Collider Challenges for QCD

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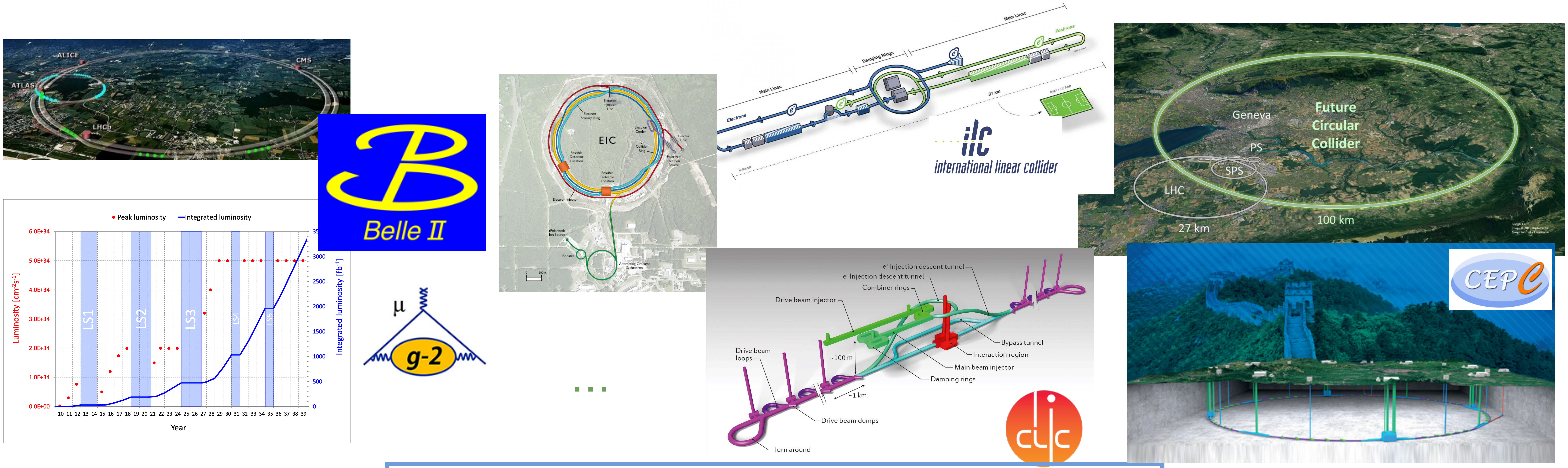
LFC 2021

Photo Credit: Kinrannoch Photography

Looking Ahead



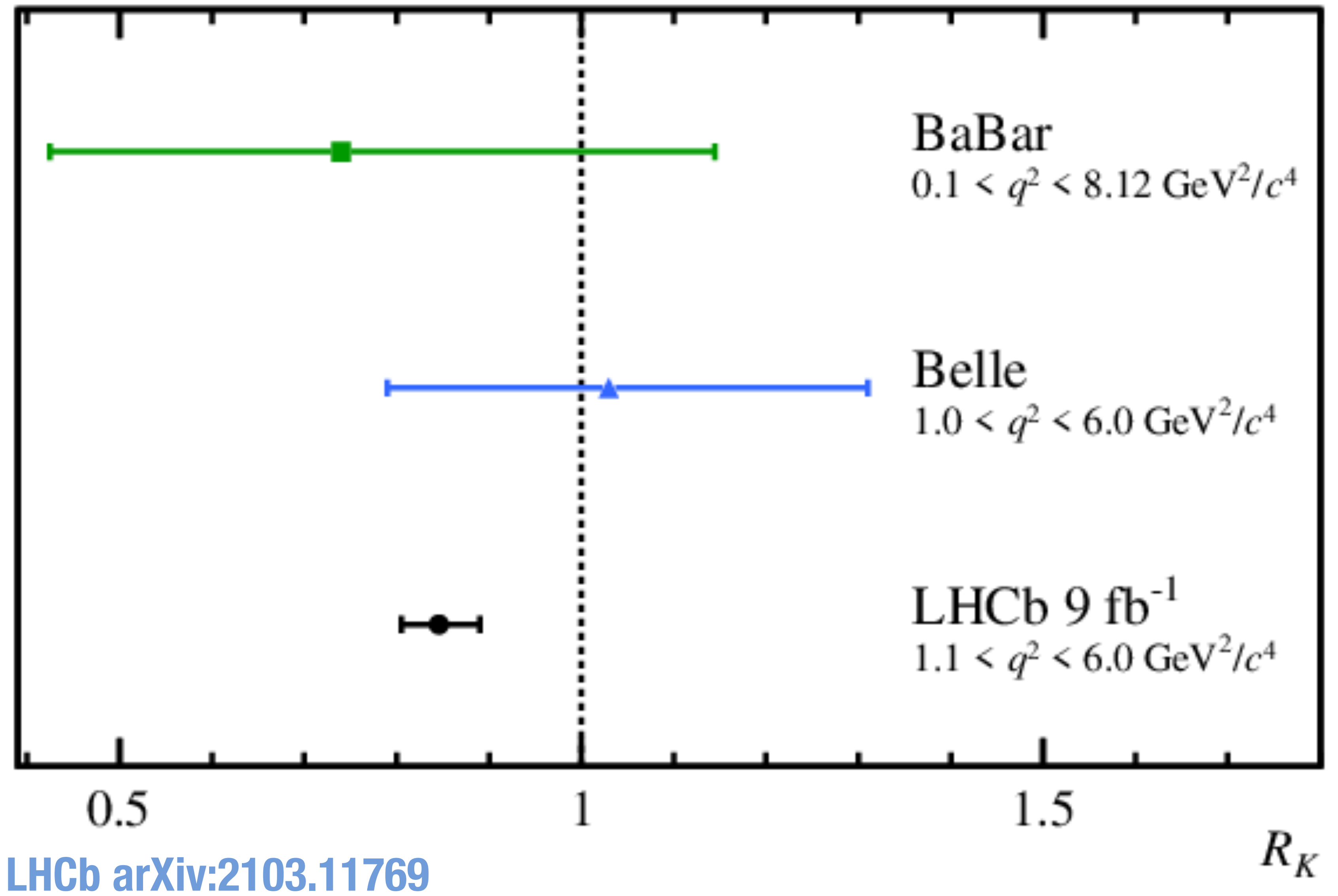
Many experiments: one theory of QCD

Two types of challenges for QCD:

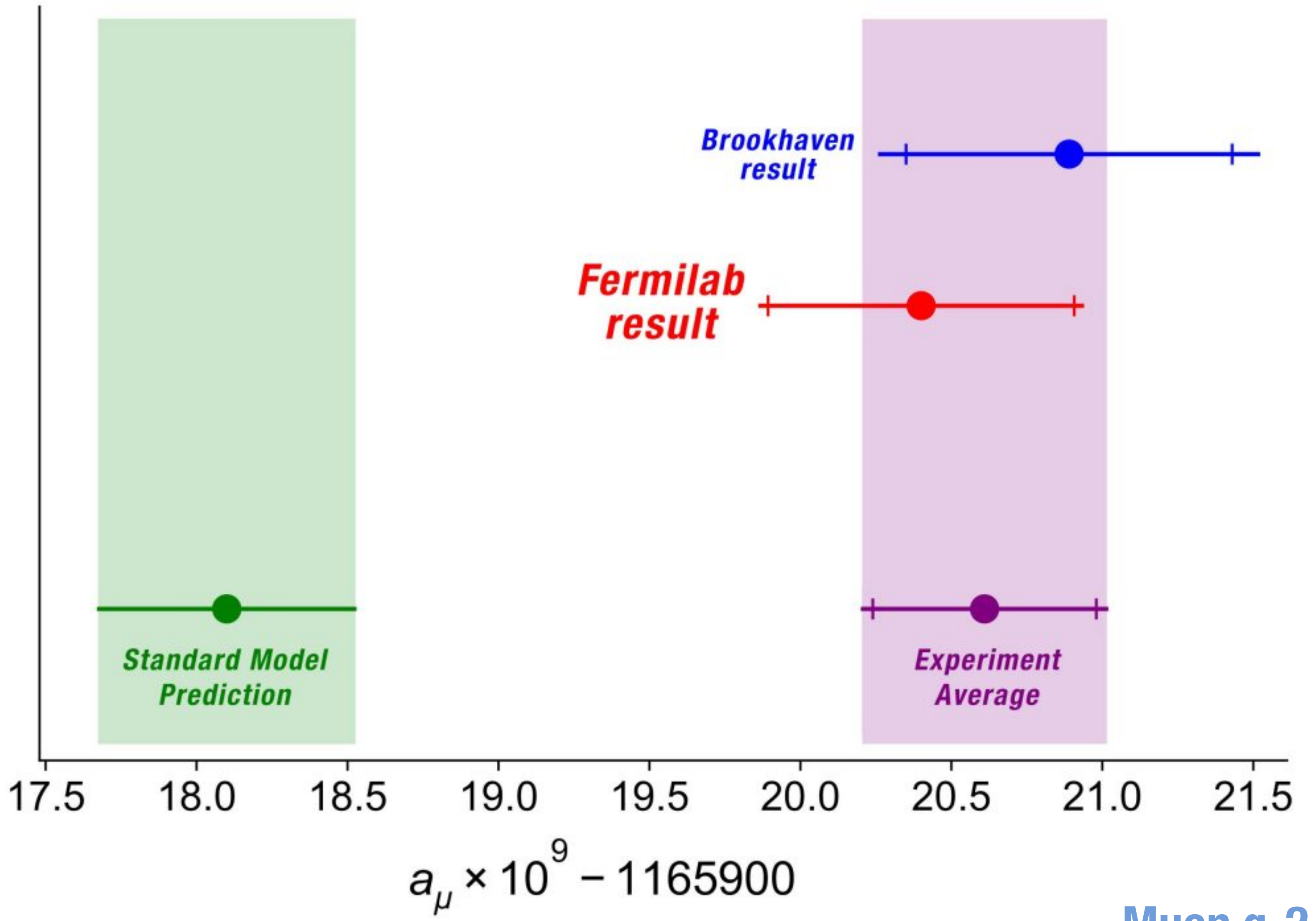
- Can it pass all these tests?
- Can we calculate well enough to see what the data is telling us?

Signs of New Physics?

We now have a few persistent possible signs of new physics



LHCb arXiv:2103.11769



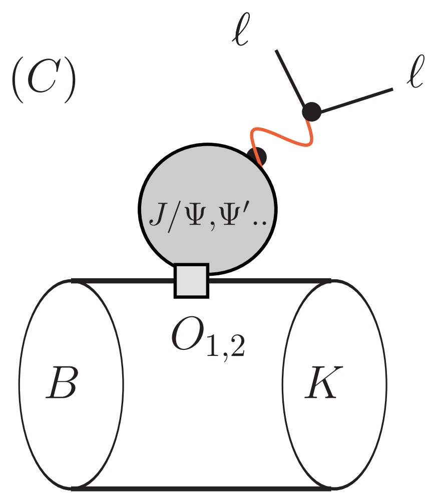
Muon g-2 arXiv:2104.03281

$$R_{K^X} = \frac{\mathcal{B}(B \to K^X \mu^+ \mu^-)}{\mathcal{B}(B \to K^X e^+ e^-)}$$

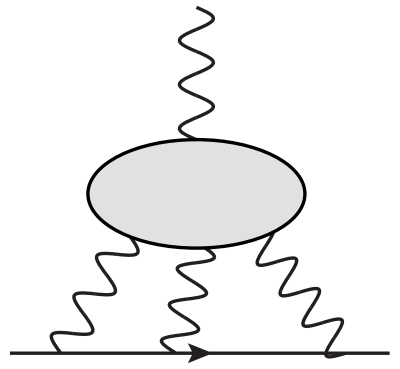
See Zupan's Talk

$$a_\mu = g - 2$$

See Gerardine's Talk



- Both hint at greater differences between electrons and muons than in the SM
- Both require difficult calculations of hadronic contributions



Exotic New Physics

But we definitely have many new particles

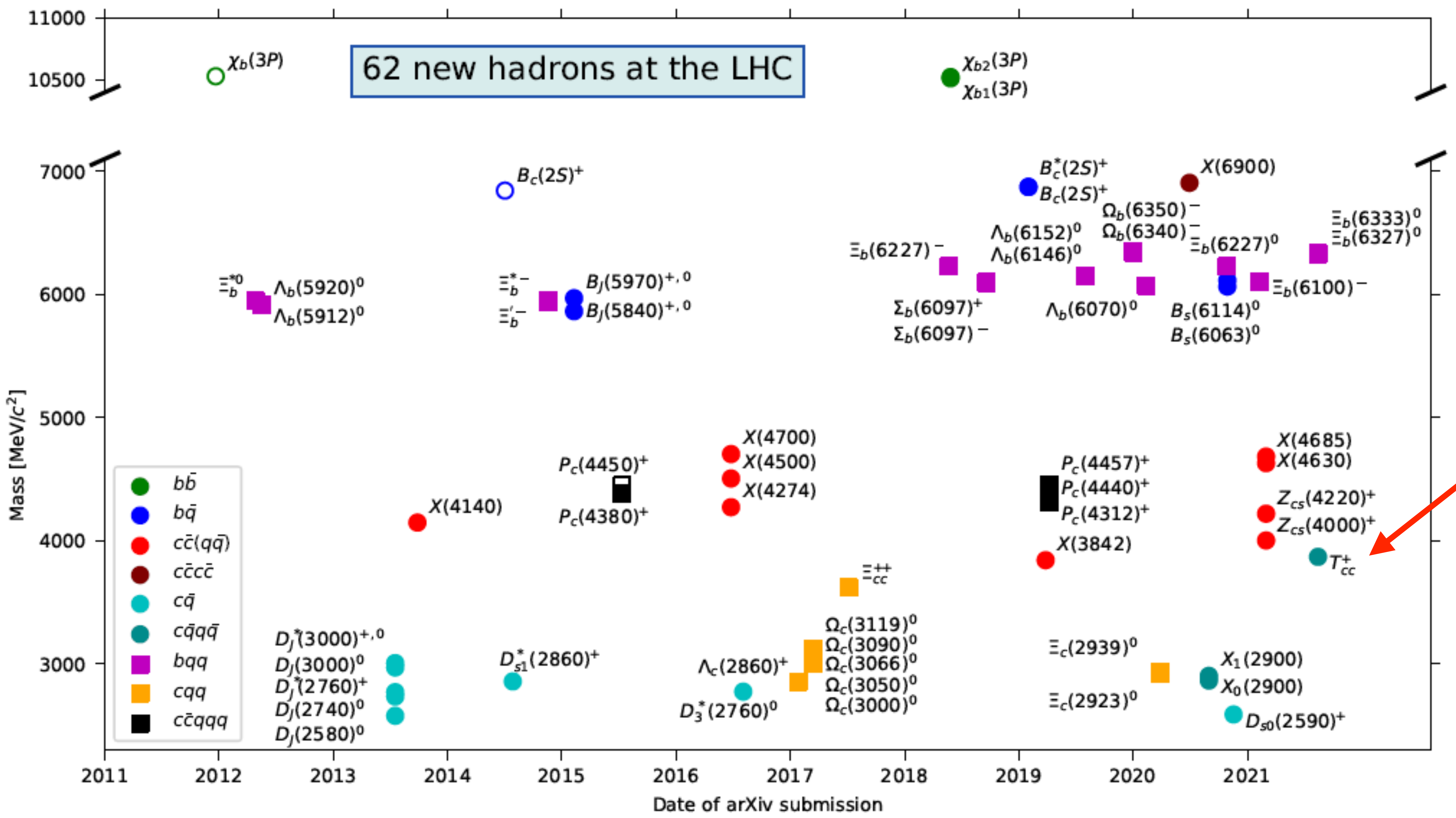
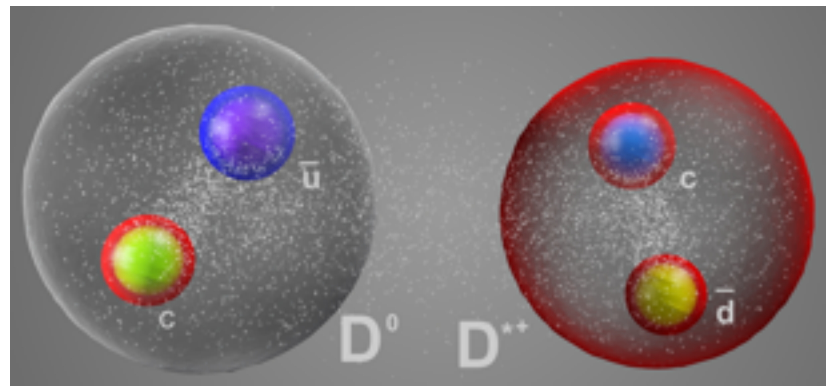
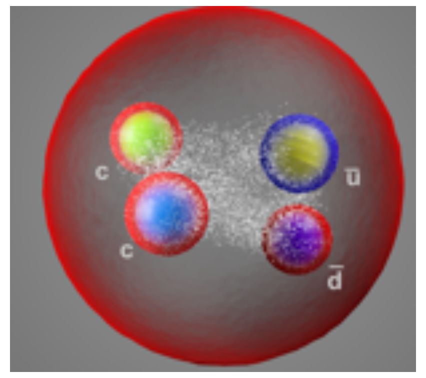


Image Copyright CERN

New in Aug 2021 at LHCb: $T_{cc}^+ = cc\overline{ud}$

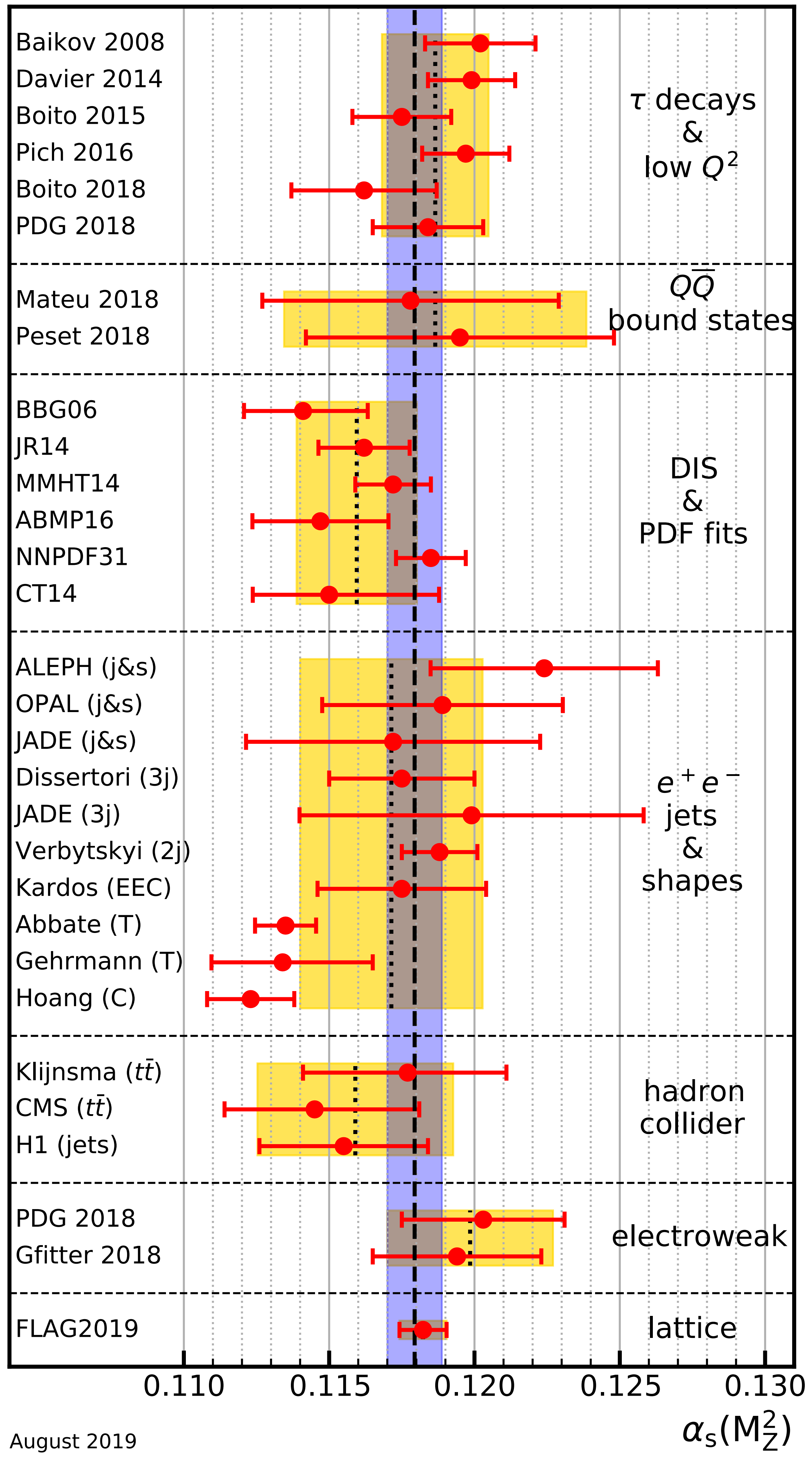
The first observed doubly-charmed tetraquark





Meson-meson molecule or tightly-bound state?

Strong Coupling



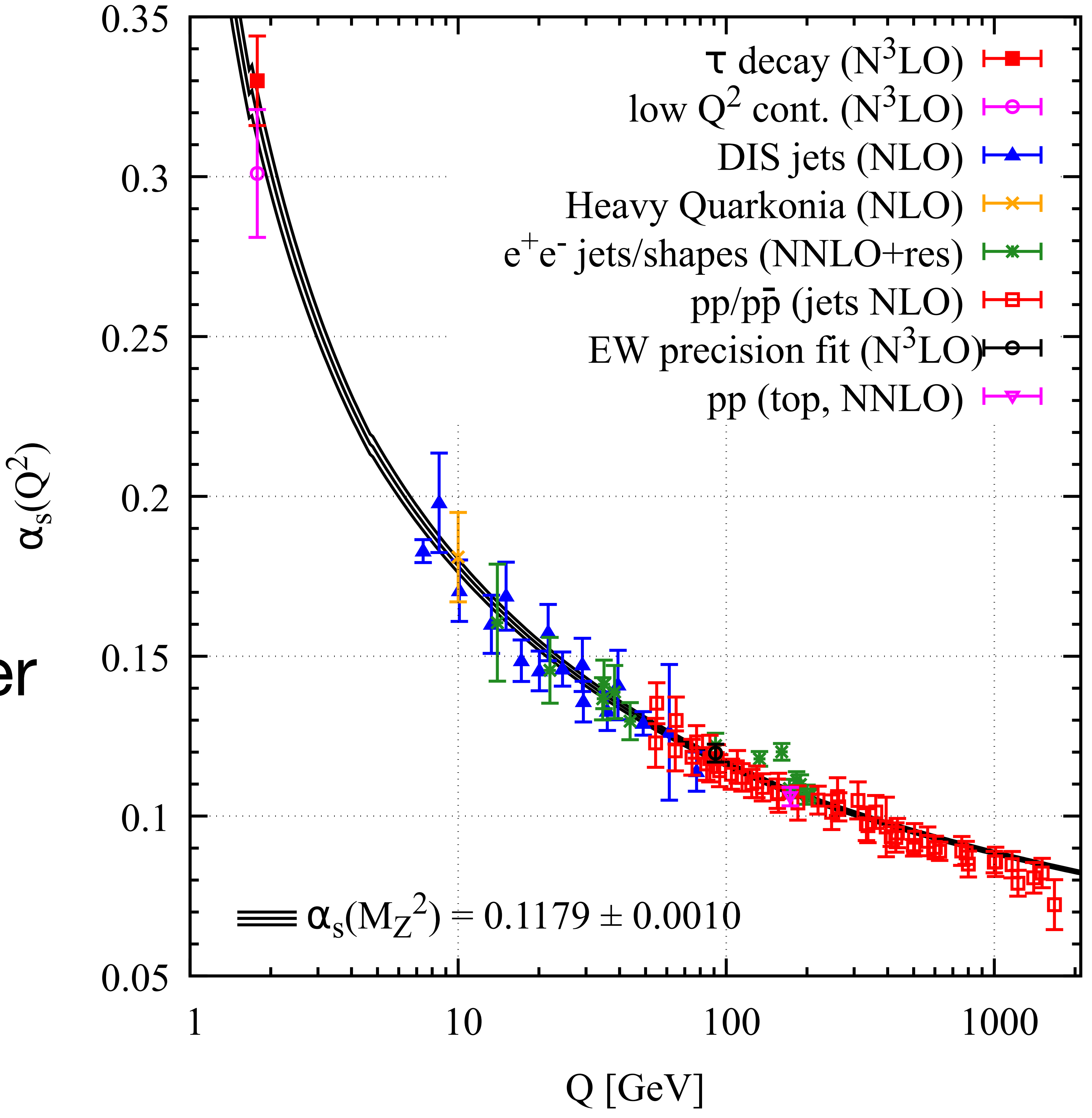
PDG Review 2020

Evaluated in many channels with many methods with incredible level of agreement

Some are new methods applied to older data (re-analysis of HERA data)

Tightest constraints currently from lattice

See Camarda and d'Enterria's Talks



PDG Review 2020

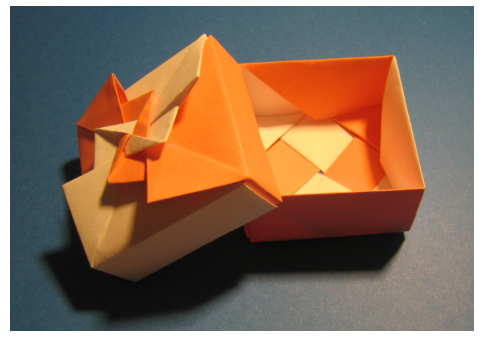
Perturbative Expansions

Matrix elements at high energies calculated by expansion in couplings, e.g.

$$\sigma = \mathcal{C}_2\alpha_s^2 + \mathcal{C}_3\alpha_s^3 + \mathcal{C}_3'\alpha_s^2\alpha_W + \mathcal{C}_4\alpha_s^4 + \mathcal{C}_4'\alpha_s^3\alpha_W + \dots$$

Madgraph5_aMC@NLO

Sherpa



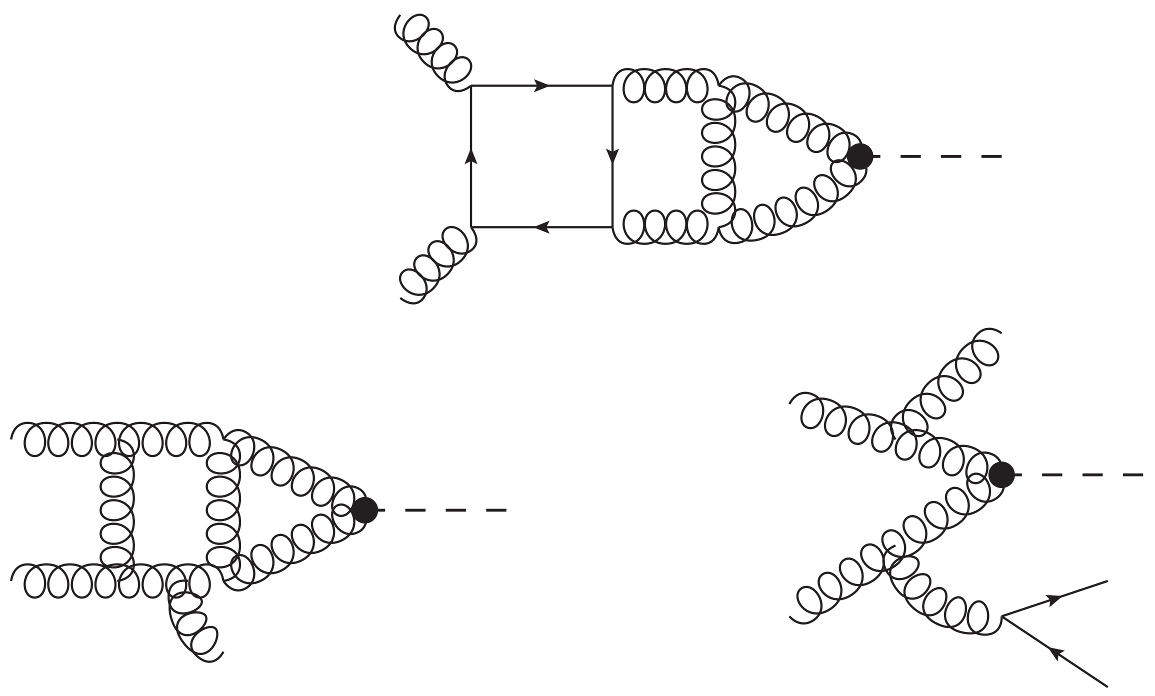
PowhegBox

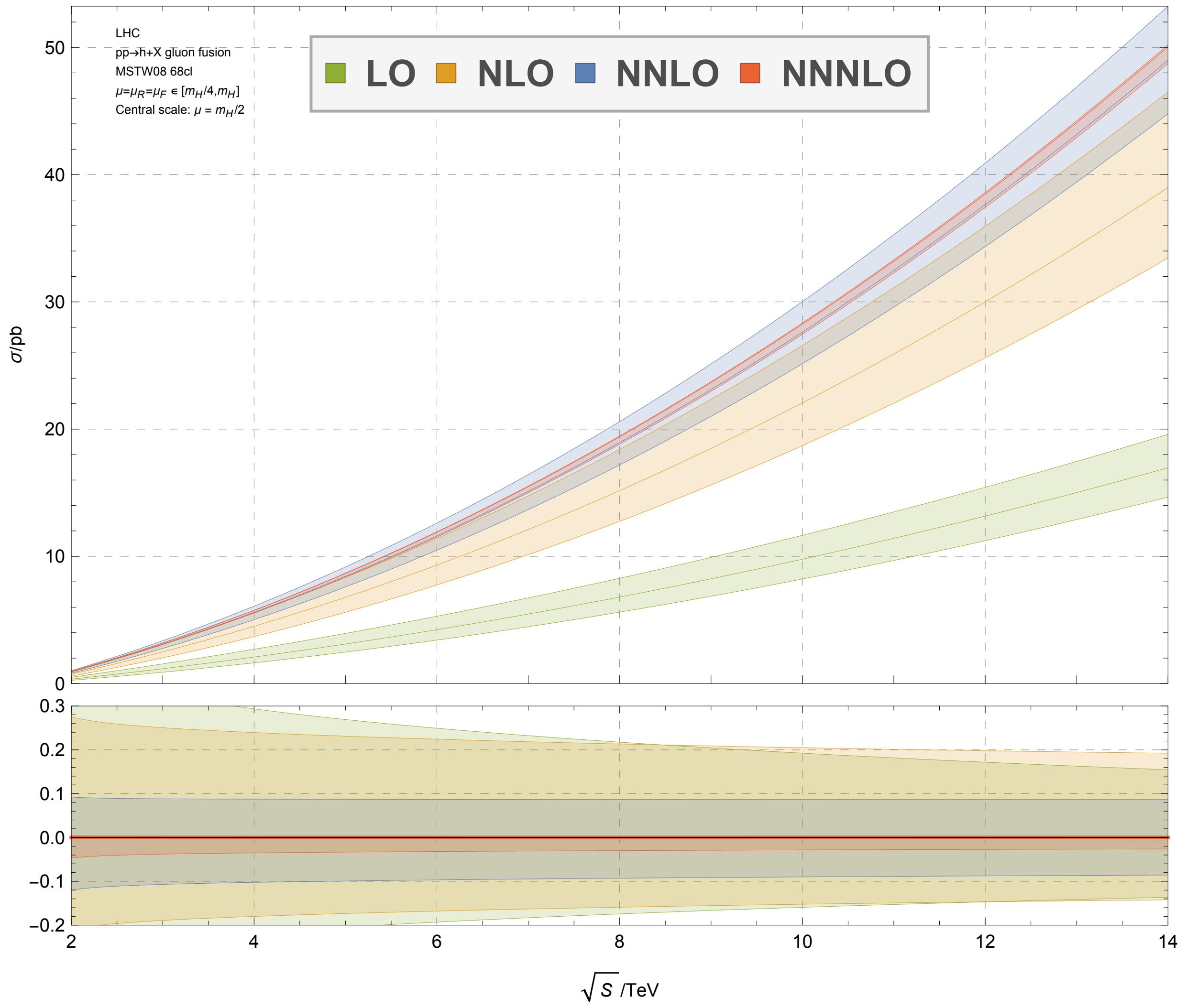
Herwig 7

Standard for LHC is Next-to-Leading-Order (NLO) for SM and BSM

Possible due to

- Unitarity revolution
- Automation of subtraction
- Combination with parton showers (MC@NLO, POWHEG)





A few KEY processes at N3LO

First cross section, $gg \to H$

Anastasiou, Duhr, Dulat, Herzog, Mislberger arXiv:1503.06056

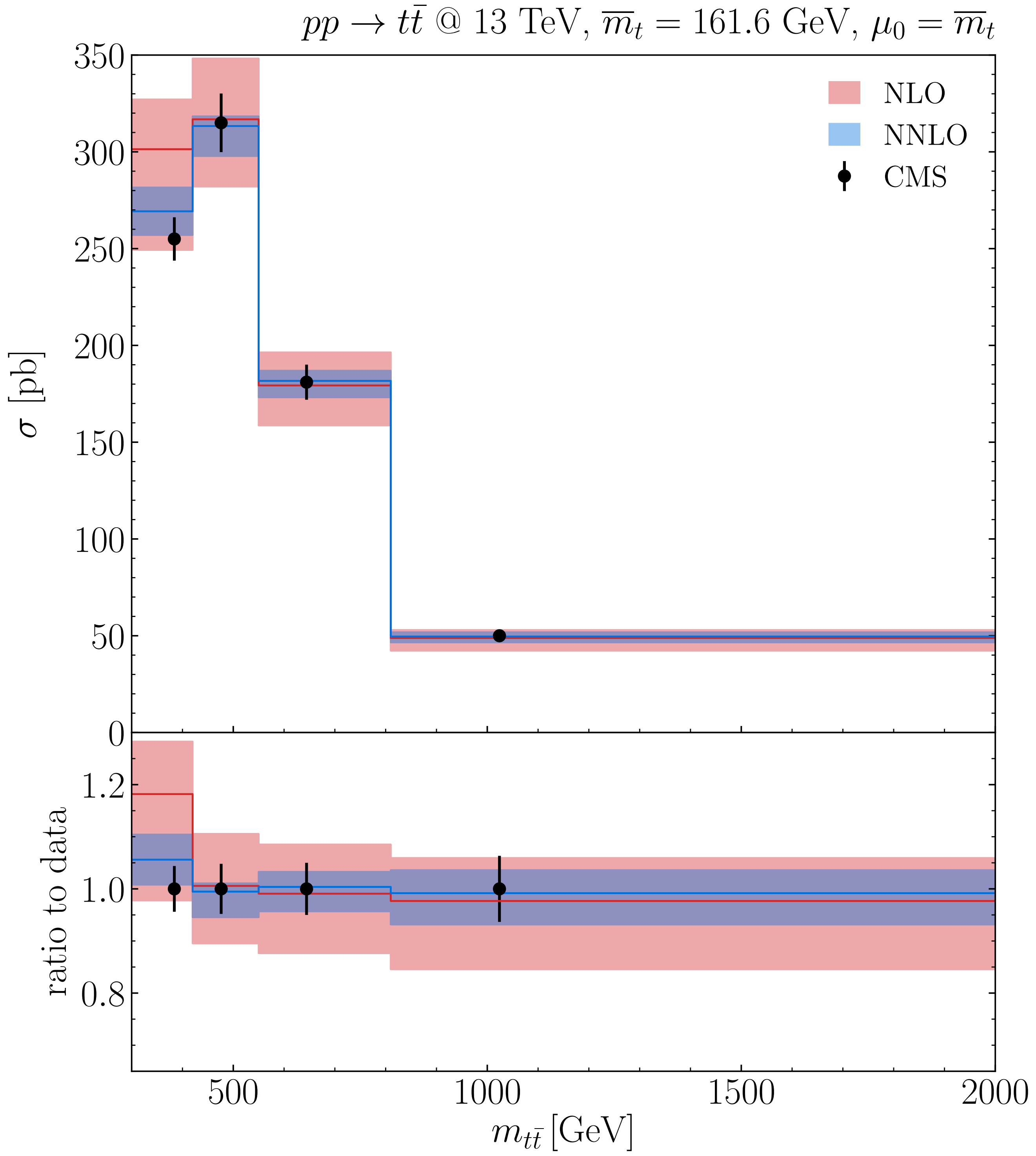
Now: full $gg \to H$, VBF Higgs, $b\bar{b} \to H$, Drell-Yan

Dreyer, Karlberg arXiv: 1606.00840, 1811.07906; Mistlberger arXiv:1802.00833
Chen, Gehrmann, Glover, Huss, Li, Neill, Schulze, Stewart, Zhu arXiv: 1805.00736
Duhr, Dulat, Hirschi, Mistlberger arXiv:1904.09990, 2004.04752
Duhr, Dulat, Mistlberger arXiv:2001.07717
Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni arXiv:2102.07607

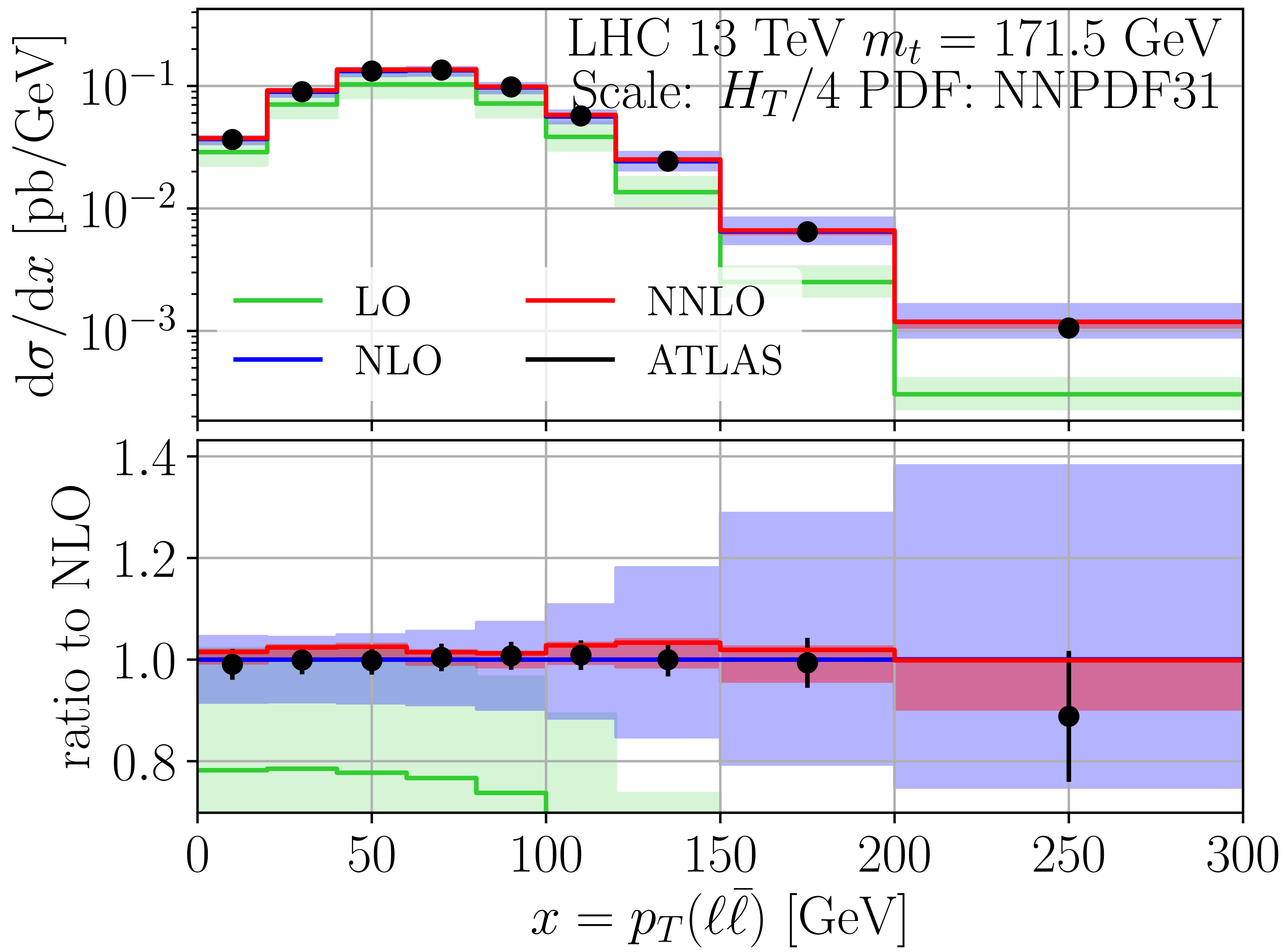
The Race for NNLO

Now have specialised calculations for many processes at NNLO (to roughly give %-level uncertainties), including $t\bar{t}$

See Grazzini's Talk



Catani, Devoto, Grazzini, Kallweit, Mazzitelli arXiv:2005.00557



Czakon, Mitov, Poncelet arXiv:2008.11133

Light jet final states more difficult, but have e.g. $pp \to j, pp \to H+j, pp \to W+j, pp \to 2j, pp \to 2\gamma + j$ and very recently first study of $\boxed{pp \to 3j}$

Czakon, Mitov, Poncelet arXiv:2106.05331

The Race for NNLO

Two key fronts:

2-loop Amplitudes

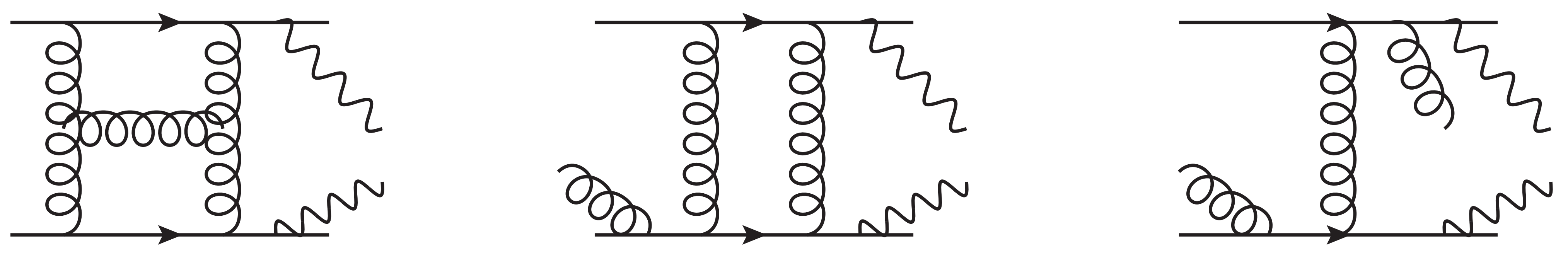
2021 Analytic results for:

$$u\bar{d} \to W^+ b\bar{b},\ gg \to t\bar{t},\ pp \to 3j,\ pp \to 2\gamma + j$$

Badger, Bayu Hartanto, Zoia arXiv:2102.02516
Badger, Chaubey, Bayu Hartanto, Marzucca arXiv:2102.13450
Abreu, Febres Cordero, Ita, Page, Sotnikov arXiv:2102.13609
Chawdhry, Czakon, Mitov, Poncelet arXiv:2103.04319

Emphasis now on numerical stability and efficiency

Cancellation of Divergences



$$\infty \quad + \quad \infty \quad + \quad \infty \quad = N$$

Competing Approaches

q_T Subtraction
Antenna Subtraction
Nested soft-collinear

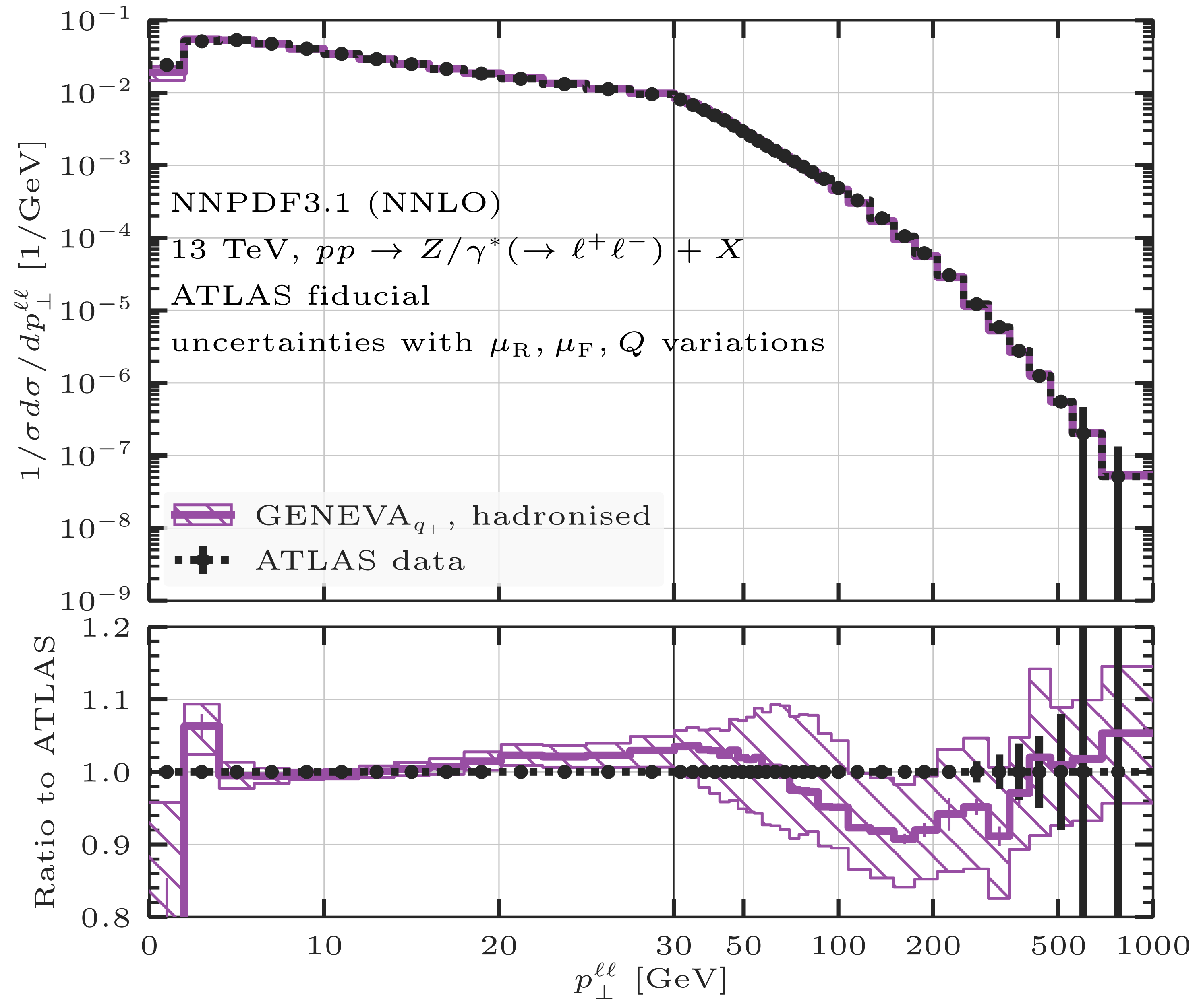
N-Jettiness
Forest Formulas
…

NNLO Plus…

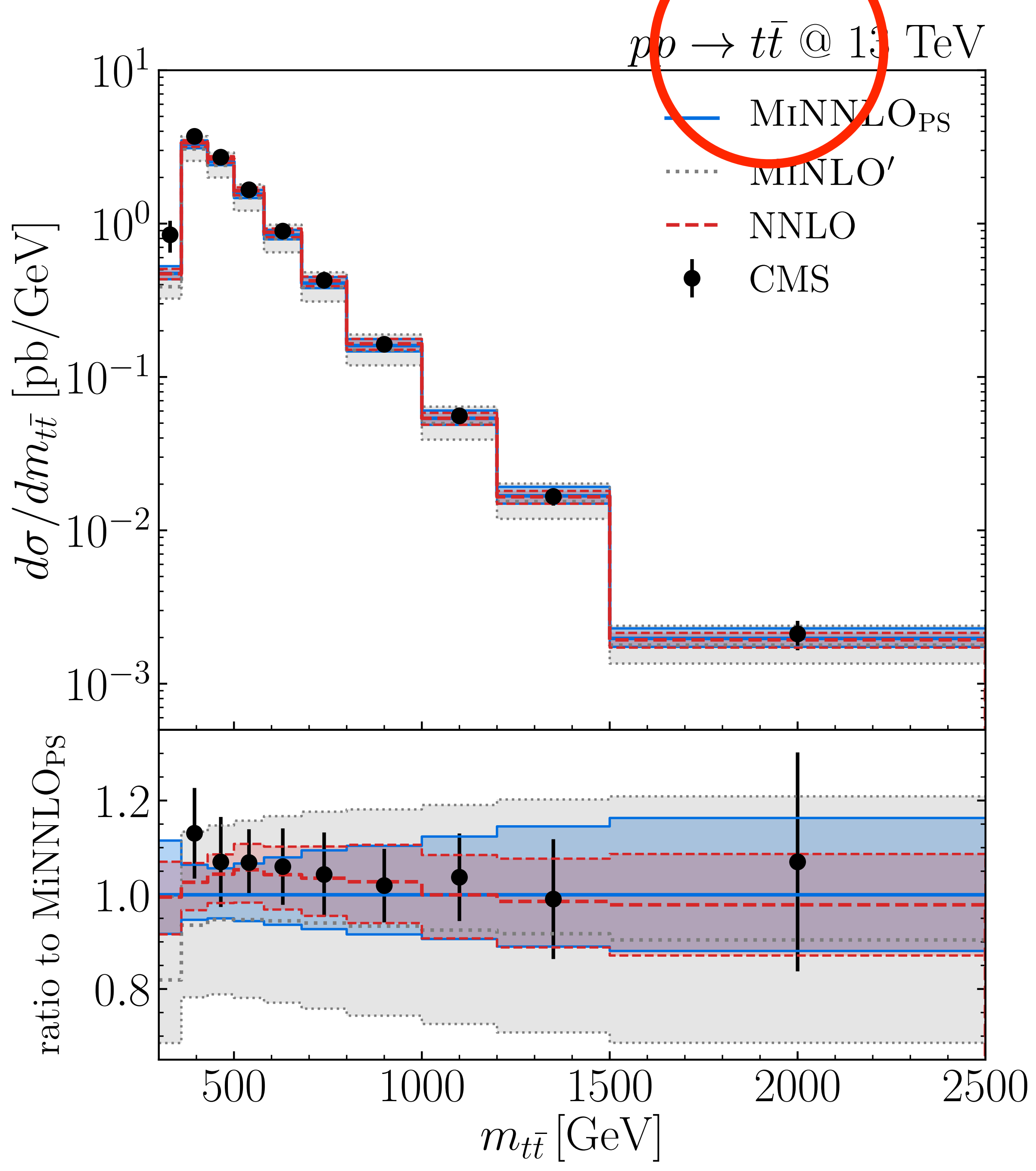
Fast development of methods to match NNLO and parton shower

MiNNLO$_{PS}$, GENEVA, UNNLOPS

GENEVA =
NNLO QCD
+ N3LL q_T (RADISH)
+ shower/ hadronisation (PYTHIA8)



Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, Rottoli arXiv:2102.08390



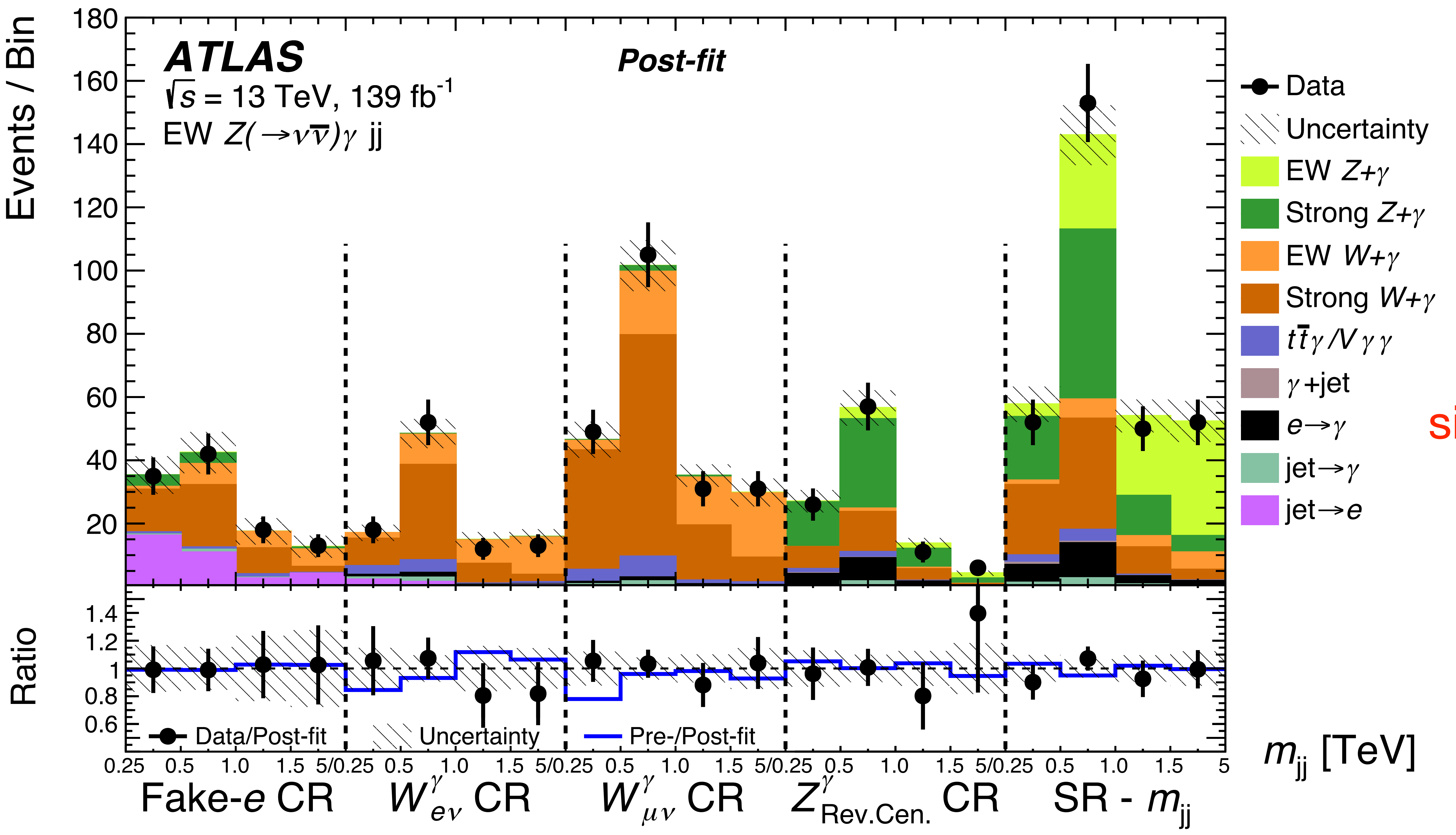
First NNLO+PS with colour-charged particles in final state

Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi arXiv:2102.08390

Event Generators

Event Generators are central to majority of physics analyses at high energy colliders: **signal** & **background**

And they're very successful!

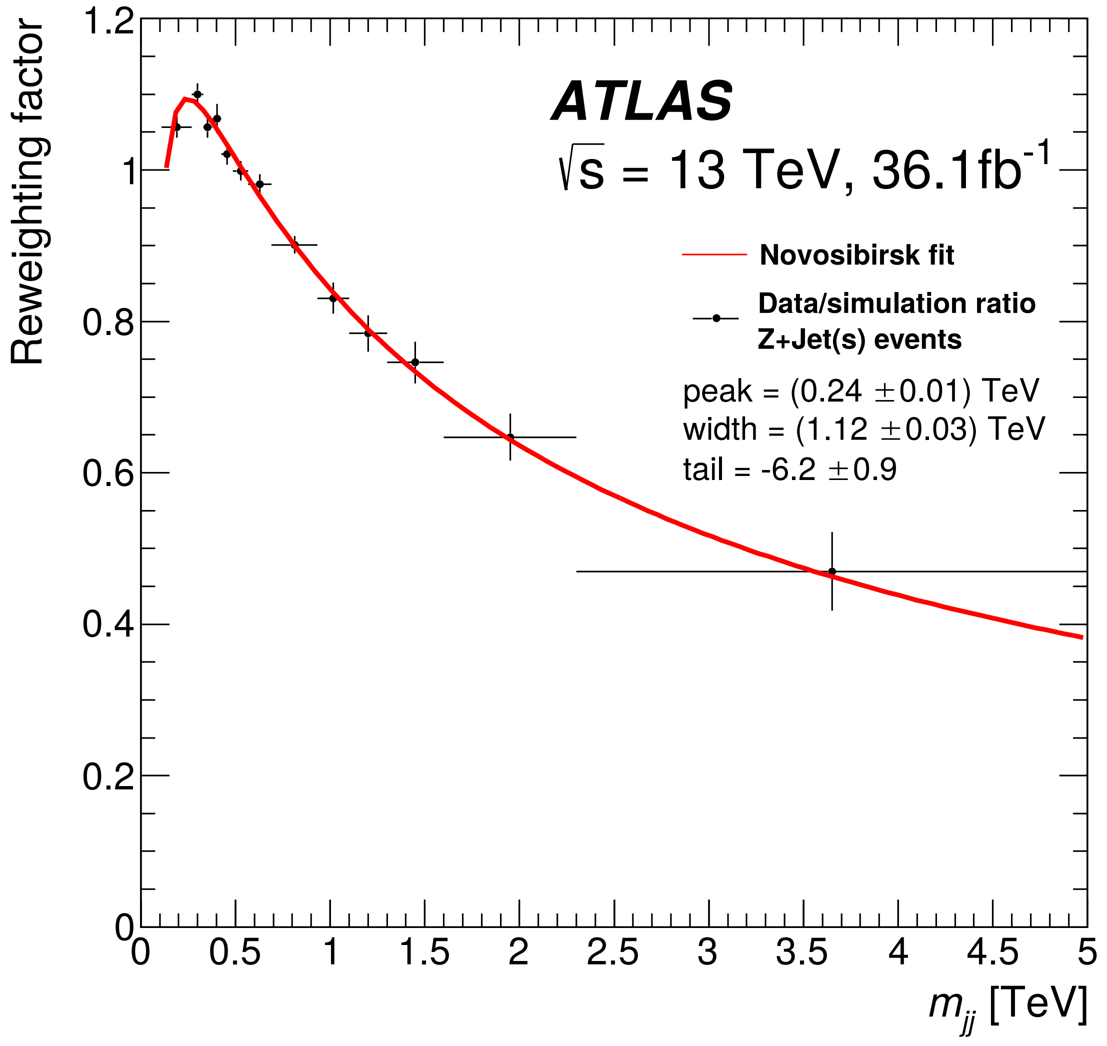


ATLAS arXiv:2109.00925

Many simulations in every analysis

Process	Generator	ME Order	PDF	Parton Shower	Tune
		SM process samples			
Strong $V\gamma$ + jets	Sherpa 2.2.8	NLO (up to 1-jet), LO (up to 3-jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
EW $V\gamma$ + jets	MadGraph5_aMC@NLO 2.6.5	LO	NNPDF3.1lo	Pythia 8.240	A14
EW VV+ jets	Sherpa 2.2.1 or Sherpa v2.2.2	LO	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
VV+ jets	Sherpa 2.2.1 or Sherpa 2.2.2	NLO (up to 1-jet), LO (up to 3-jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
EW V+ jets	Herwig 7.1.3 or Herwig 7.2.0	NLO	MMHT2014nlo68cl	Herwig 7.1.3	Herwig 7
Strong $W(\rightarrow\mu\nu)$ + jets/ $W(\rightarrow\tau\nu)$ + jets	Sherpa 2.2.7	NLO (up to 2-jets), LO (up to 4-jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
$t\bar{t}\gamma$	MadGraph5_aMC@NLO 2.2.3	NLO	NNPDF2.3lo	Pythia 8.186	A14
$t\bar{t}/Wt$	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8.230	A14
$V\gamma\gamma$	Sherpa 2.2.2 (at 0-jet), LO (up to 2-jets)	NLO	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
γ + jet	Sherpa 2.2.2	NLO (up to 2-jets), LO (up to 4-jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
		Higgs-related samples			
ggF Higgs	Powheg v2 NNLOPS	NNLO	PDF4LHC15	Pythia 8.230	AZNLO
Higgs + γ	MadGraph5_aMC@NLO 2.6.2	NLO	PDF4LHC15	Herwig 7.1.3p1	A14
ggF Higgs$\rightarrow\gamma\gamma_d$	Powheg v2 NNLOPS	NNLO	PDF4LHC15	Pythia 8.244p3	AZNLO
VBF Higgs$\rightarrow\gamma\gamma_d$	Powheg v2	NLO	CTEQ6L1	Pythia 8.244p3	AZNLO
		Systematic variation samples			
$V\gamma$ + jets α^4 interference	MadGraph5_aMC@NLO 2.6.2	LO	NNPDF3.1lo	Pythia 8.240	AZNLO

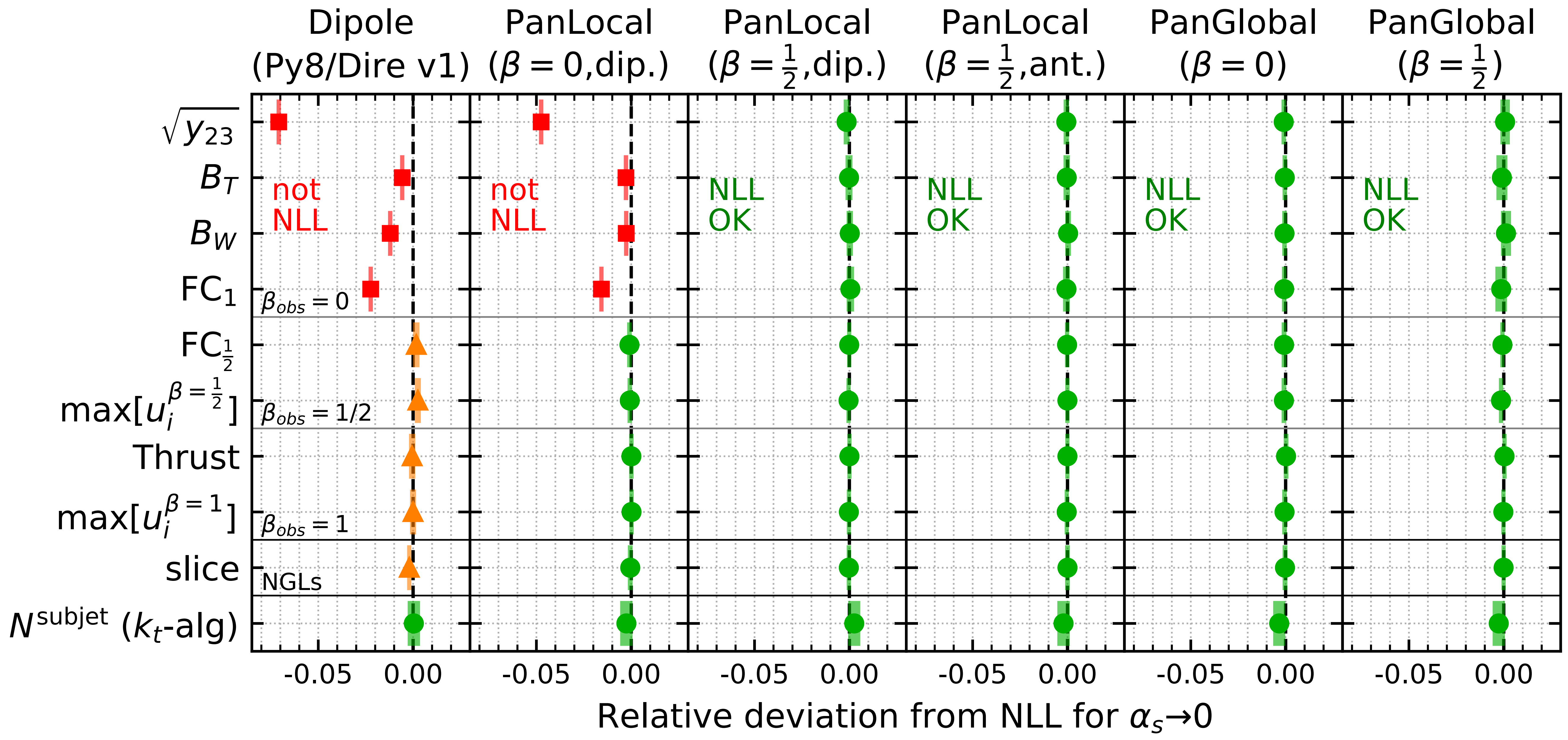
Event Generators



BUT MC uncertainties (often differences between tools) can be substantial

And can require large correction factors

Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez arXiv:2002.11114



Current topics of development (driven by experiment needs):

- Merging with higher-order fixed order
- Logarithmic accuracy - defining and increasing
- Improved colour description

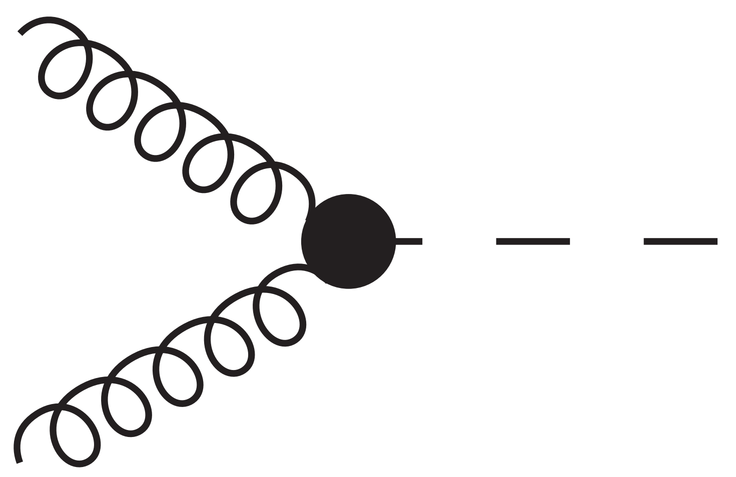
With a close eye on computational requirements - an issue already for HL-LHC, also for FCC…

The Need to go Beyond Fixed Order

Parton showers for soft/coll. emissions at all α_s^n are perfect example where fixed order not enough
In general:

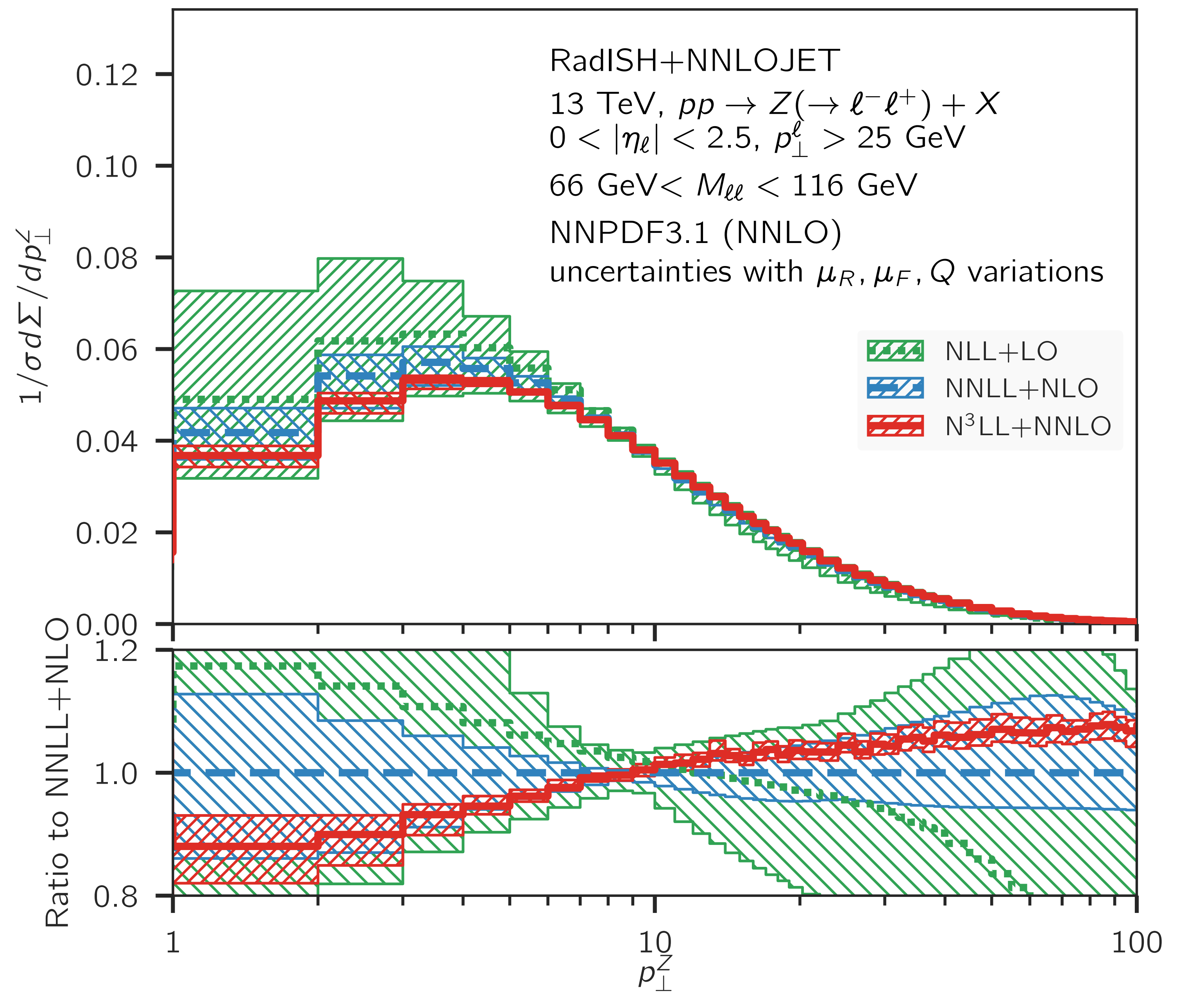
Multiple scales $\longrightarrow$ Logs
Disparate scales $\longrightarrow$ Trouble

See de Florian's Talk

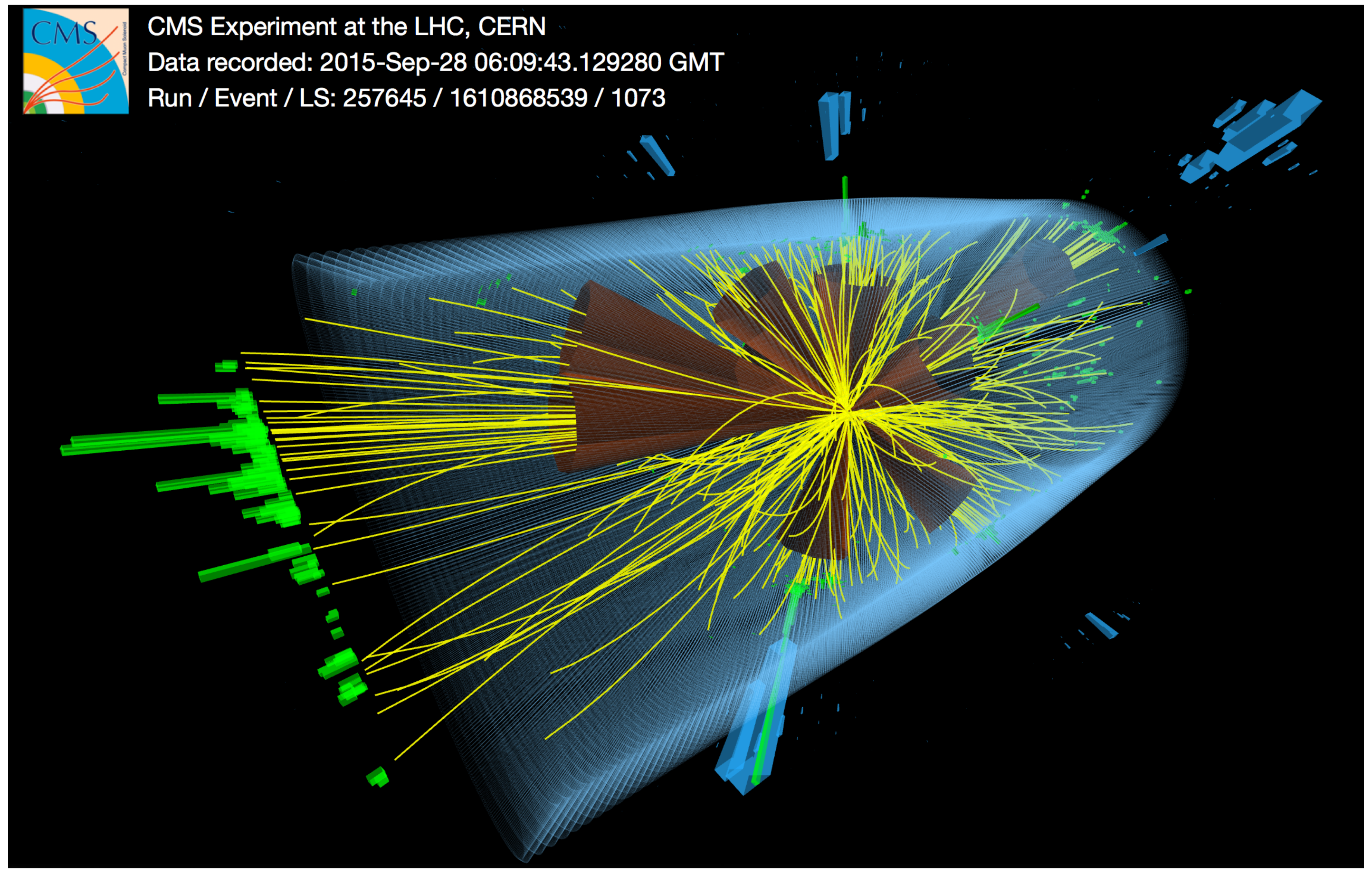


$\log(p_T/m_H)$

NNLL Cieri, Coradeschi, de Florian arXiv:1505.03162



Bizoń, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Walker arXiv:1905.05171



12 jets with p_T > **50 GeV** at CMS (13 TeV)

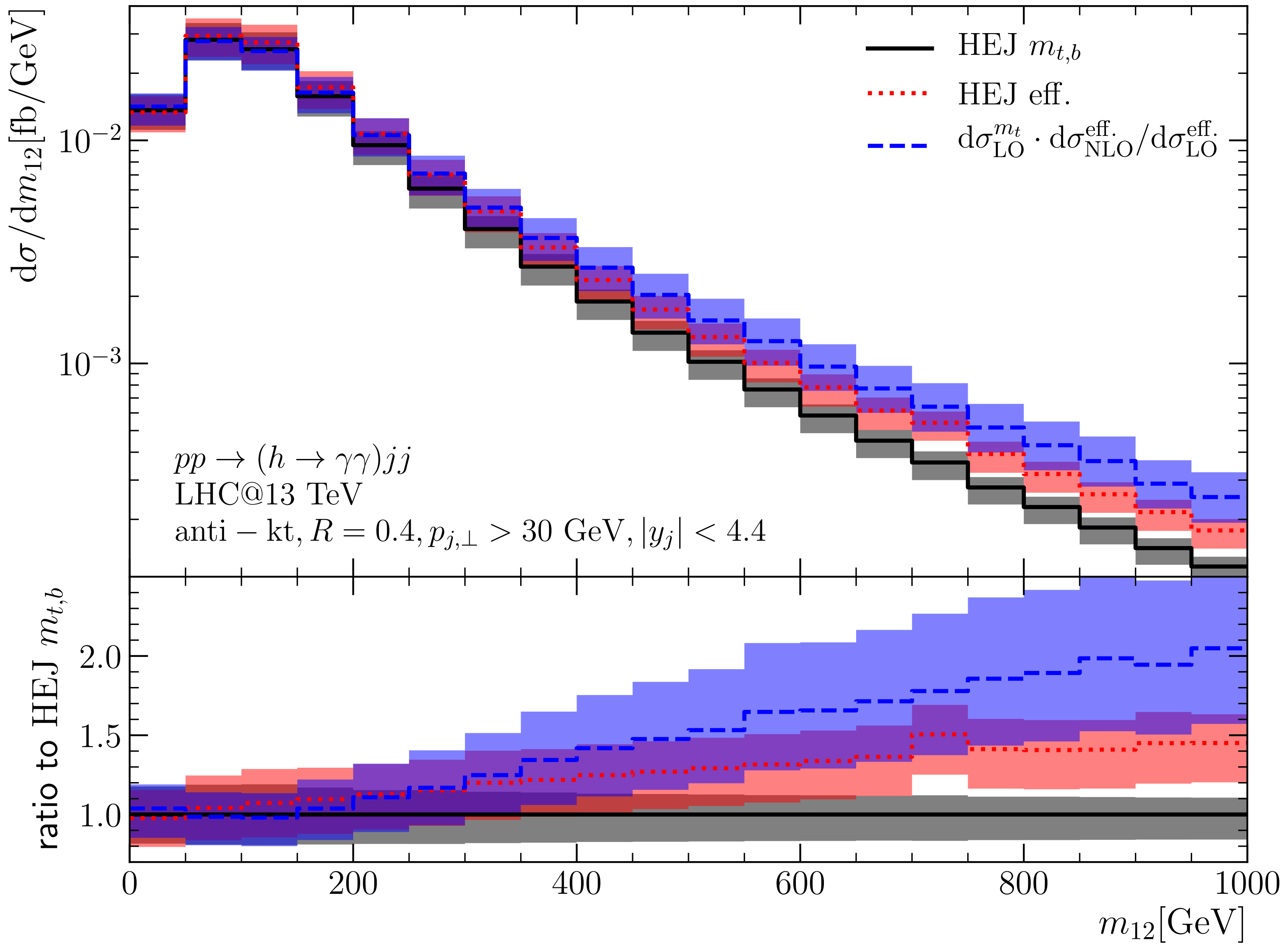
Many coloured-charged, hard particles with p_T, s_{ij}, $\hat{s}$

Large logs in s_{ij}/p_T^2 damage convergence of pert. expansion

Fortunately, the matrix elements of these processes simplify in the High Energy limit: $s_{ij} \to \infty$, $|p_{Ti}|$ finite

Can sum up all $\alpha_s^{2+k} \log^k(\hat{s}/p_T^2)$ implemented in High Energy Jets (HEJ)

Andersen, JMS arXiv:0908.2786, 0910.5113

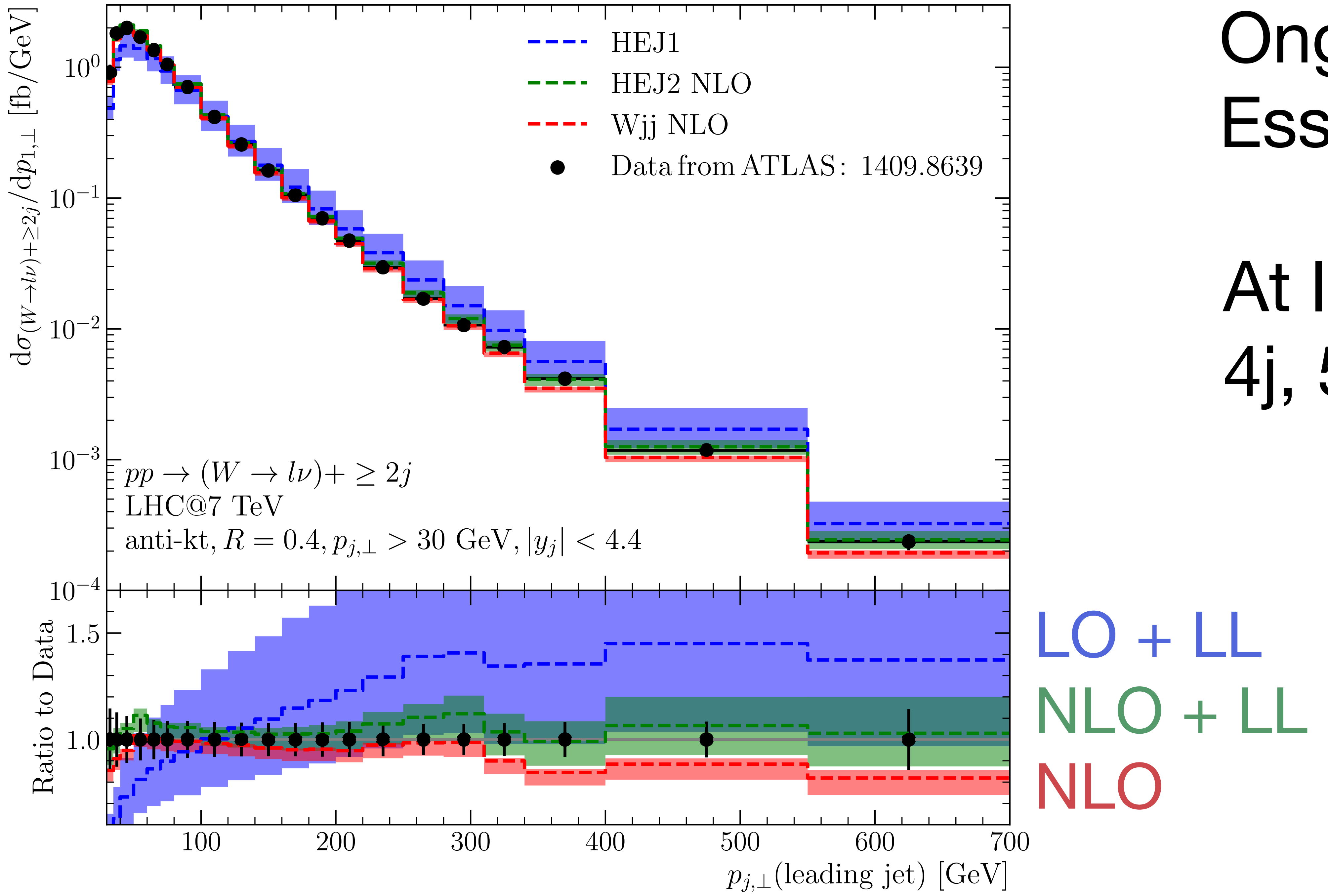


Andersen, Cockburn, Heil, Maier, JMS arXiv:1812.08072

Simpler form allows inclusion of quark masses in Higgs couplings to arbitrary multiplicity (fixed order, H+3j LO)

Cuts to study HWW couplings in Hjj (VBF) require large rapidity and m_{jj}
This exactly enhances the logs!

High Energy Logs



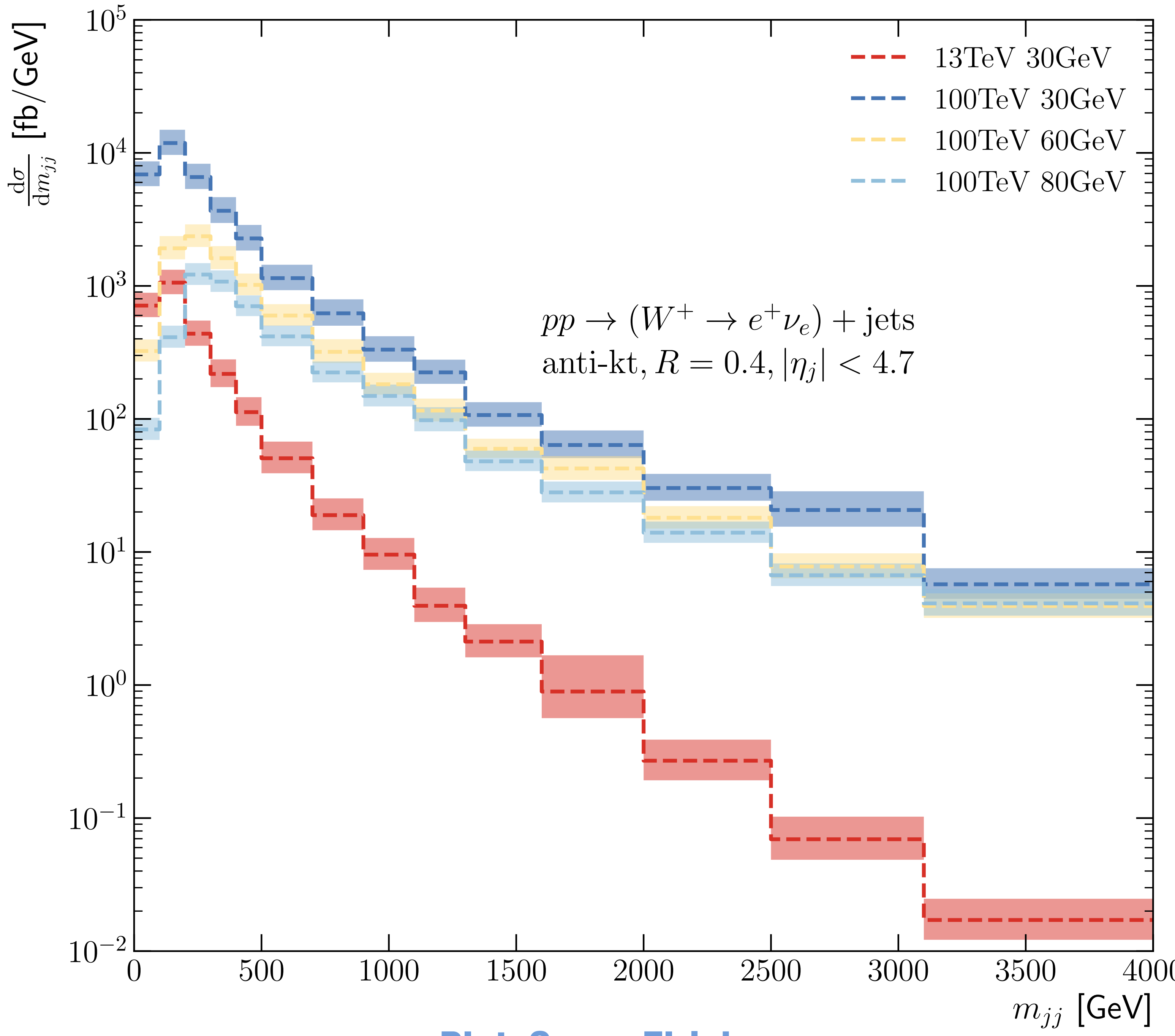
Andersen, Black, Brooks, Byrne, Maier, JMS arXiv:2012.10310

Ongoing work to combine log treatment with NLO and PS
Essential for large p_T

At large values of p_T in this *dijet* sample, contribution from 4j, 5j, … components numerically significant

Impact of logs enhanced again with increase to 13 TeV, and much more at 100 TeV

Increased min jet p_T controls cross section, but tails fall much less steeply



Plot: Conor Elrick

PDFs

Scale uncertainties reduced low enough that other sources of error become very significant

$$\sigma(pp \to Hb\bar{b})$$

S [TeV]	σ [pb]	δ(scale) [%]	$\delta(\alpha_s + \mathrm{PDF})$ [%]	δ(PDF-TH) [%]	$\delta(m_b)$ [%]
7	0.172	$^{+2.50}_{-2.63}$	$\pm$ 9.05	$\pm$3.85	$^{+1.44}_{-0.95}$
8	0.222	$^{+2.64}_{-3.01}$	$\pm$ 9.02	$\pm$3.54	$^{+1.44}_{-0.95}$
13	0.535	$^{+2.52}_{-4.11}$	$\pm$ 8.37	$\pm$2.49	$^{+1.44}_{-0.95}$
14	0.604	$^{+2.67}_{-4.31}$	$\pm$ 8.31	$\pm$2.36	$^{+1.44}_{-0.95}$
27	1.68	$^{+2.57}_{-5.92}$	$\pm$ 7.59	$\pm$1.22	$^{+1.44}_{-0.95}$
100	9.21	$^{+3.26}_{-9.38}$	$\pm$ 6.68	$\pm$1.00	$^{+1.44}_{-0.95}$

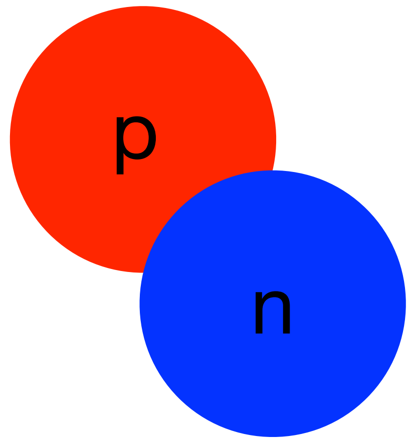
Duhr, Dulat, Hirschi, Mistlberger arXiv:2004.04752

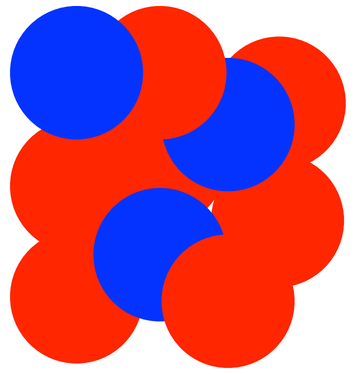
Within pdf fits, experimental errors now low enough that other sources of error become very significant

E.g. W/Z p_T data from LHC causes issues in standard fits: exp error ~0.1%, th. error ~1%

Inclusion of theory errors is subtle, but important

Harland-Lang, Thorne arXiv:1811.08434
Ball, Pearson arXiv:2105.05114





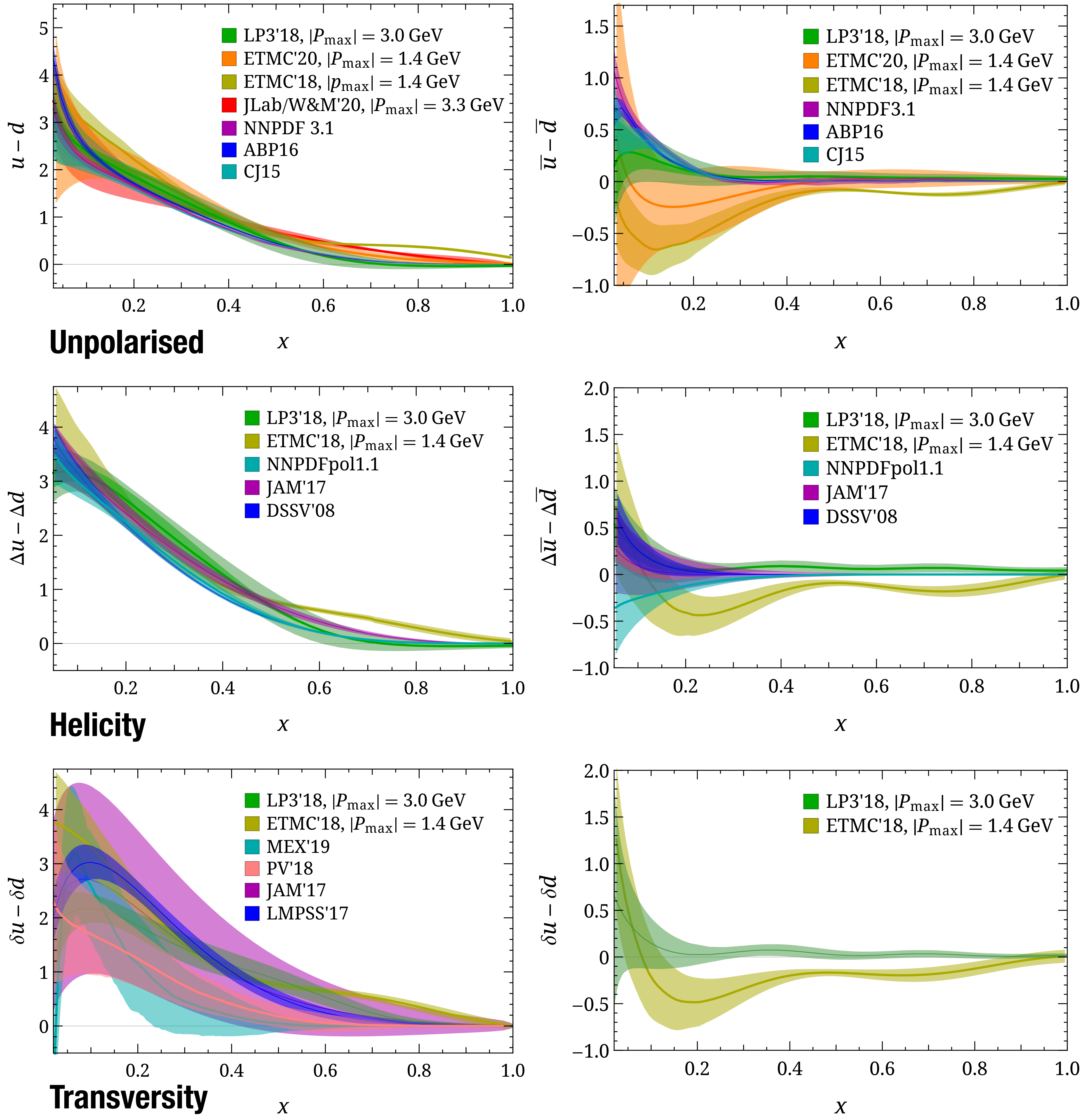
Nuclear effects also important

+EW

New PDF Input

Now have possibility to calculate pdfs on the lattice

E.g. Xiangdong Ji arXiv:1305.1539

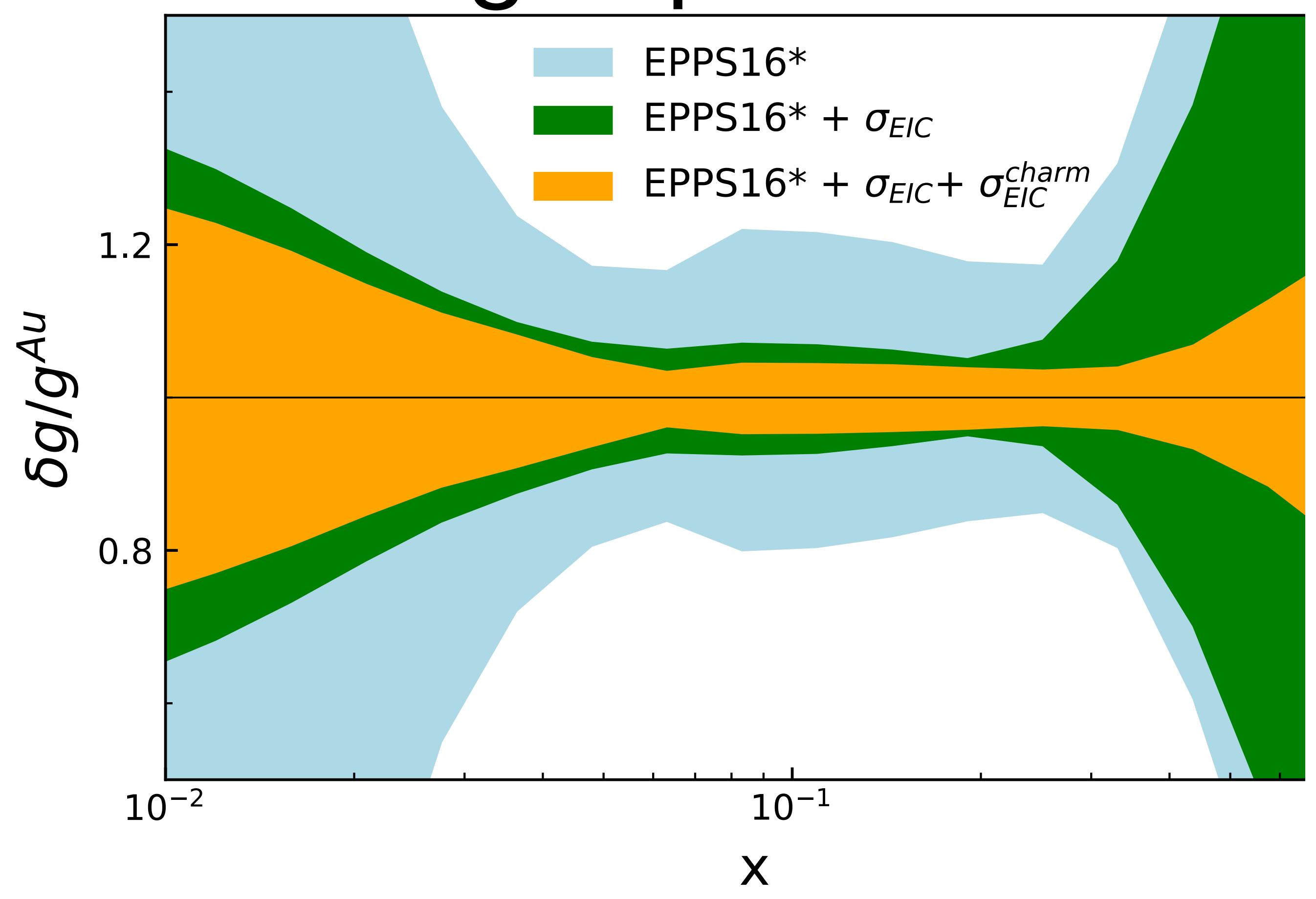


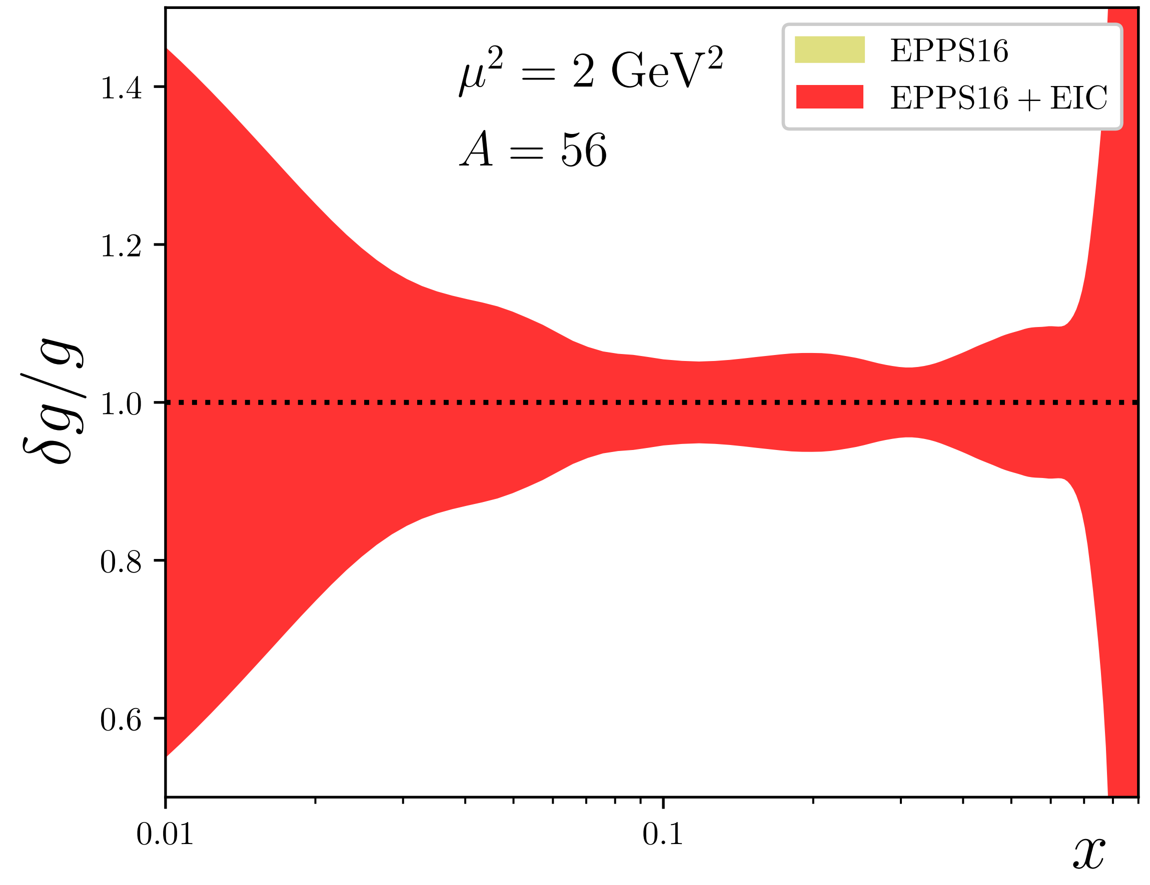
2020 PDFLattice Review arXiv:2006.08636

Mature enough to compare with state-of-the-art global fits

Opportunities for approaches to improve each other (also nPDFs, TMDs, GPDs)

New data from EIC & SMOG2 will add to existing experiments





EIC Yellow Report arXiv:2103.05419

Polarised PDFs

Quark spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{Q+G}$$

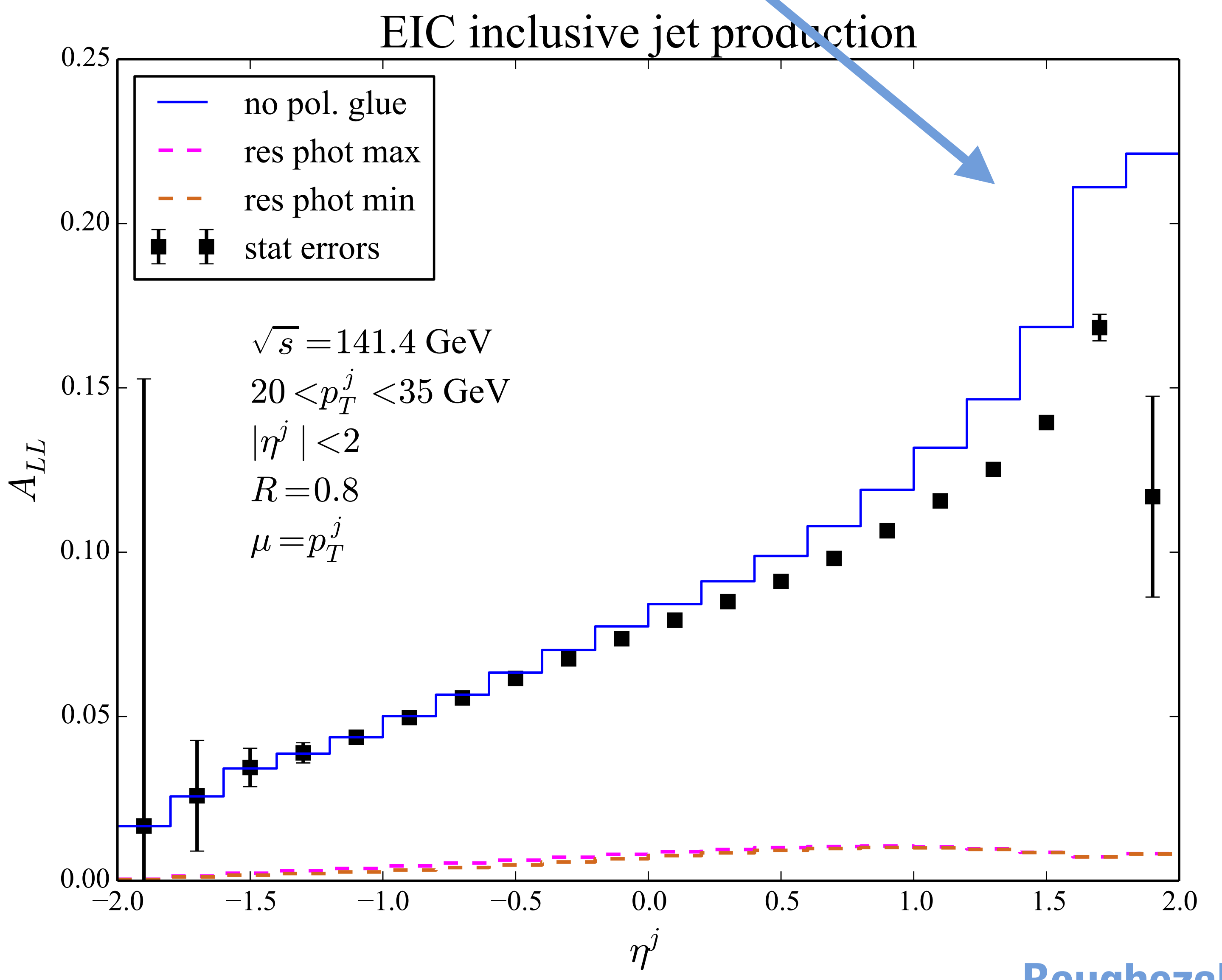
Angular momenta

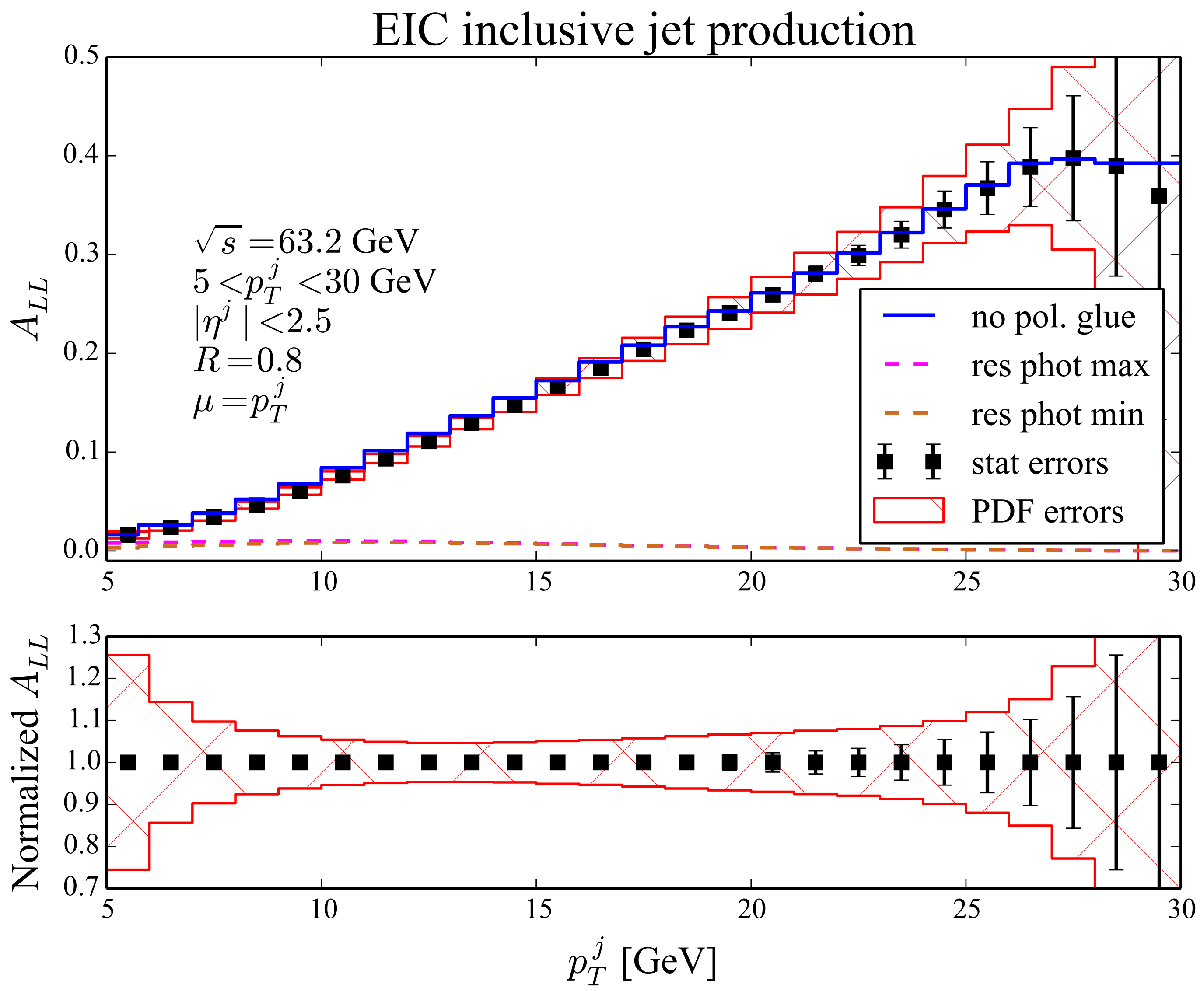
Gluon spin

Where does the proton spin come from?

Access to the polarised gluon pdf via

$$\mathcal{A}_{LL} = \frac{d\sigma^{++} - d\sigma^{+-} - d\sigma^{-+} + d\sigma^{--}}{d\sigma^{++} + d\sigma^{+-} + d\sigma^{-+} + d\sigma^{--}} \qquad \sigma^{h_\ell h_p}$$



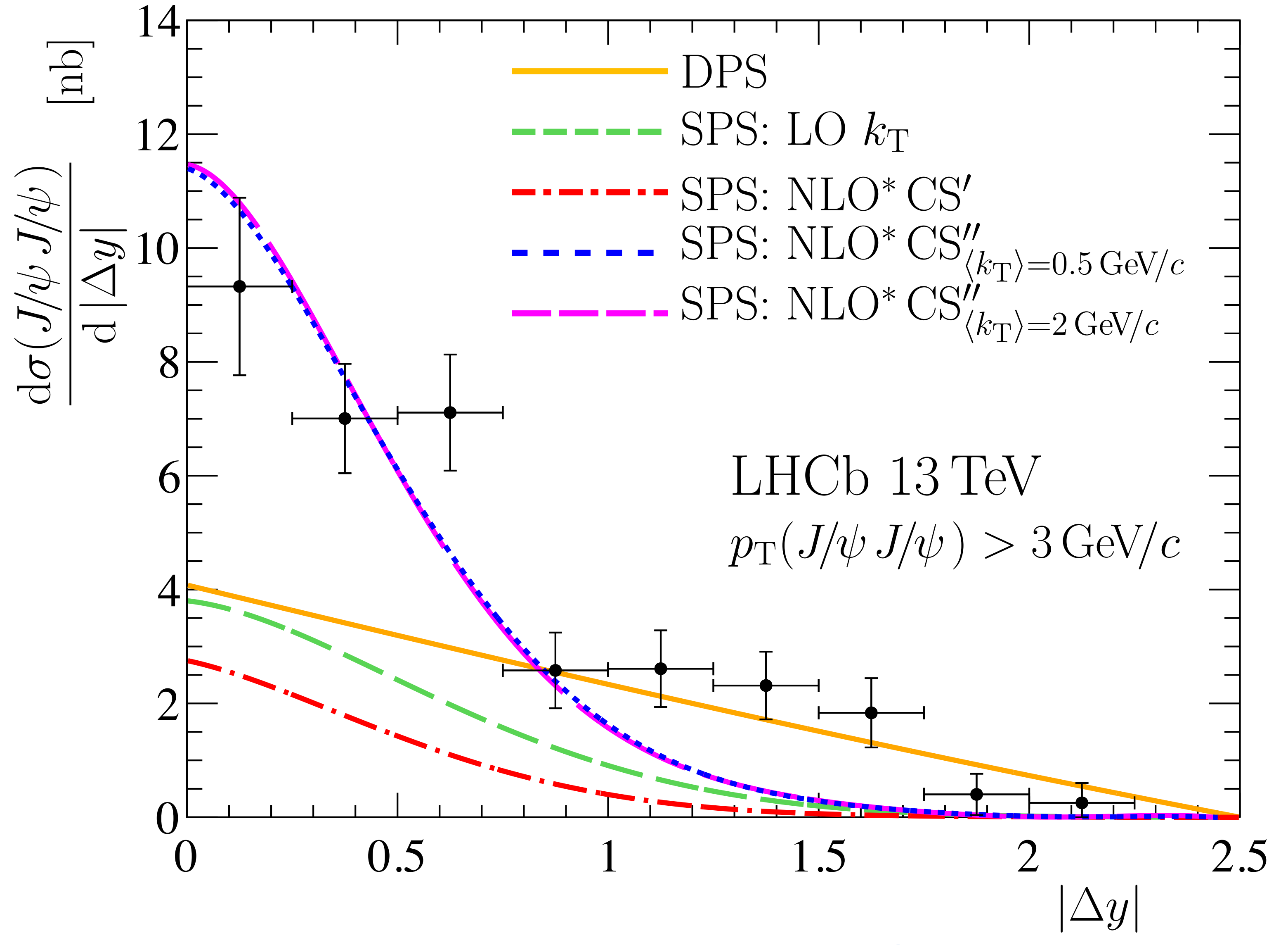


Projected stat errors lower than pdf errors

→ can constrain

Boughezal, Petriello, Xing arXiv:1806.07311

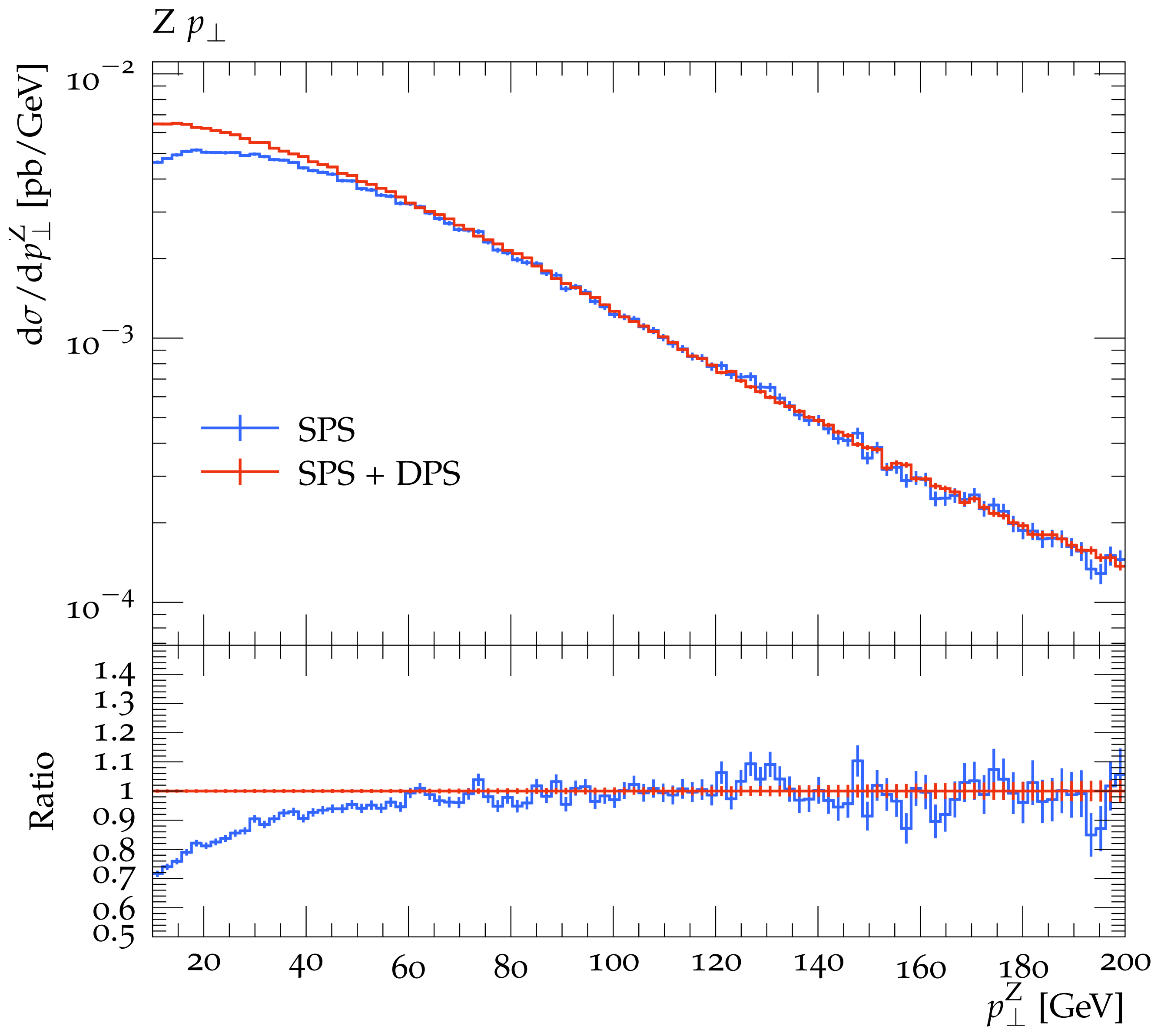
Double Parton Scattering (DPS)

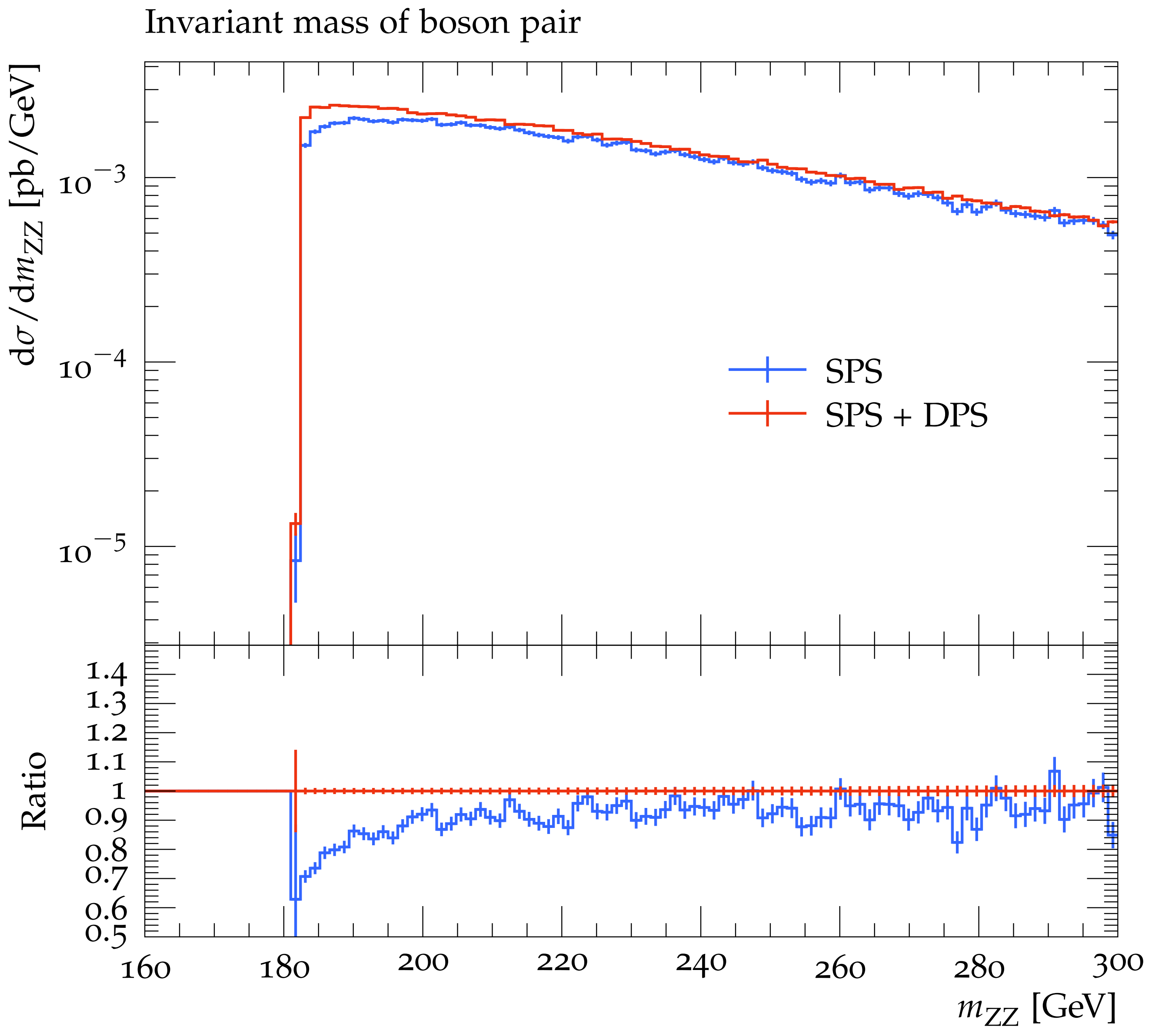


LHCb arXiv:1612.07451

DPS: one collision contains **two separate** hard scatters
E.g. Evidence of impact in J/ψ data from LHCb

"A fit to the differential cross sections using simple DPS plus SPS models indicates a significant DPS contribution."





Toy model

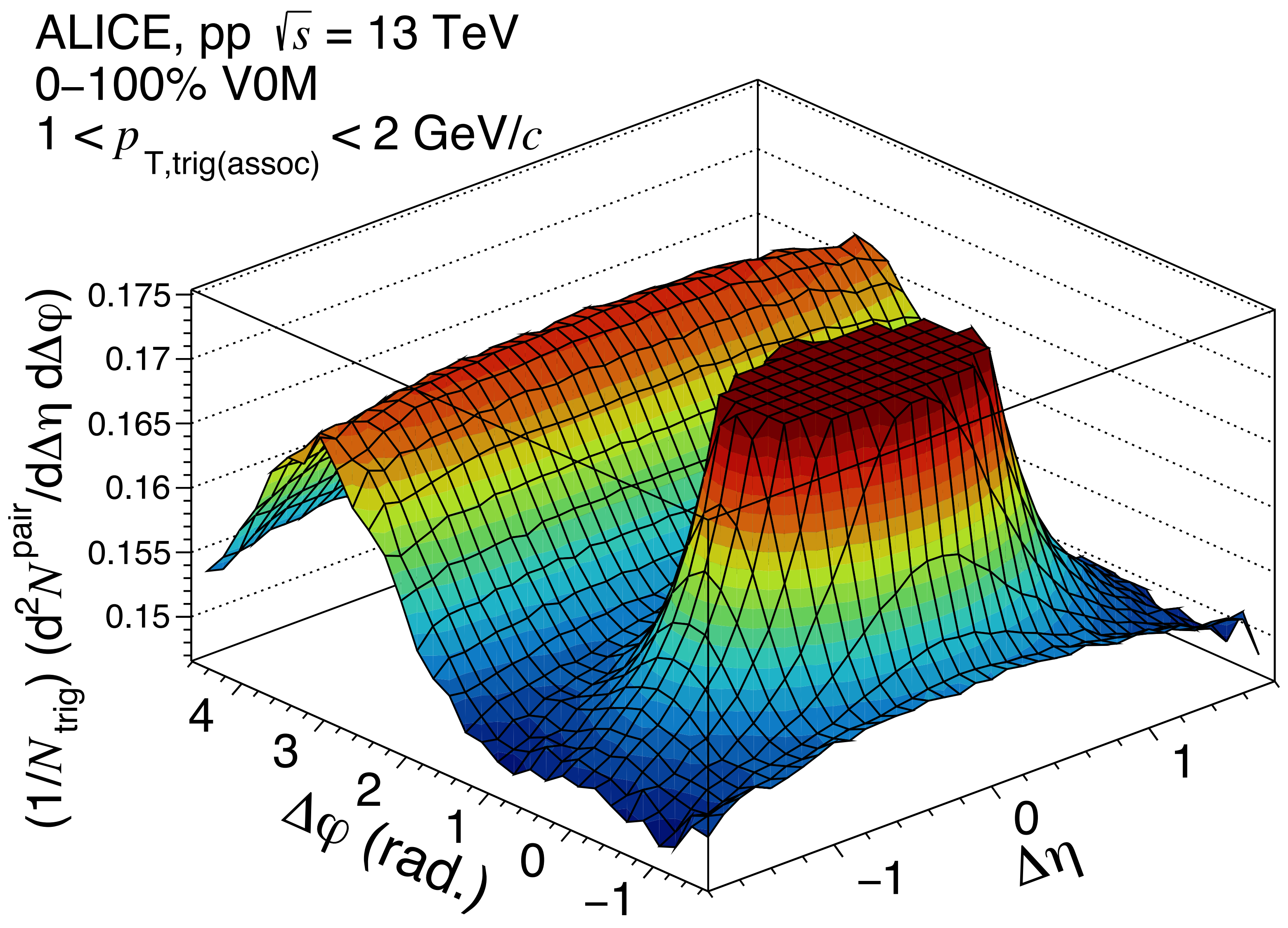
New Monte Carlo implementation of DPS, dShower, allows combination of SPS and DPS at same time
Cabouat, Gaunt, Ostrolenk arXiv:1906.04669, 2008.01442

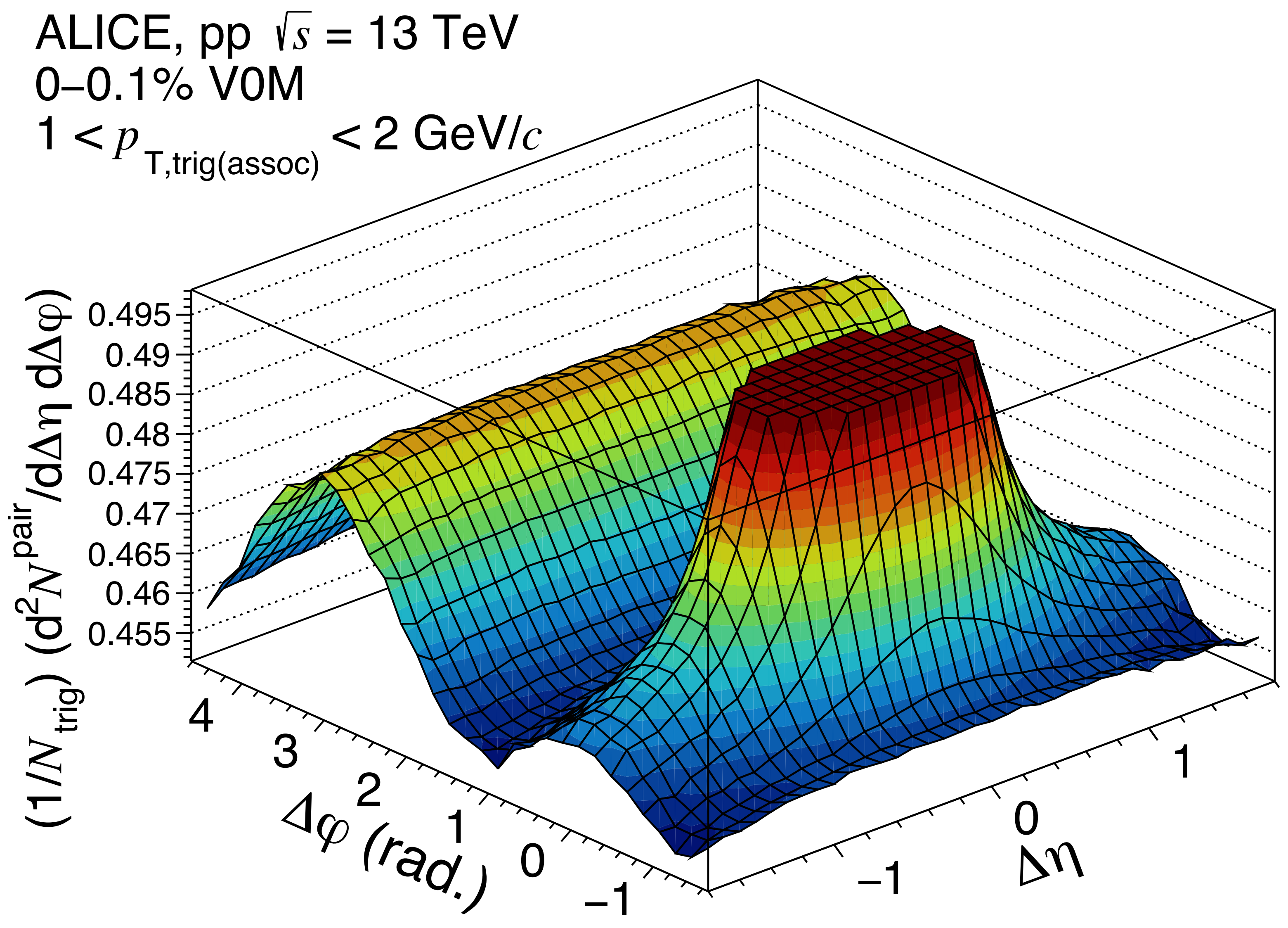
For a process at a fixed scale, increase in collider energy gives an increase in DPS relative to SPS

Collective Behaviour

Unexpected result from the LHC is the observation of flow-like effects in p-p collisions

Low p_T and multi-particle correlation measurements at ALICE, ATLAS & CMS all well-described by fluid dynamics



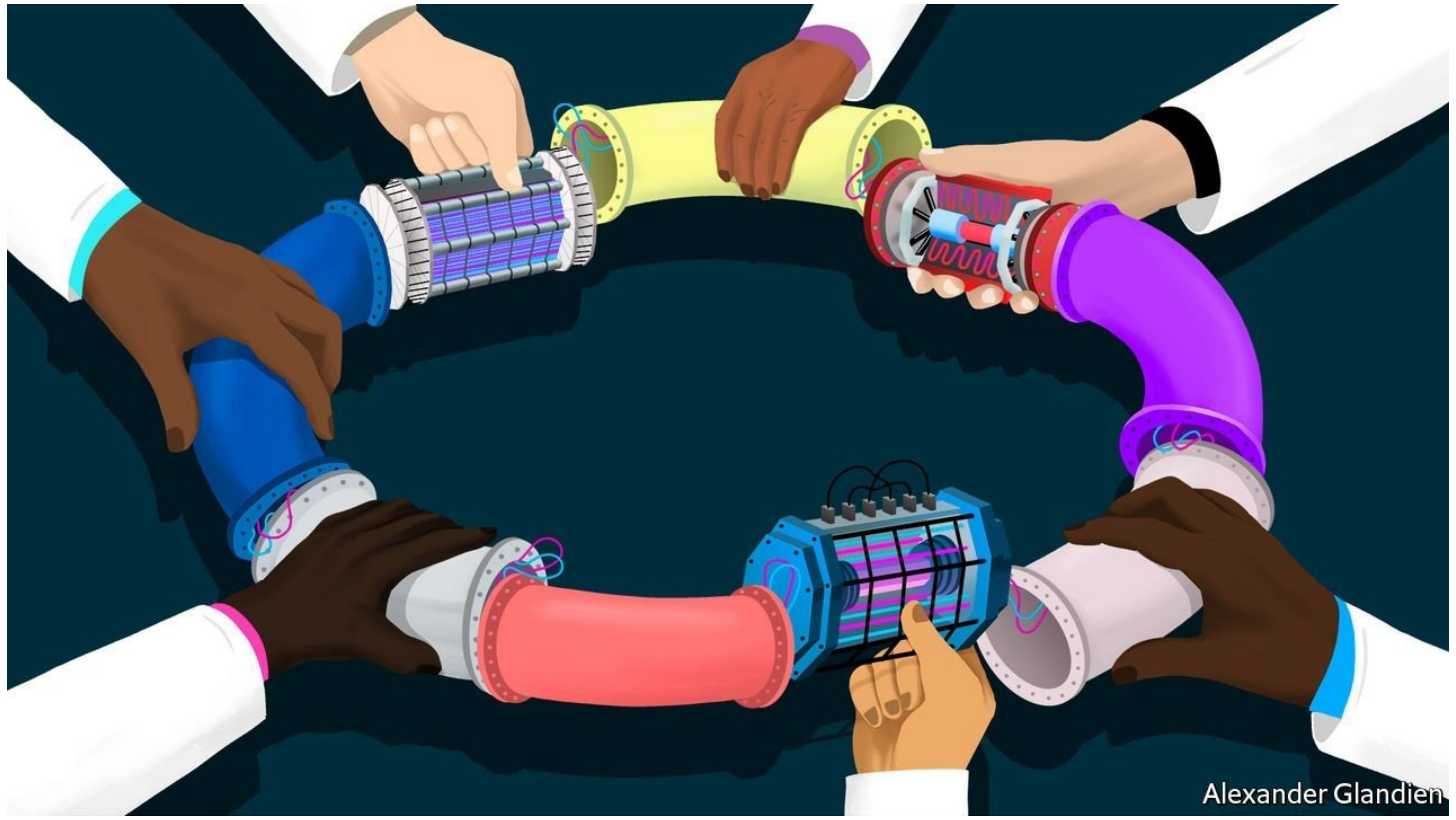


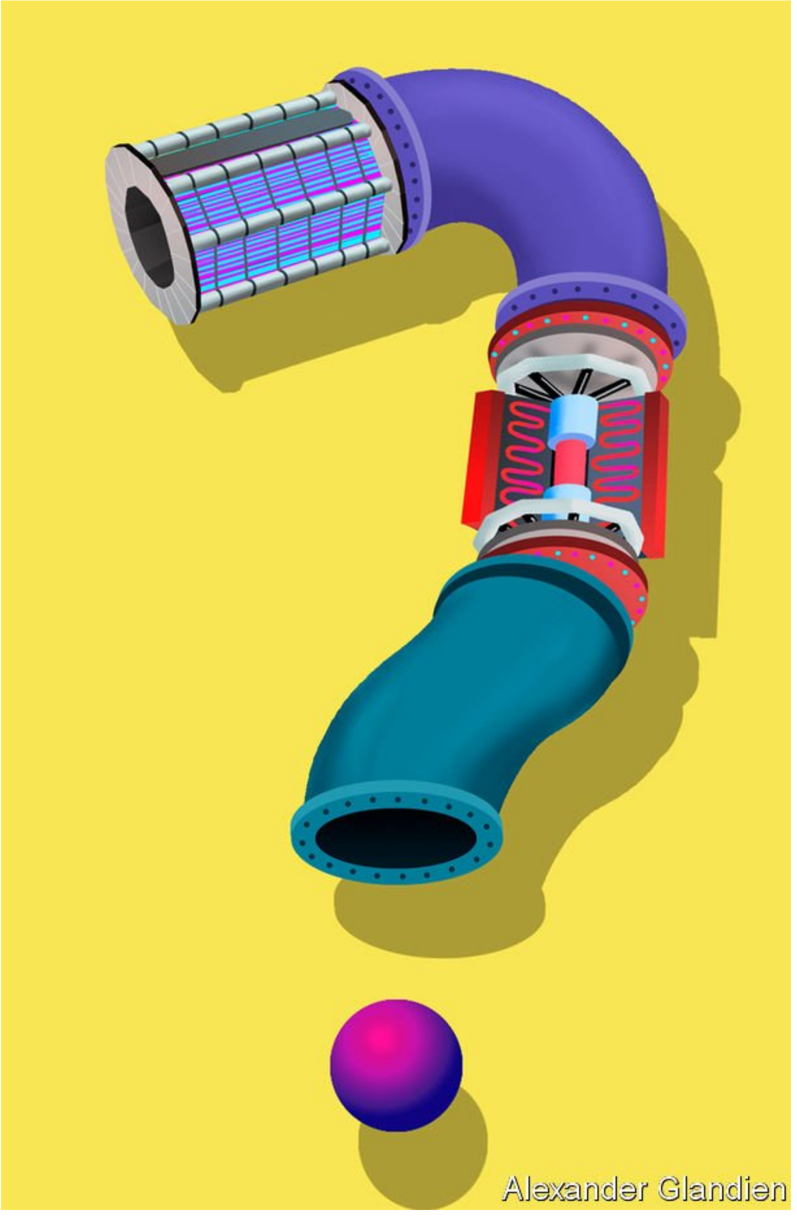
ALICE arXiv:2101.03110

It's important to remember that we can still be caught by surprise!

Outlook

- We still have a lot to learn from the LHC! At least 15 more years of data, integrated luminosity x 20!
- Tantalising programme of different experiments to come
- Experimental precision is pushing theory to the limit… and we're responding!





Exciting times ahead!