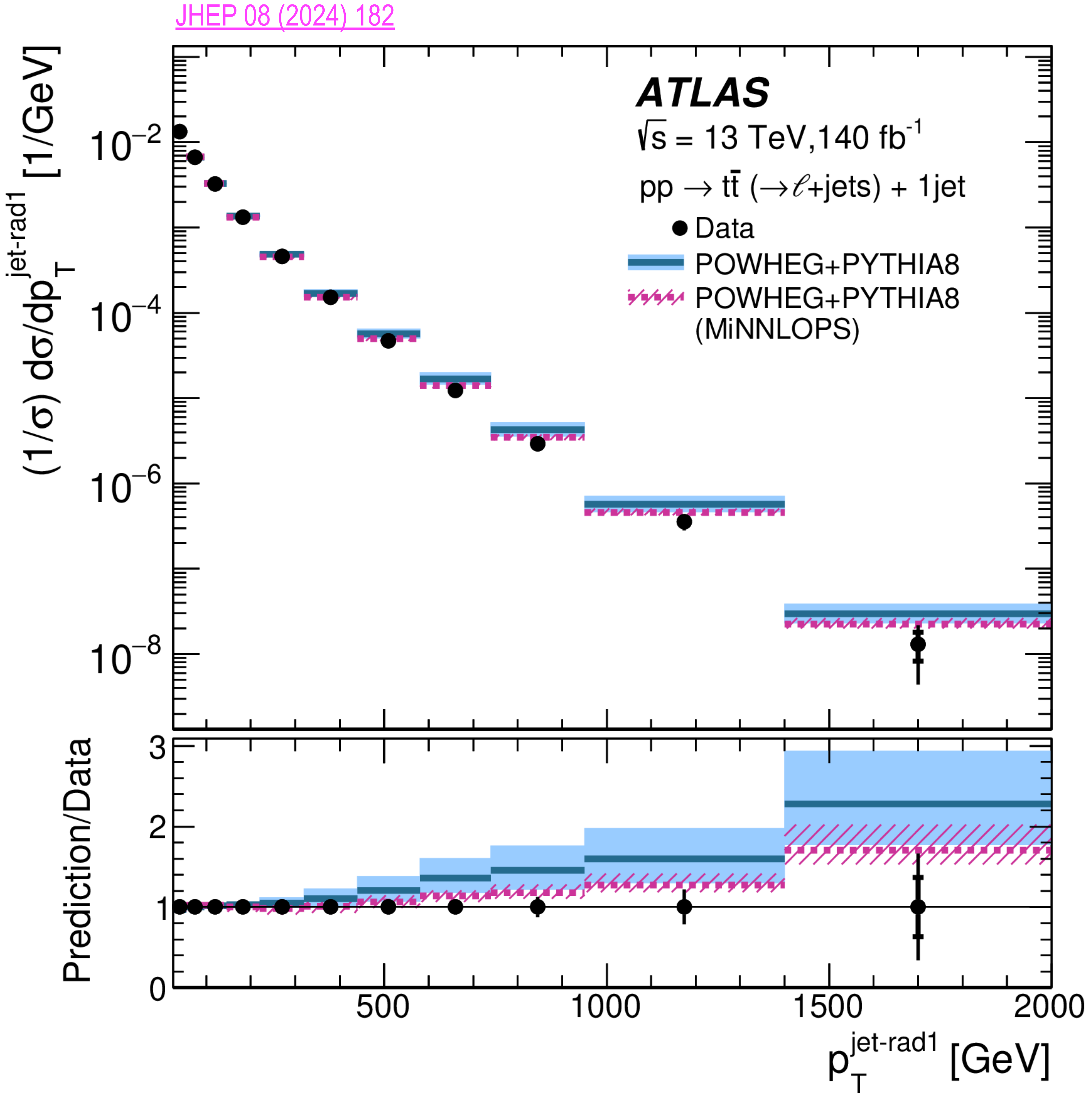


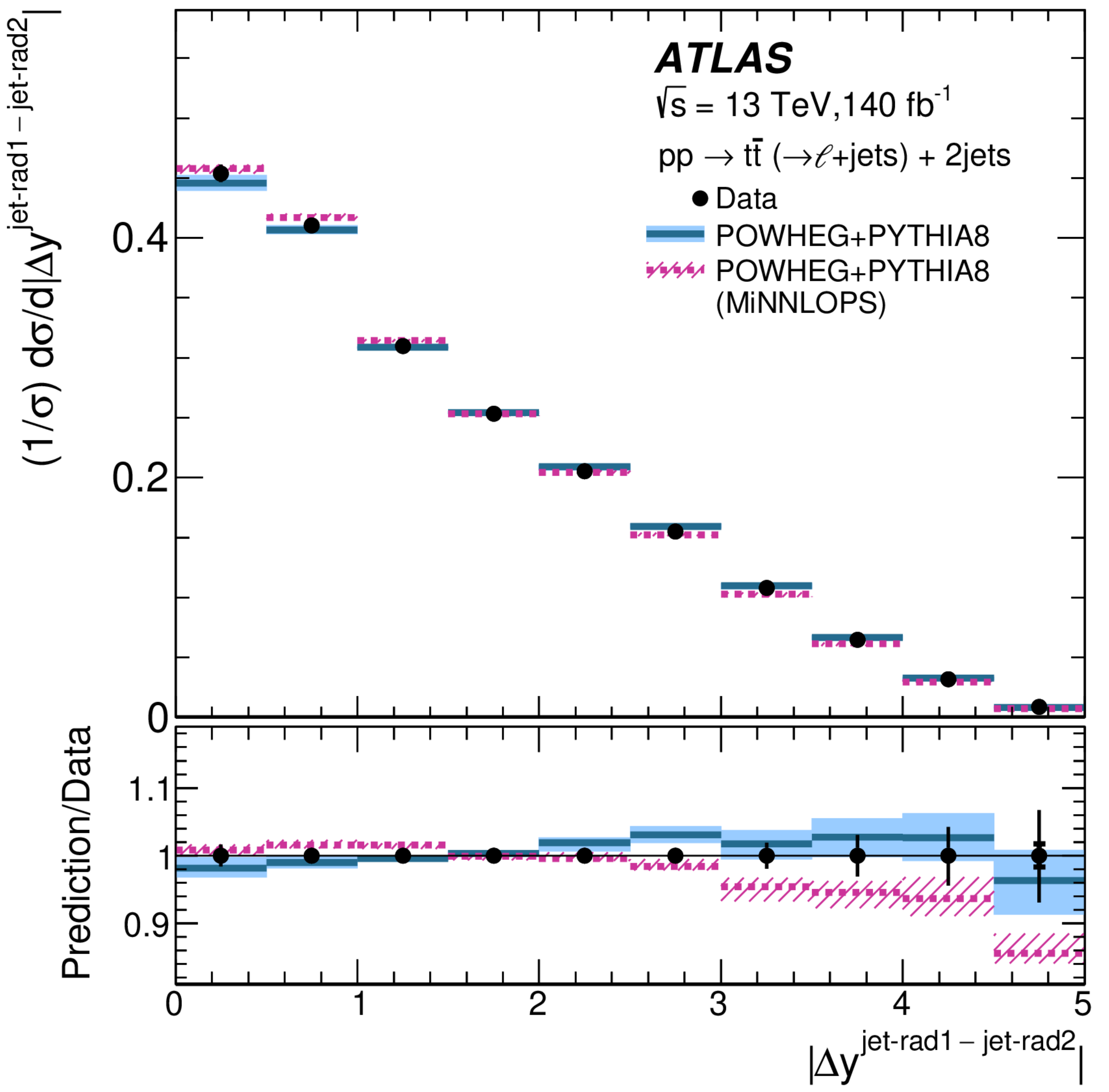
⇒ Excellent description by POW, maybe also because MC tunes were tested against earlier ATLAS & CMS $t\bar{t}$+jet data?

$p_T^{\text{jet-rad1}}$

$|\Delta y^{\text{jet-rad1 - jet-rad2}}|$







⇒ MiNNLOPS:

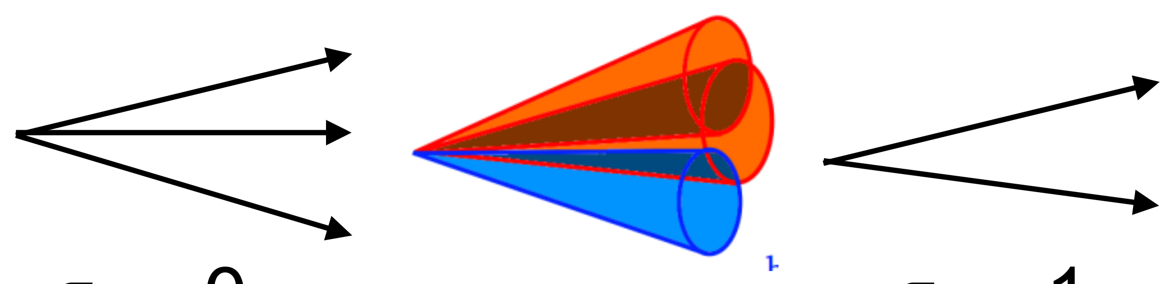
- improves leading jet p_T description
- fails in the rapidity separation to the 2nd leading jet: that is an $o(\alpha_s^4)$ observable

Looking even deeper into $t\bar{t}$ events: particle flow

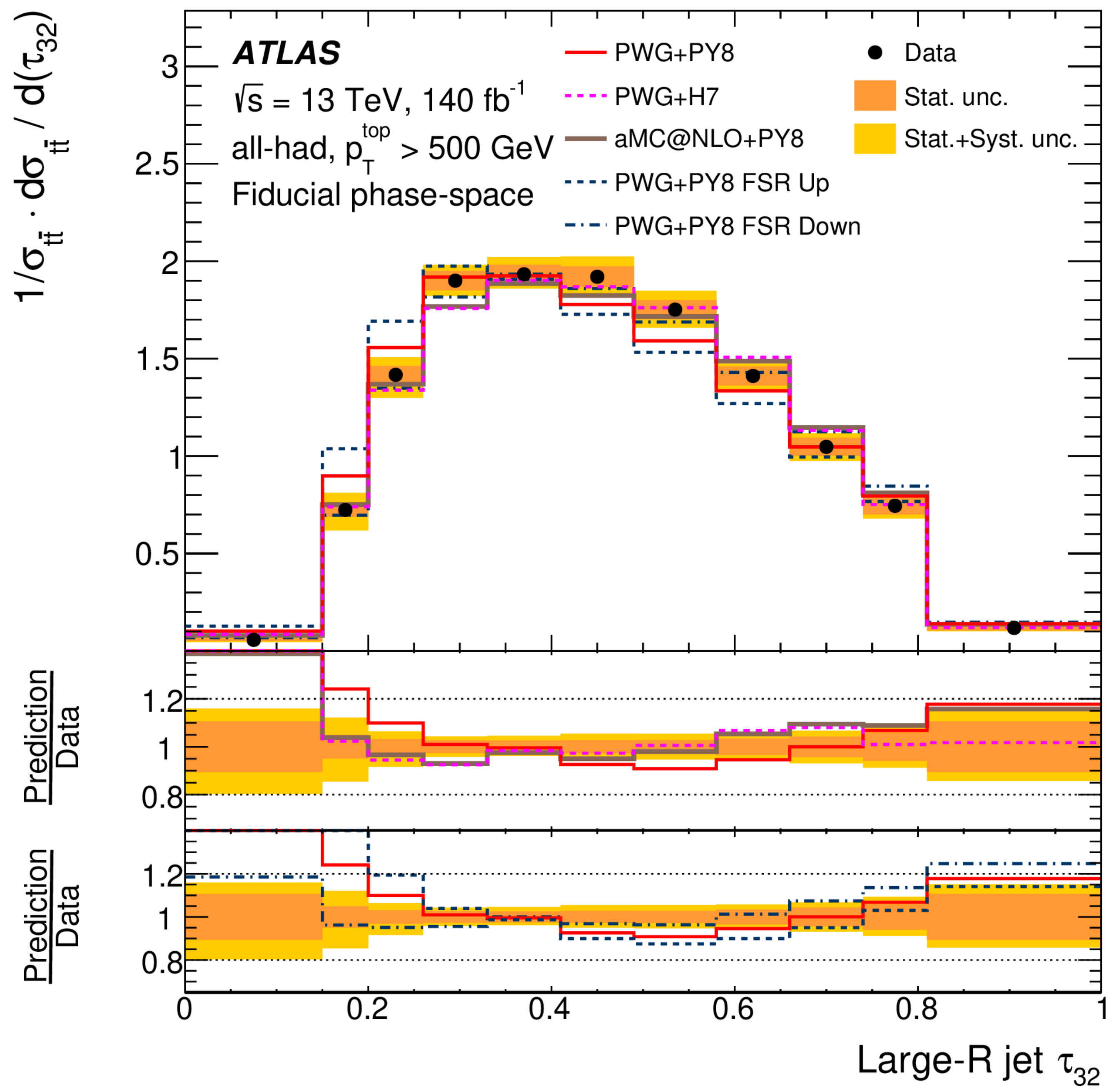
PRD 109 (2024) 112016

Boosted top Jet-substructure l+jets, all had

3 jets Boosted top 2 jets



τ_{32}~0 τ_{32}~1



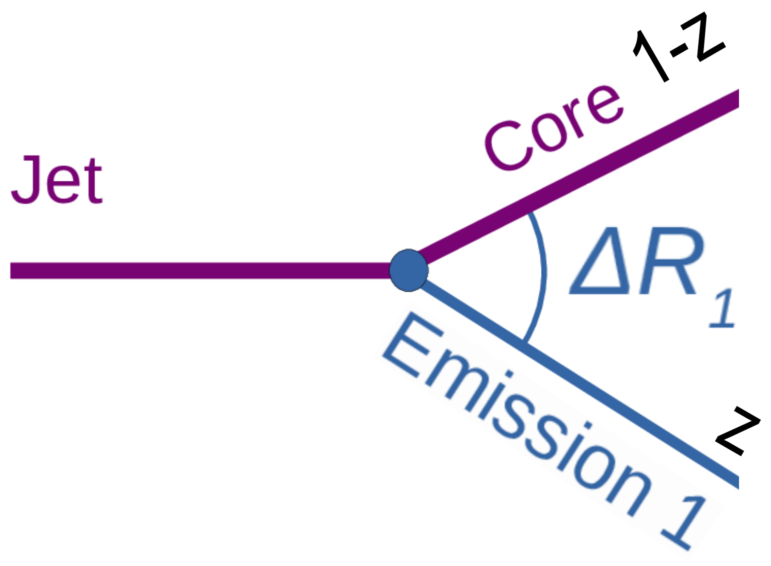
POW/ATLAS:  1.0

⇒ POW predicts more 3 jets like topologies

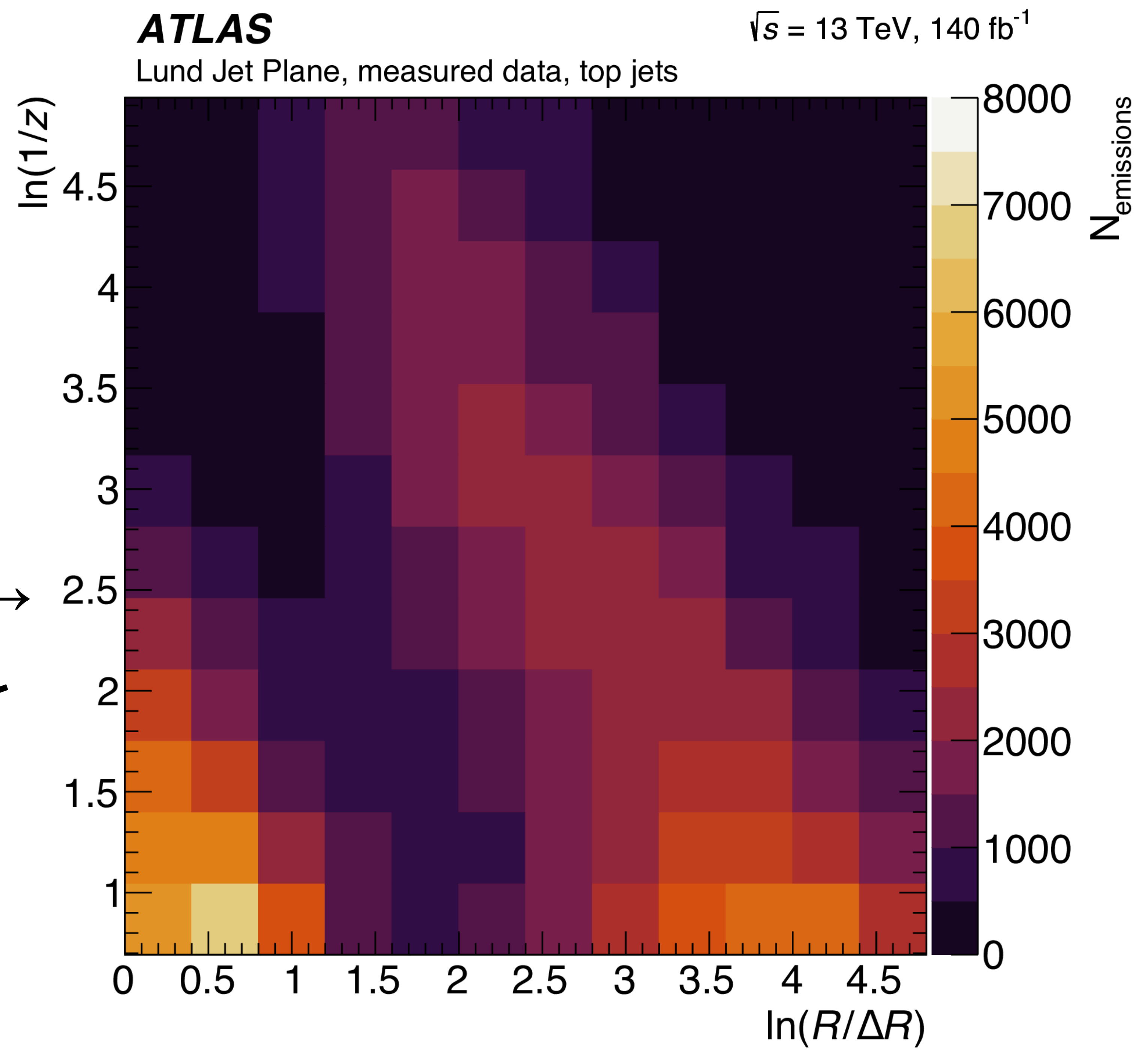
2407.10879

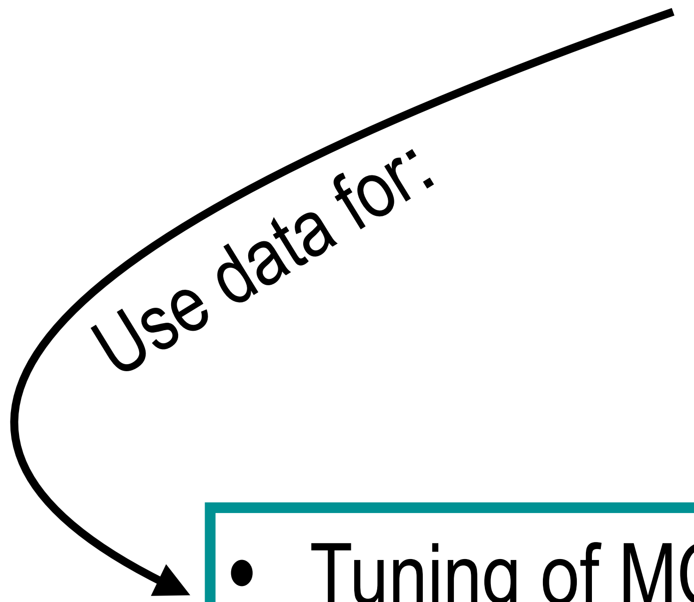
Measurement of the Lund jet plane l+jets

- Hadronically decaying top jets, R=1, p_T>350 GeV, cluster from tracks
- Go backwards in the clustering, reinterpret mergings as emissions



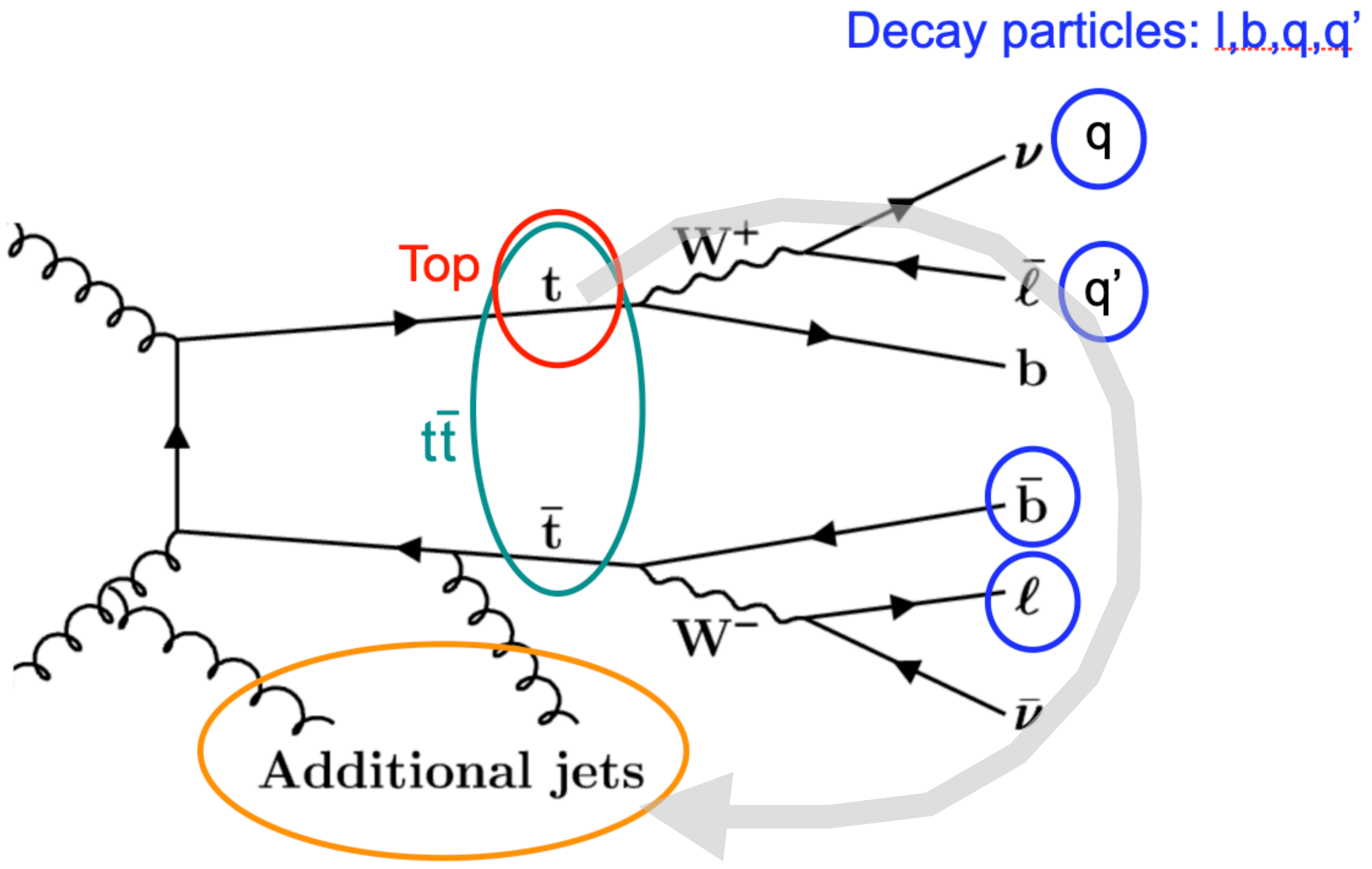
- Measure emission density →





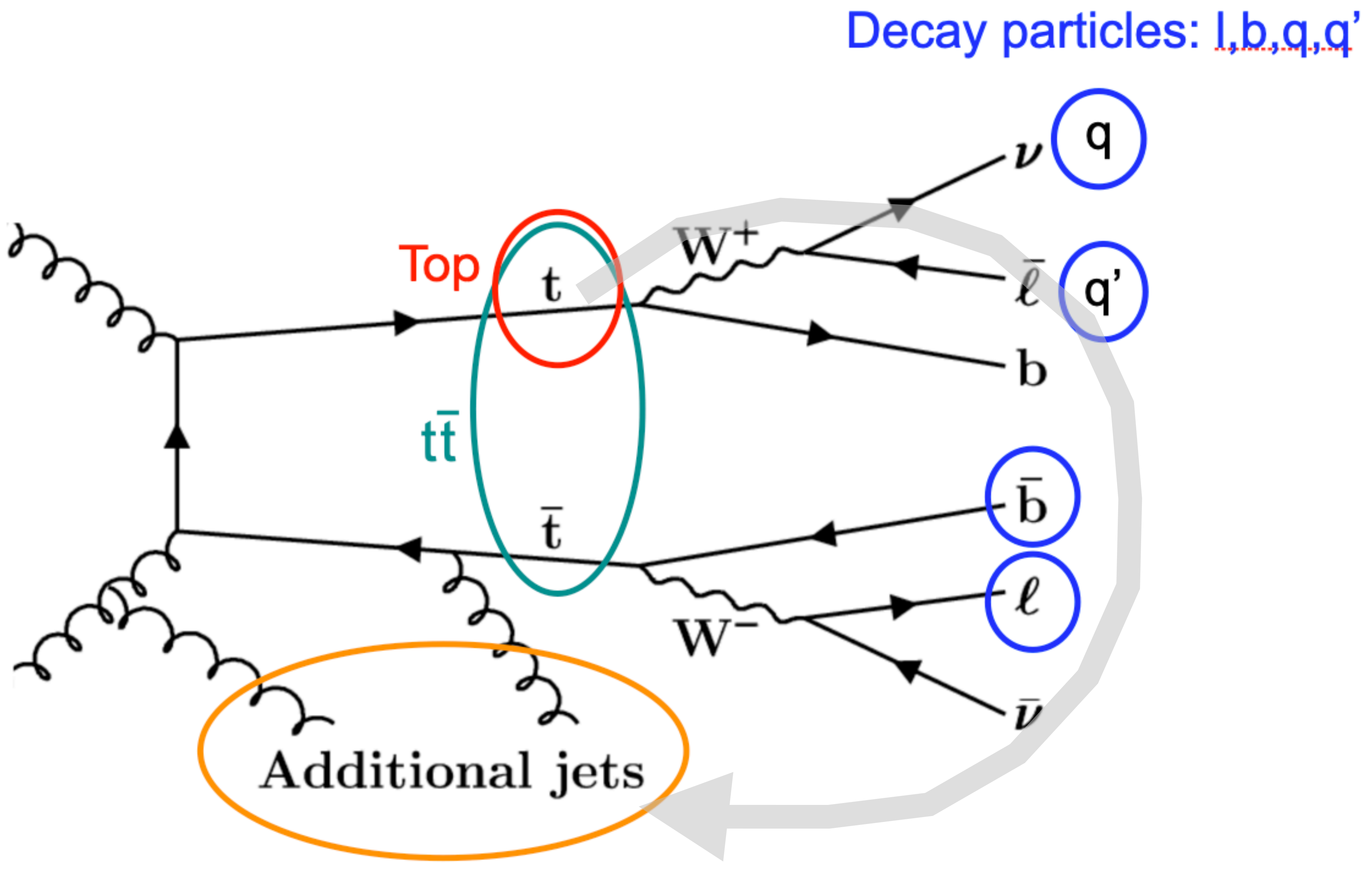
- Tuning of MC generators
- Better modelling of heavy quarks and boson hadronic decays
- Improve performance of jet taggers

Conclusion



- **Broad wealth** of topologies and object kinematic distributions in $t\bar{t}$ events studied by ATLAS & CMS with RUN 2 Data, with total samples of o(10M) $t\bar{t}$ events after event selections
- **No model** is able to describe all distributions
- **NNLO improves NLO+PS descriptions** for LO observables, e.g. $P_T(t)$, but not so much for higher order observables, e.g. $P_T(t\bar{t})$
- **Multi-differential distributions** seem less well described, example: the precise ATLAS measurements of $|\Delta\Phi^{e\mu}|$: $m^{e\mu}$

Outlook

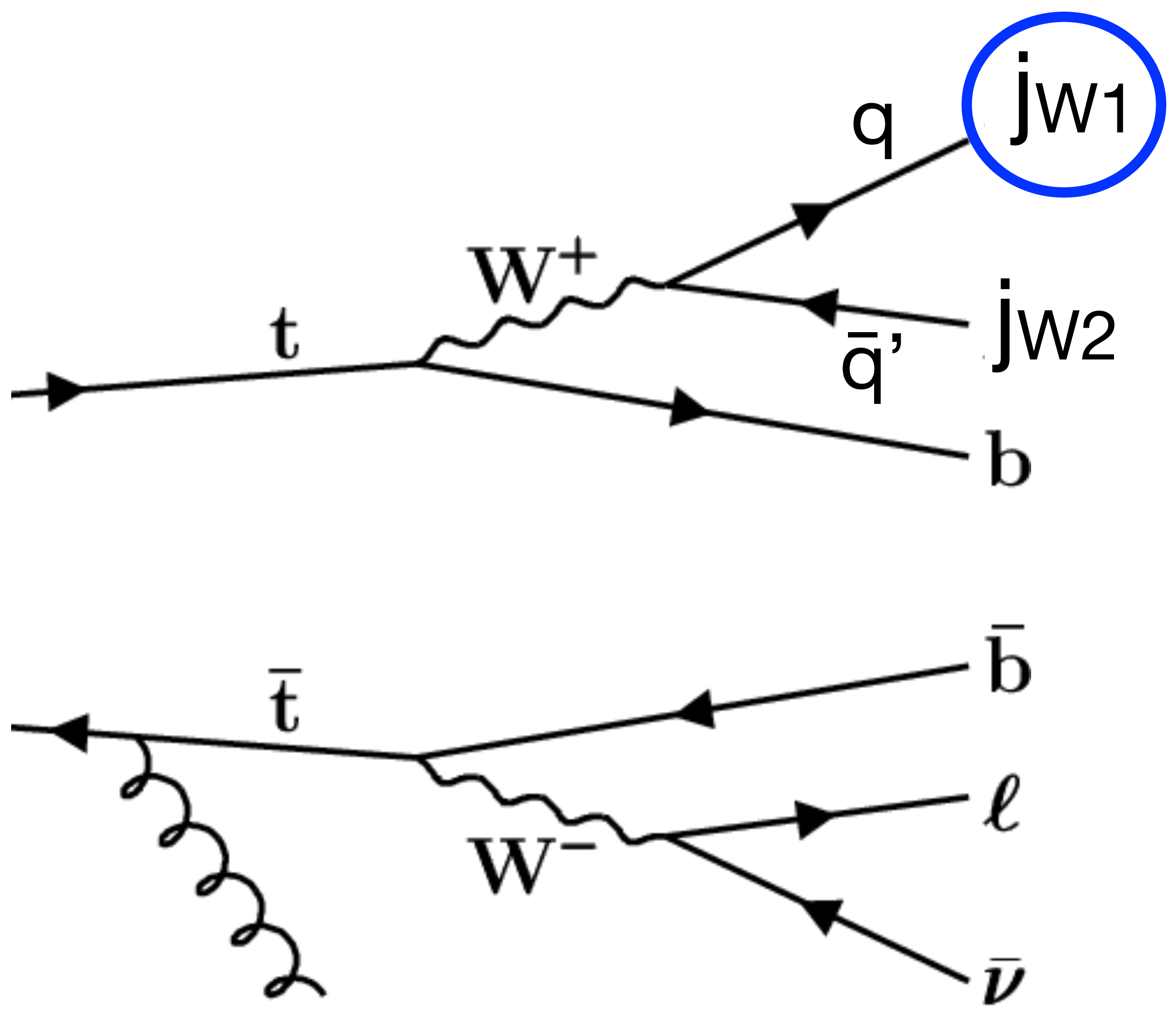


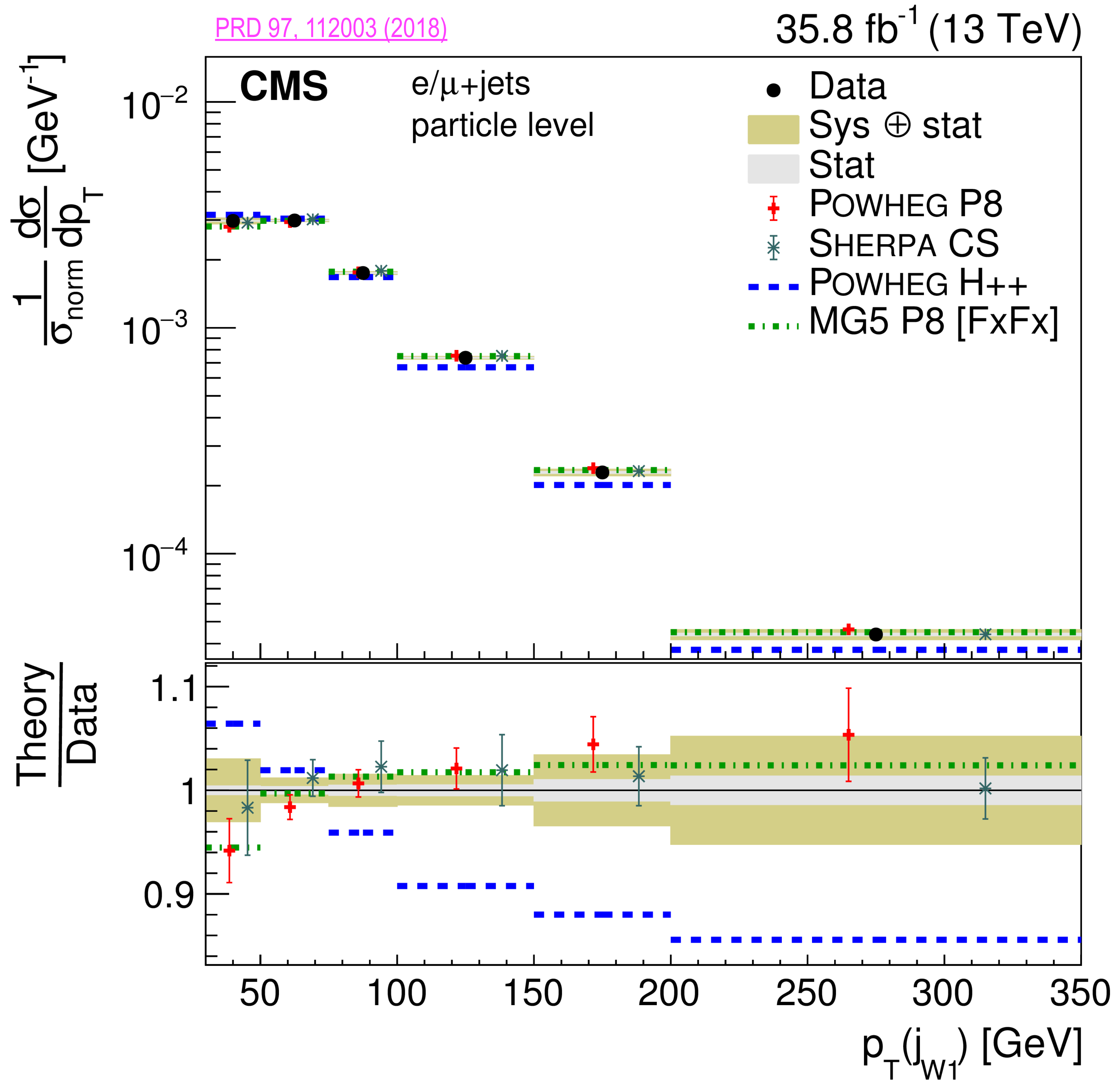
- **Run 3:**
  - Awaiting first differential σ_{tt} results
  - Expect to collect ~200M+ $t\bar{t}$ events per experiment (end 2025)
- **Exciting new methodic avenues** ahead:
  - **$d^m\sigma_{tt}/dx^m$** using Machine Learning (ML) unfolding, example: ATLAS Z+jets 2405.20041 with m=24; Find here recent overview talk on ML Unfolding
    - Providing deep tomography, perhaps even anomaly detection
    - Compete with/complementary to profile likelihood fit unfolding?
  - **ML based improved top tagging and kinematic reconstructions**
    - rapidly growing field ⇒ measure more accurately and in finer bins

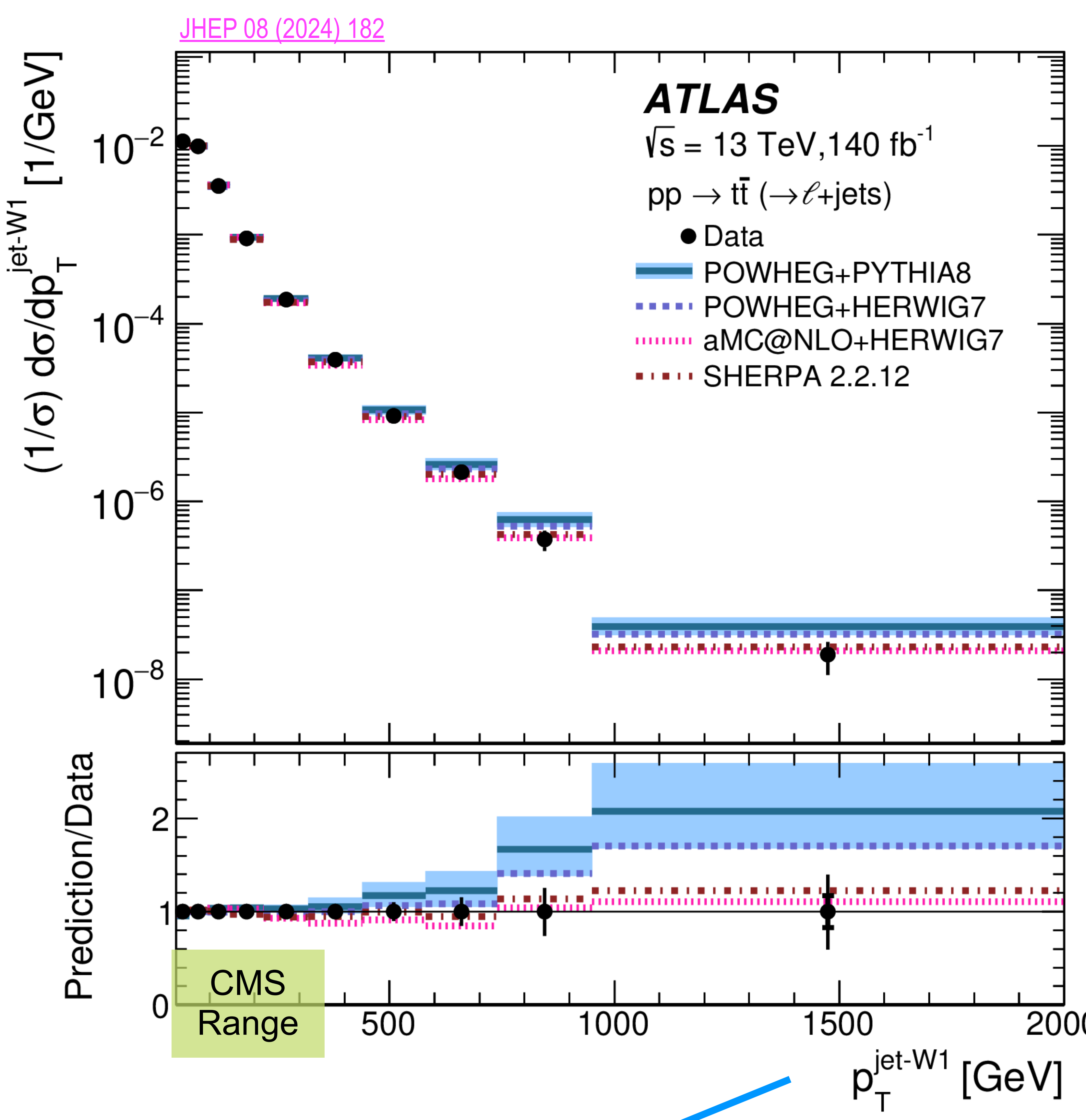
Backup

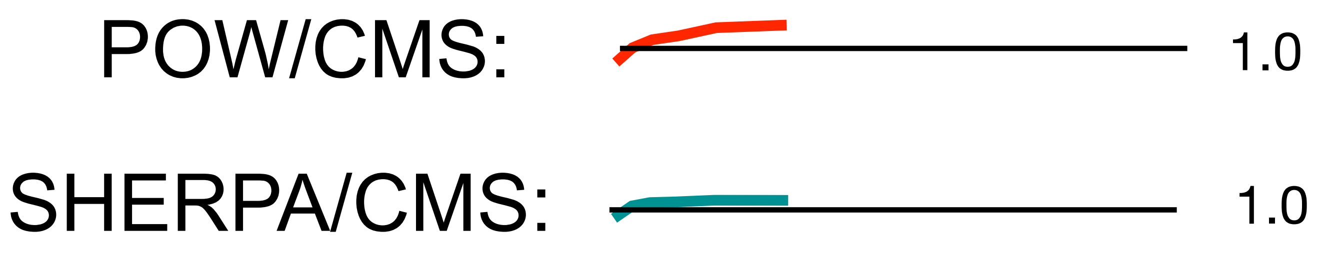
$p_T(j_{W1})$

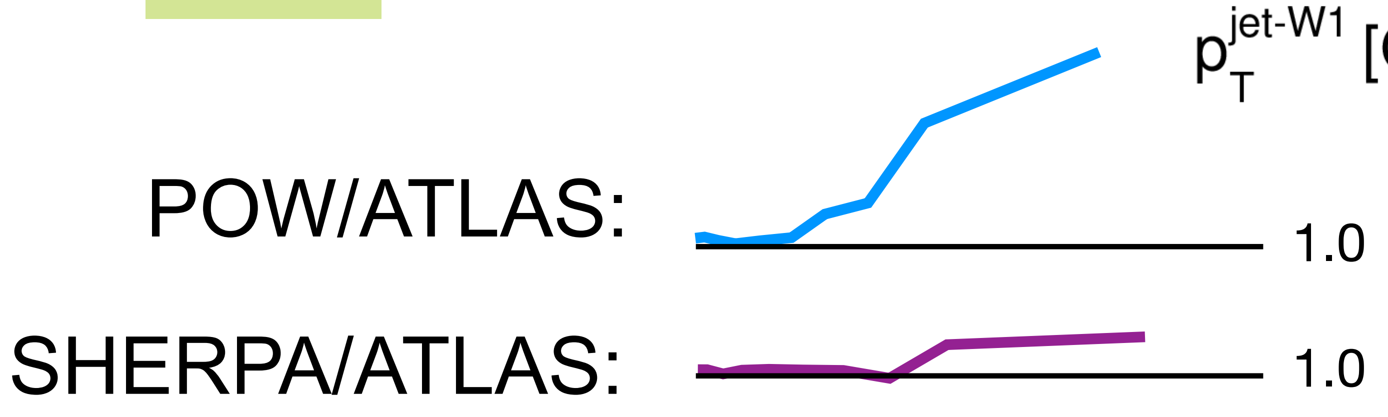
l+jets, Particle level, Resolved









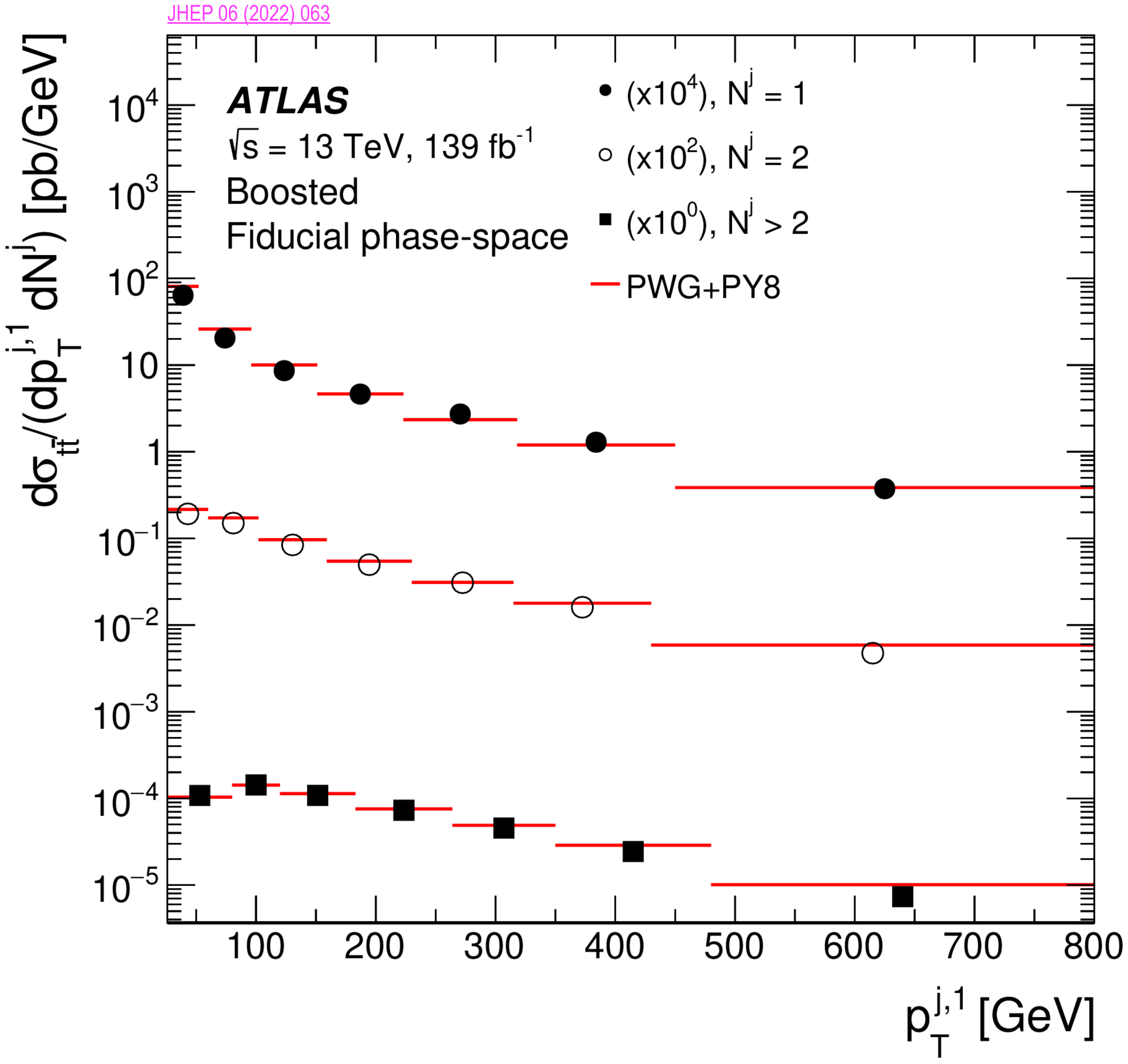


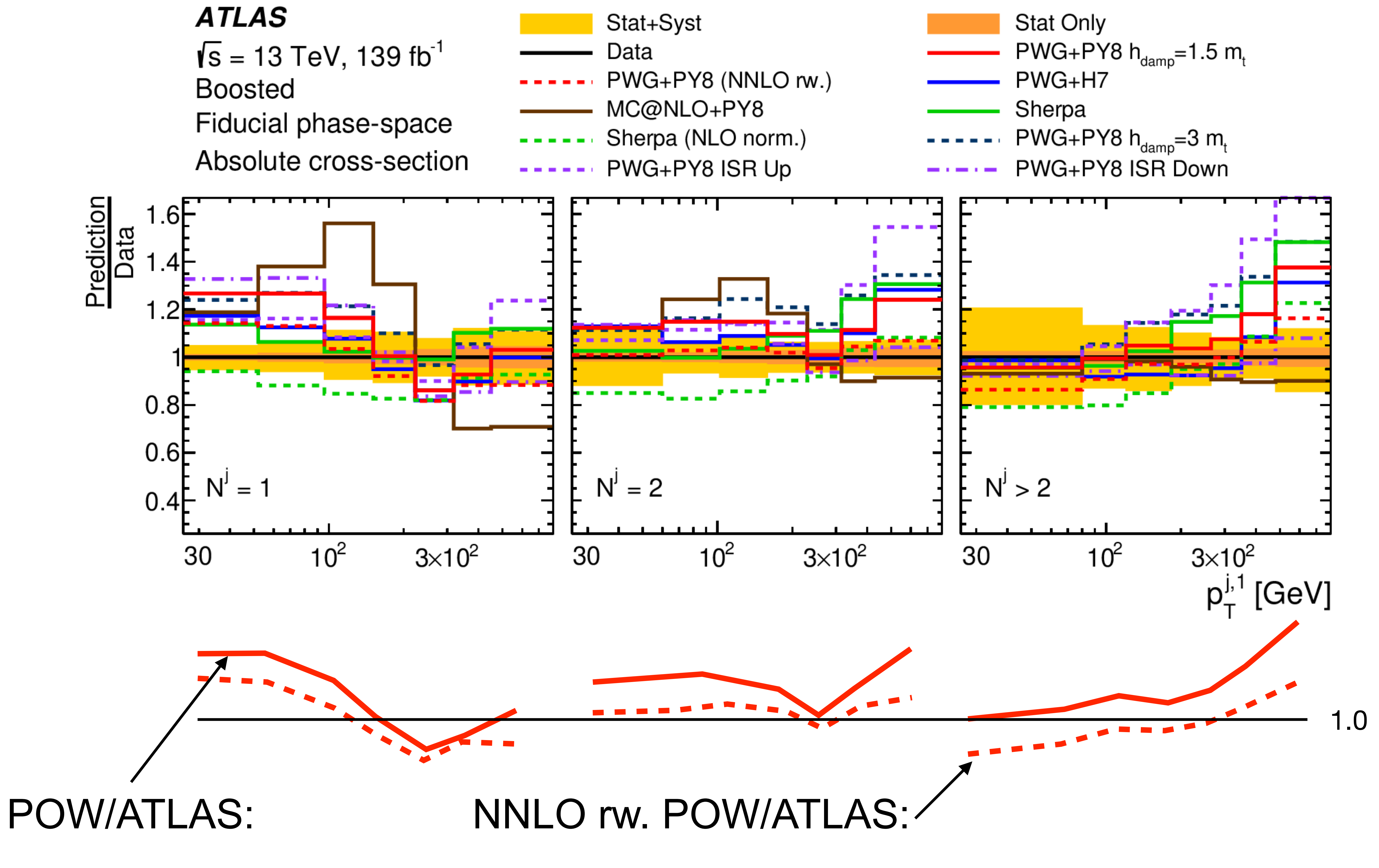
⇒ ATLAS expands jet p_T to **2 TeV!**

⇒ SHERPA provides improved description

$p_T(j,1)$

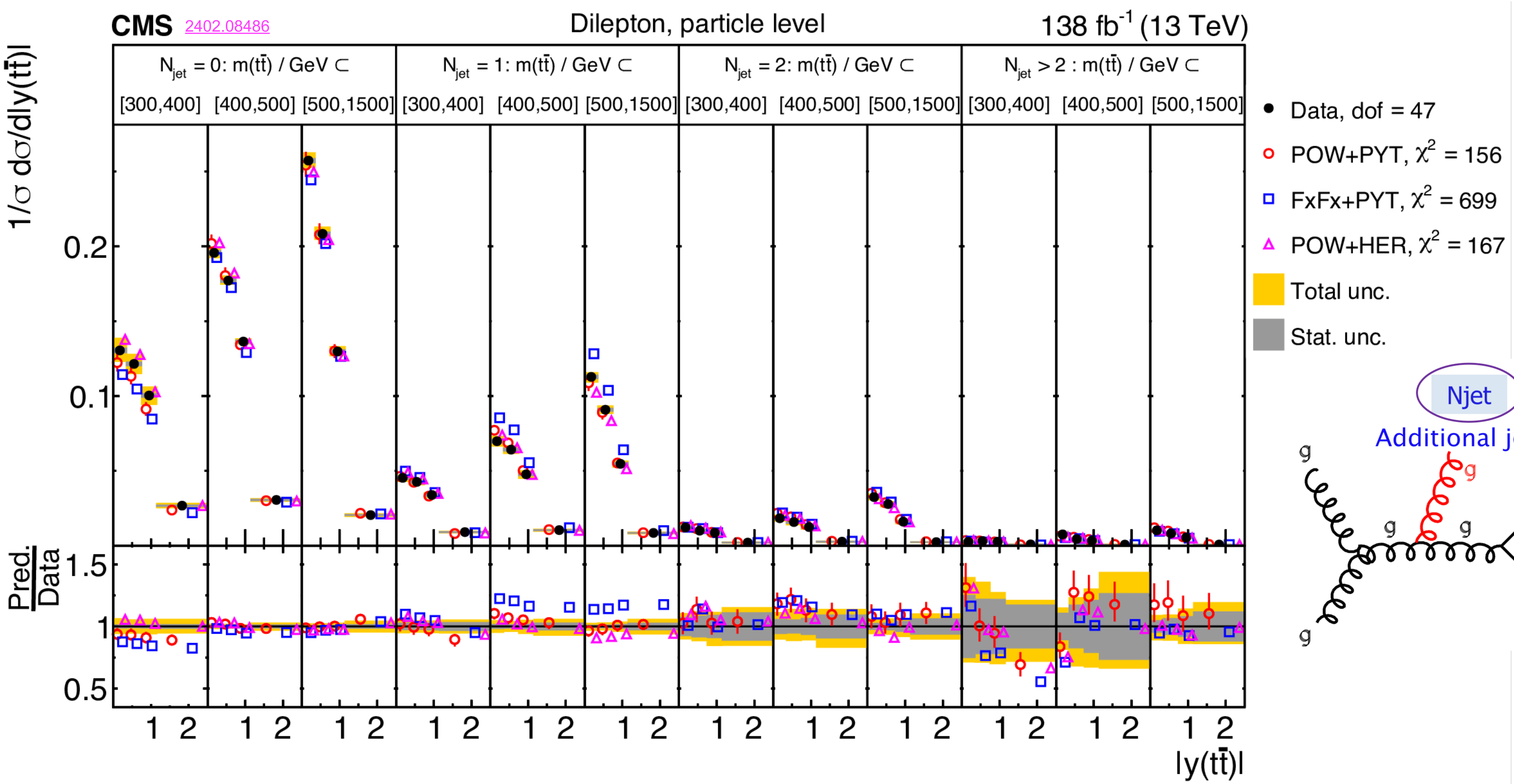
Particle level, with 1 boosted top quark

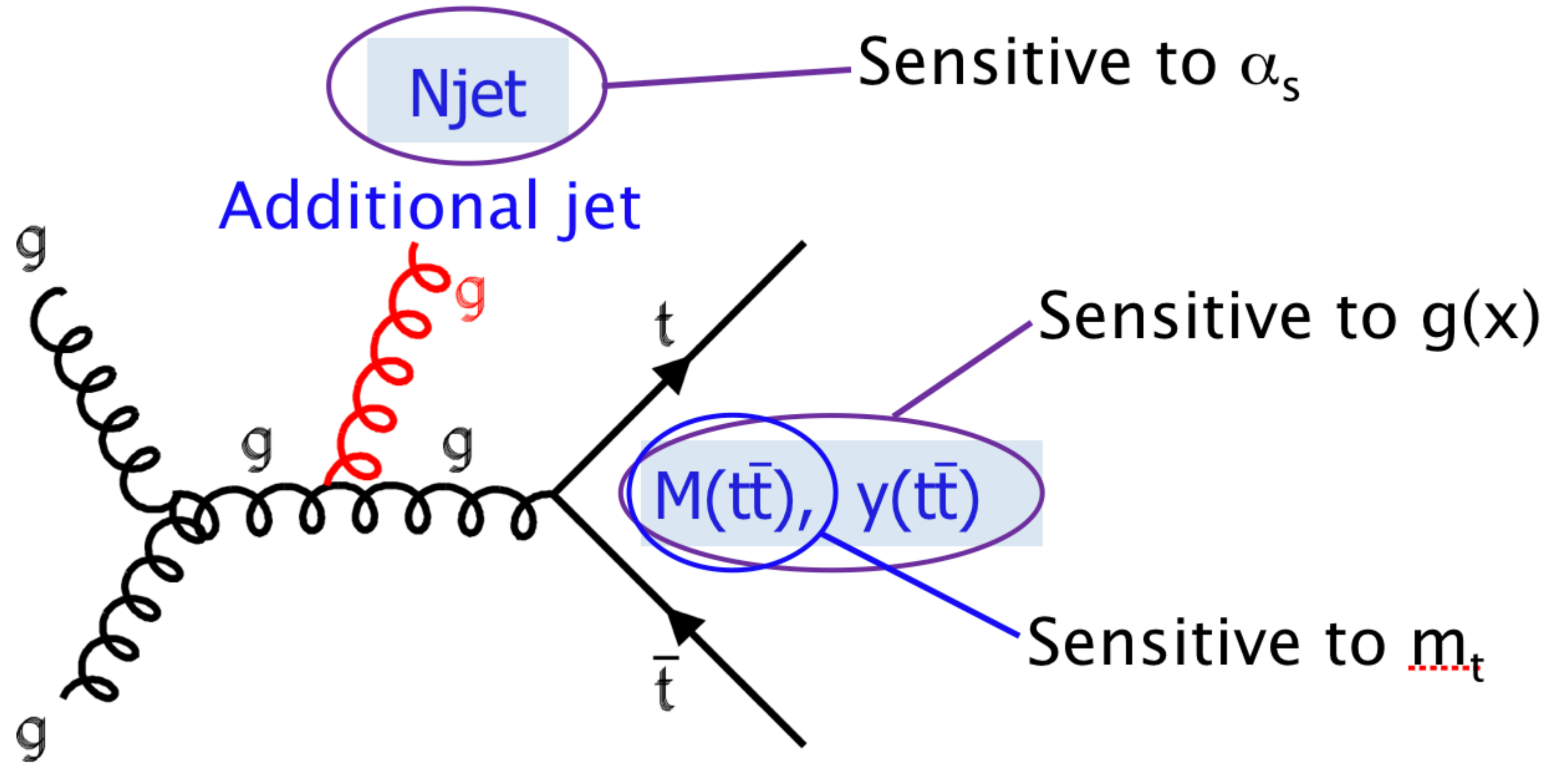




⇒ POW with problems for leading additional jet p_T distribution, for various $N^{\text{extra jets}}$
NNLO reweighting helps!

y(tt) vs m(tt) in bins of $N^{extra\ jet}$





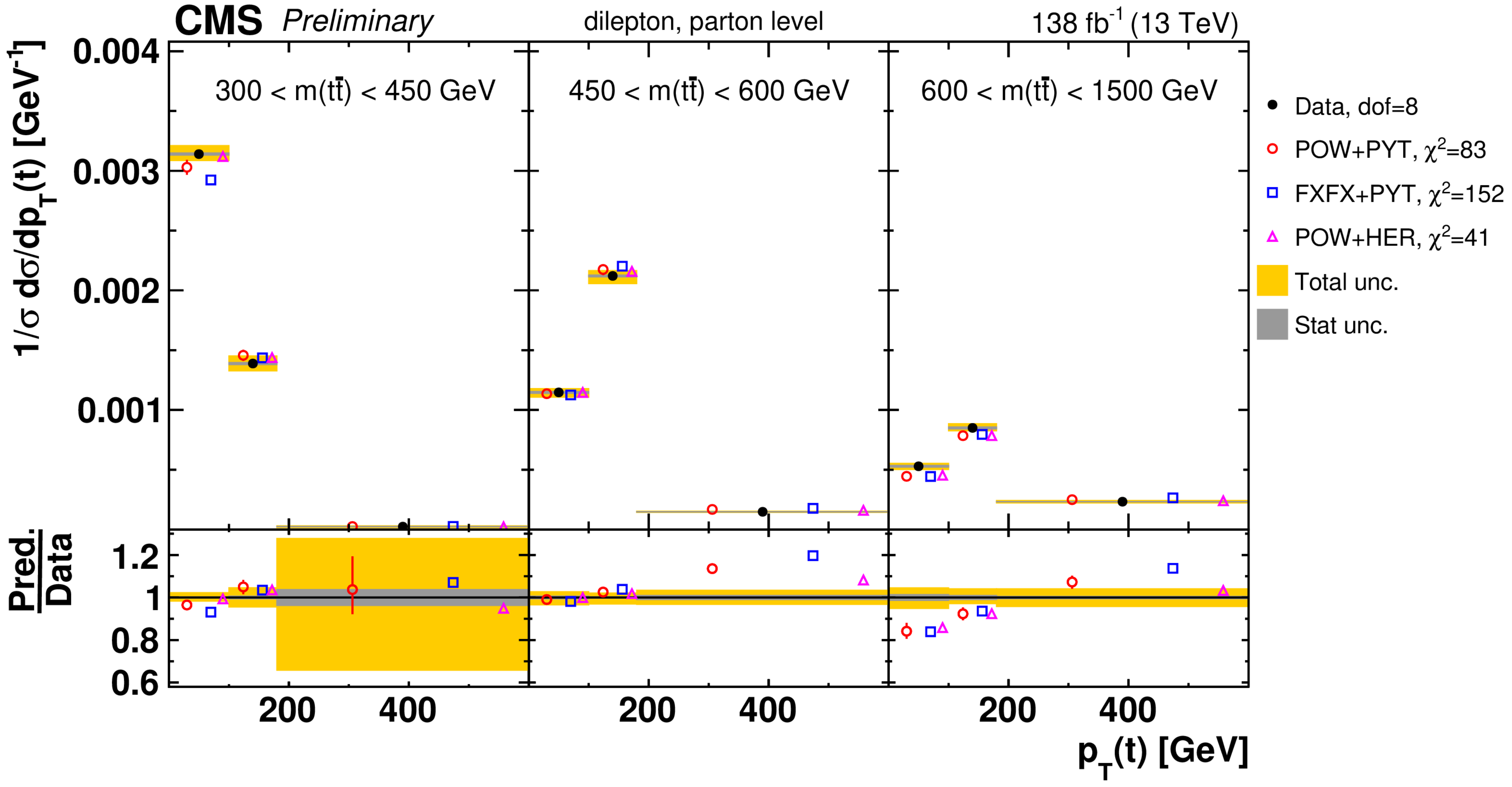
⇒ Known from 1904.05237 to provide simultaneous sensitivity to m_t, α_s and g(x)

Could still explore a great variety of not yet measured triple differential σ_{tt}, e.g. y(t):p_T(t):m($t\bar{t}$)

$p_T(t)$ in bins of $m(t\bar{t})$

Dilepton, Parton level

2402.08486



⇒ $p_T(t)$ distribution: POW/Data positive slope increasing with $m(t\bar{t})$

$\Delta\eta(t,\bar{t})$ in bins of m(t$\bar{t}$)

Dilepton, Parton level

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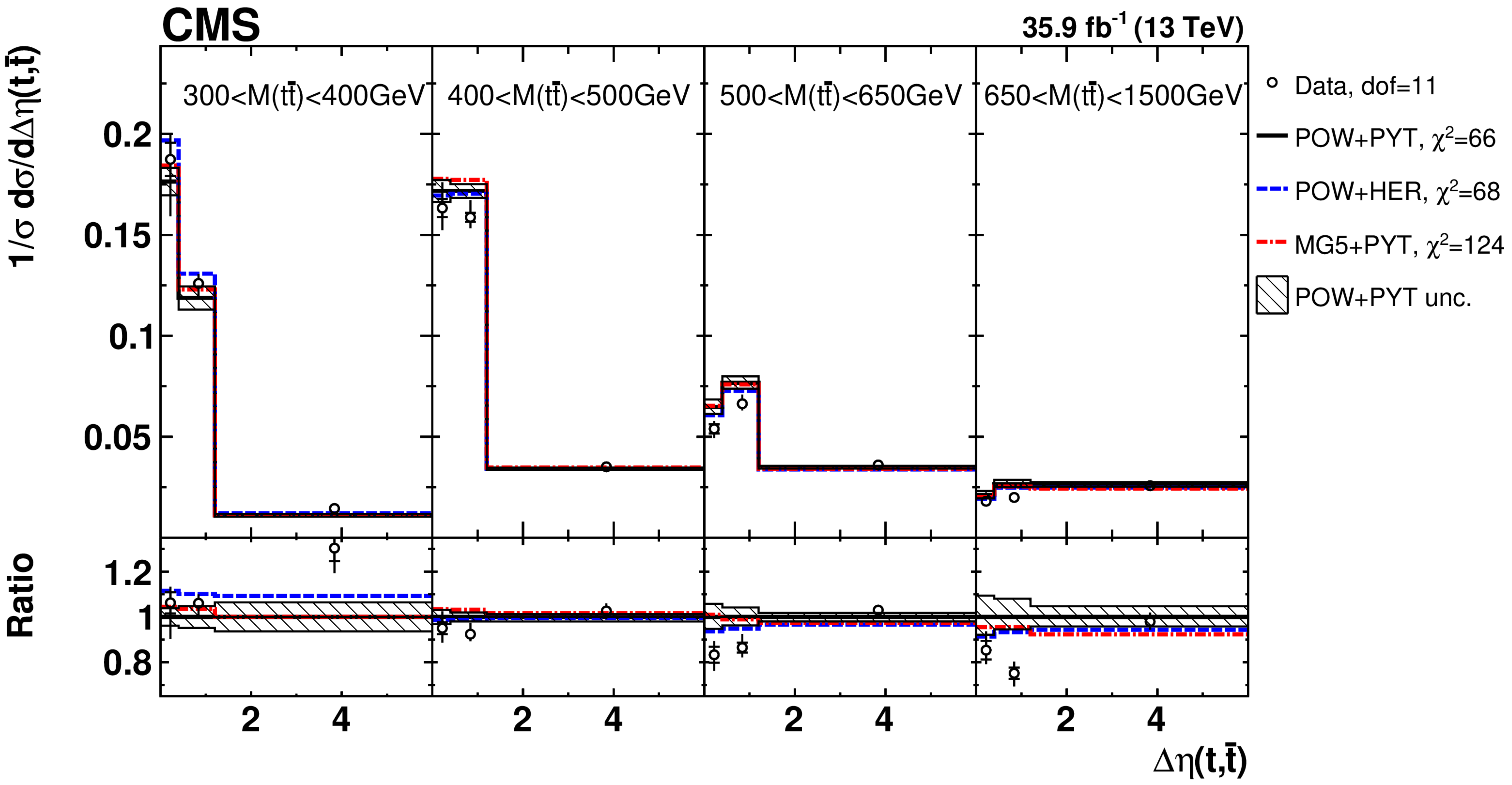

⇒ $\Delta\eta(t,\bar{t})$ distribution: Data/POW positive slope increasing with m(t$\bar{t}$)