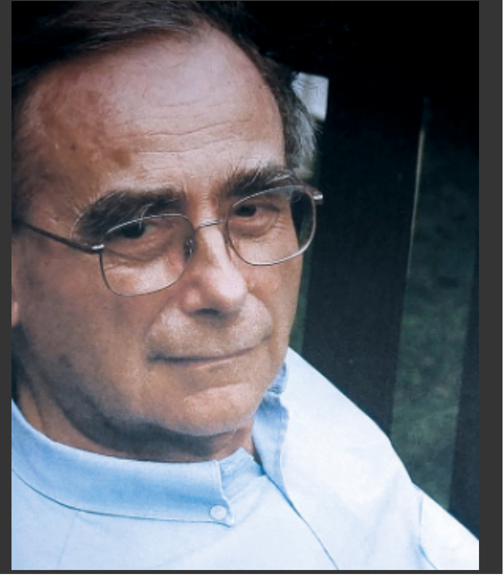
École normale supérieure Summer Institute
Claude Bouchiat memorial
ENS 12-13 July 2023



QCD jets as measurement and discovery probes

Michelangelo L. Mangano
TH Department
CERN

7.A.2 Nuclear Physics B34 (1971) 157-176. North-Holland Publishing Company

GALILEAN INVARIANCE IN THE INFINITE MOMENTUM FRAME AND THE PARTON MODEL

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Laboratoire de Physique Théorique et Hautes Energies, Orsay, France *

Received 21 June 1971

Whether an infinite momentum frame field theory can be built in a consistent and fundamental way has not concerned us here. Rather, we prefer to adopt the view that this scheme is a short-cut to high-energy behaviour, in very much the same way the Schrödinger picture is a short-cut to non-relativistic properties. At least, in our opinion, it has the merit of possessing considerable intuitive power for suggesting models and deriving their consequences.

Abstract: Field theory in the infinite momentum frame variables is used to derive the parton model, and to stress the implications of transverse Galilean and longitudinal Lorentz boost invariances. The elastic nucleon electromagnetic form factor and inelastic structure functions are expressed as density and correlation functions for partons in the transverse plane, in direct analogy with expressions of non-relativistic atomic physics. A connection is established between the transverse momentum cut-off and the q^2 dependence of the electromagnetic elastic form factor. The scaling law for the parton model is derived under conditions which appear in a rather transparent way. The corresponding sum rules are studied. A generalization of the Bjorken-Feynman scaling is obtained in the non-forward Compton scattering amplitude relevant to the two-photon correction in very high-energy electron-nucleon elastic scattering.

Positivity and renormalization of parton densities

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(Dated: April 28, 2022)

There have been recent debates about whether $\overline{\text{MS}}$ parton densities exactly obey positivity bounds (including the Soffer bound), and whether the bounds should be applied as a constraint on global fits to parton densities and on nonperturbative calculations. A recent paper (JHEP **11** (2020) 129) appears to provide a proof of positivity in contradiction with earlier work by other authors. We examine their derivation and find that its primary failure is in the apparently uncontroversial statement that bare pdfs are always positive. We show that under the conditions used in the derivation, that statement fails. This is associated with the use of dimensional regularization for both

[...]

II. TRACK-A: RENORMALIZATION AND LIGHT-CONE PDFS

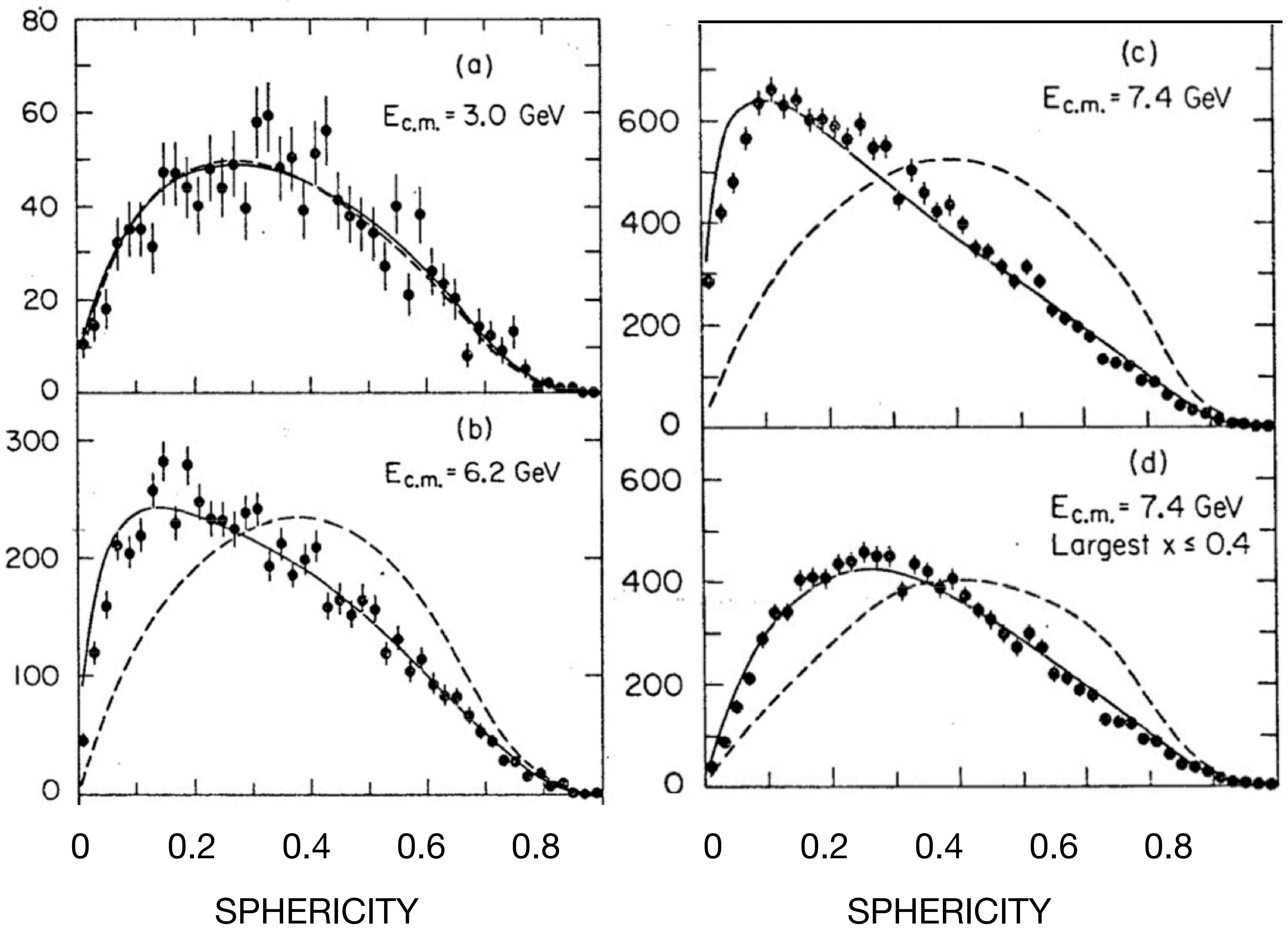
One of the motivating points of track-A was work to provide a definite field-theoretical implementation of the original pdf concept. At the beginning, this led to the insight that light-front quantization provides a suitable candidate definition as the expectation of a light-front number operator [17–19], provided that no

[17] J. B. Kogut and D. E. Soper, Quantum electrodynamics in the infinite momentum frame, Phys. Rev. **D1**, 2901 (1970).
[18] C. Bouchiat, P. Fayet, and P. Meyer, Galilean invariance in the infinite momentum frame and the parton model, Nucl. Phys. **B34**, 157 (1971).
[19] D. E. Soper, The Parton Model and the Bethe-Salpeter Wave Function, Phys. Rev. D **15**, 1141 (1977).

The dawn of jet physics: e^+e^-

1975, discovery of 2-jet structure
(SLAC-LBL detector at SPEAR, 3-7.4 GeV)

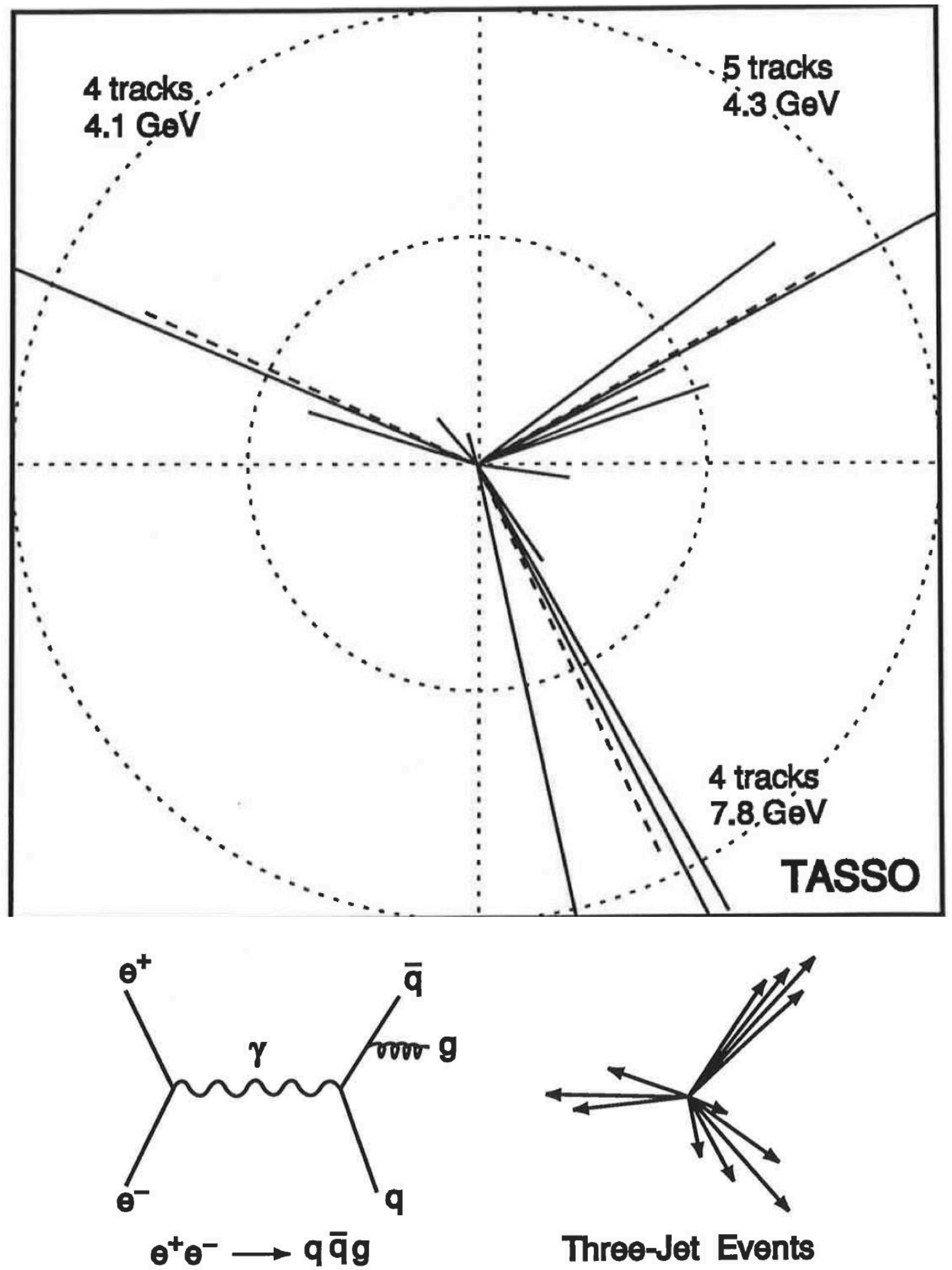
Phys.Rev.Lett. 35 (1975) 1609



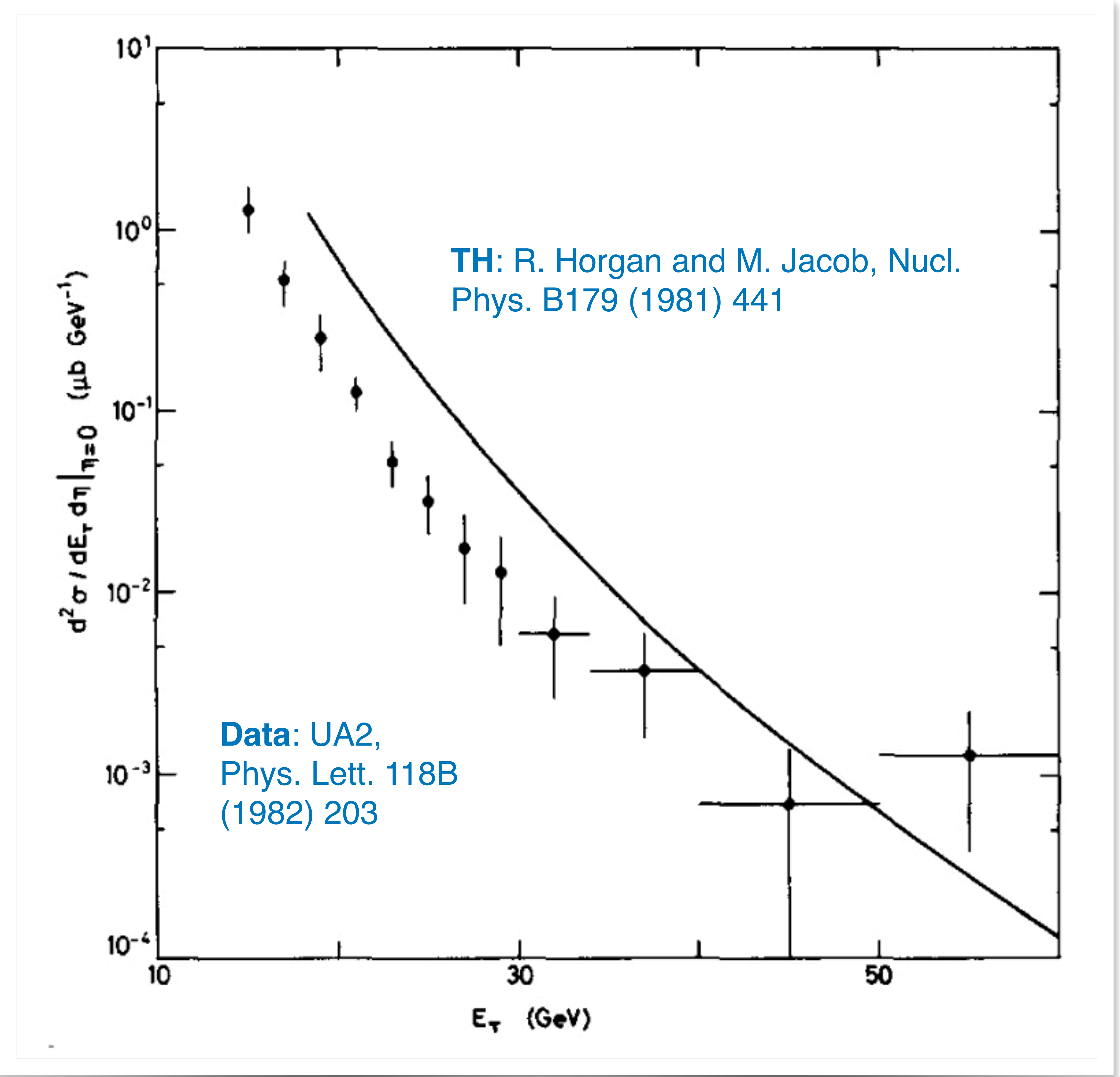
dashes: phase-space, solid: jet model

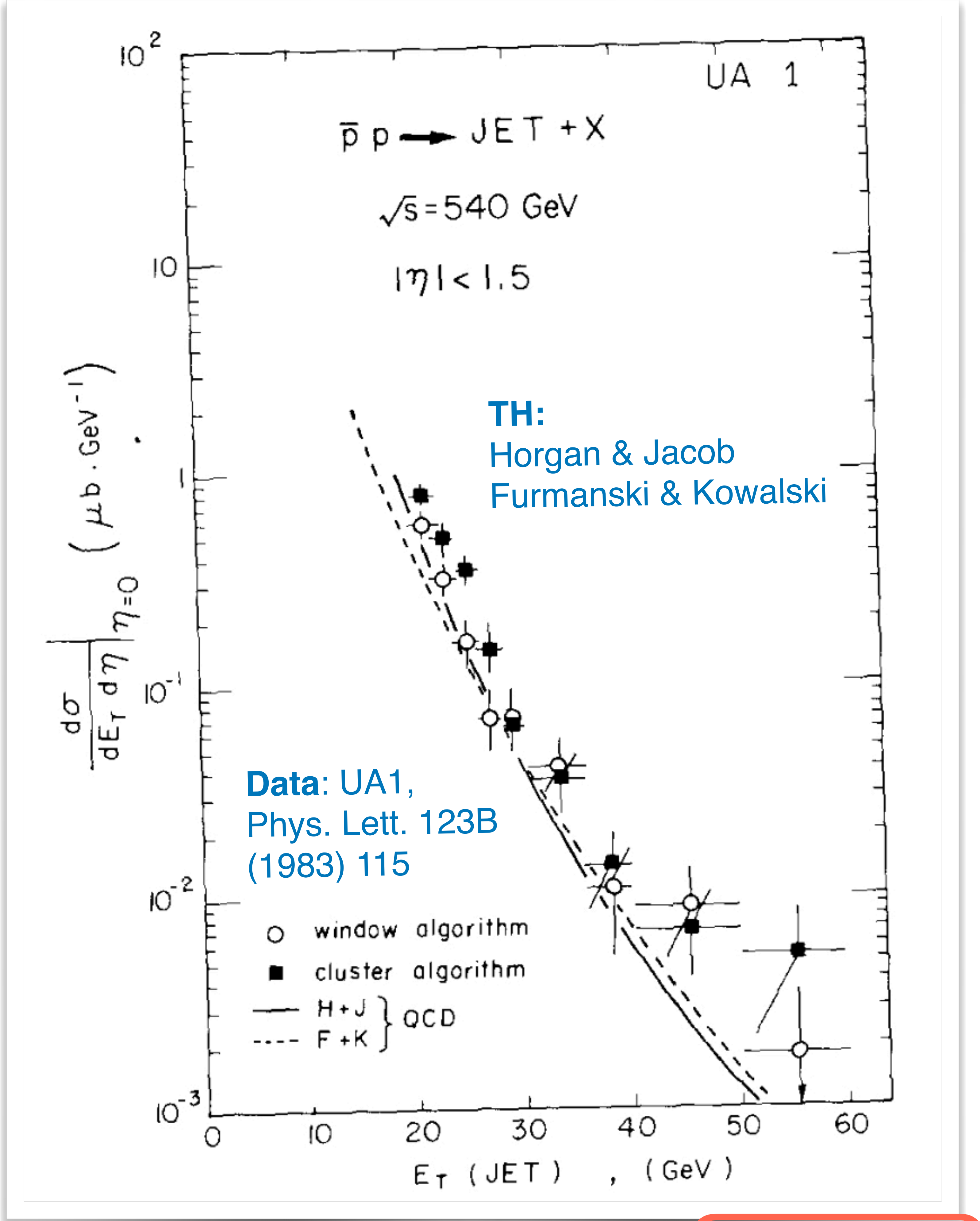
1979, the first "gluon-jet" event recorded
(TASSO at PETRA, $\sqrt{s} = 27.4\ \text{GeV}$)

Phys.Lett.B 86 (1979) 243



The dawn of jet physics: $p\bar{p}$





Volume 118B, number 1, 2, 3 PHYSICS LETTERS 2 December 1982

OBSERVATION OF VERY LARGE TRANSVERSE MOMENTUM JETS AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

Volume 123B, number 1,2 PHYSICS LETTERS 24 March 1983

OBSERVATION OF JETS IN HIGH TRANSVERSE ENERGY EVENTS AT THE CERN PROTON ANTIPROTON COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

Volume 122B, number 1 PHYSICS LETTERS 24 February 1983

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

Volume 122B, number 5,6 PHYSICS LETTERS 17 March 1983

OBSERVATION OF SINGLE ISOLATED ELECTRONS OF HIGH TRANSVERSE MOMENTUM IN EVENTS WITH MISSING TRANSVERSE ENERGY AT THE CERN $\bar{p}p$ COLLIDER

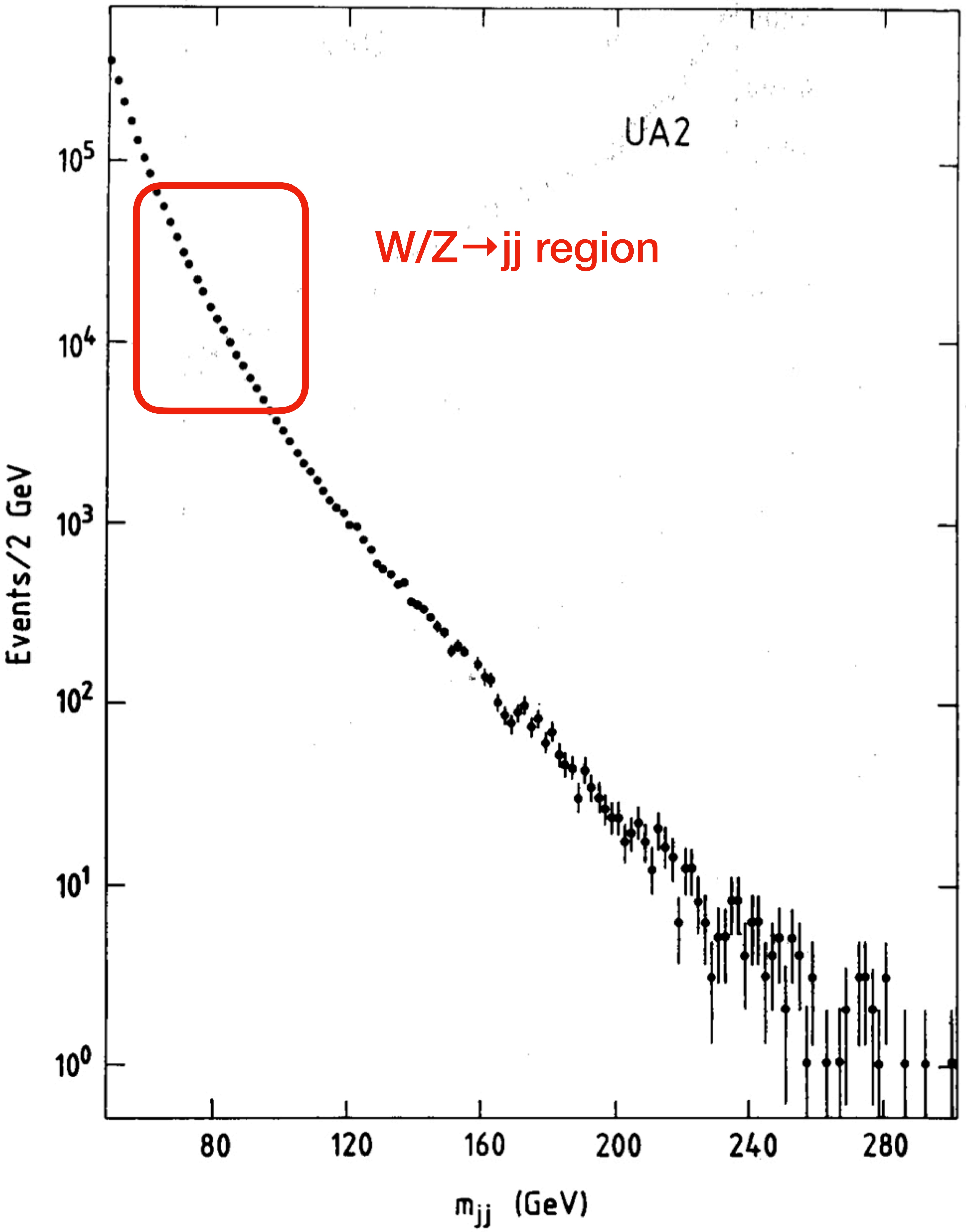
The UA2 Collaboration

The discovery of jets in hadronic collisions was not a granted or easy task:

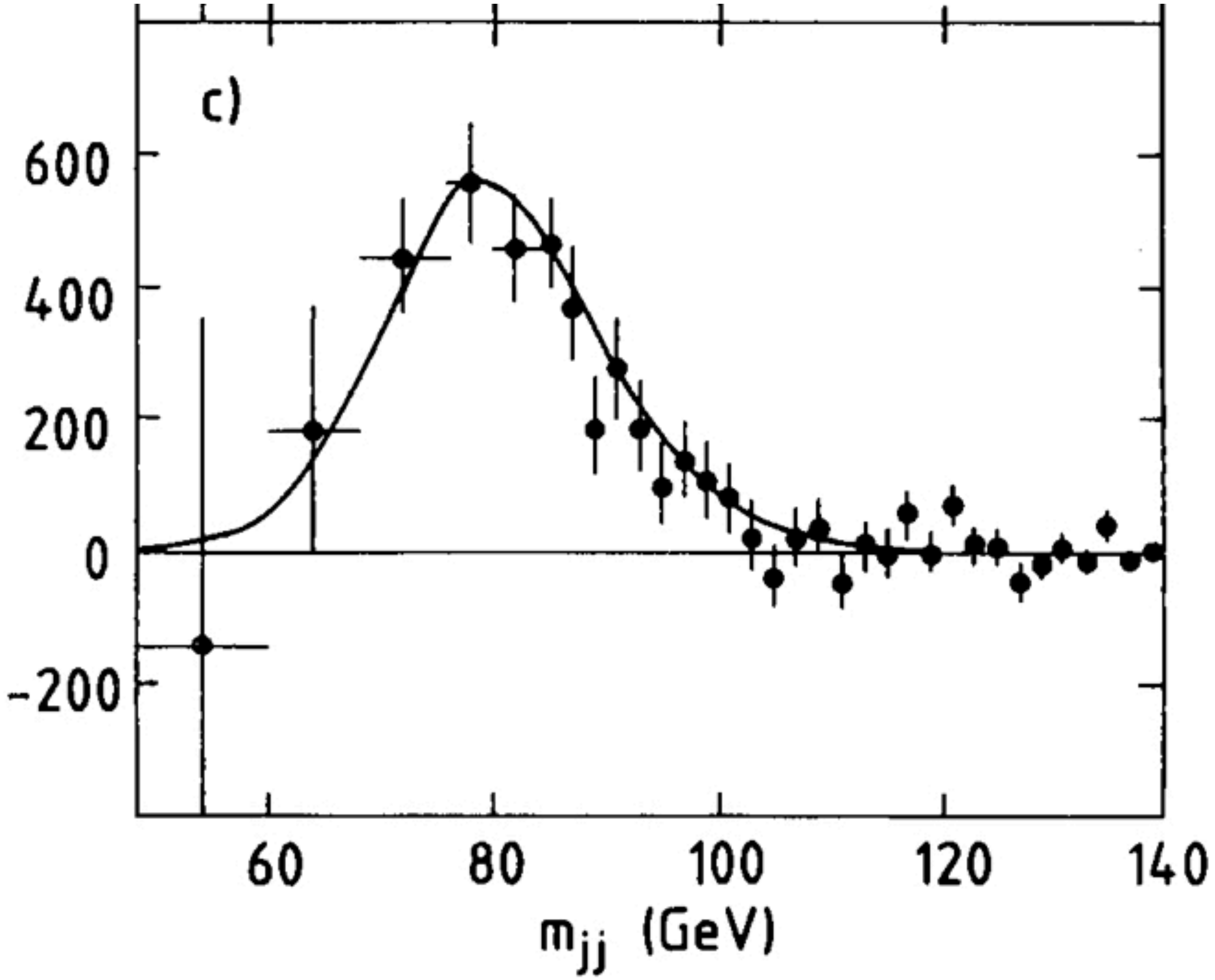
UA1 discovered the W boson before it discovered jets!

The challenge of using jets to discover/measure heavy particles decays

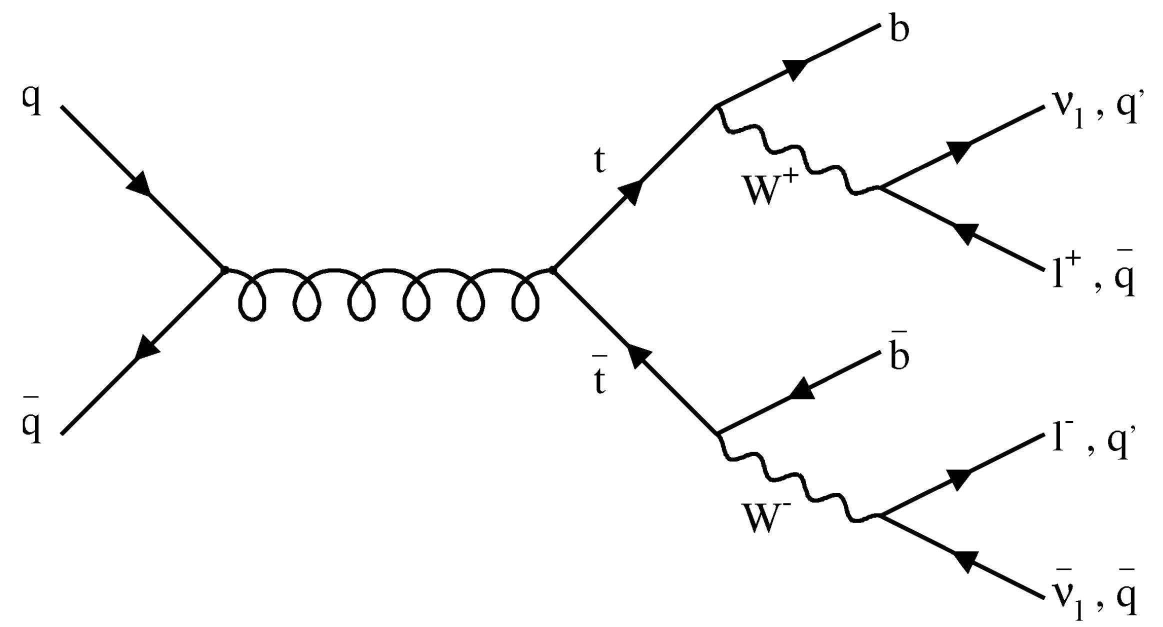
UA2, [Z.Phys.C 49 (1991) 17]



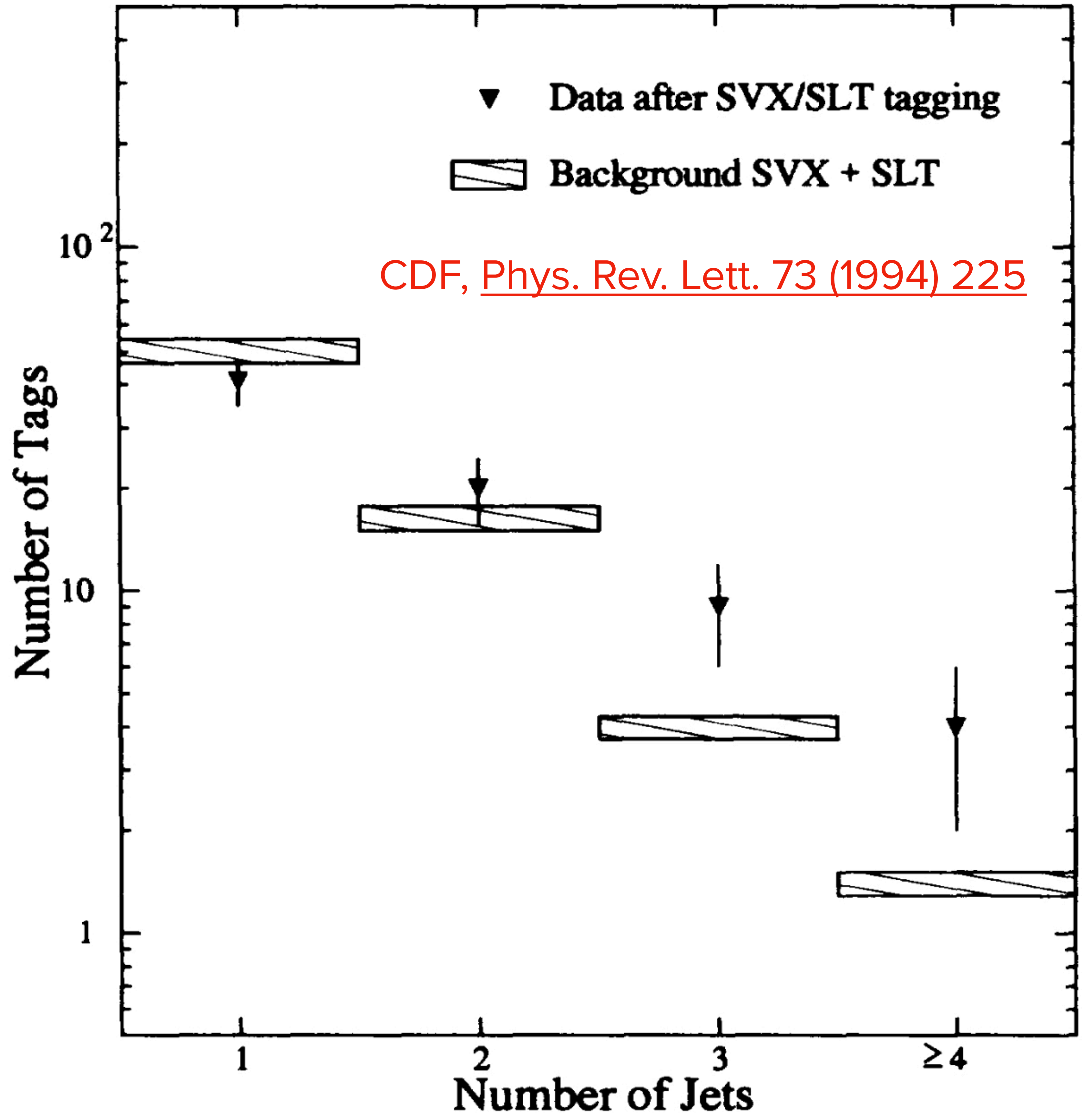
Data – fitted QCD background

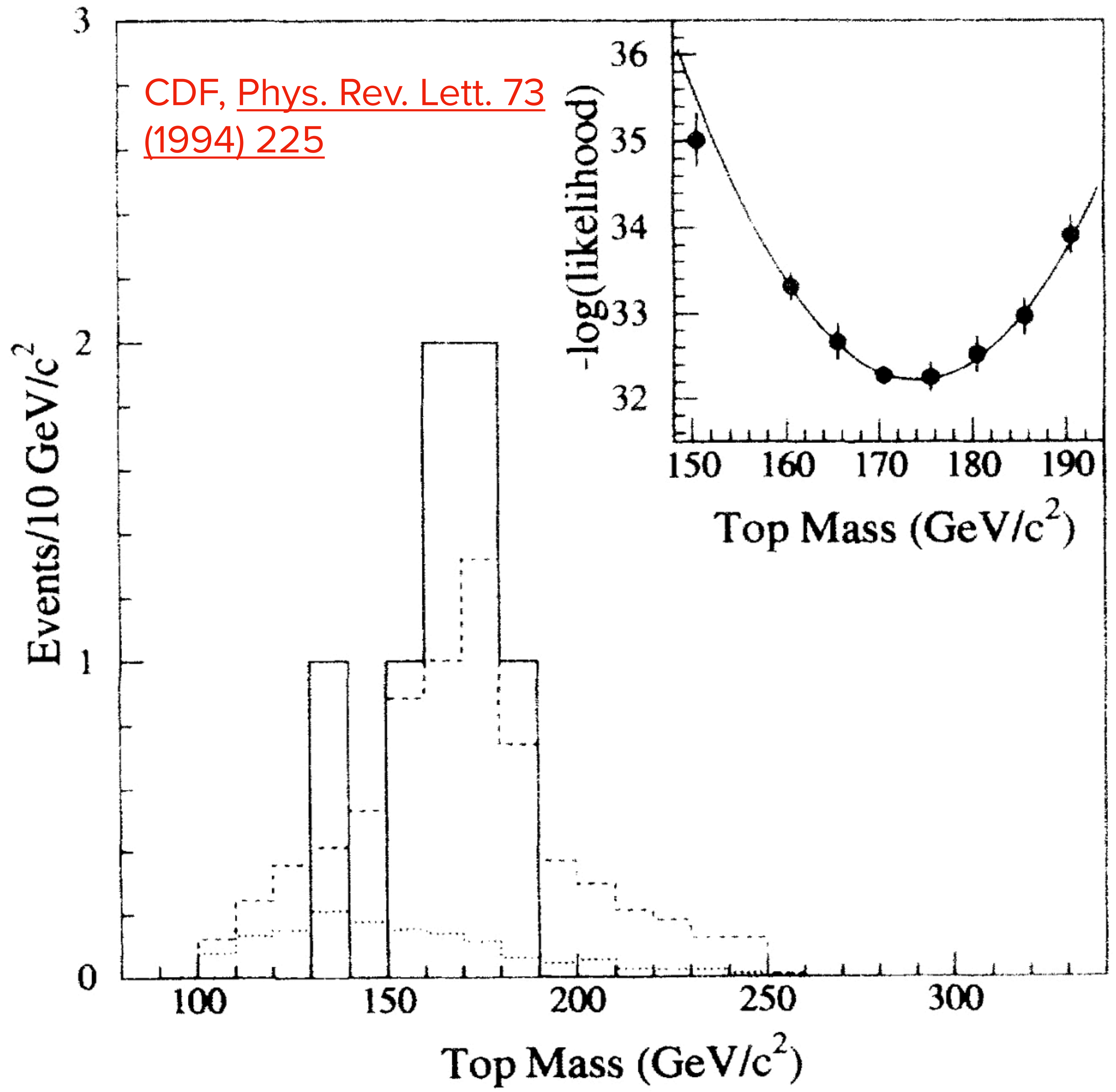


Top quark: the first *discovery* with jets (1994-95)



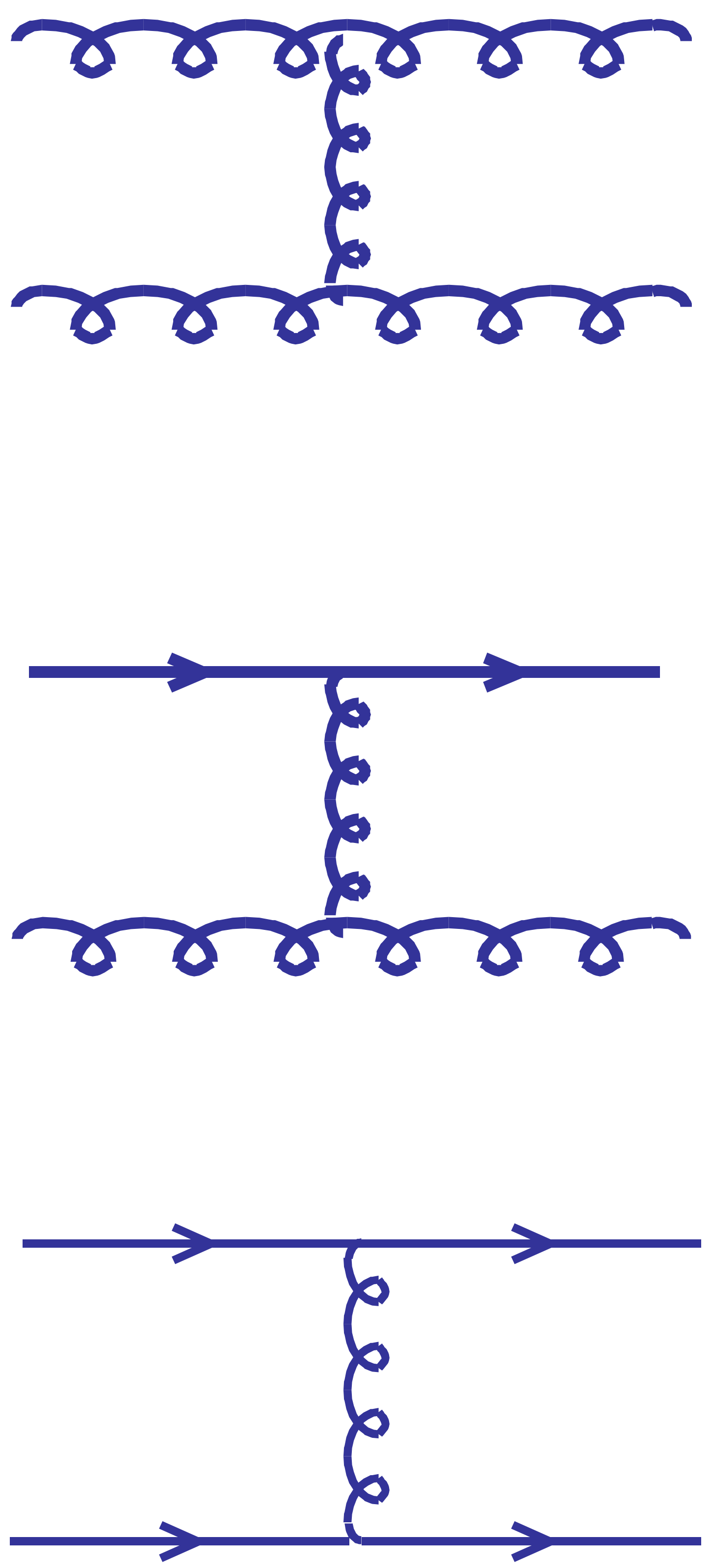
$$q\bar{q}/gg \to t\bar{t} \to bW^+\bar{b}W^- \begin{cases} b\bar{b} + 4\,\text{jets} \\ b\bar{b} + 2\,\text{jets} + \ell\nu \\ b\bar{b} + \ell\ell\nu\nu \end{cases}$$

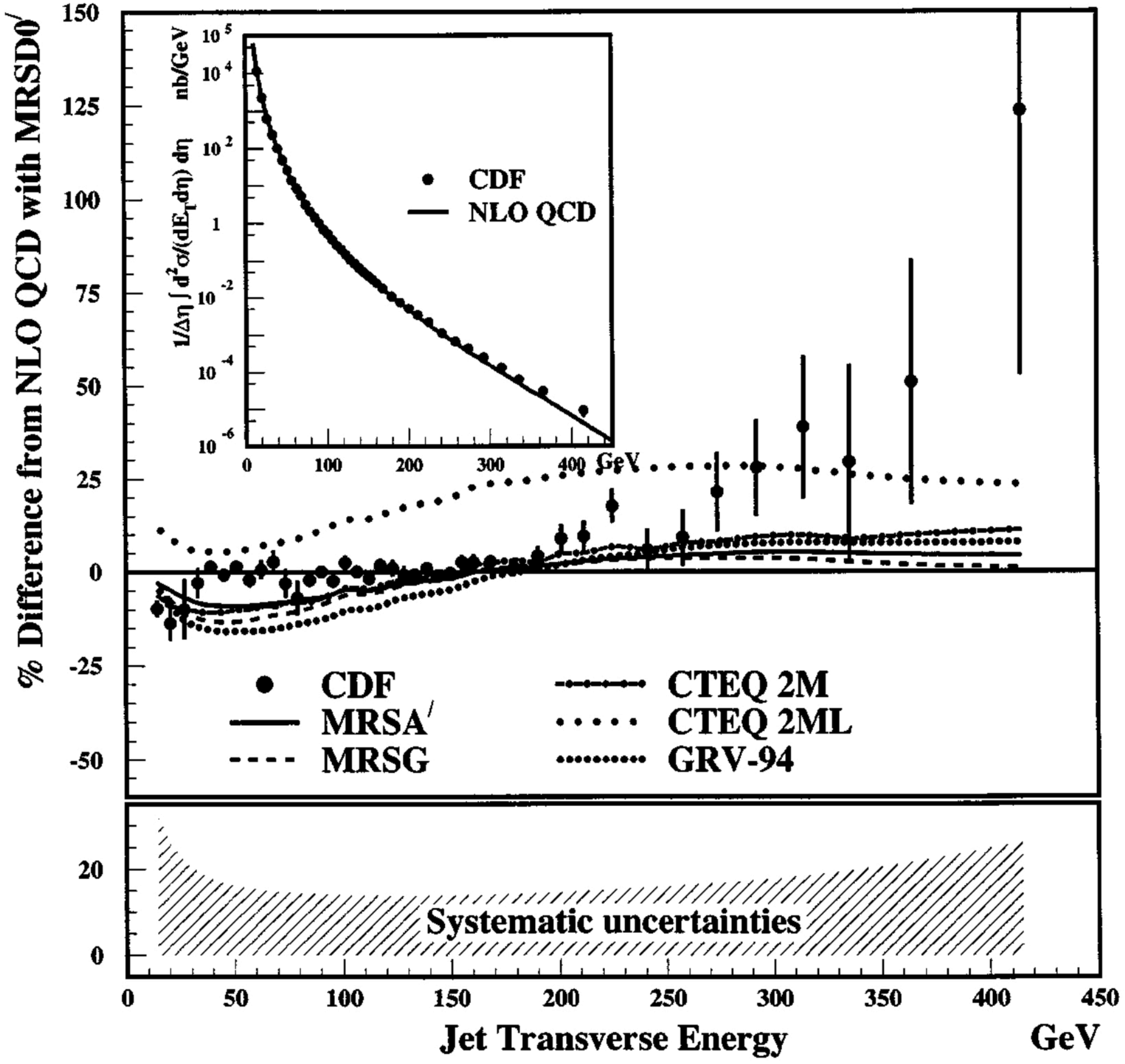




1996: CDF high-E_T jet anomaly

CDF, Phys. Rev. Lett. 77 (1996) 438

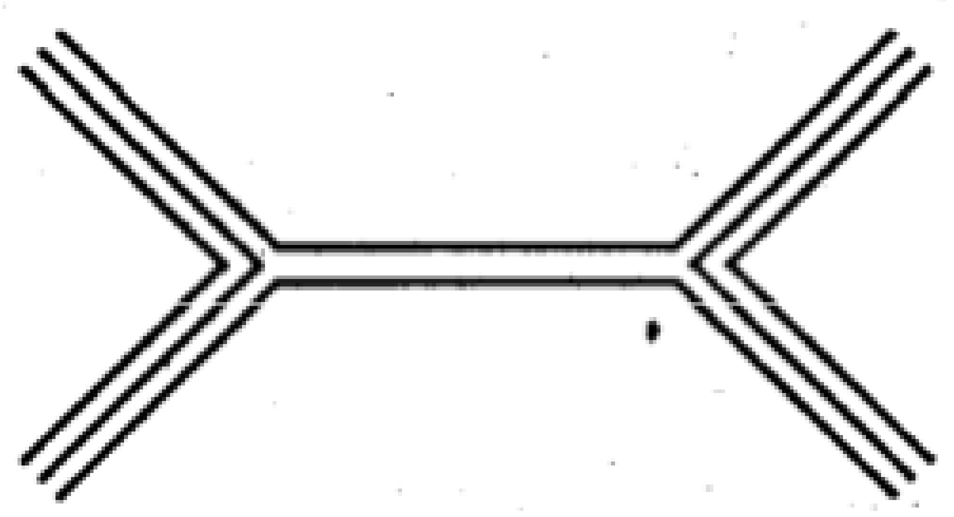




Quark substructure?

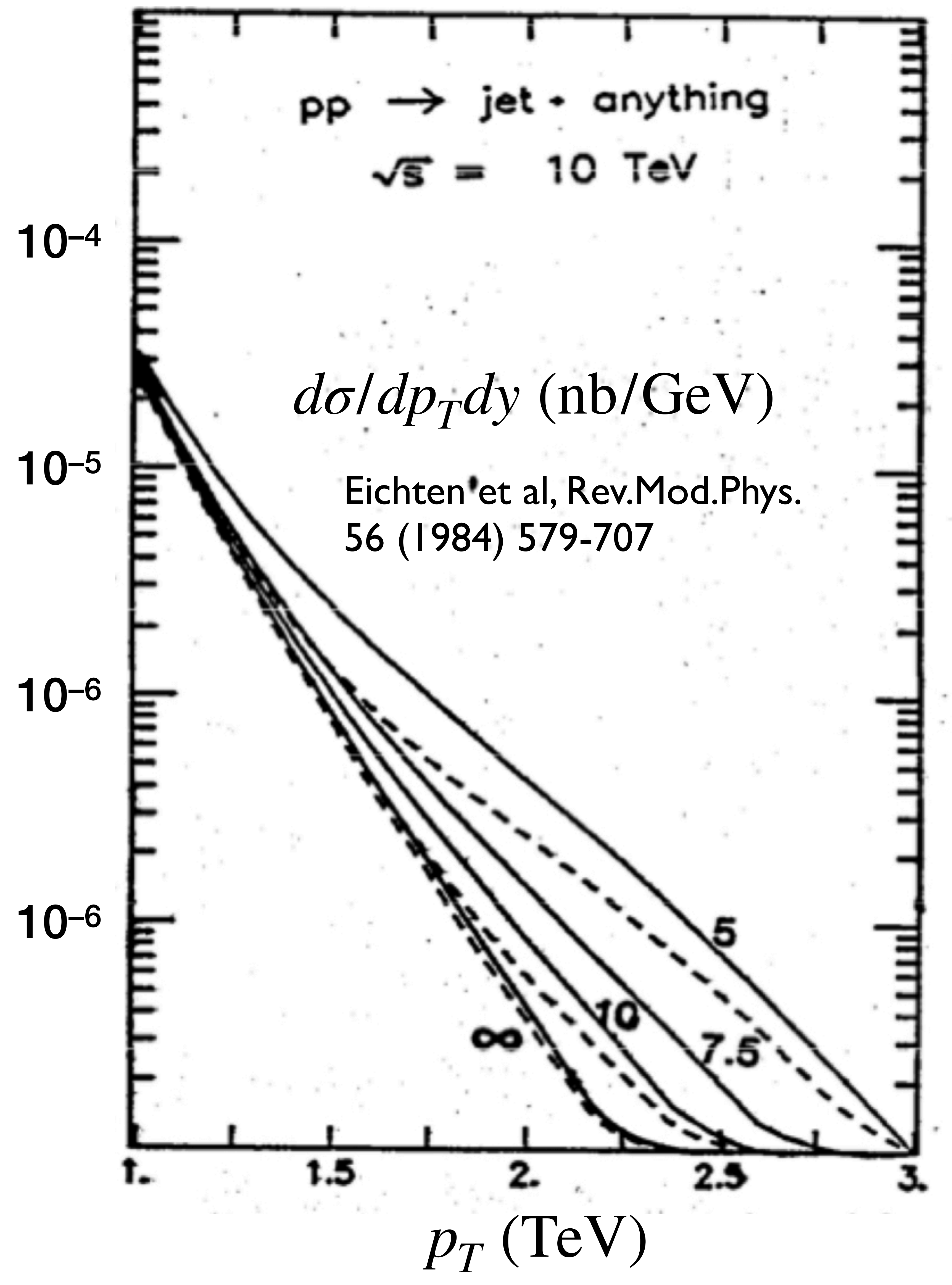
The presence of a quark substructure would manifest itself via contact interactions (as in Fermi's theory of weak interactions). On one side these new interactions would lead to an increase in cross-section, on the other they would affect the jets' angular distributions. In the dijet CMF, QCD implies Rutherford law, and extra point-like interactions can then be isolated using a fit.

Eichten, Lane, Peskin, PRL 50 (1983) 811-814



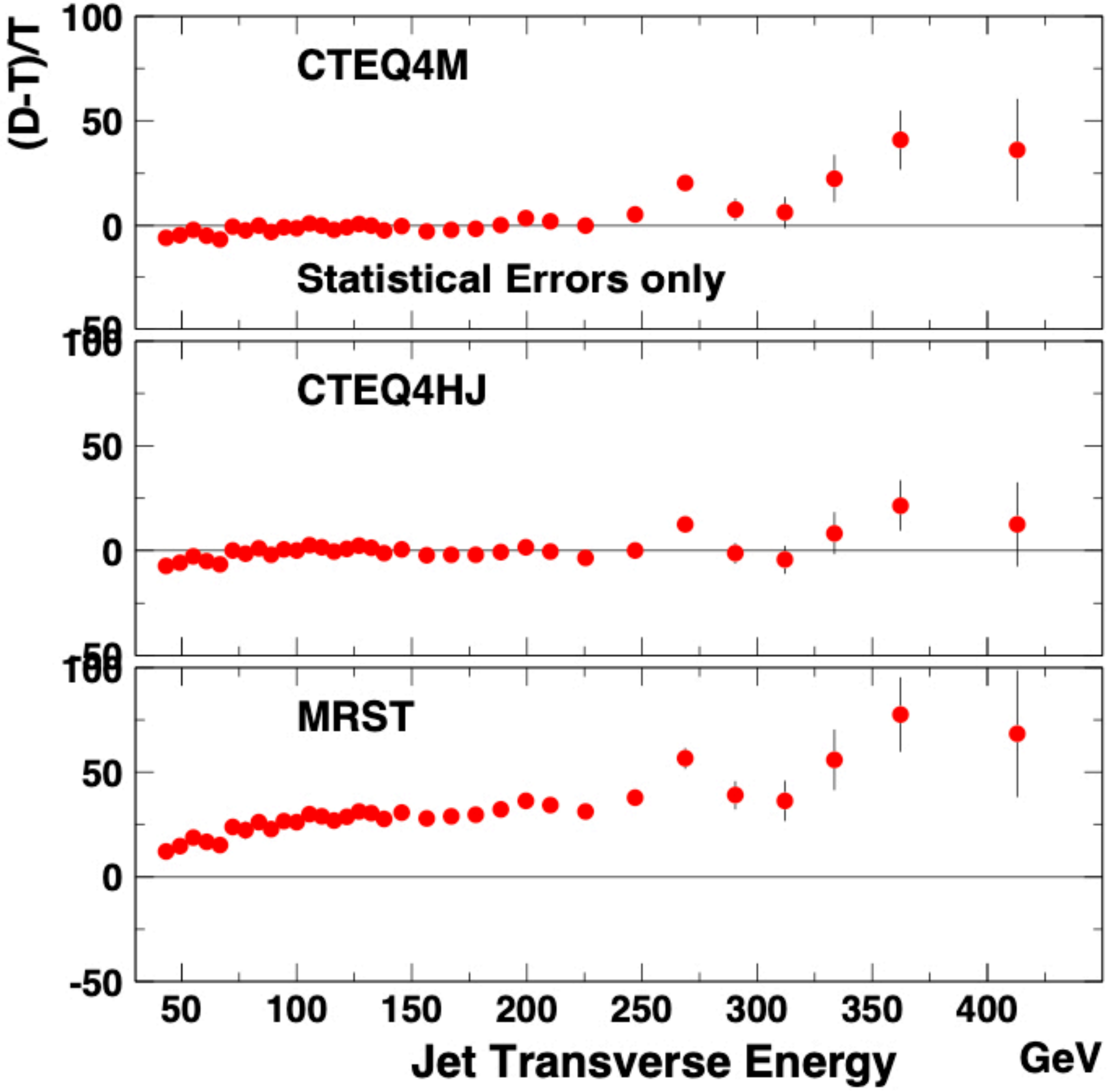
$$|A(q\bar{q} \to q\bar{q})|^2 = \text{QCD} + \frac{8}{9}\eta\frac{\alpha_S}{\Lambda^2}\boxed{\frac{u^3}{st}} + \mathcal{O}(\frac{1}{\Lambda^4})$$

grows like E^2 at large p_T



… or PDF systematics ?

$$\frac{\text{(CDF data)} - \text{(NLO QCD)}}{\text{(NLO QCD)}}$$

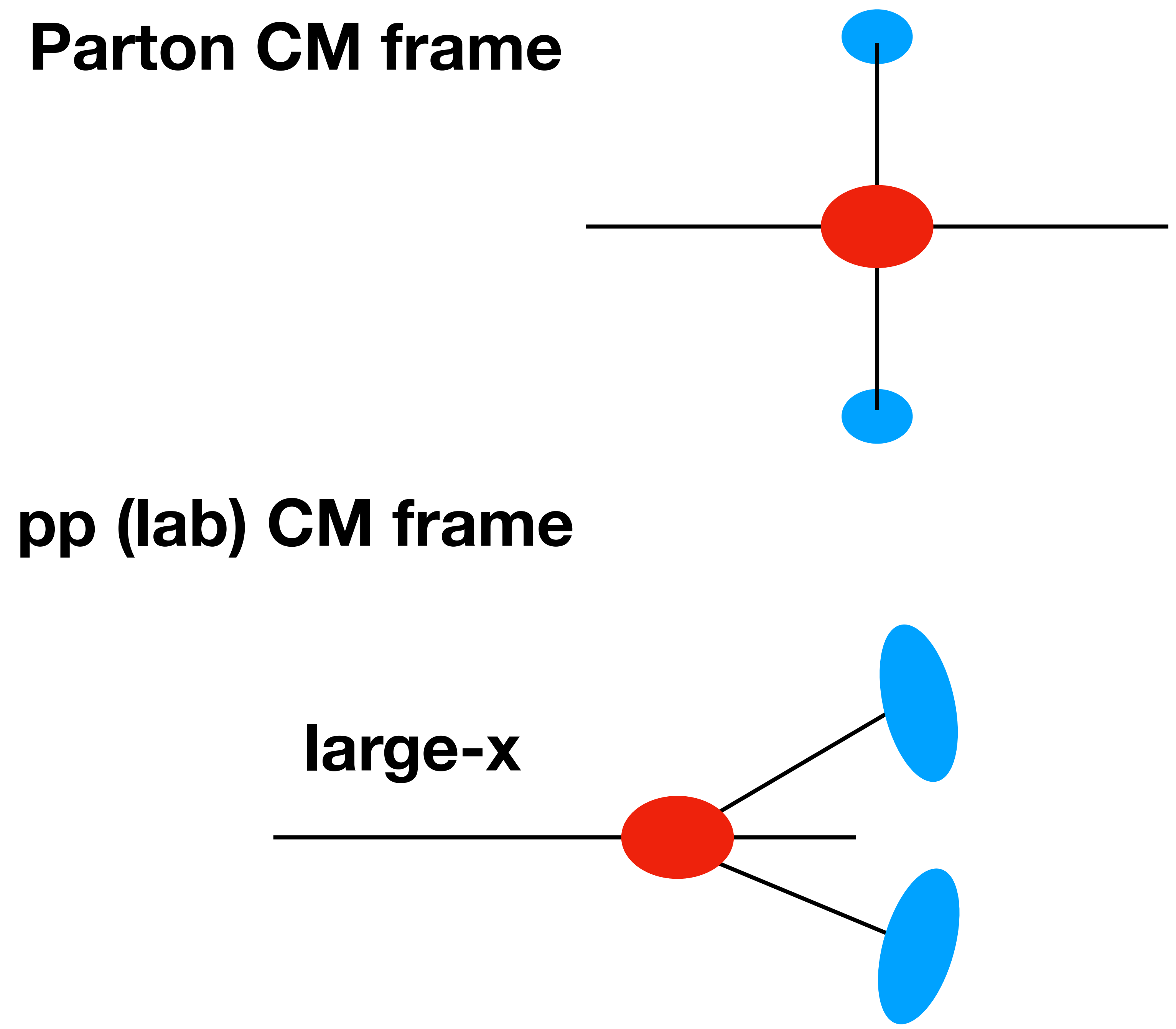


global PDF fit including the CDF high-ET jet data

CTEQ4, hep-ph/9606399

How to tell whether the anomaly is due to new physics or to the wrong description of the PDFs in the proton at large x ??

=> select events at small $\sqrt{\hat{s}}$ (new physics cannot hide there) but with a large longitudinal boost (thus probing large-x PDFs):



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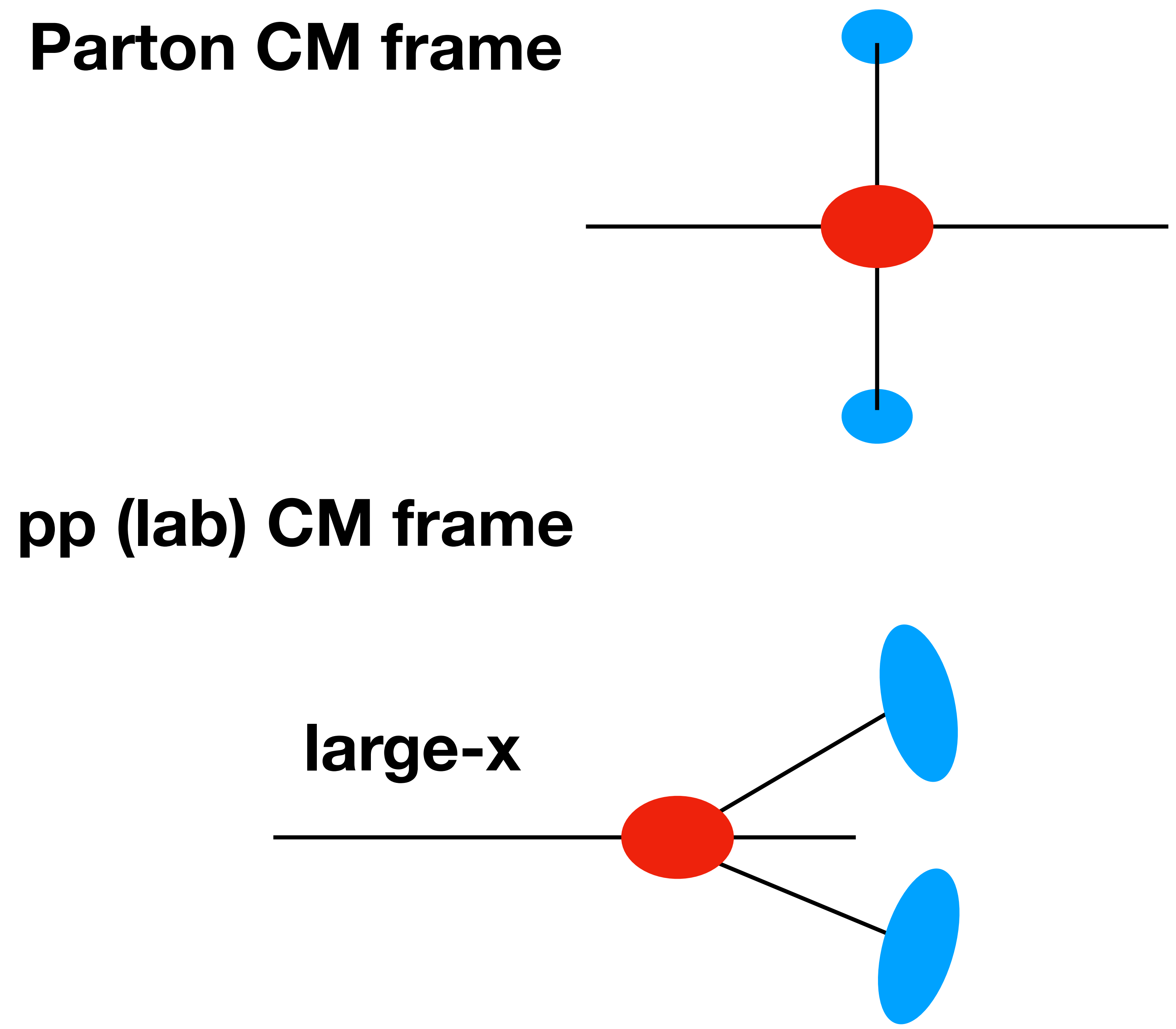
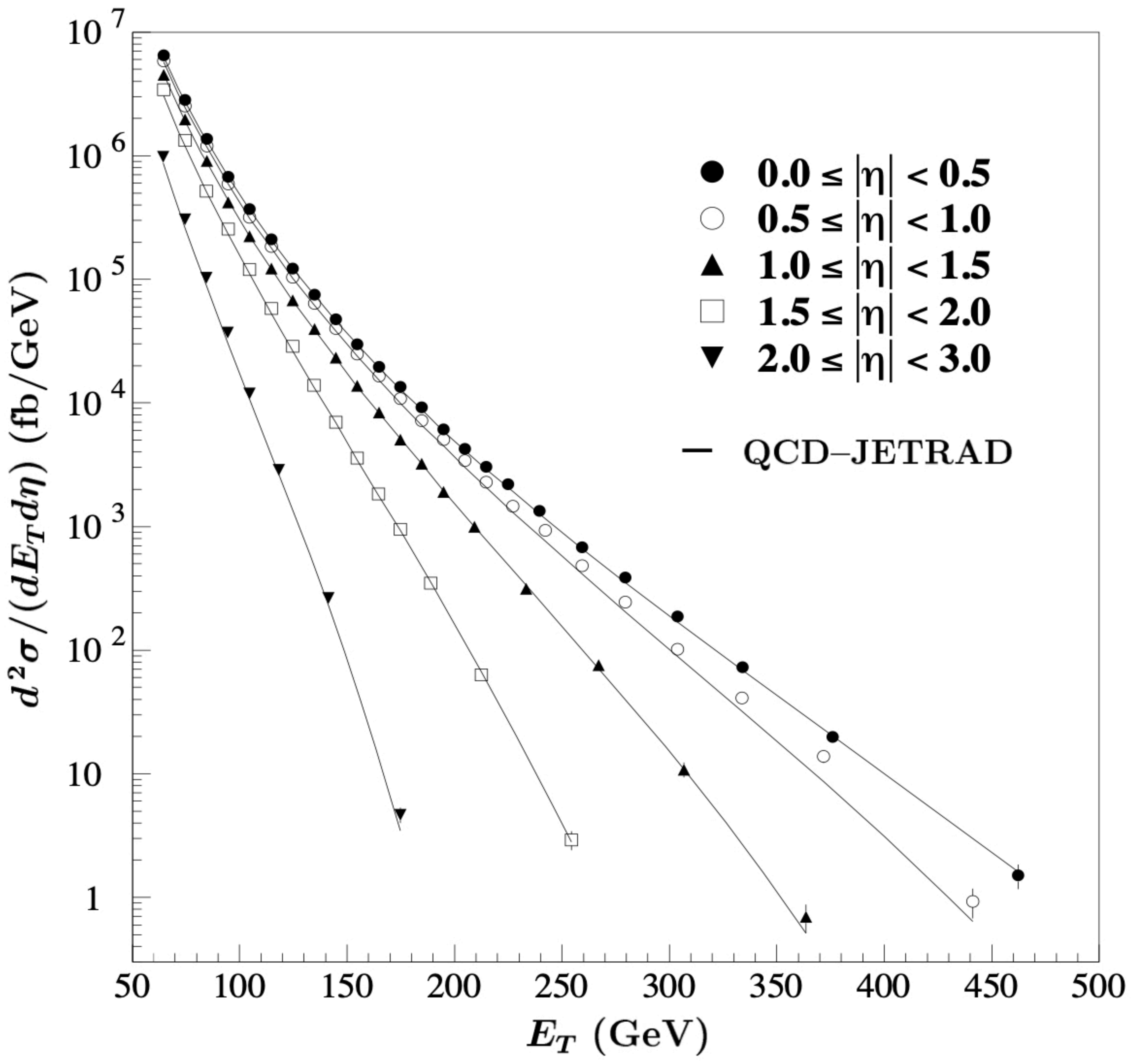


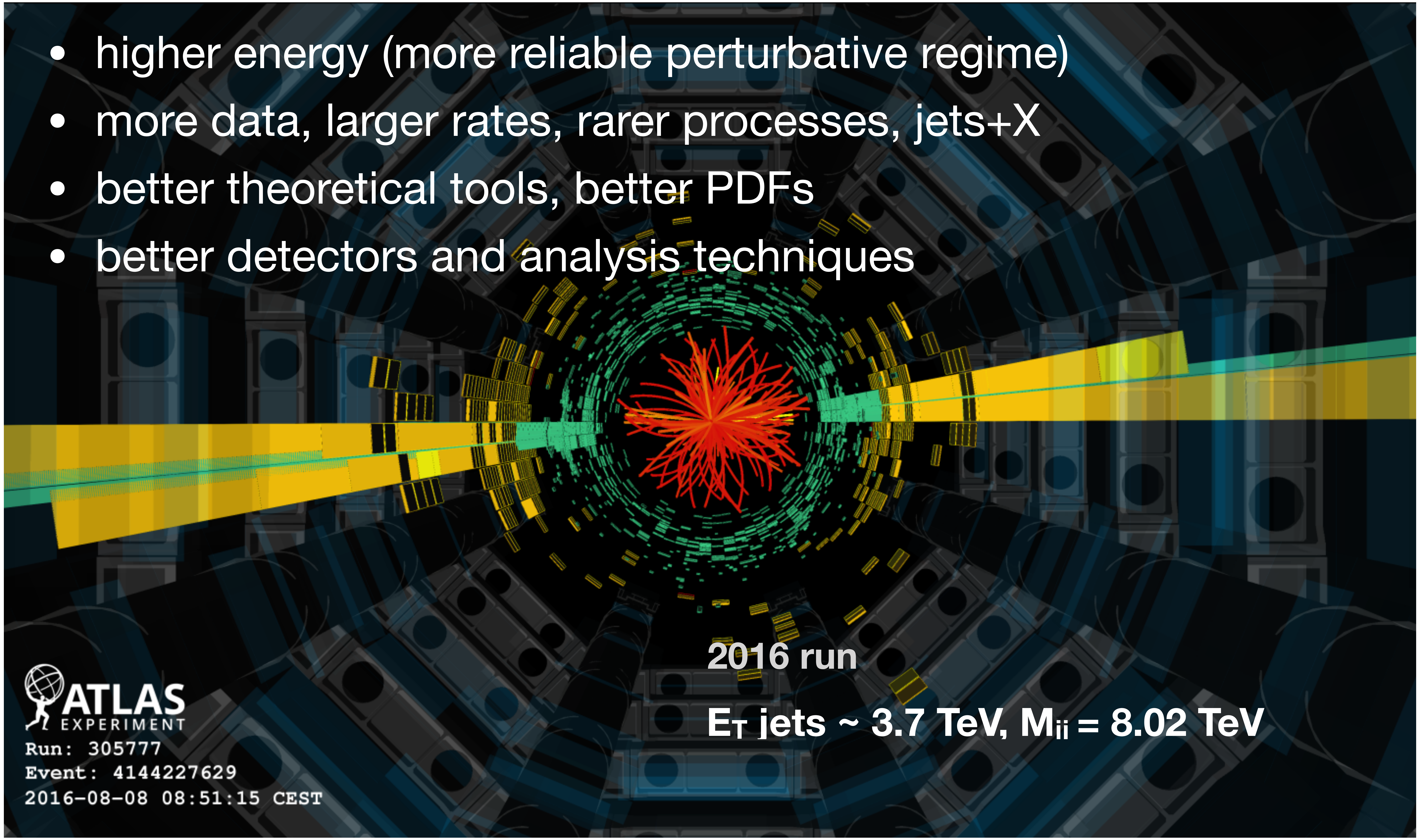
D0, hep-ex/0011036



The study of forward jet production confirmed the problem with PDF parameterizations, biased by the choice of an incorrect functional form, which artificially controlled and constrained the large-x behaviour

fast forward to the LHC …

- higher energy (more reliable perturbative regime)
- more data, larger rates, rarer processes, jets+X
- better theoretical tools, better PDFs
- better detectors and analysis techniques



Over 25% of published papers by ATLAS and CMS have the word “jet” in the title!

~ 600 papers in total!

50% of papers on “jets” have the word “search(es)” in the title!

Recent ATLAS examples…

- Search for excited τ-leptons and **leptoquarks** in the final state with τ-leptons and jets
- Search for **long-lived, massive particles** in events with displaced vertices and multiple jets
- Search for supersymmetry in final states with missing transverse momentum and three or more b-jets
- Searches for new phenomena in final states involving leptons and jets
- Search for **heavy resonances** decaying into a Z or W boson and a Higgs boson in final states with leptons and b-jets
- Search for new phenomena in final states with photons, jets and missing transverse momentum
- Search for neutral long-lived particles … that decay into displaced hadronic jets in the ATLAS calorimeter
- Observation of electroweak production of two jets in association with an isolated photon and missing transverse momentum, and search for a Higgs boson decaying into invisible particles
- Search for heavy particles in the b-tagged dijet mass distribution with additional b-tagged jets

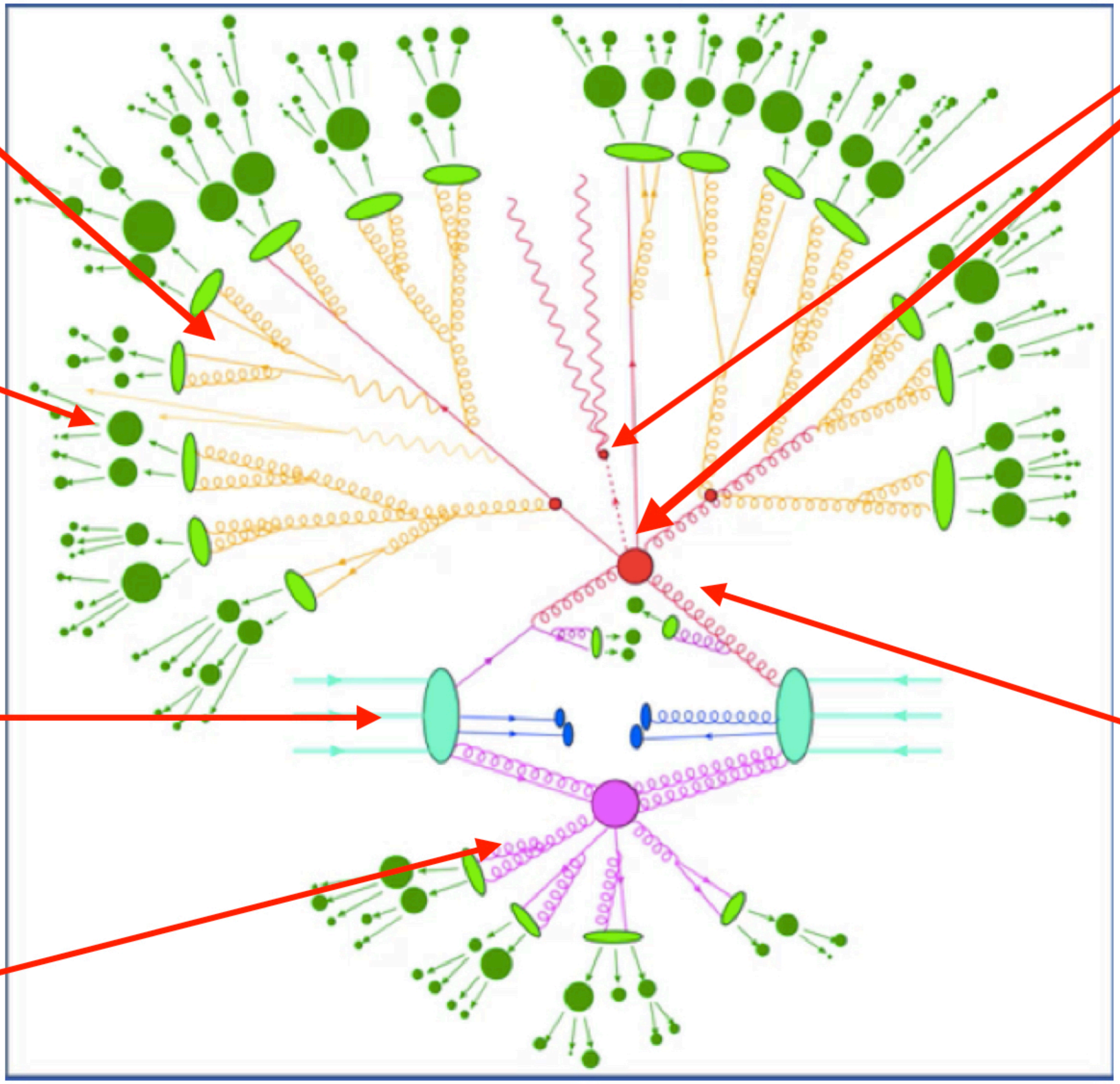
Deep inside the collision

parton shower

hadronisation

parton distribution functions (PDFs)

underlying event



artwork by G.Luisoni

fixed order calculations (production and decay)

reduce scale uncertainties

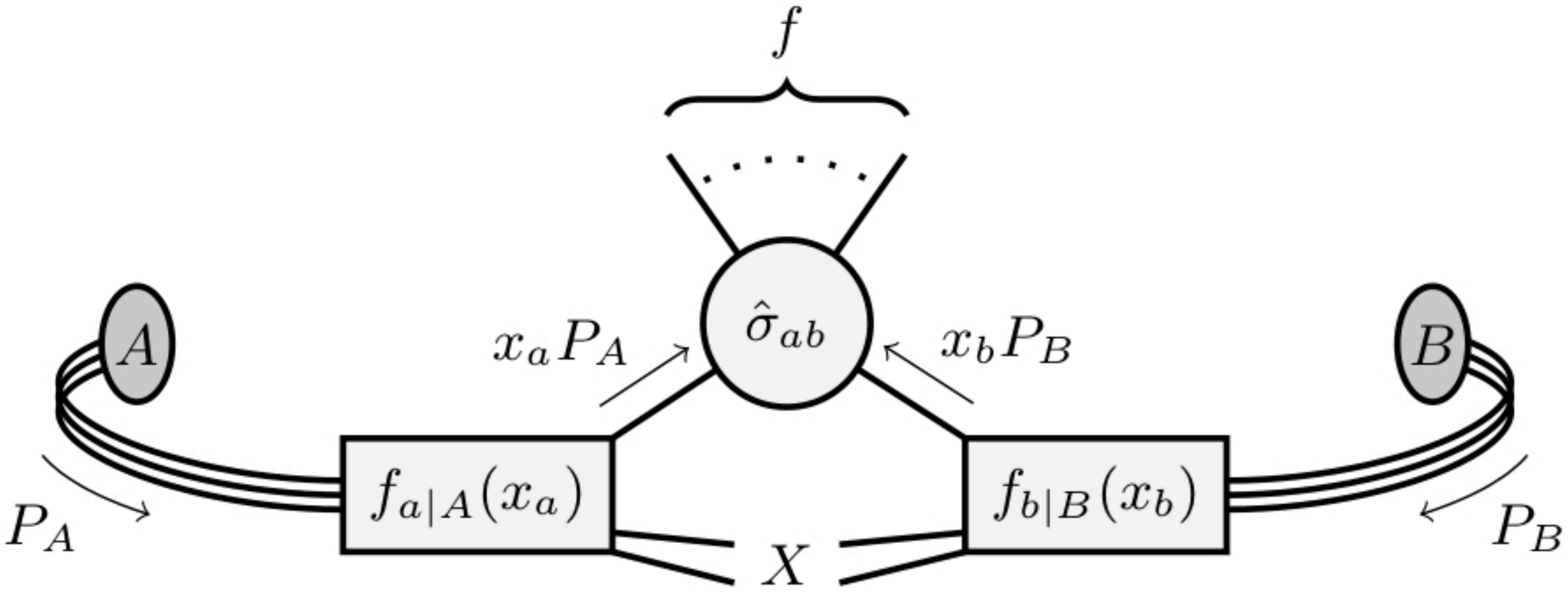
μ_r, μ_f-dependence

reduce parametric uncertainties (couplings, masses)

resummation

reduce uncertainties in particular kinematic regions

From complexity to simplicity: factorization



parton distribution functions (PDFs)

parton-level cross-section

$$\sigma_{pp\to O+X} = \sum_{a,b=q,g} \int_0^1 \int_0^1 dx_1\, dx_2\, f_a(x_1)\, f_b(x_2) \times \hat{\sigma}_{ab\to\hat{O}}(x_1, x_2) \times \left[1 + \mathcal{O}(\Lambda_{QCD}/Q)\right]$$

non-perturbative effects

times a unitary, collinear/IR-safe evolution of the partonic final state $\hat{O} \to O$

Jet production at high perturbative order: state of the art

- 2 jets NNLO with full colour [X. Chen et al. 2204.10173]
- 3 jets NNLO with (almost) full colour [Czakon, Mitov, Poncelet 2106.05331]
  (2-loop virtual amplitudes leading colour from [Abreu, Febres Cordero, Ita, Page, Sotnikov 2102.13609])
- 3-loop amplitudes for

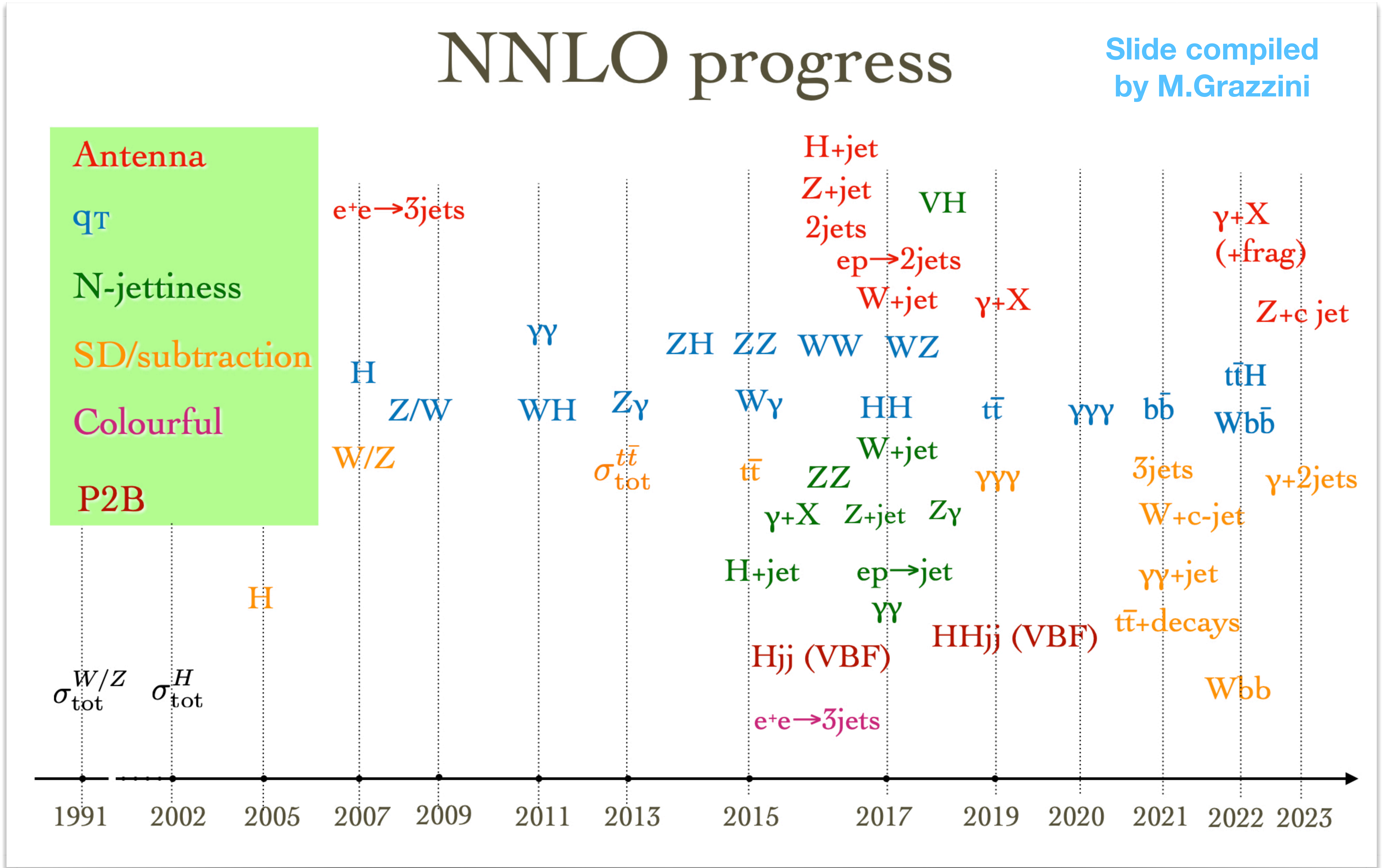
  $q\bar{q} \to q'\bar{q}'$ Caola, Chakraborty, Gambuti, von Manteuffel, Tancredi '21

  $gg \to gg$ Caola, Chakraborty, Gambuti, von Manteuffel, Tancredi '21

  $q\bar{q} \to gg$ Caola, Chakraborty, Gambuti, von Manteuffel, Tancredi '22

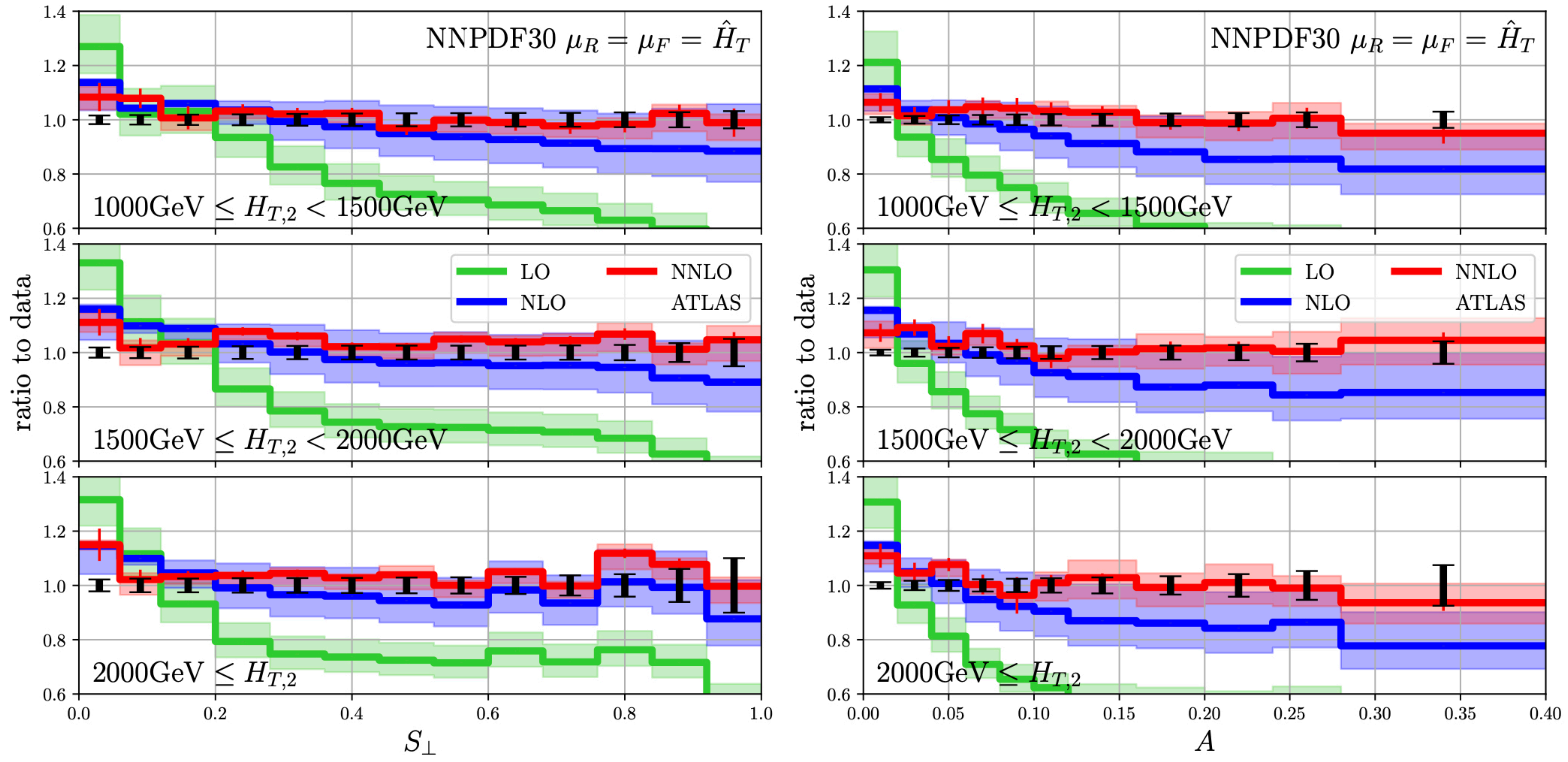
  will enter 2-jet production at N3LO

Part of a more general recent *explosion* of new techniques and results



The key role of higher-order perturbative results: NNLO vs NLO vs LO description of jet final state shape variables

Czakon, Mitov, Poncelet, 2106.05331



Transverse sphericity **Aplanarity**

(see next page for def's)

where:

$$\mathcal{M}_{xyz} = \frac{1}{\sum_i |\vec{p}_i|} \sum_i \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} & p_{x,i}p_{z,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 & p_{y,i}p_{z,i} \\ p_{z,i}p_{x,i} & p_{z,i}p_{y,i} & p_{z,i}^2 \end{pmatrix}$$

with eigenvalues $\lambda_{1,2,3} \rightarrow$ $A = \frac{3}{2}\lambda_3$

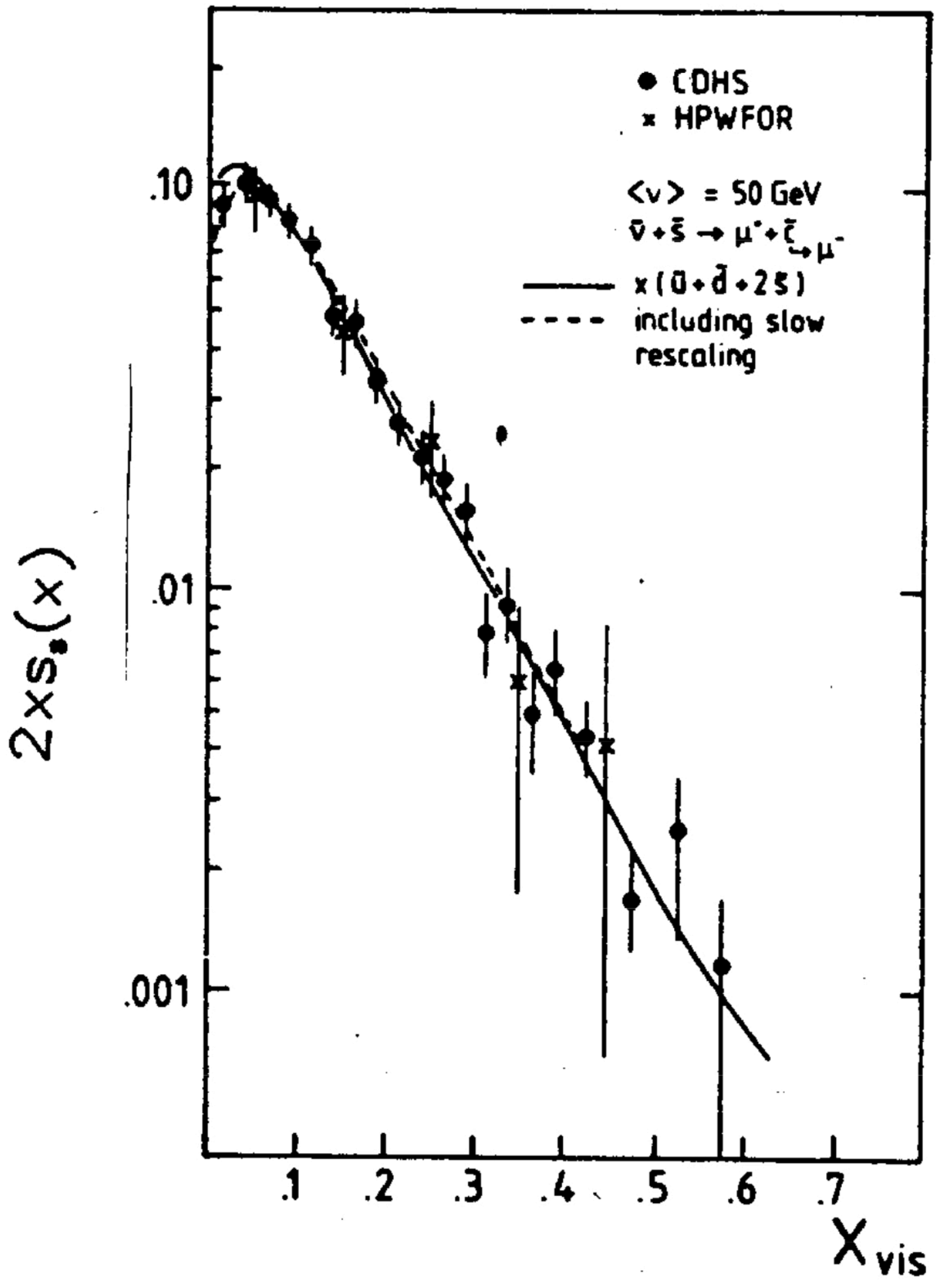
$$\mathcal{M}_{xy} = \frac{1}{\sum_i |\vec{p}_{T,i}|} \sum_i \frac{1}{|\vec{p}_{T,i}|} \begin{pmatrix} p_{x,i}^2 & p_{x,i}p_{y,i} \\ p_{y,i}p_{x,i} & p_{y,i}^2 \end{pmatrix}$$

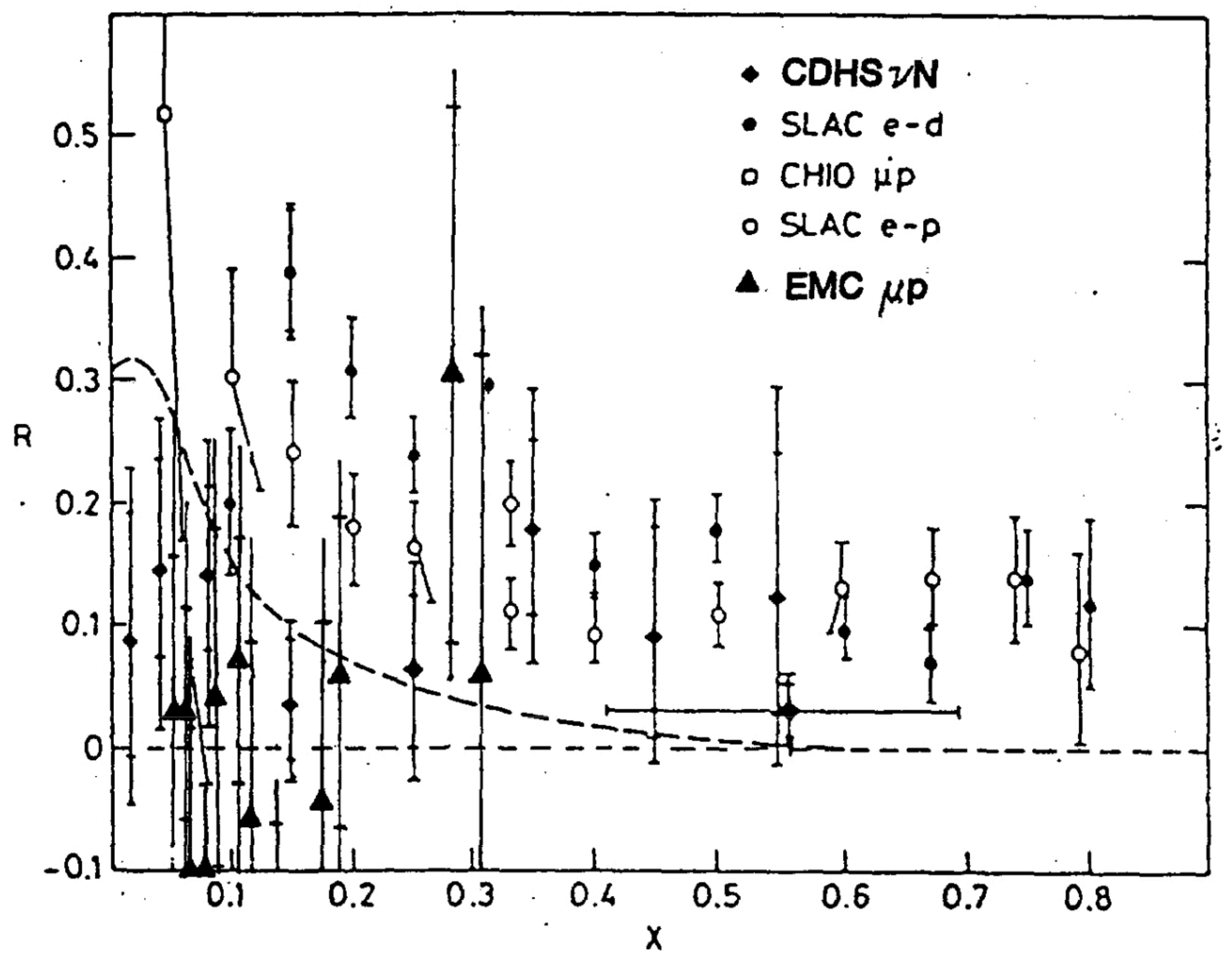
with eigenvalues $\mu_{1,2} \rightarrow$ $S_\perp = \frac{\mu_2}{\mu_1 + \mu_2}$

The early days of PDFs

Parisi & Sourlas, *A simple parametrization of the* Q^2 *dependence of the quark distributions in QCD,*
Nucl.Phys.B 151 (1979) 421

$$F(x,Q^2) = x^{\beta}(1-x)^{\alpha(Q^2)} \sum_{n=0}^{N} P_n^{(\alpha,\beta)}(x) f_n(Q^2)$$
$$= x^{\beta}(1-x)^{\alpha(Q^2)} \sum_{n=0}^{N} d(N,n,Q^2) x^n ,$$





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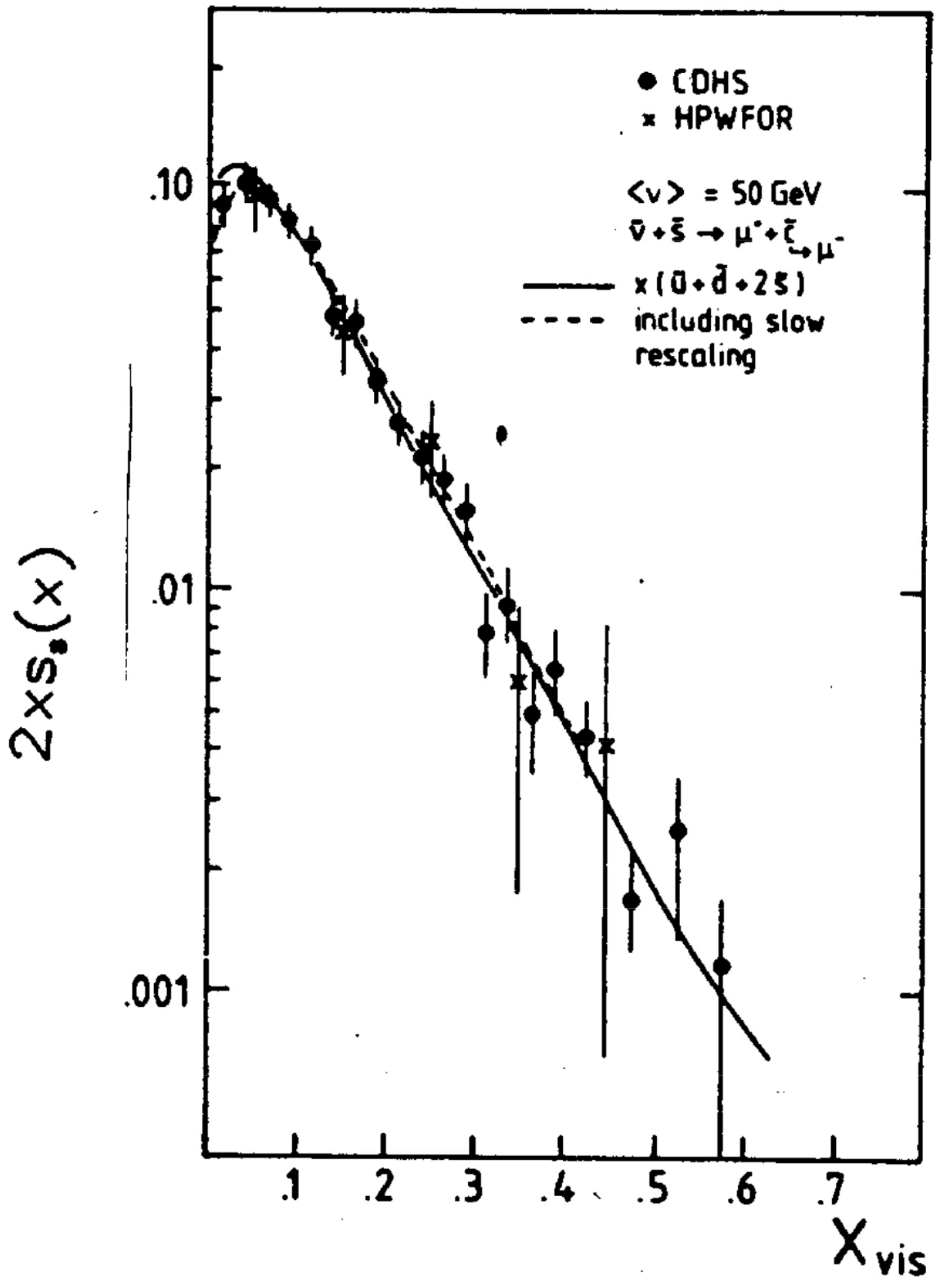
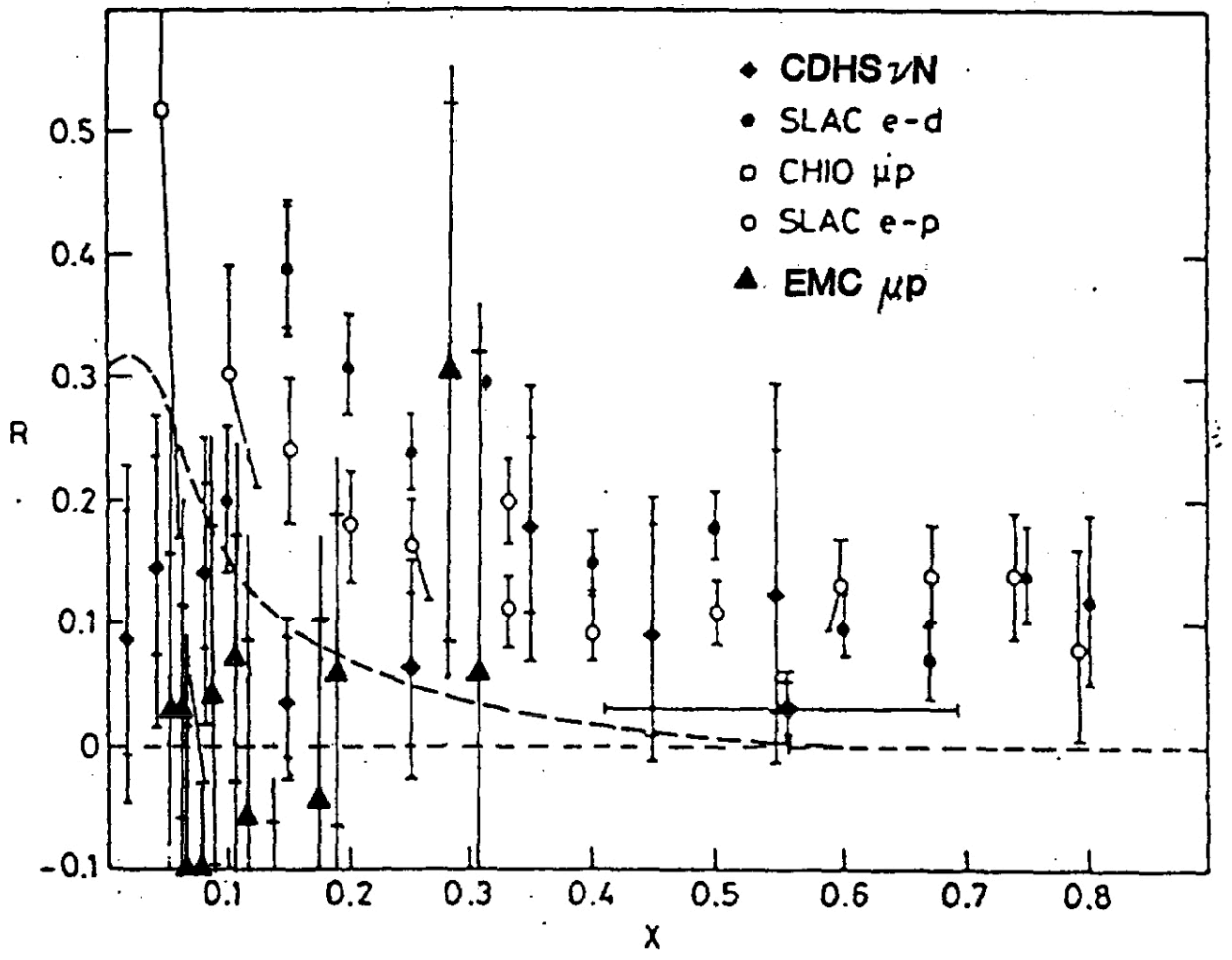
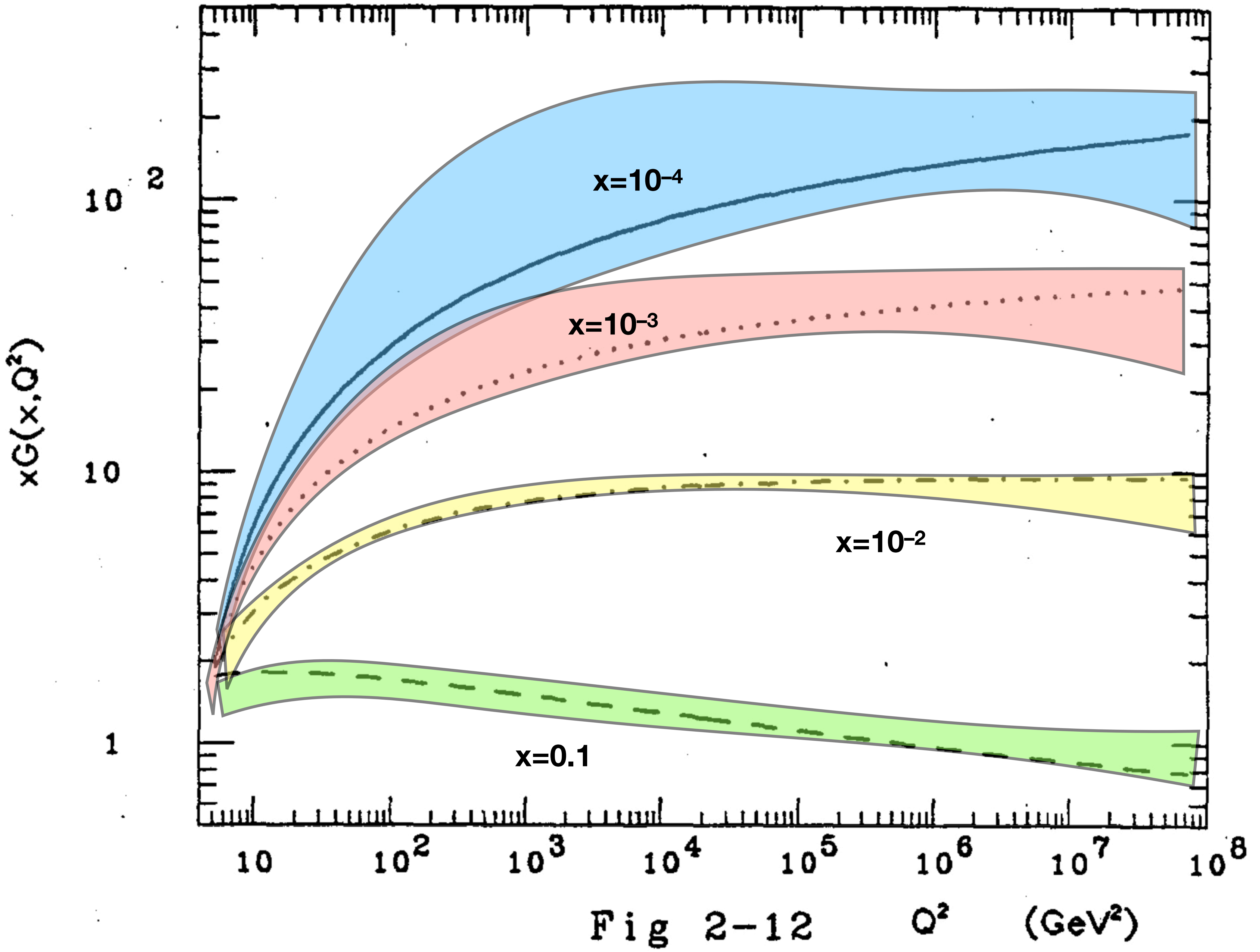


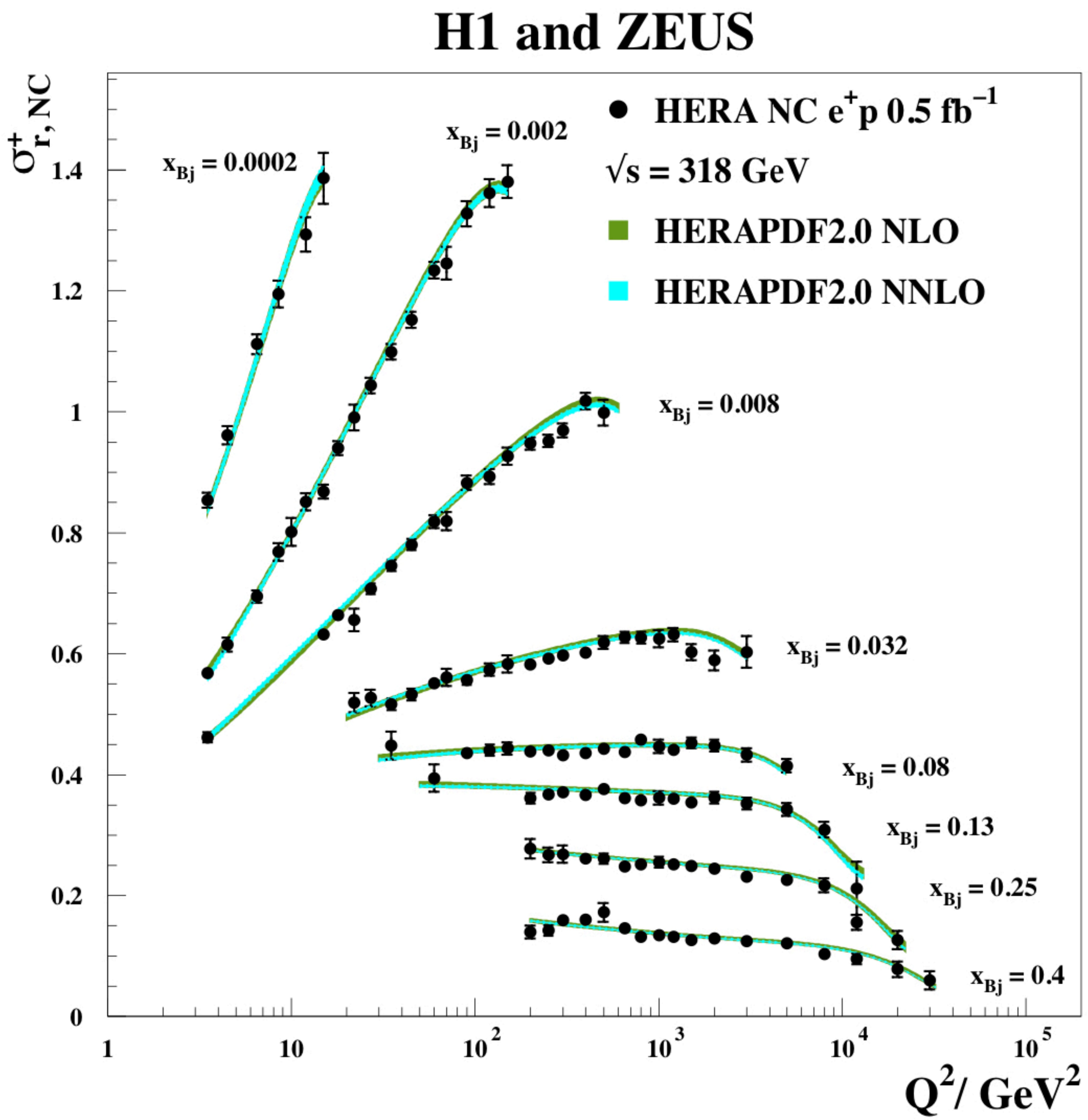


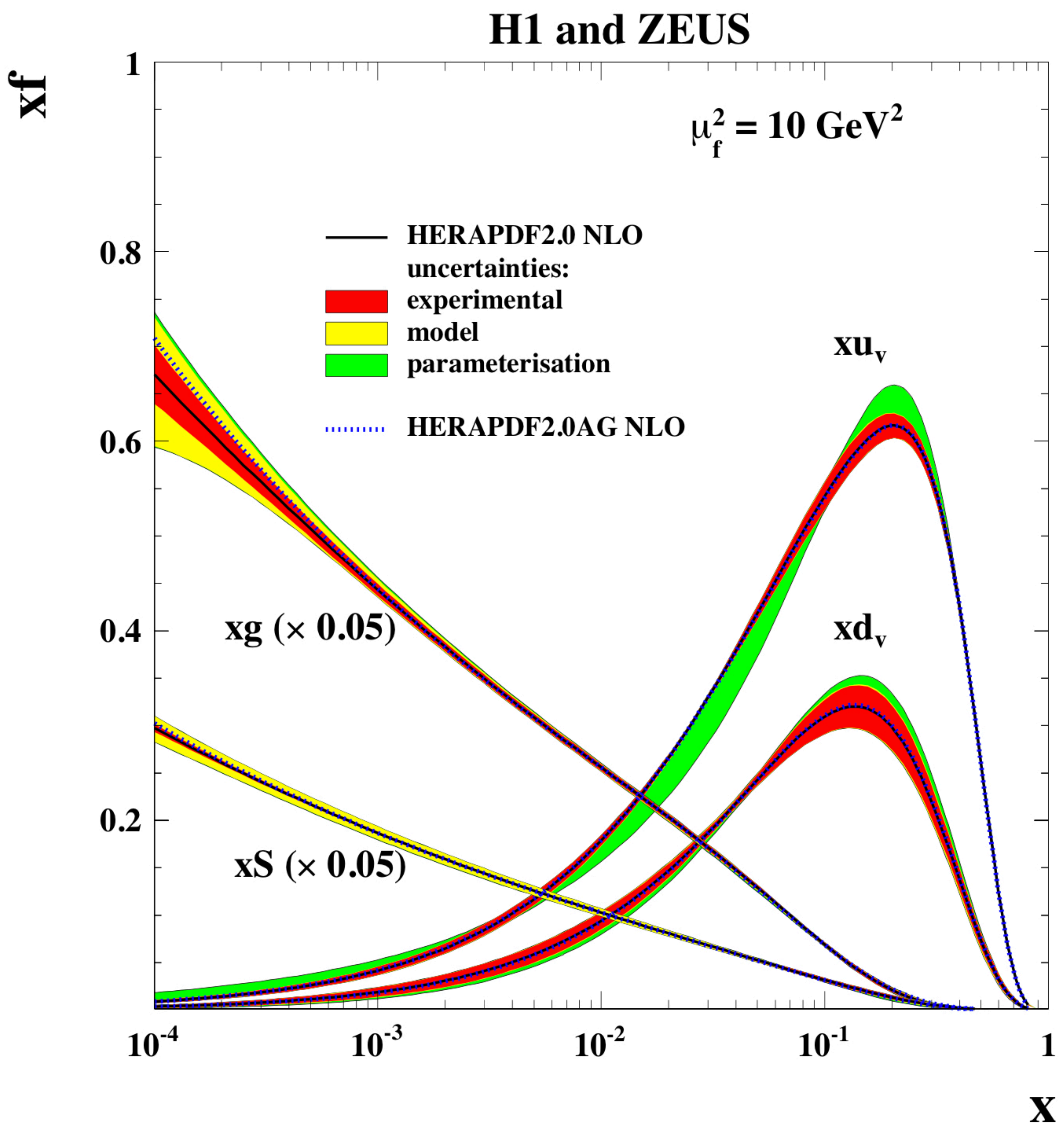


EHLQ (1984) https://inspirehep.net/literature/201469

DGLAP analysis of HERA data

Variation	Standard Value	Lower Limit	Upper Limit
$Q^2_{\rm min}$ [GeV^2]	3.5	2.5	5.0
$Q^2_{\rm min}$ [GeV^2] HiQ2	10.0	7.5	12.5
M_c(NLO) [GeV]	1.47	1.41	1.53
M_c (NNLO) [GeV]	1.43	1.37	1.49
M_b [GeV]	4.5	4.25	4.75
f_s	0.4	0.3	0.5
$\alpha_s(M_Z^2)$	0.118	–	–
μ_{f_0} [GeV]	1.9	1.6	2.2





⇒ No evidence for deviations from DGLAP evolution over 4 orders of magnitude in Q^2

TH progress (1)

$$\mathbf{P}(z, \alpha_s) = \alpha_s \left(\mathbf{P_0}(z) + \alpha_s \mathbf{P_1}(z) + \alpha_s^2 \mathbf{P_2}(z) + \alpha_s^3 \mathbf{P_3}(z) + \ldots \right)$$

LO (AP '77)

NLO ('79-'81):

Floratos et al, Nucl Phys B 152 (1979) 493, Nucl.Phys.B 192 (1981) 417

A. Gonzalez-Arroyo and C. Lopez, Nucl. Phys. B 166, 429 (1980)

G. Curci, W. Furmanski and R. Petronzio, Nucl. Phys. B175, 27 (1980)

NNLO (2004):

A. Vogt, et al, Nucl.Phys.B 691 (2004) 129, Nucl.Phys.B 688 (2004) 101

NNNLO (2017-22, still partial):

- S. Moch et al., arXiv:1707.08315
- A. Vogt et al., arXiv:1801.06085, arXiv:1808.08981
- S. Moch et al., arXiv:2111.15561

TH progress (1)

$$\mathbf{P}(z,\alpha_s) = \alpha_s\left(\mathbf{P_0}(z) + \alpha_s\mathbf{P_1}(z) + \alpha_s^2\mathbf{P_2}(z) + \alpha_s^3\mathbf{P_3}(z) + \ldots\right)$$

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A. Gonzalez-Arroyo and C. Lopez, Nucl. Phys. B 166, 429 (1980)
G. Curci, W. Furmanski and R. Petronzio, Nucl. Phys. B175, 27 (1980)

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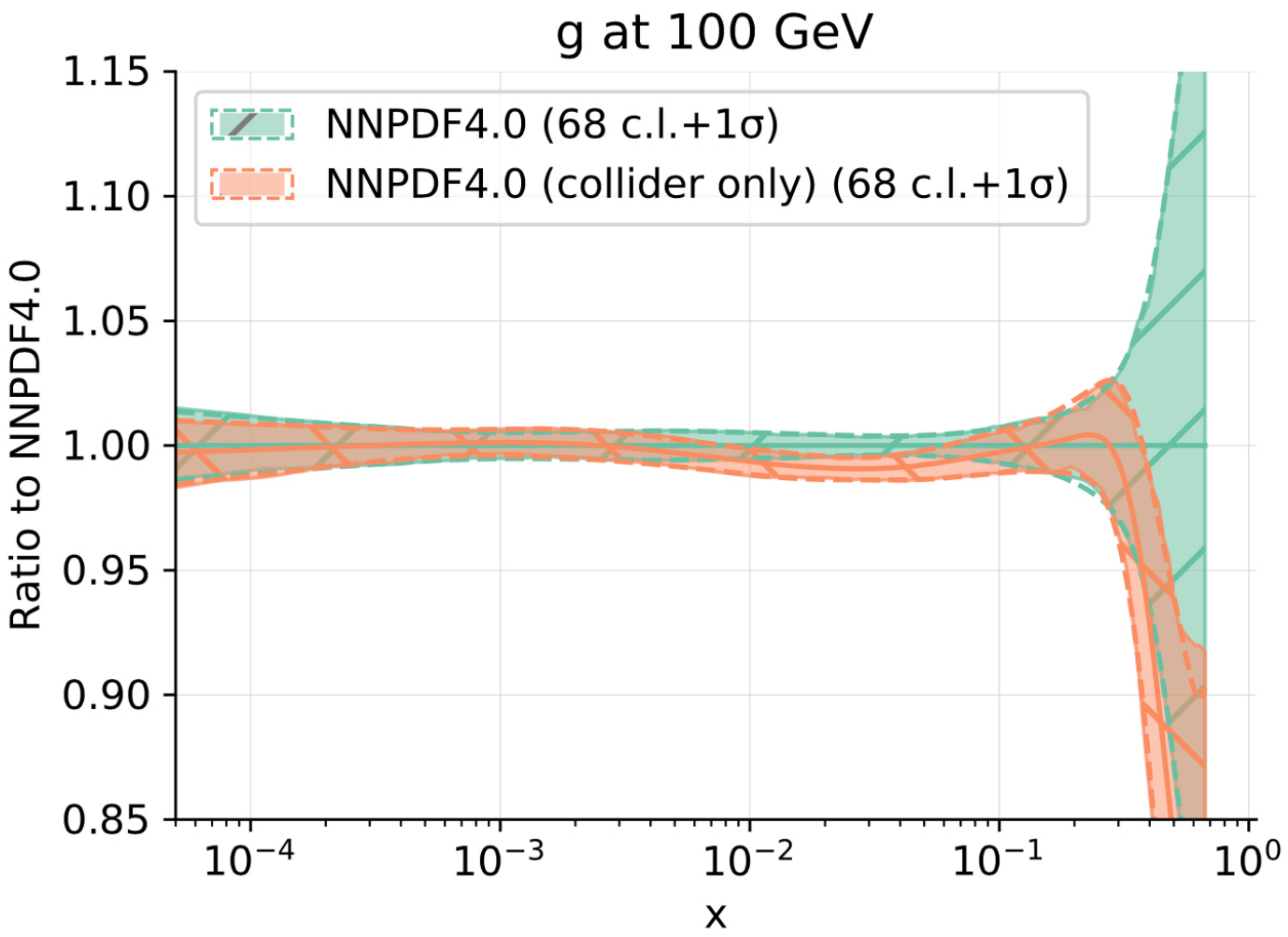
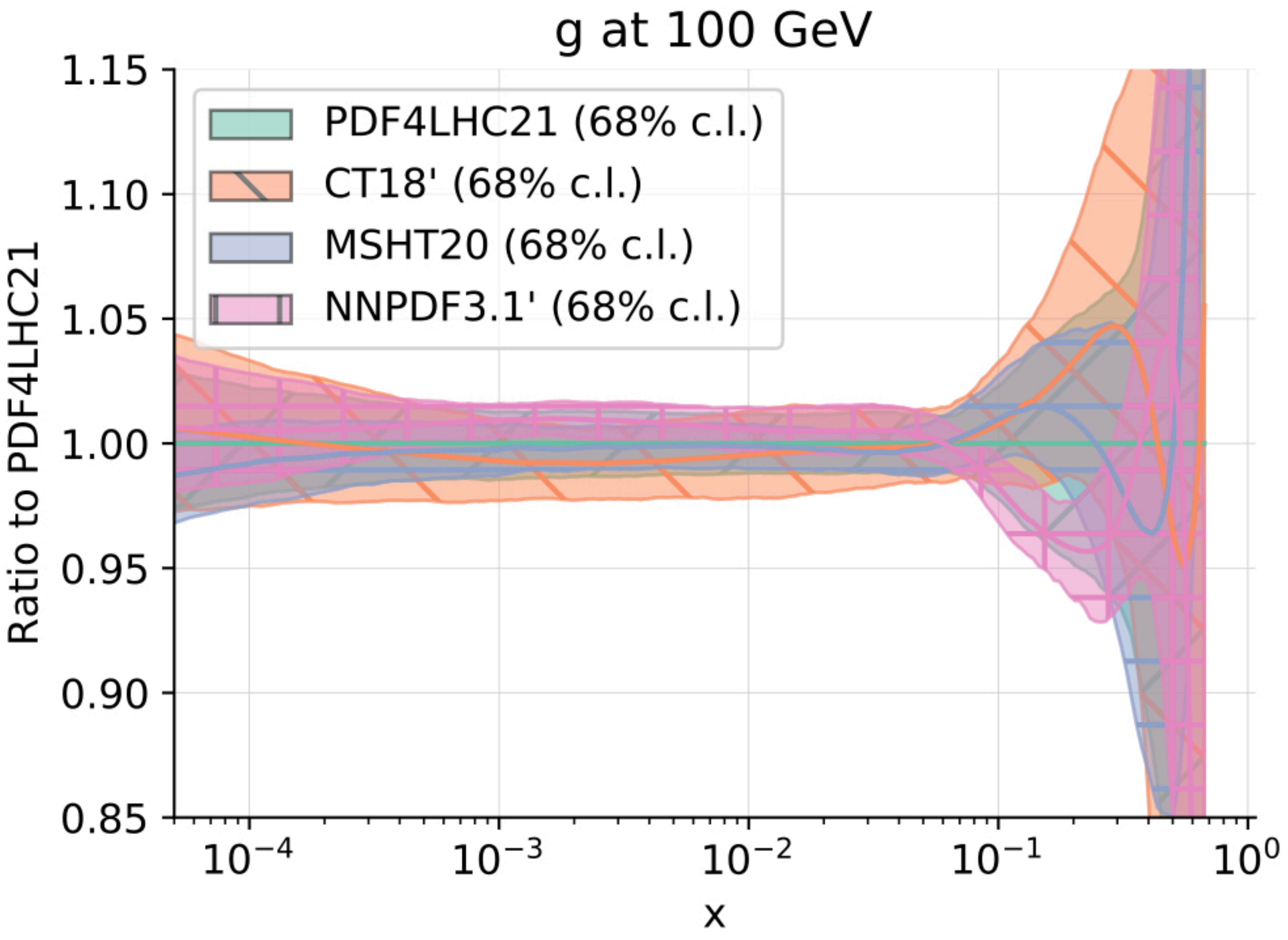
NNNLO (2017-22, still partial):
- S. Moch et al., arXiv:1707.08315
- A. Vogt et al., arXiv:1801.06085, arXiv:1808.08981
- S. Moch et al., arXiv:2111.15561

TH progress (2)

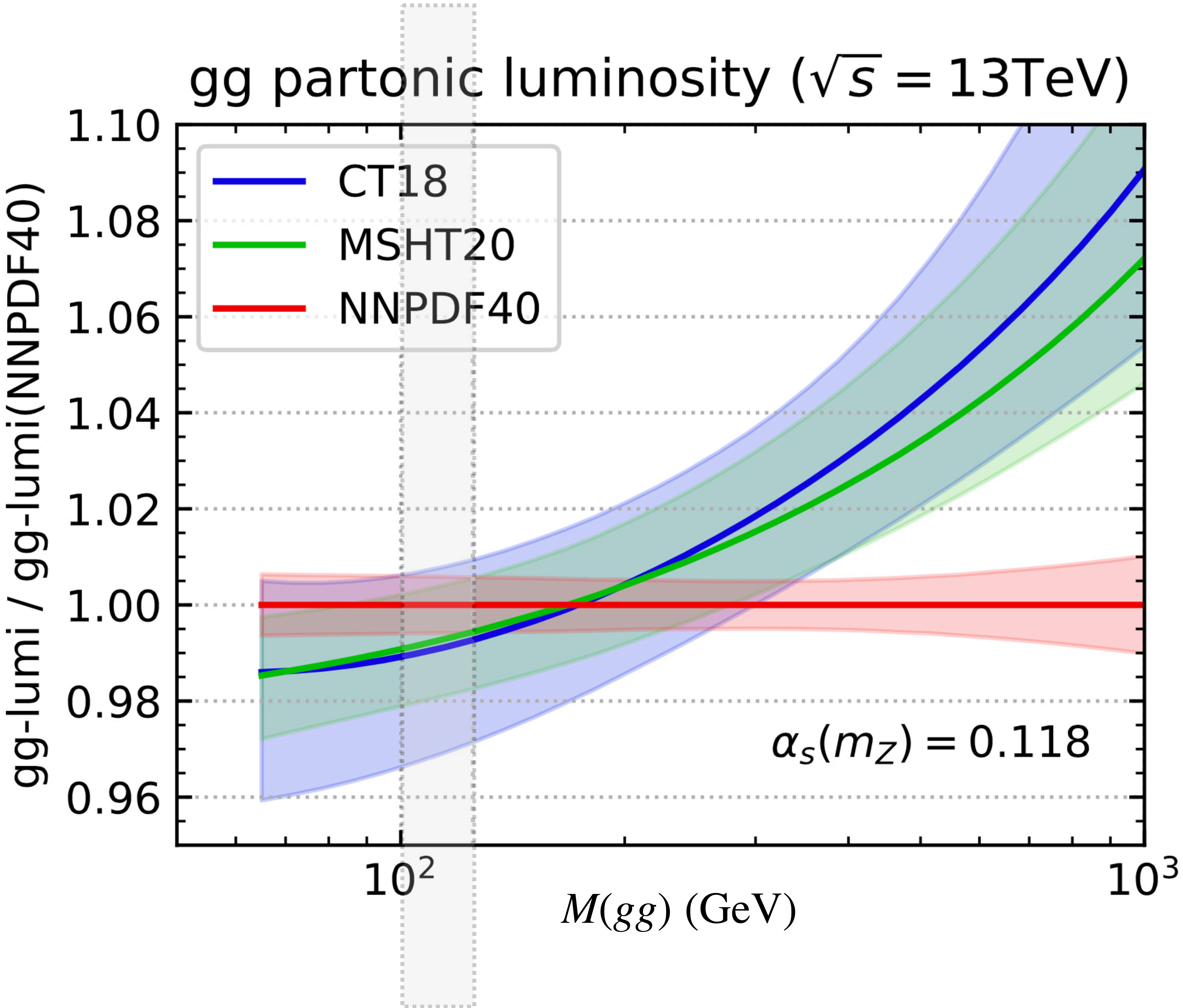
- Reduced parameterization dependence (eg use neural networks to populate functional space)
- Coherent framework for comparison/ combination of different PDF fit approaches/ systematics/…
- NNLO predictions for LHC processes => inclusion of LHC data in global fits



2022

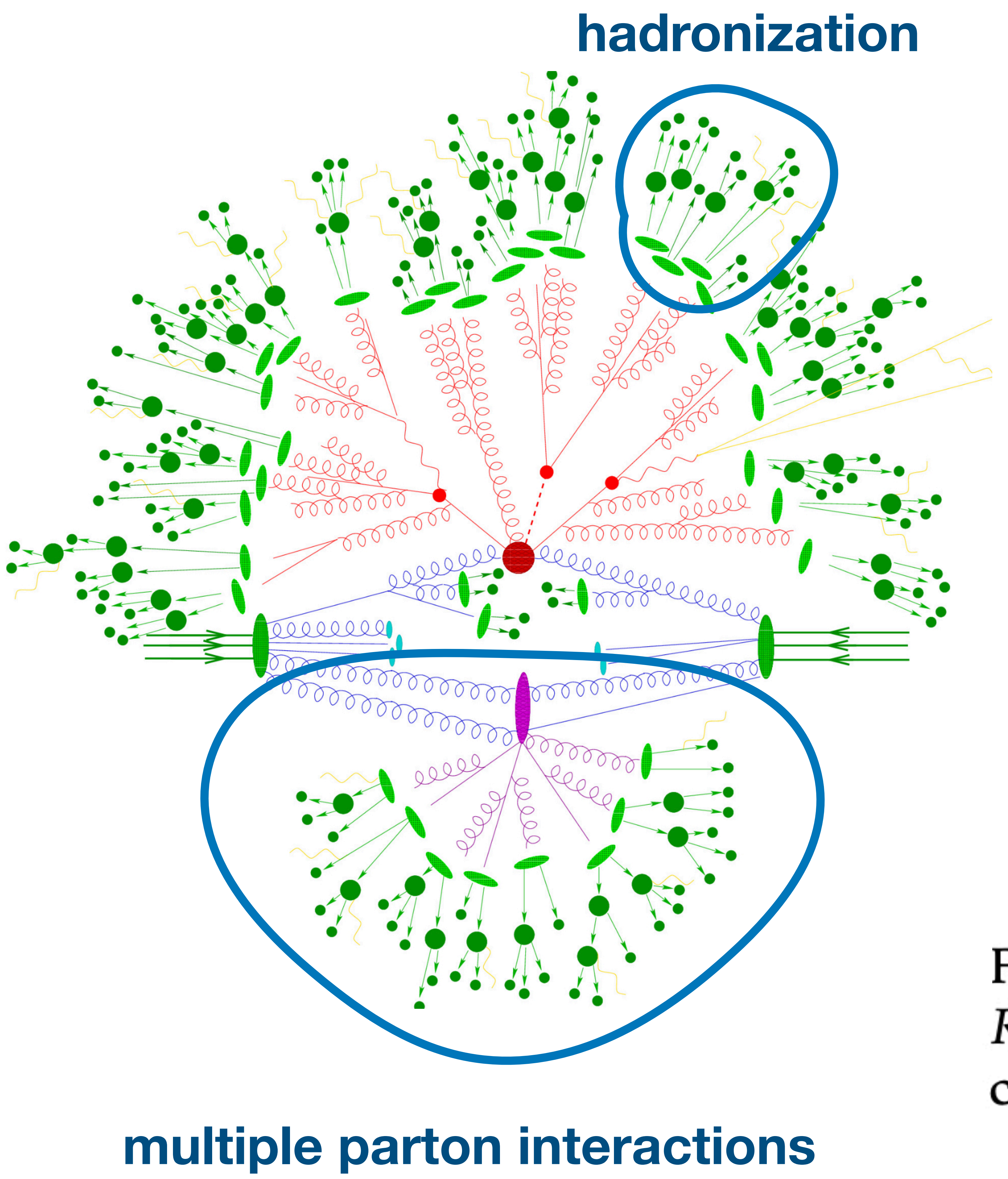


gluon PDF combination and systematics



gg→H mass window ⇒ Δ_{PDF} ~ ±1.6%

Non-perturbative corrections



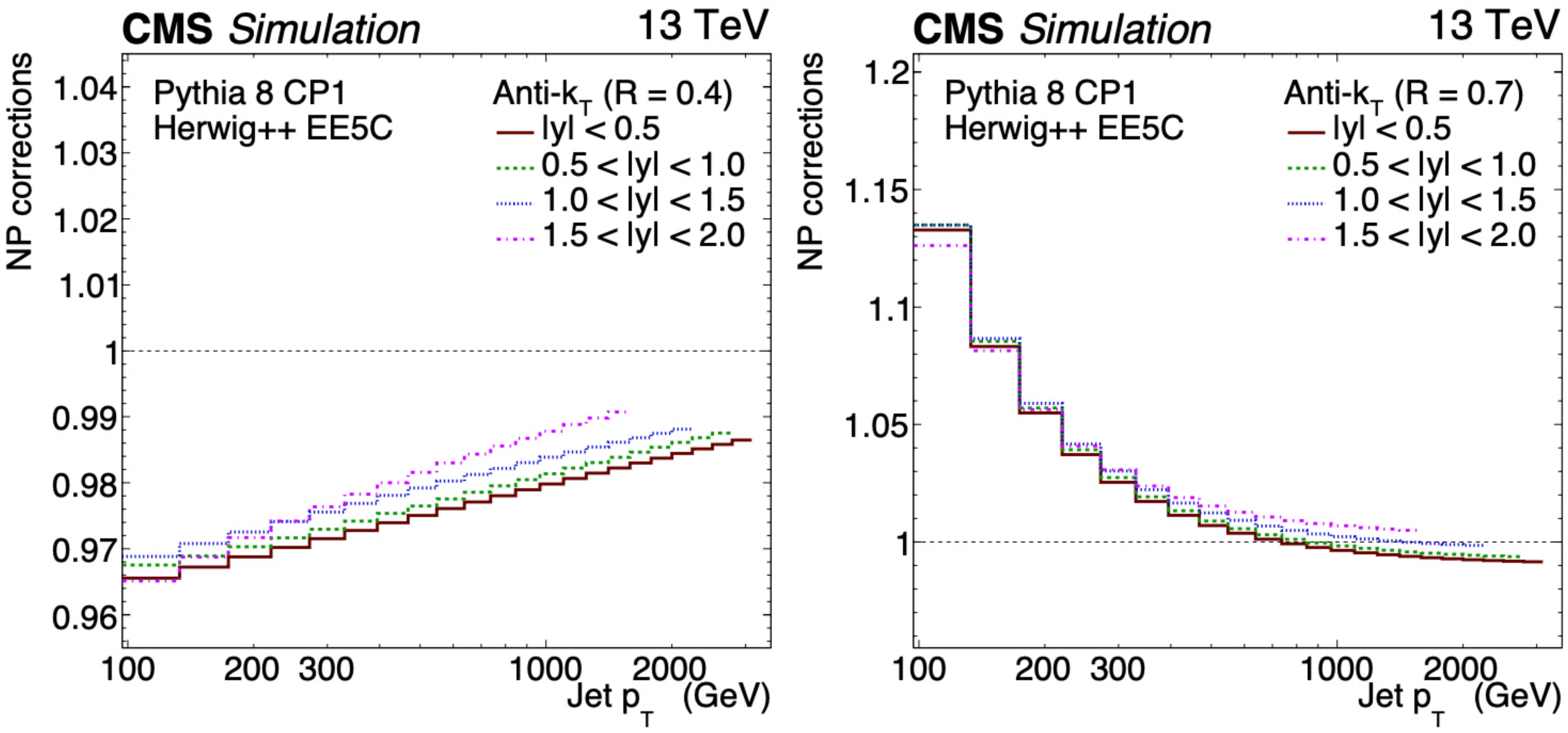


Figure 5: The values for NP corrections for inclusive jet cross sections. The values for jets with $R = 0.4$ (0.7) are shown on the left (right); each curve corresponds to a rapidity bin. The values correspond to the average of the corrections obtained with PYTHIA 8 and with HERWIG++.

$$\mathrm{NP}_i = \frac{\sigma_i^{\mathrm{MC}}(\mathrm{PS}\ \&\ \mathrm{MPI}\ \&\ \mathrm{HAD})}{\sigma_i^{\mathrm{MC}}(\mathrm{PS})},$$

EW corrections

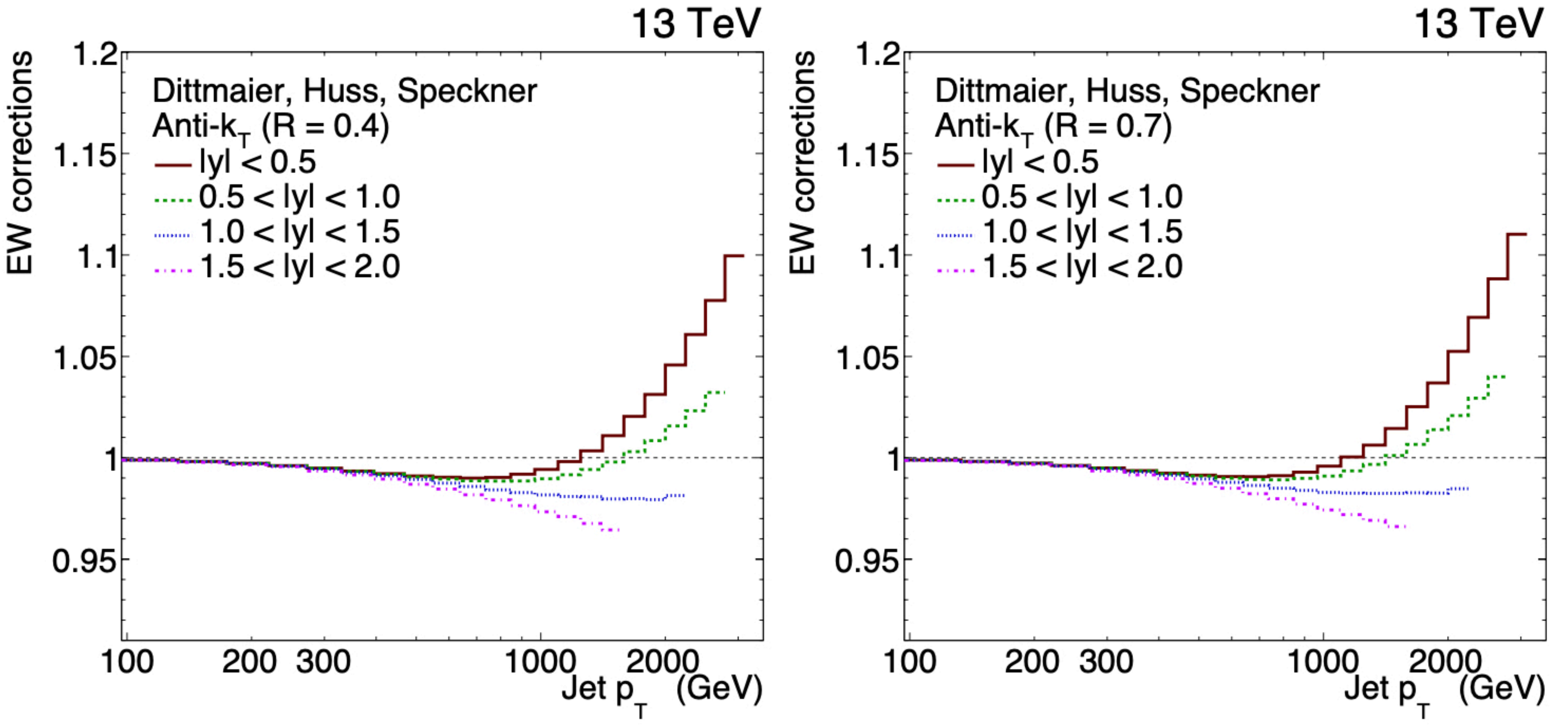
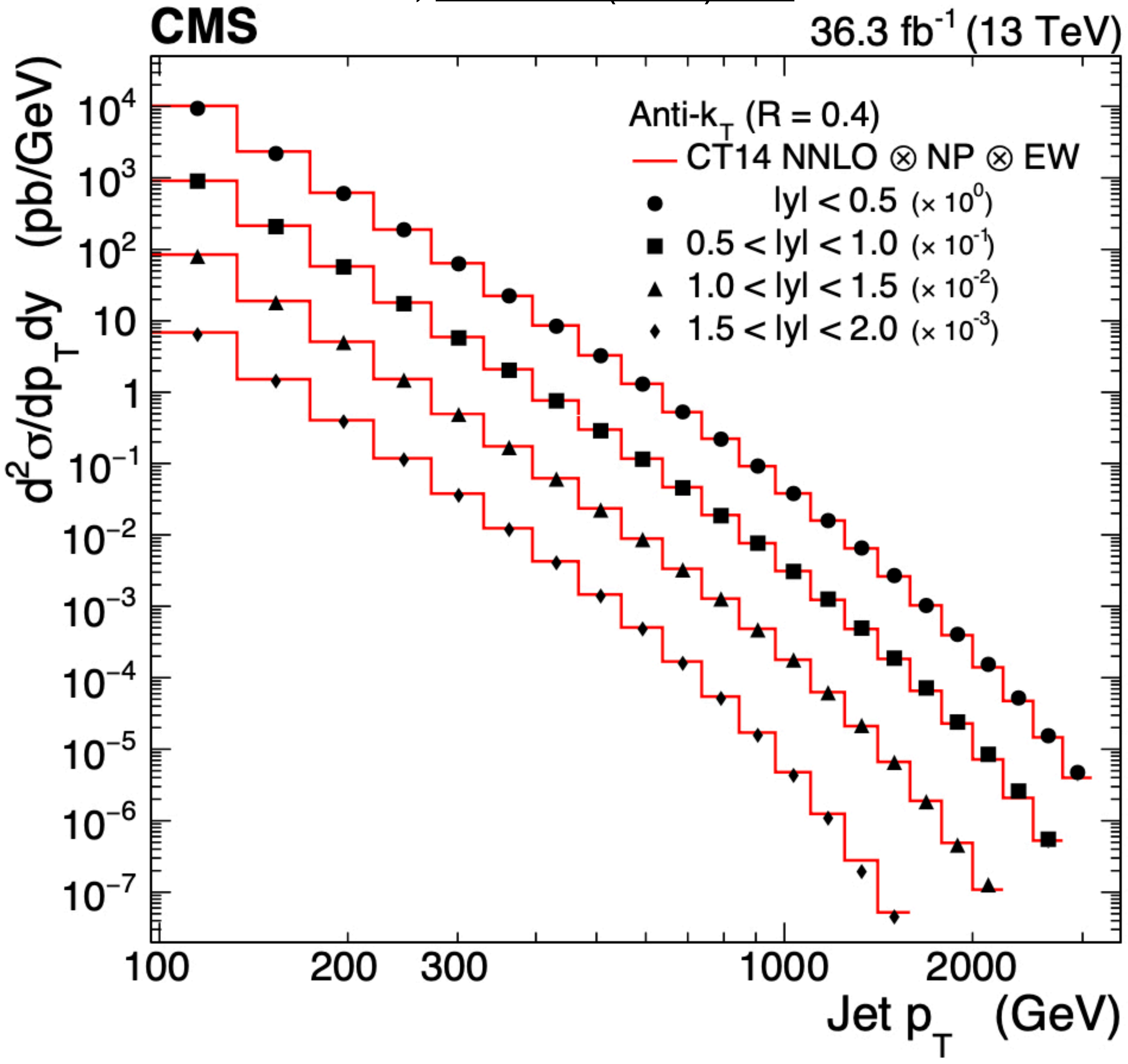


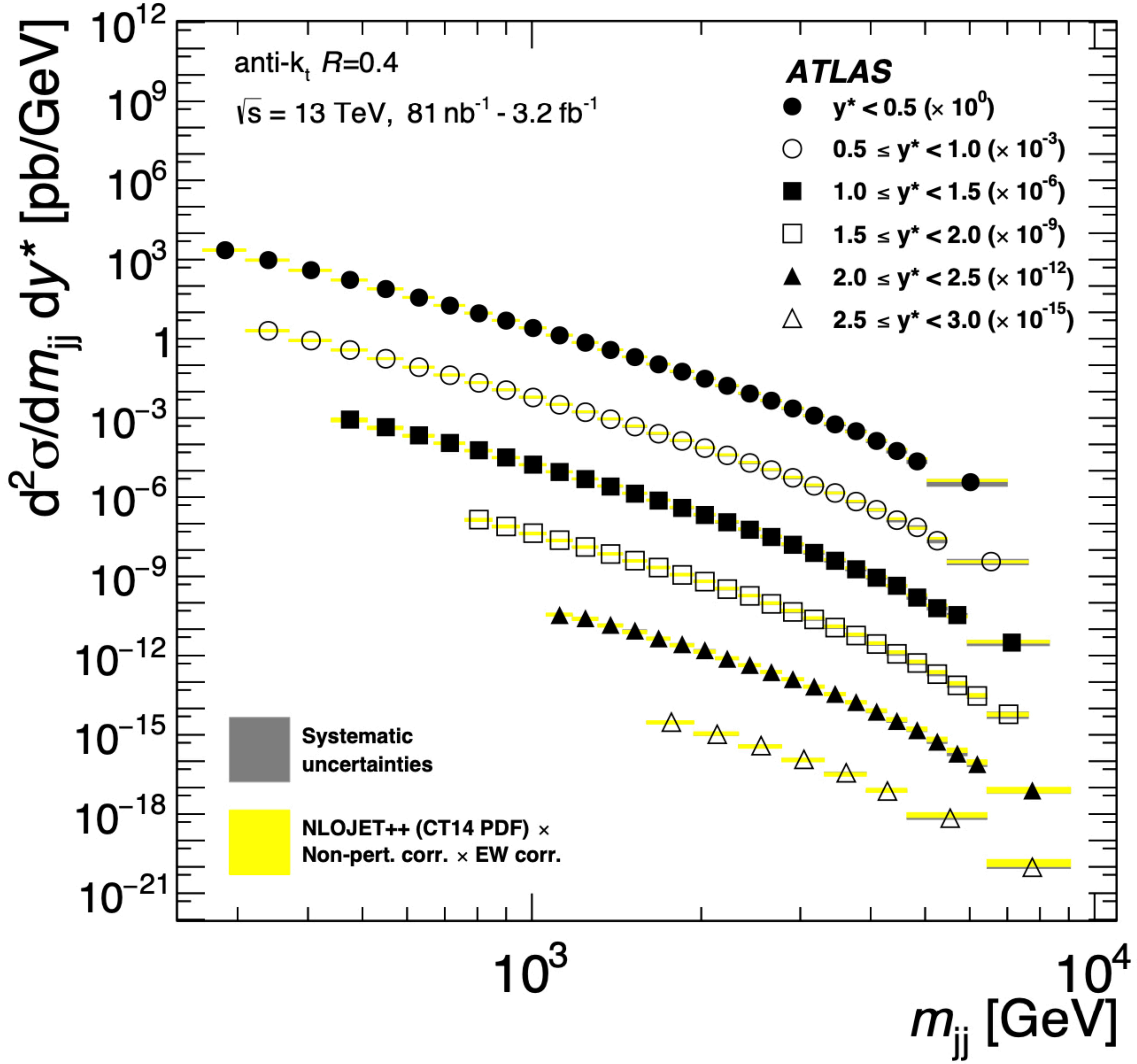
Figure 4: The EW corrections for inclusive jet cross sections, as reported in Ref. [62]. The values for jets clustered using the anti-k_{T} algorithm with $R = 0.4$ (0.7) are shown on the left (right); each curve corresponds to a rapidity bin.

Inclusive jet p_T and dijet mass distributions

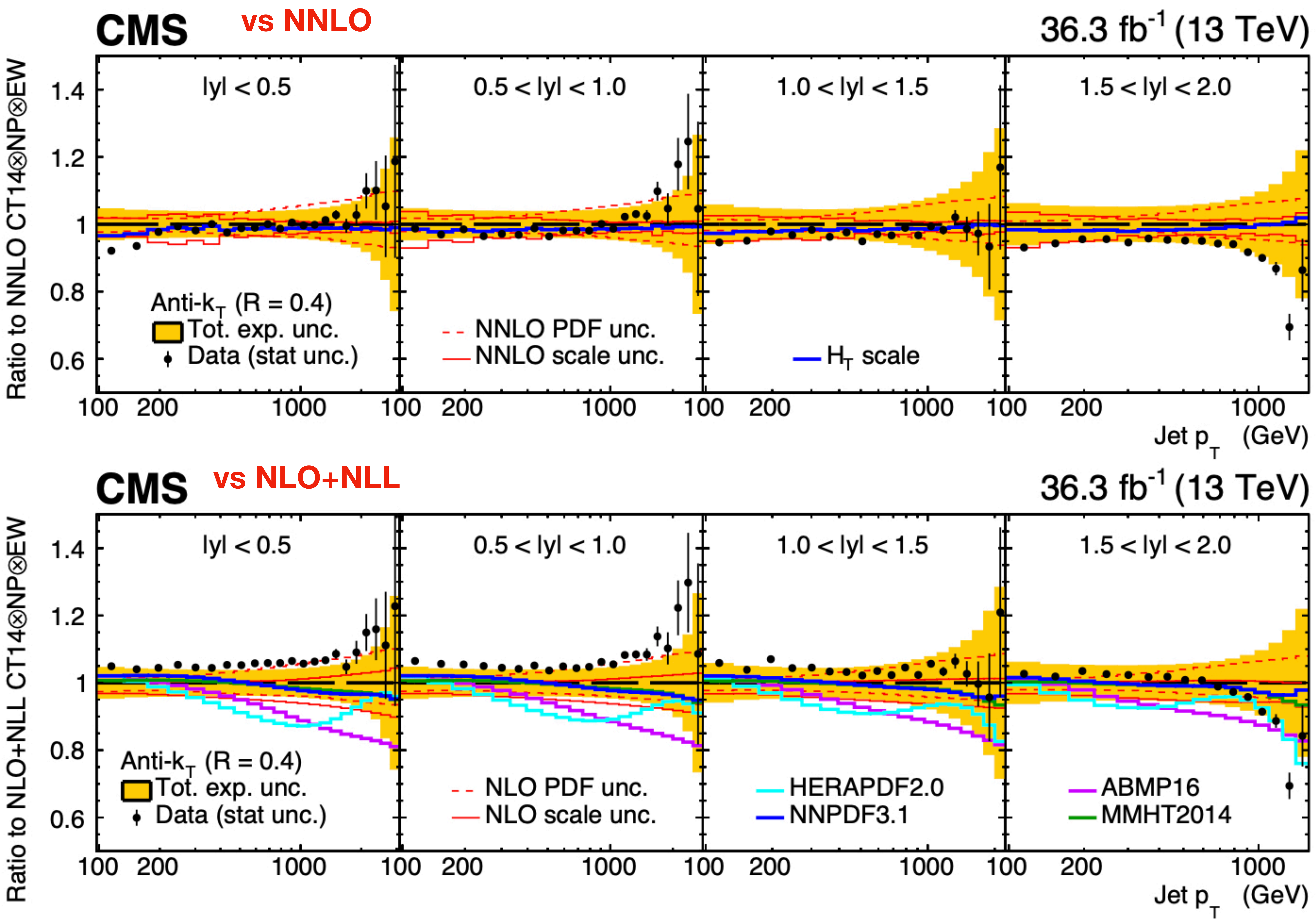
CMS, JHEP 02 (2022) 142



ATLAS, JHEP 05 (2018) 195



Comparison with QCD

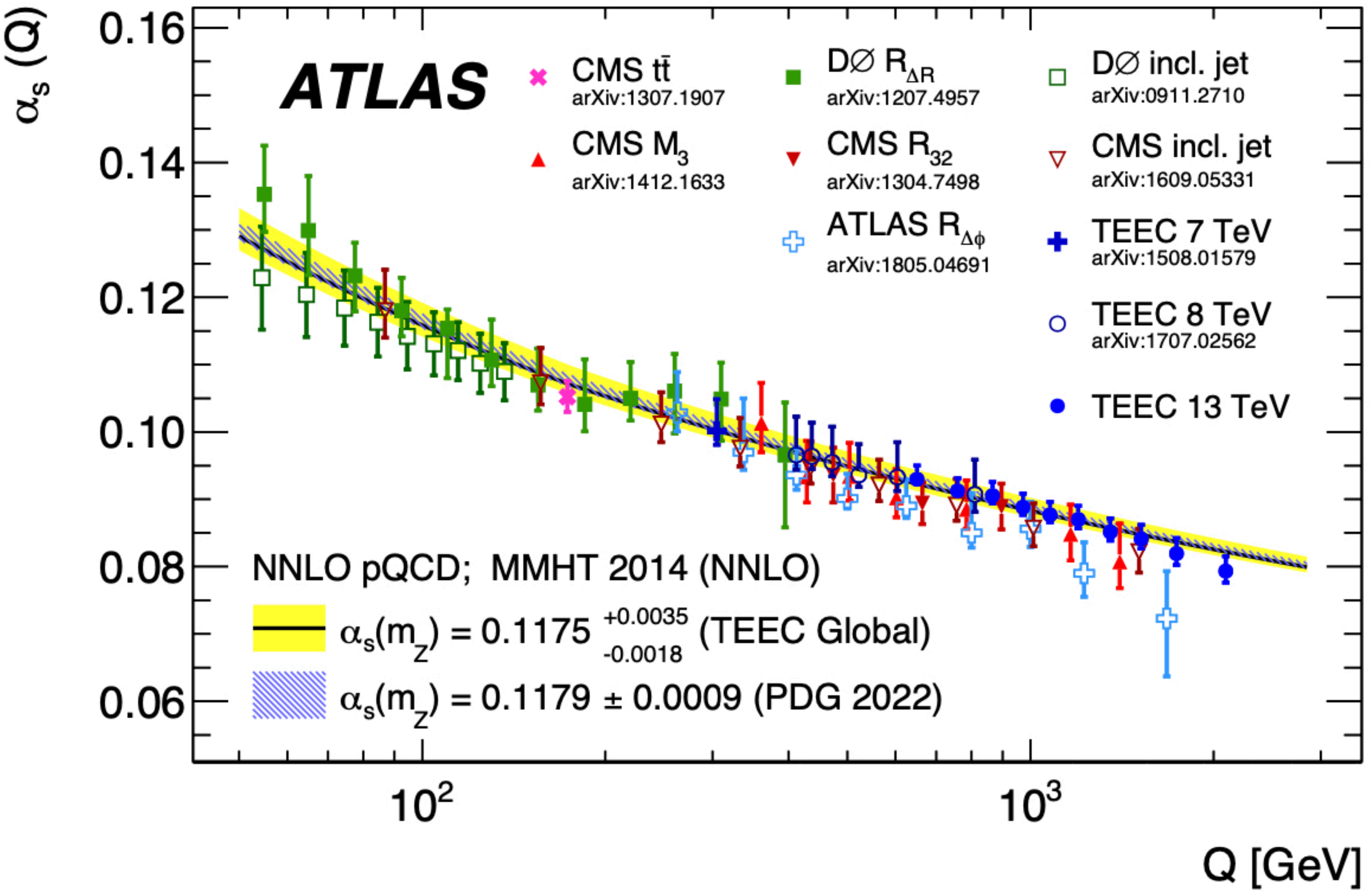


- Overall excellent agreement at the 5% level, and within exptl systematics
- NNLO improves over NLO
- PDF systematics remains dominant, esp at large p_T

α_S measurements from jets

Transverse energy-energy correlations (TEEC):

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{Ti}^{A}E_{Tj}^{A}}{\left(\sum_k E_{Tk}^{A}\right)^2}\delta(\cos\phi - \cos\varphi_{ij})$$



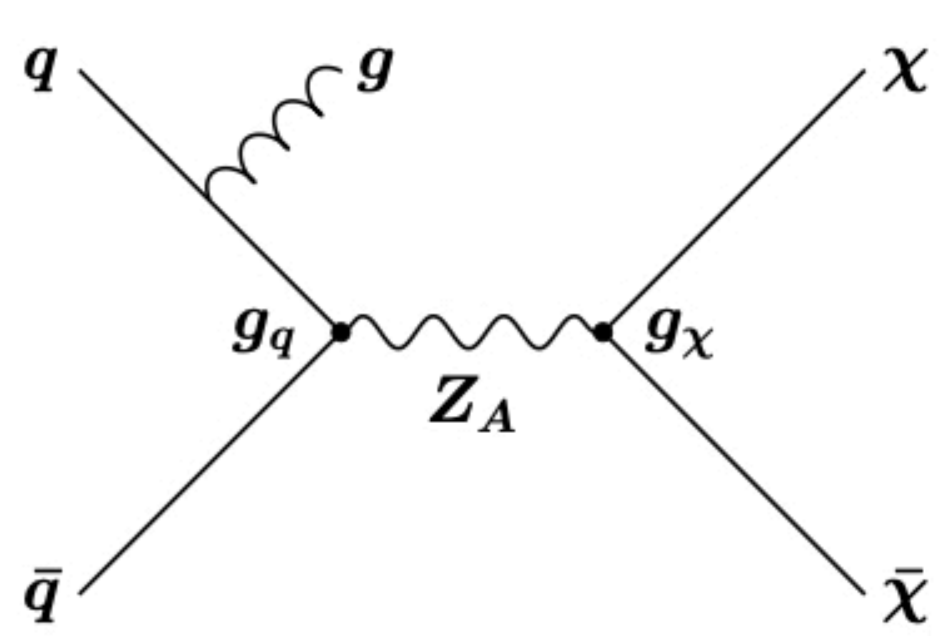
Vector bosons plus jets

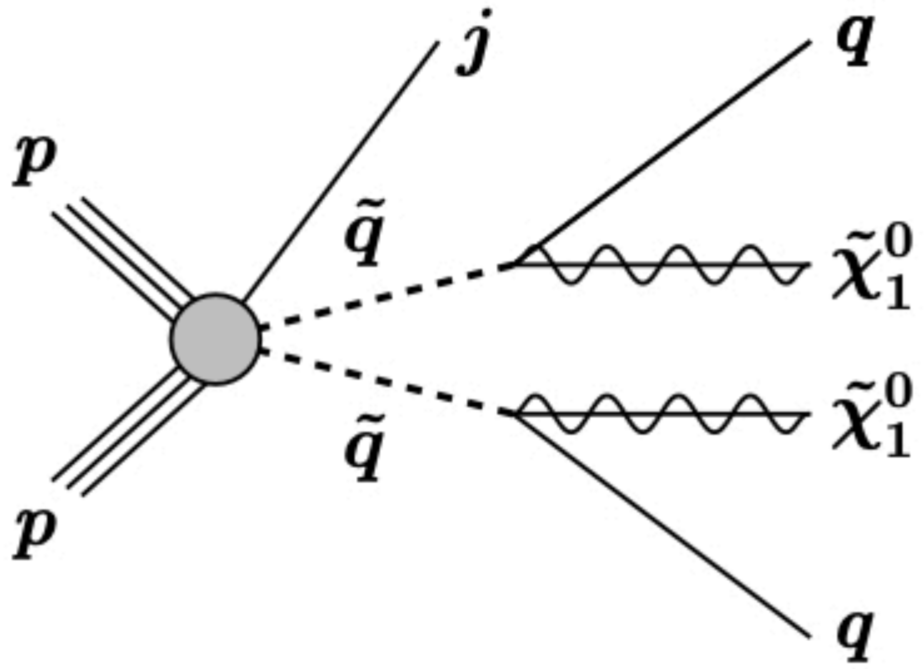
$W + \text{jets} \rightarrow \text{jets} + \ell + \nu$ (missing energy)

$Z + \text{jets} \rightarrow \text{jets} + \nu\bar{\nu}$ (missing energy)

Irreducible background to all searches for jets+missing transverse energy.

For example DM searches!





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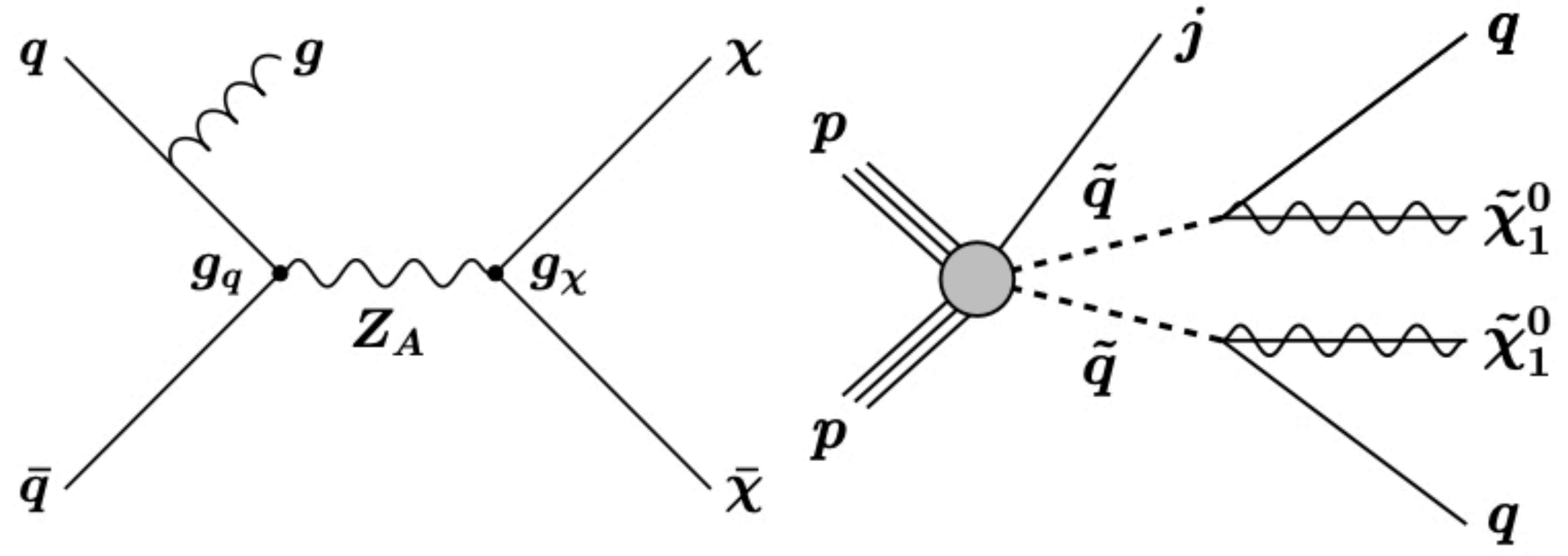
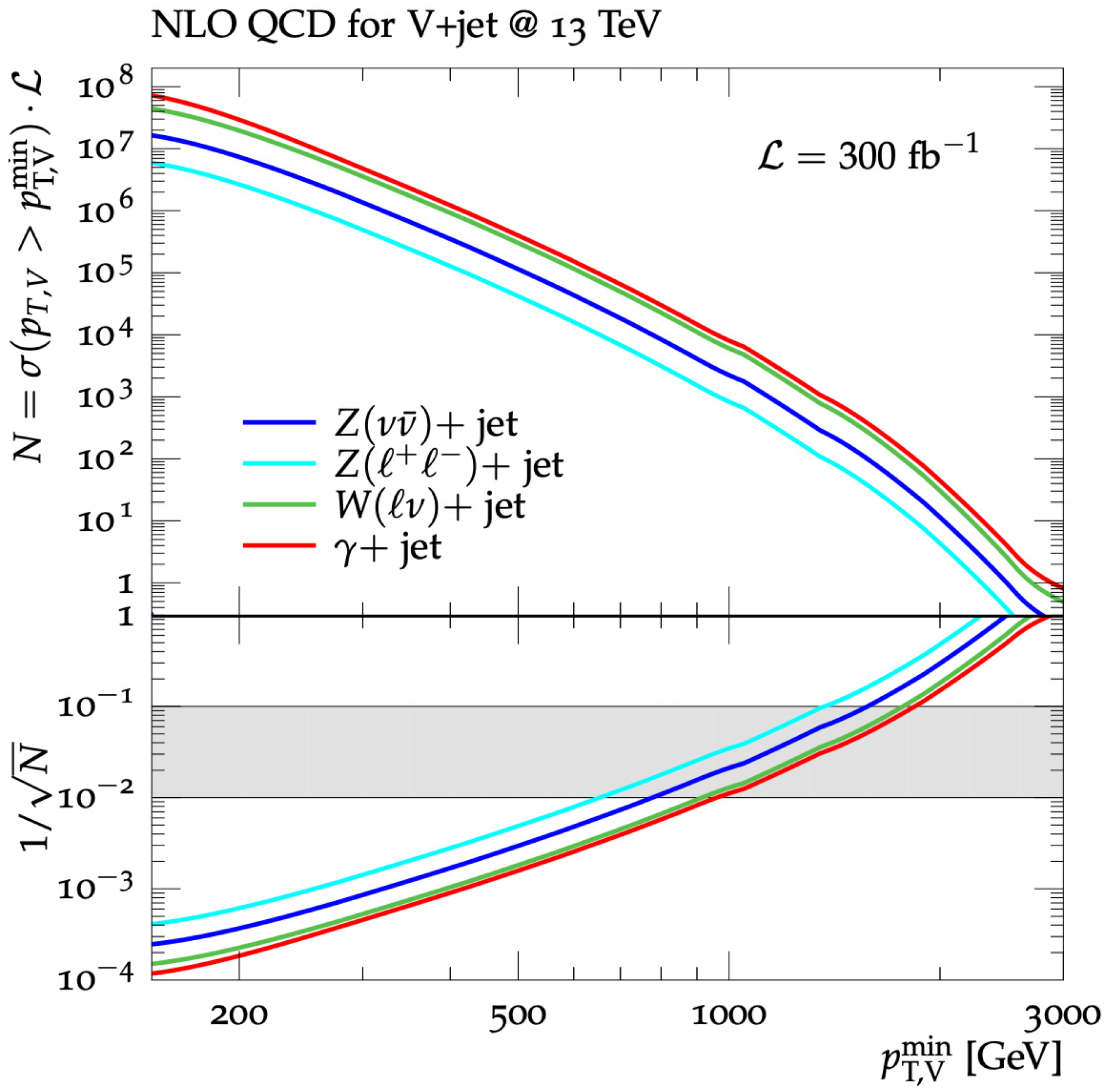
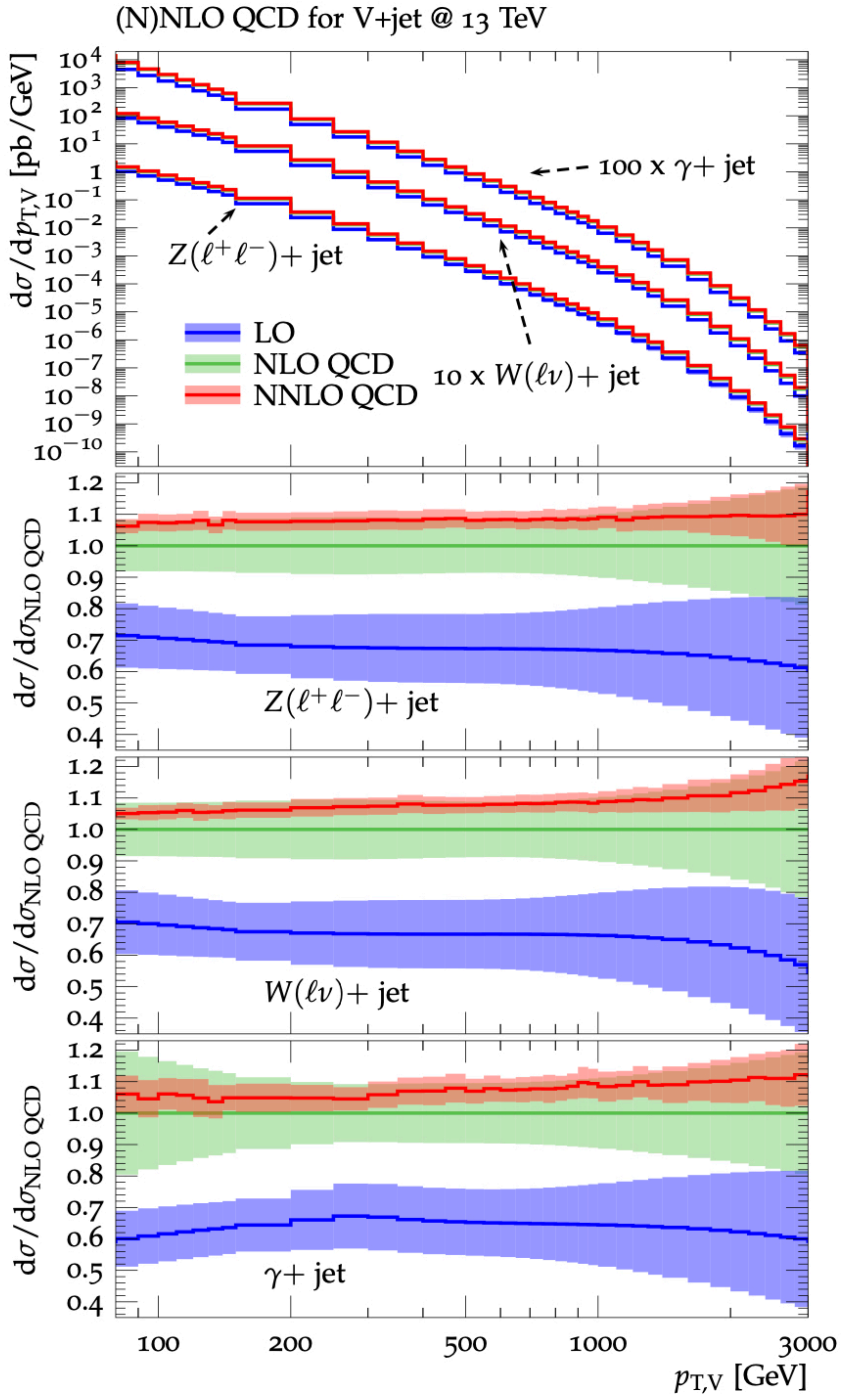




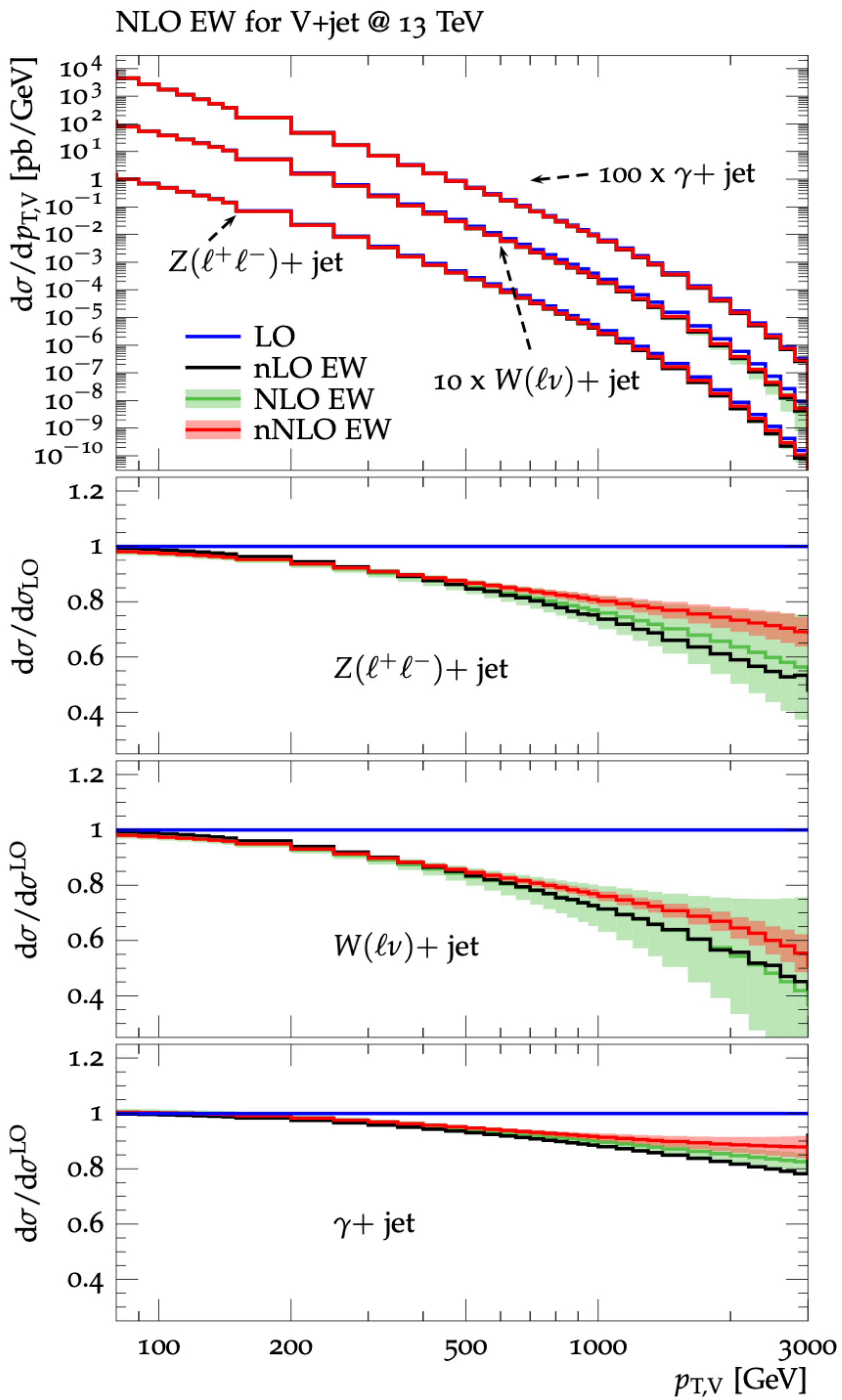
The impact of higher-order corrections



<== QCD

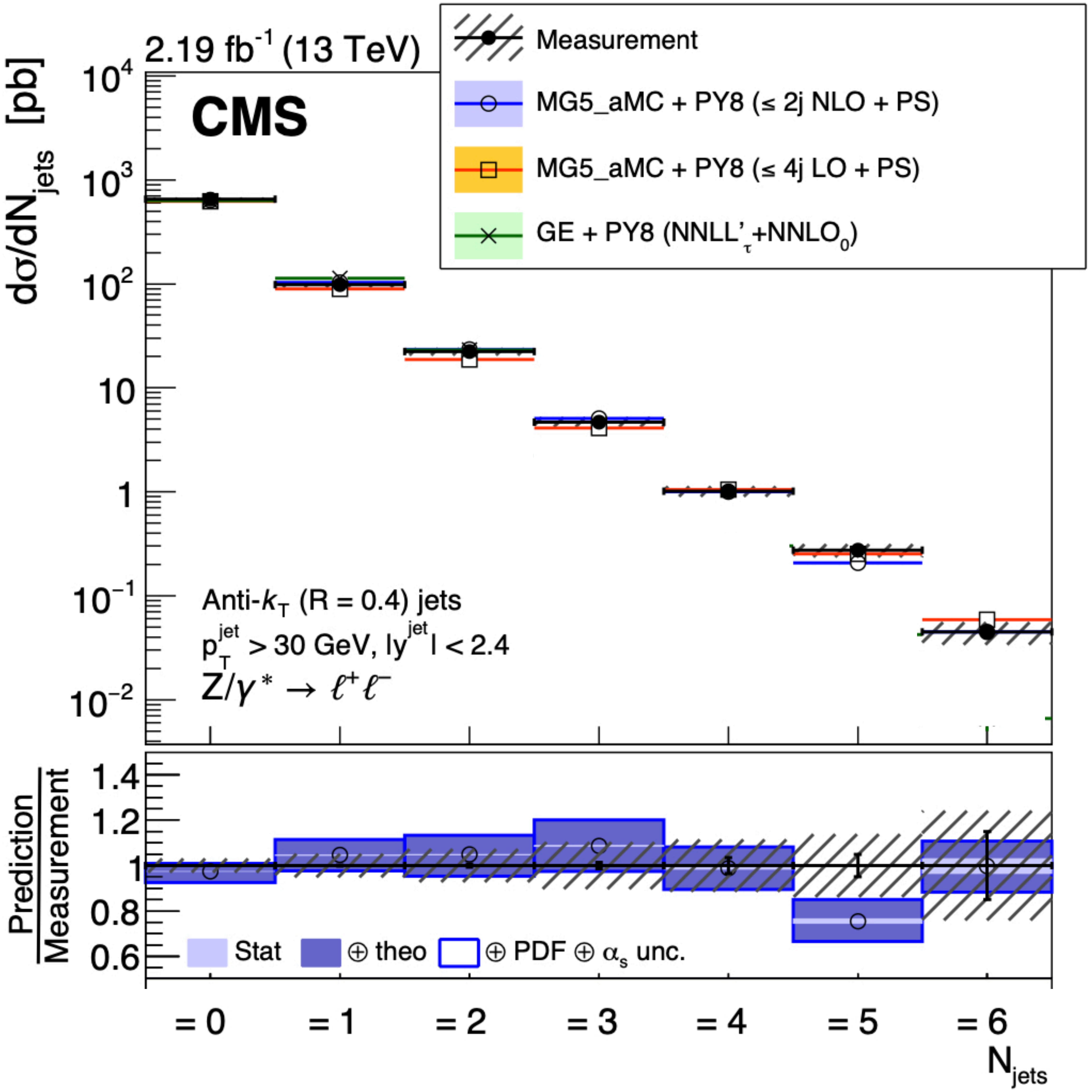
EW ==>

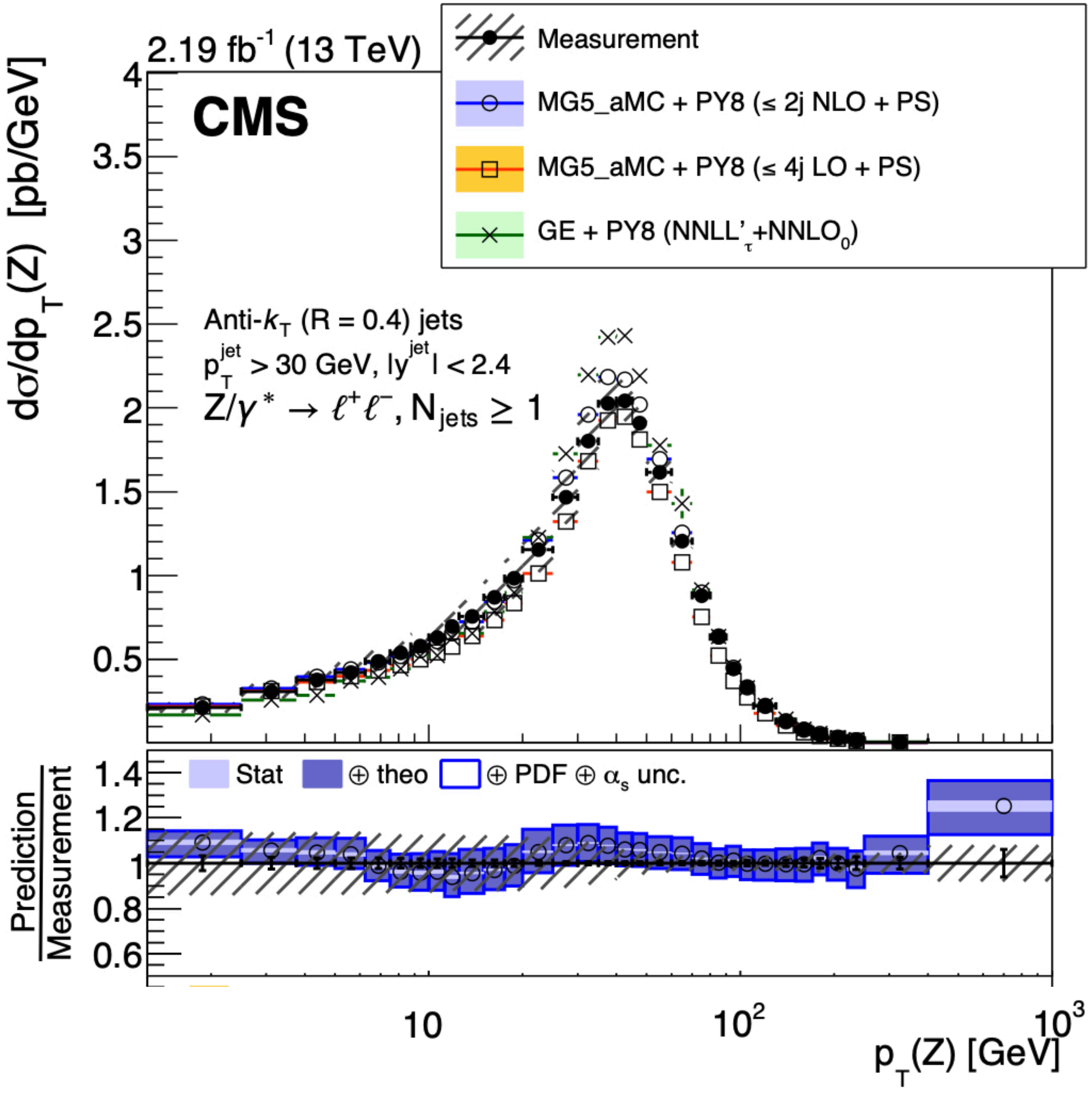
"EW Sudakov logs"



CMS, Eur.Phys.J.C 78 (2018) 11

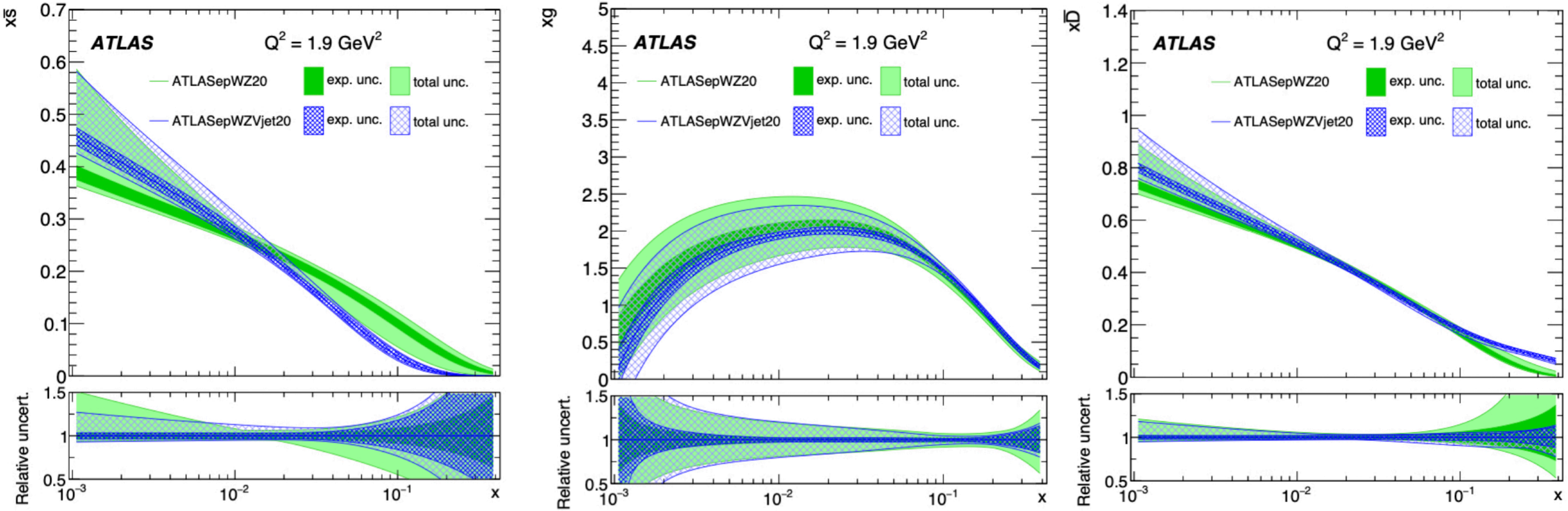
Z+jets: data vs TH





The impact of V + jets data on PDF determinations

ATLAS, JHEP 07 (2021) 223



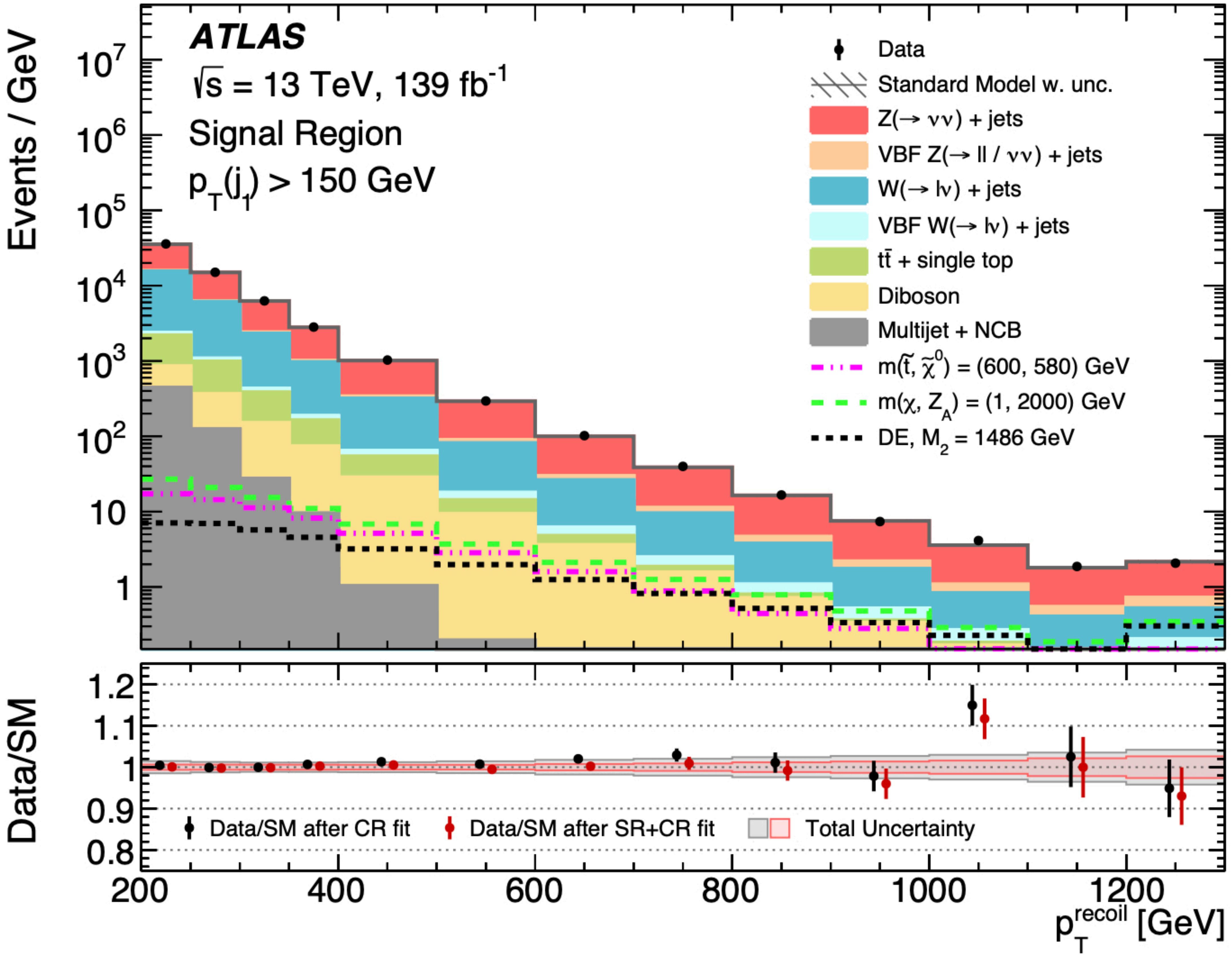
ATLASepWZ20: PDF fits using HERA ep and LHC W/Z inclusive production data

ATLASepWZVjet20: as ATLASepWZ20, plus W/Z+jets data

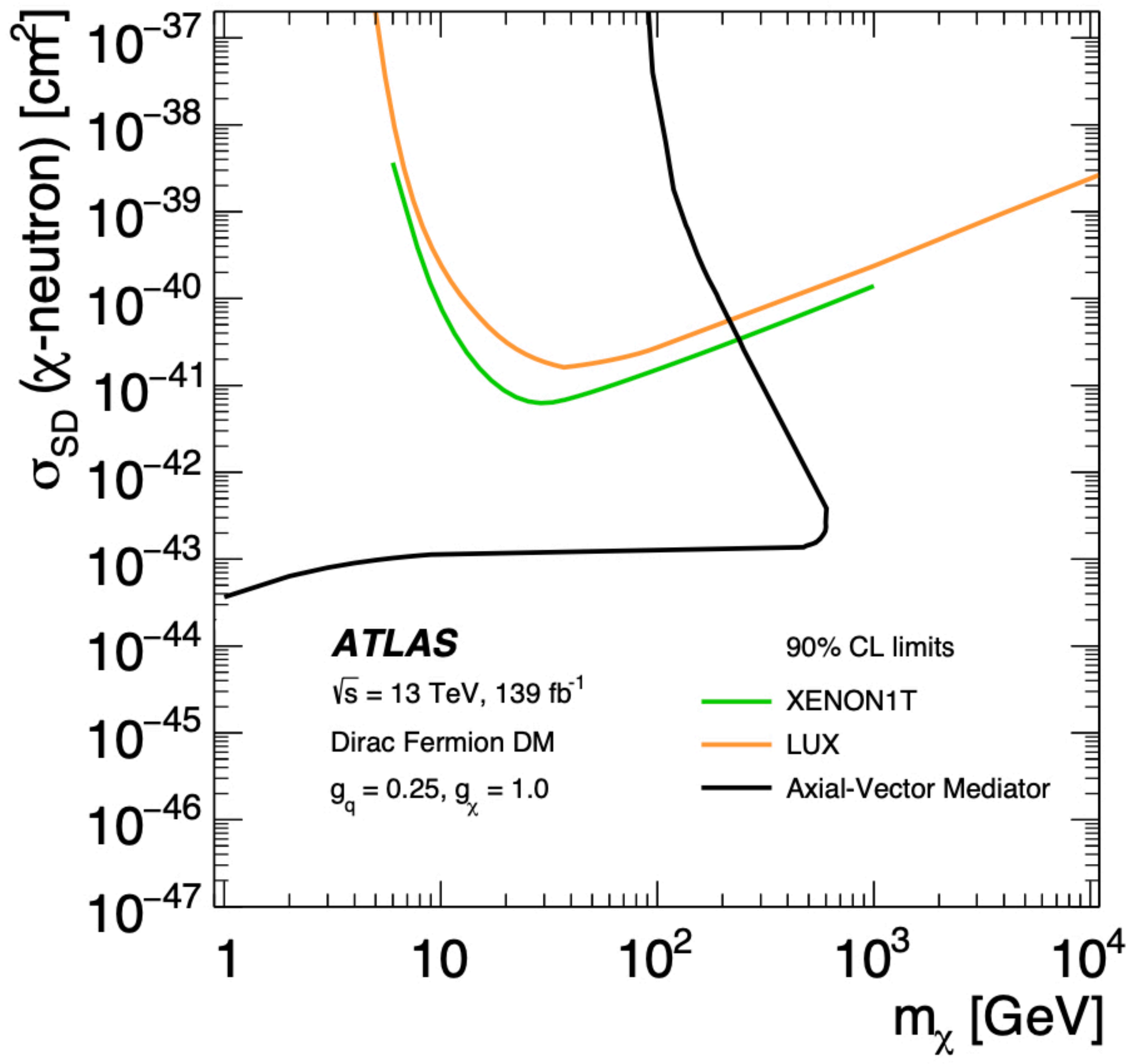
The impact on BSM missing-energy searches

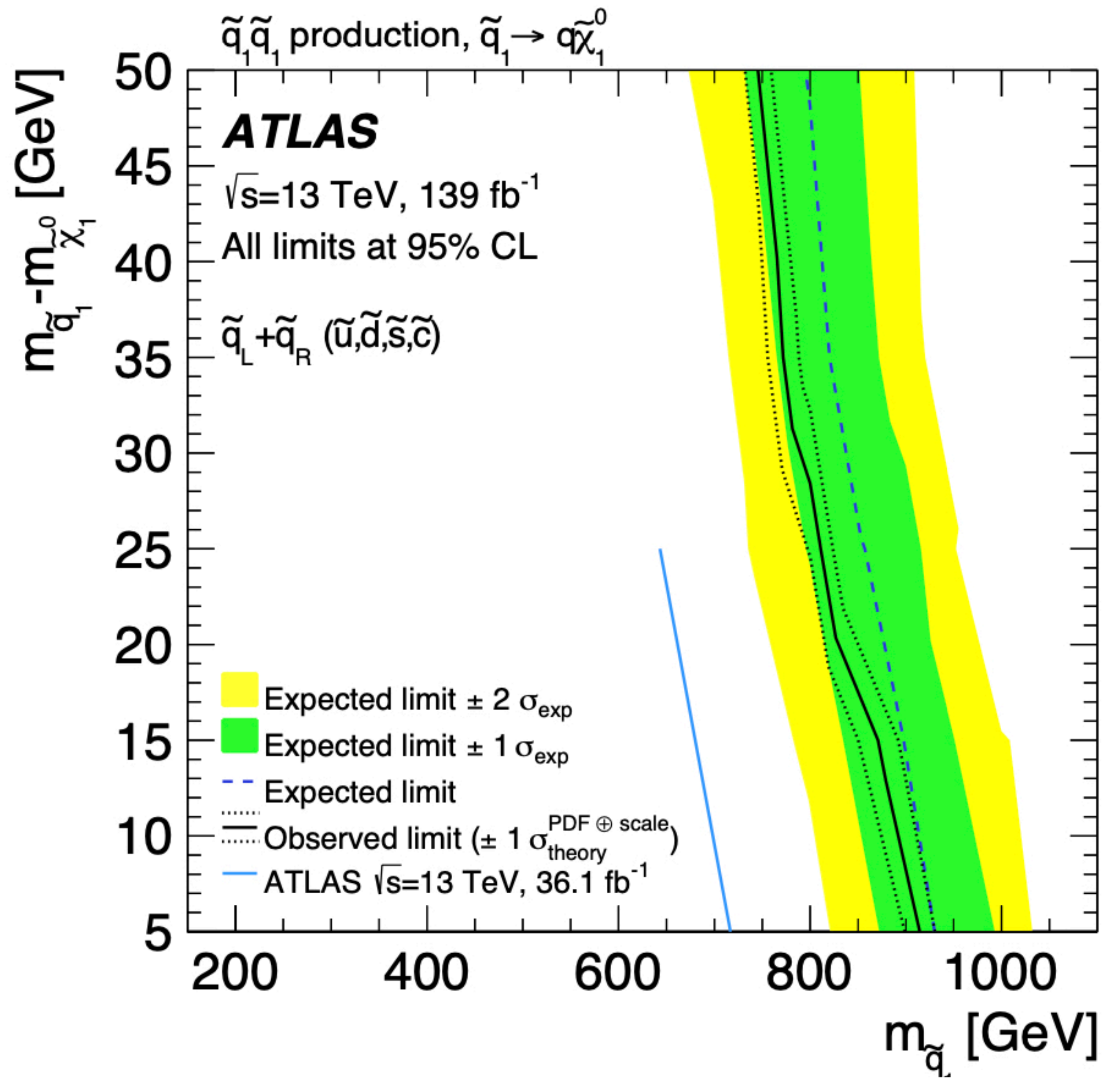
ATLAS, CERN-EP-2020-238

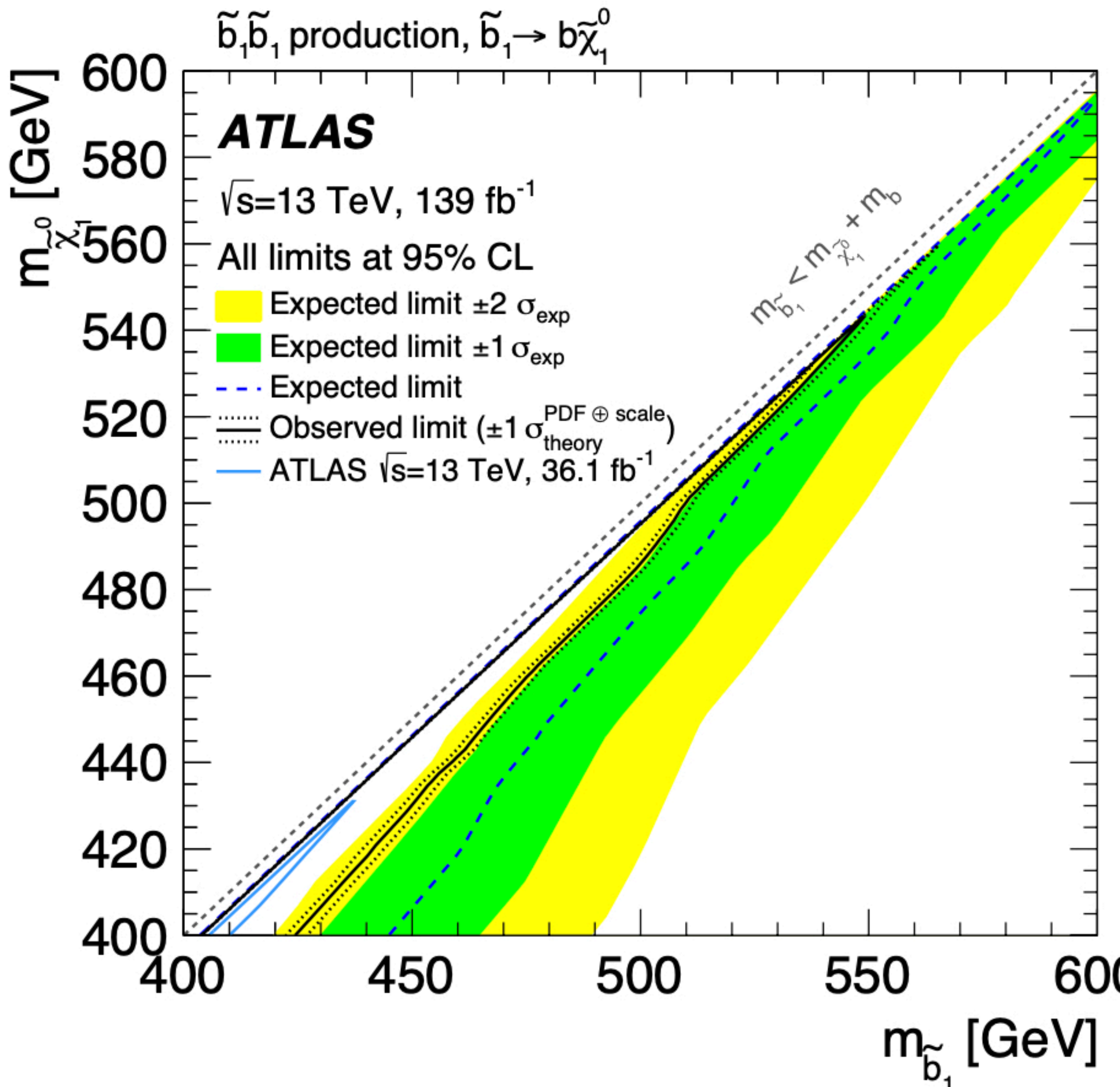
jets+MET data, vs SM bgs

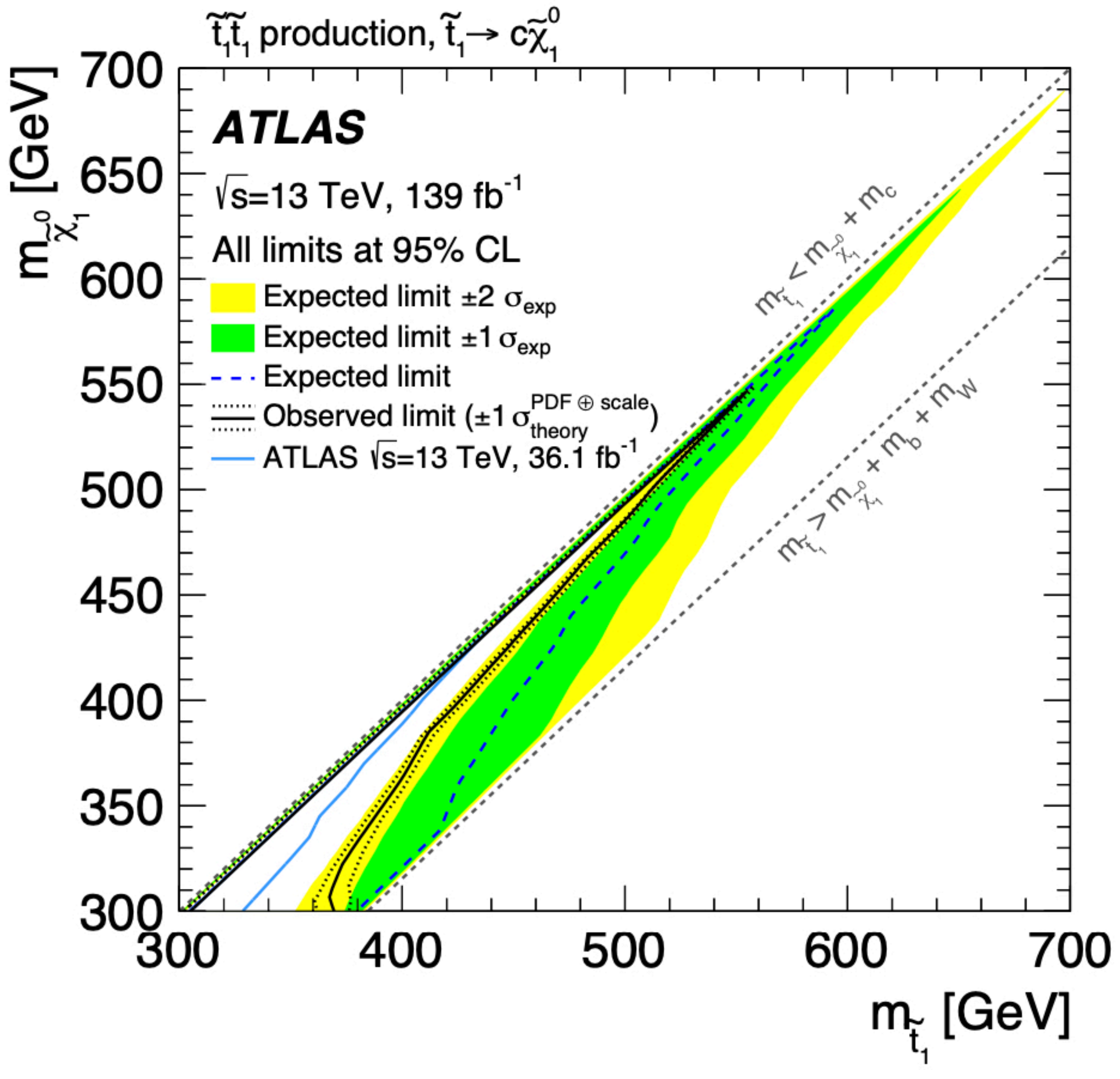


Sample constraints on BSM models



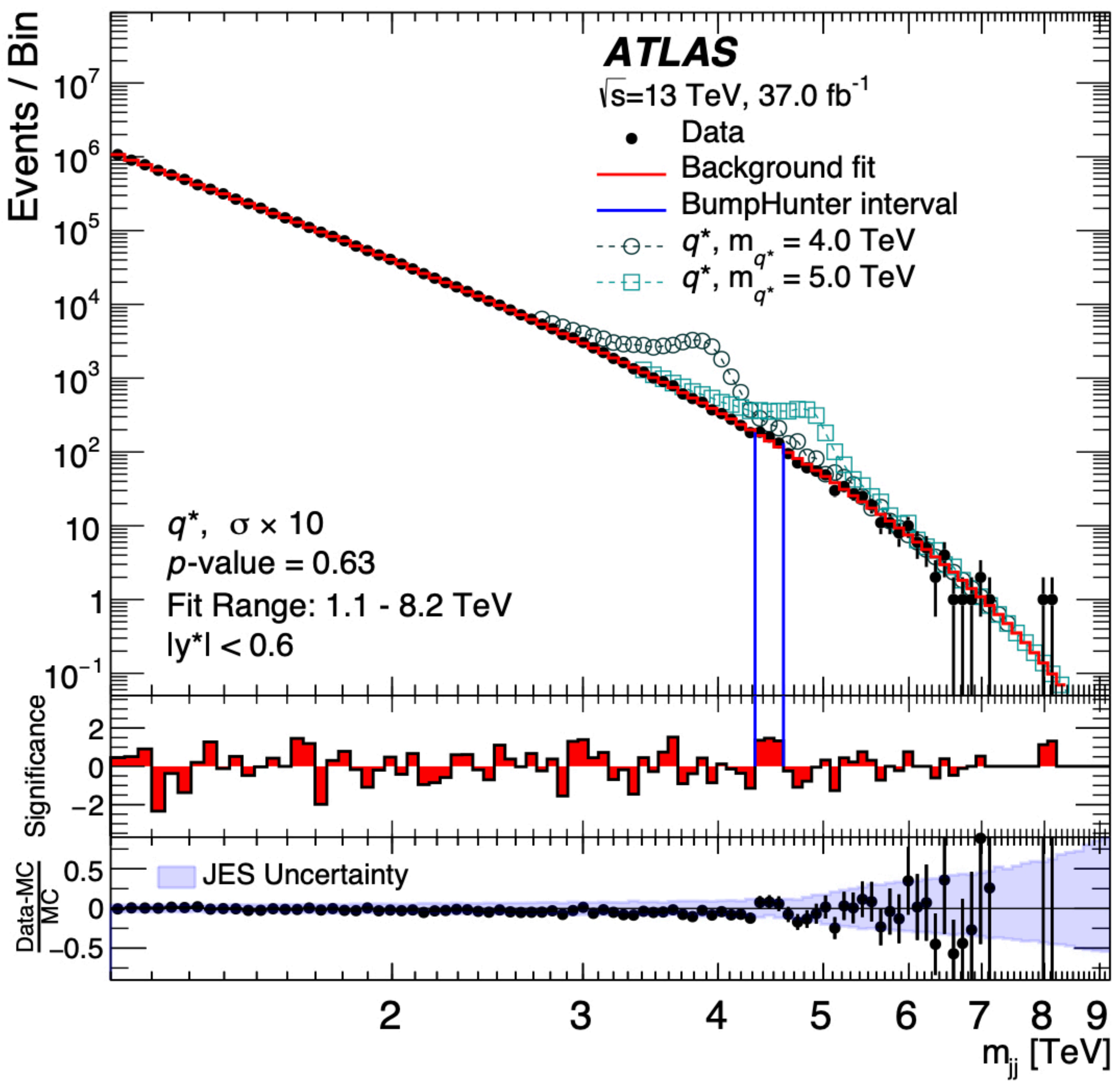






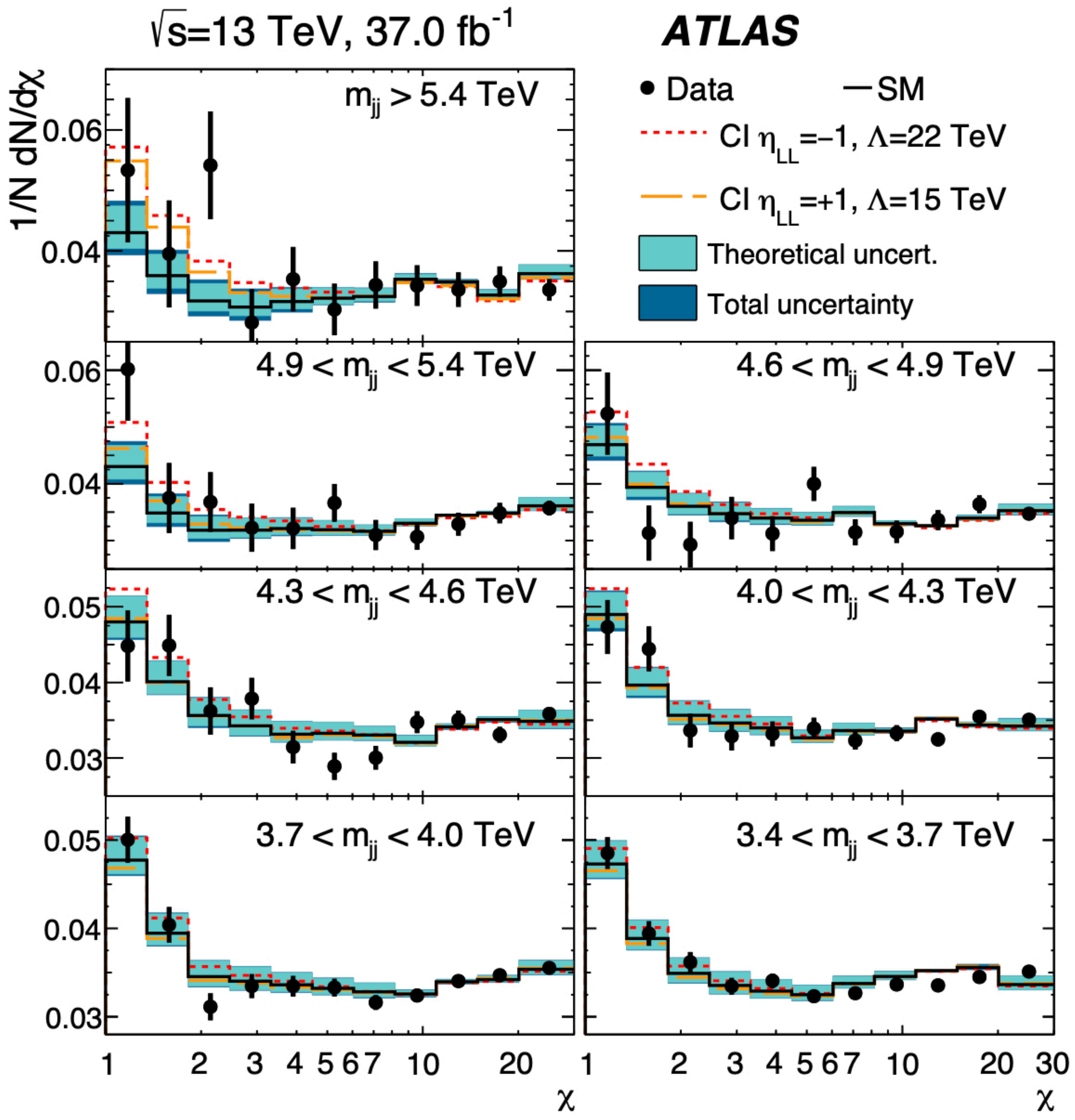
Examples of new-physics searches in 2-jet final states

Dijet resonances (q*, Z', …)



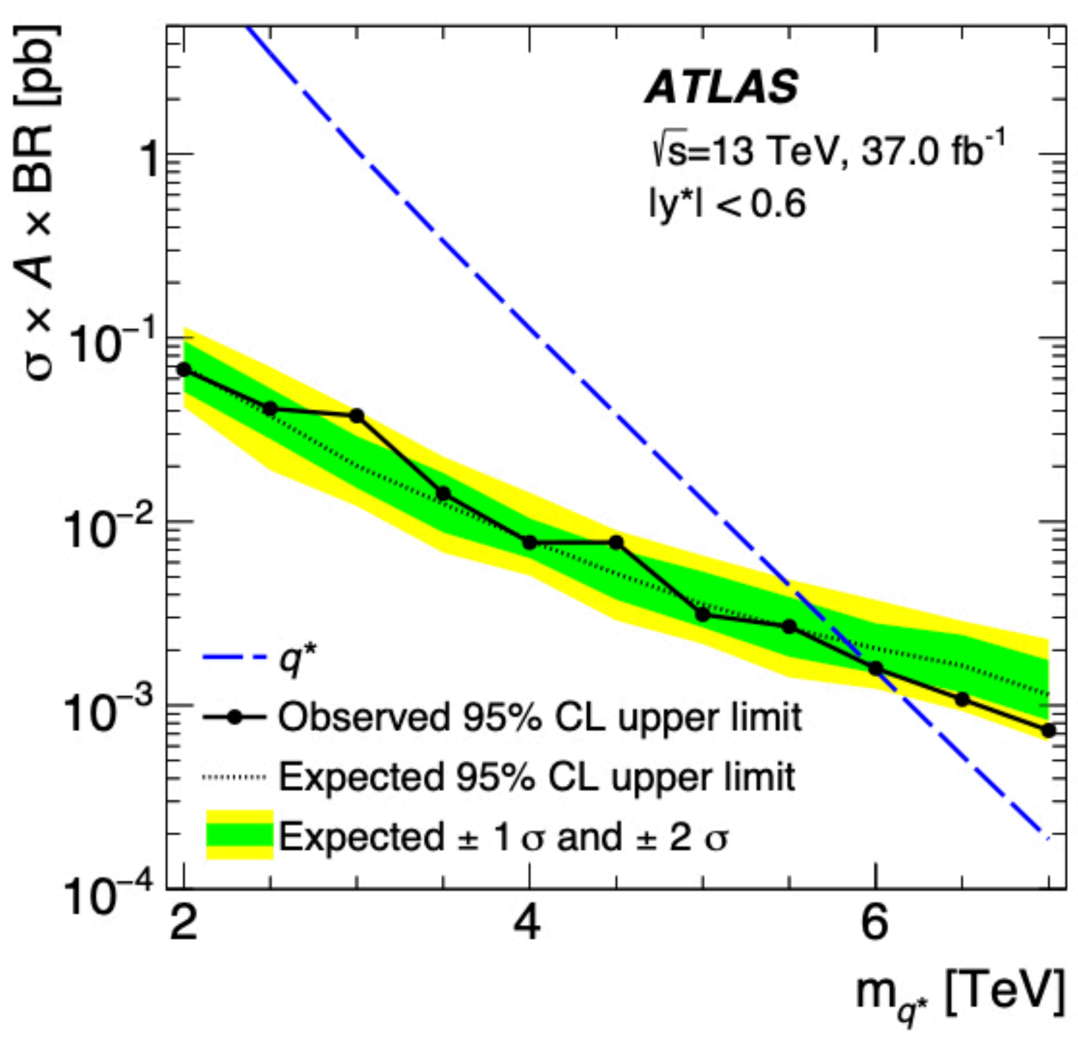
Quark substructure from angular distribution

$$\chi = e^{2|y^*|} \sim \frac{1 + \cos\theta^*}{1 - \cos\theta^*}$$

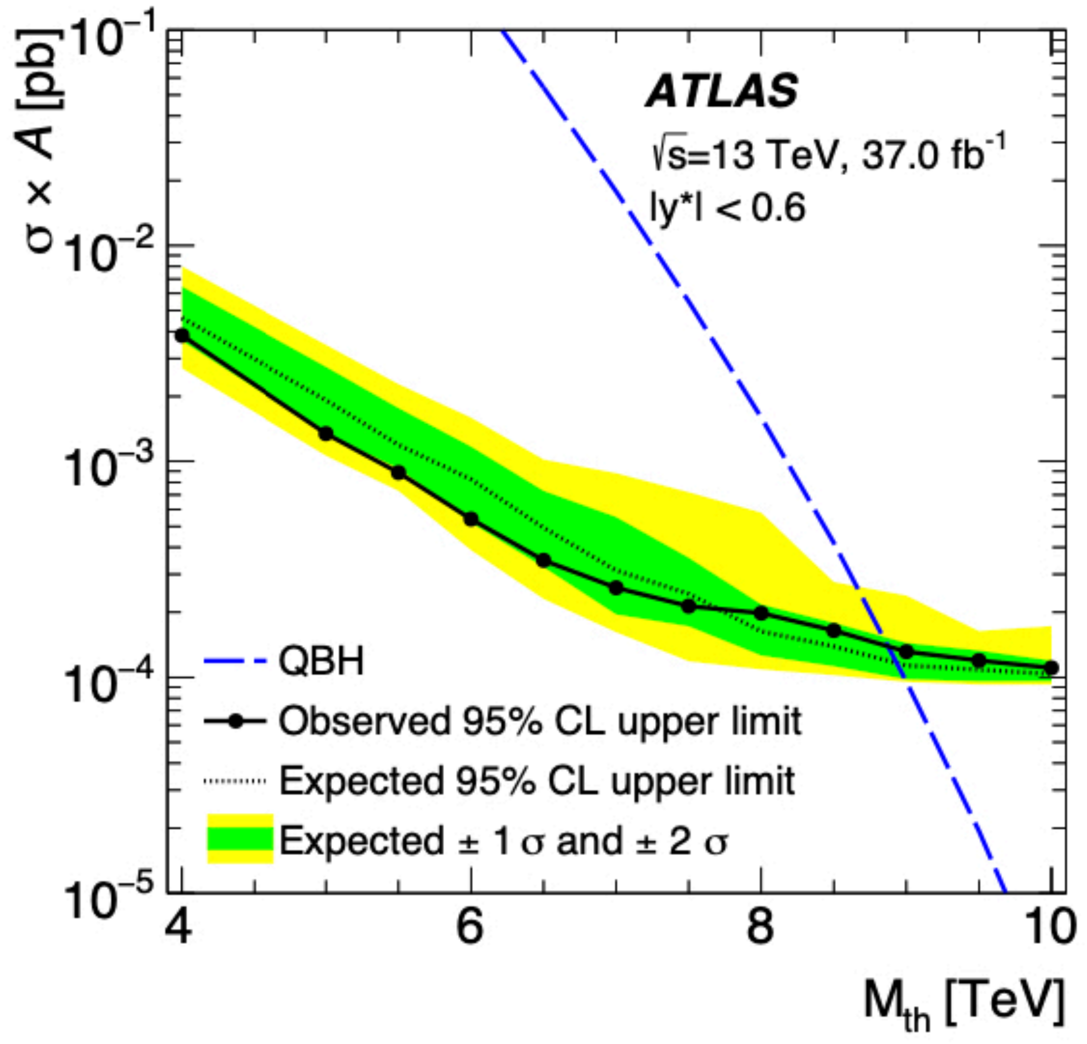


ATLAS, Phys.Rev.D 96 (2017) 5

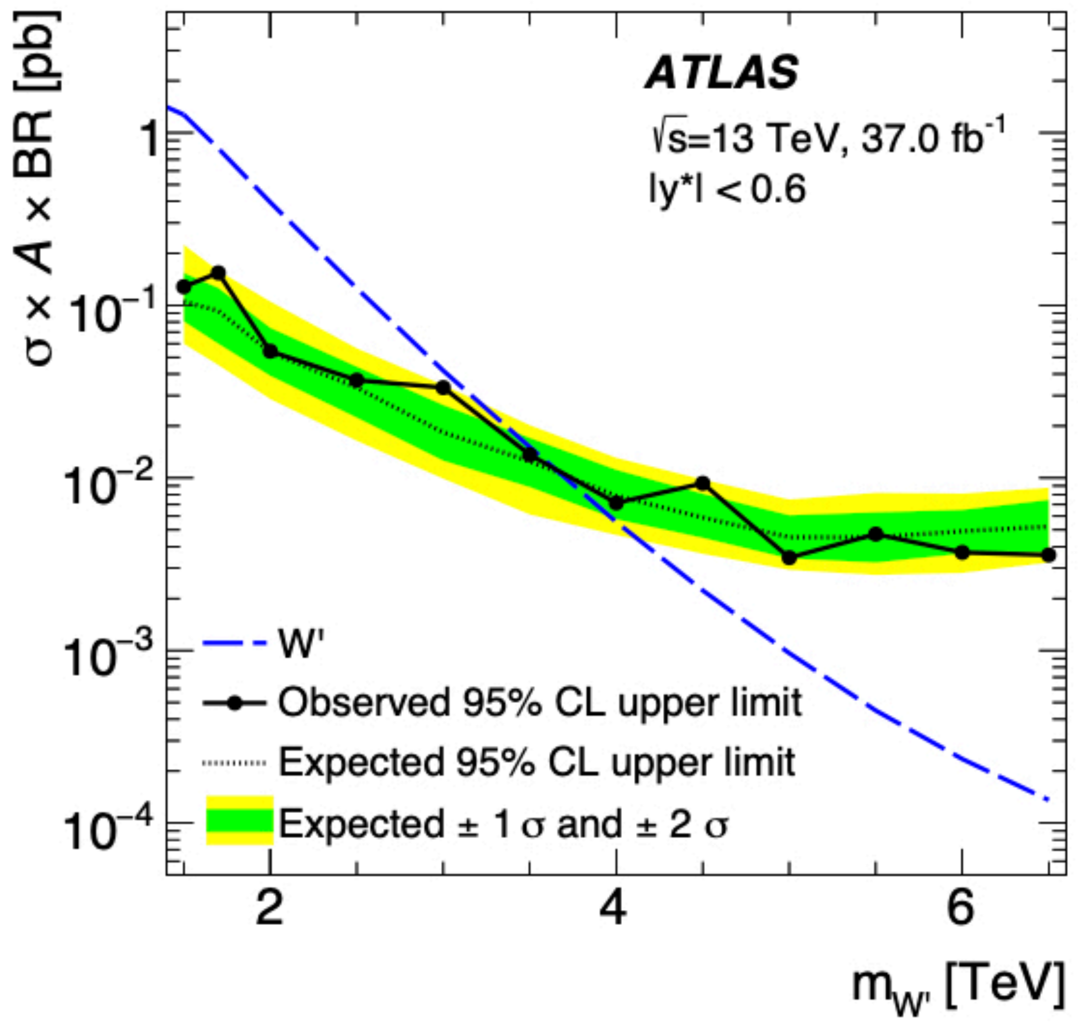
Exclusion limits



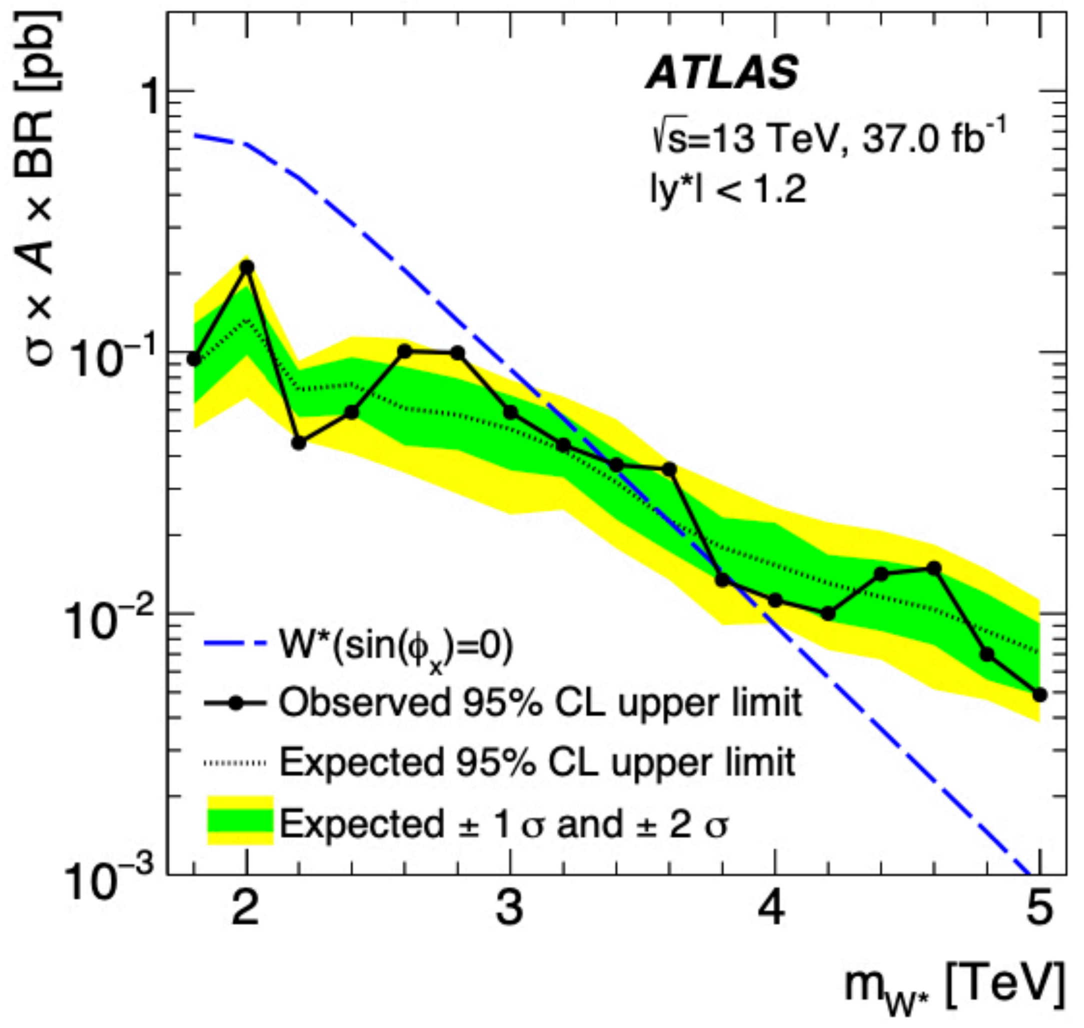
(a) q^*



(b) QBH



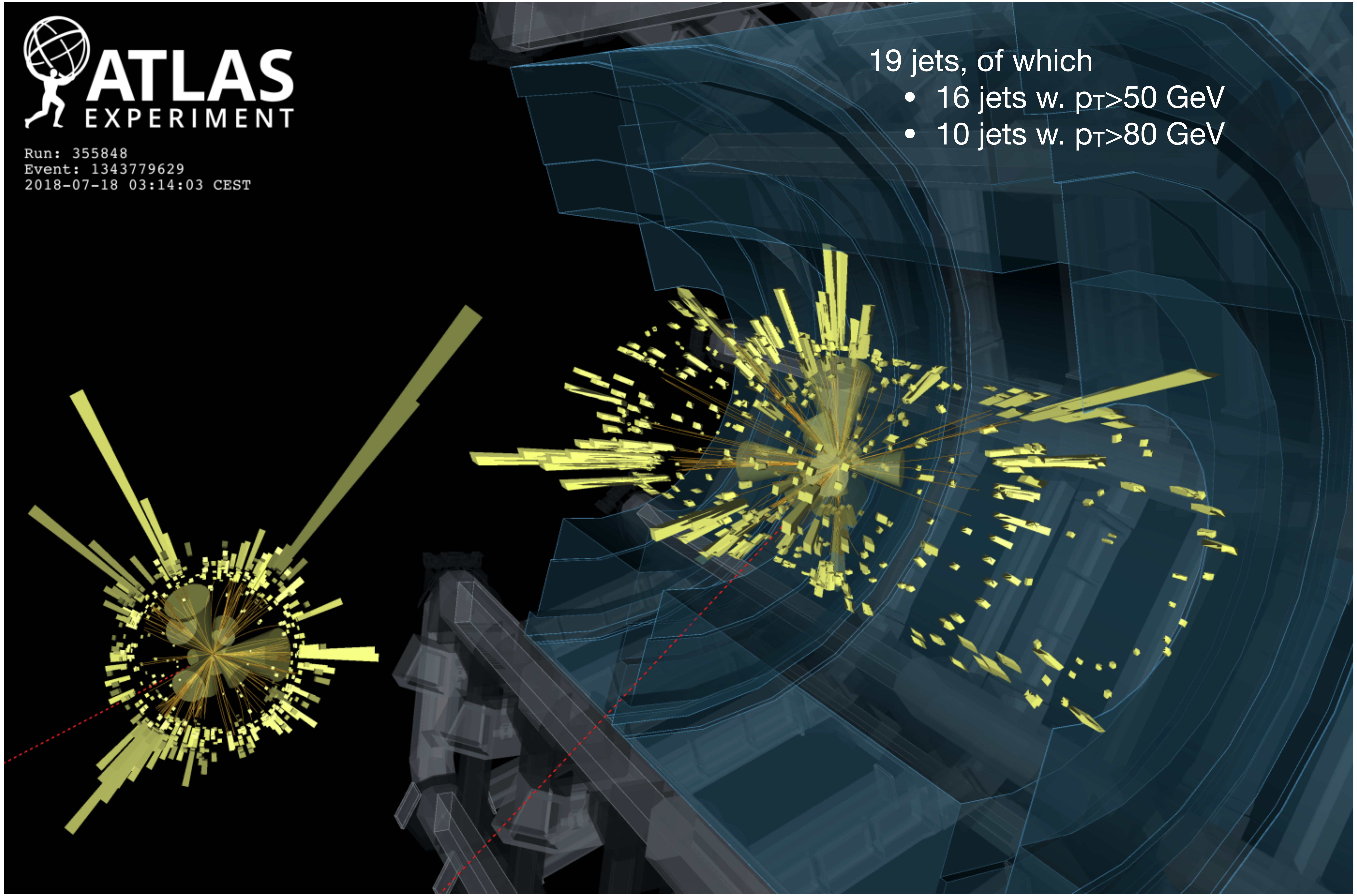
(c) W'



(d) W^*

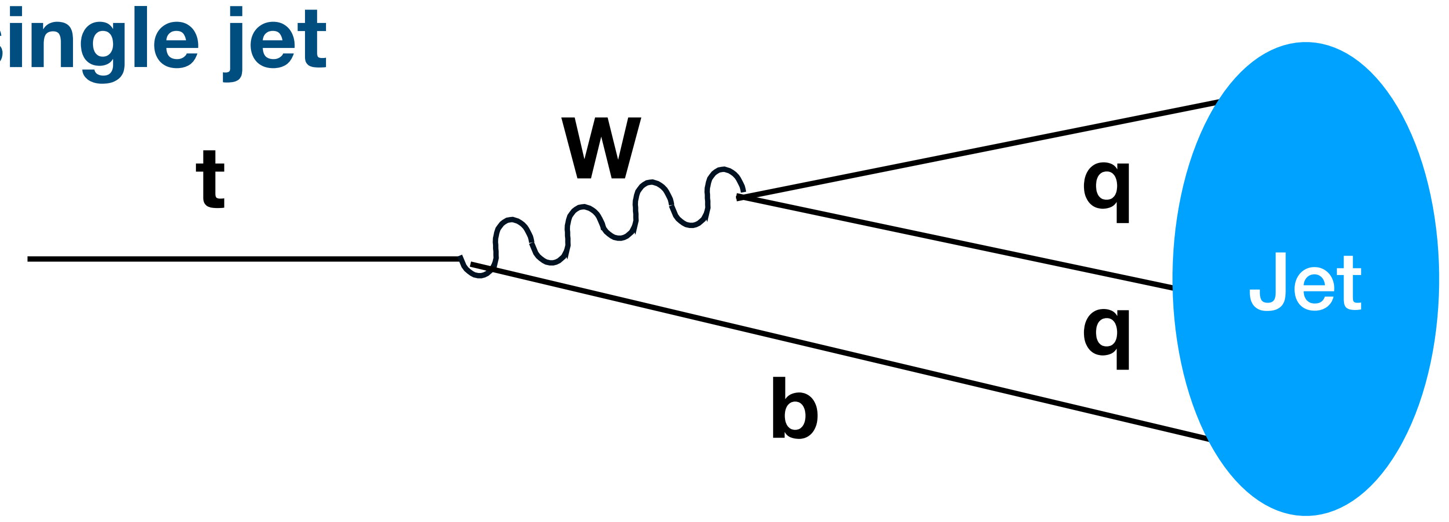
Model	95% CL exclusion limit	
	Observed	Expected
Quantum black hole	8.9 TeV	8.9 TeV
W'	3.6 TeV	3.7 TeV
W^*	3.4 TeV 3.77 TeV – 3.85 TeV	3.6 TeV
Excited quark	6.0 TeV	5.8 TeV
$Z'(g_q = 0.1)$	2.1 TeV	2.1 TeV
$Z'(g_q = 0.2)$	2.9 TeV	3.3 TeV
Contact interaction ($\eta_{LL} = -1$)	21.8 TeV	28.3 TeV
Contact interaction ($\eta_{LL} = +1$)	13.1 TeV 17.4 TeV – 29.5 TeV	15.0 TeV

Multijet final states



Can almost treat jets as individual particles

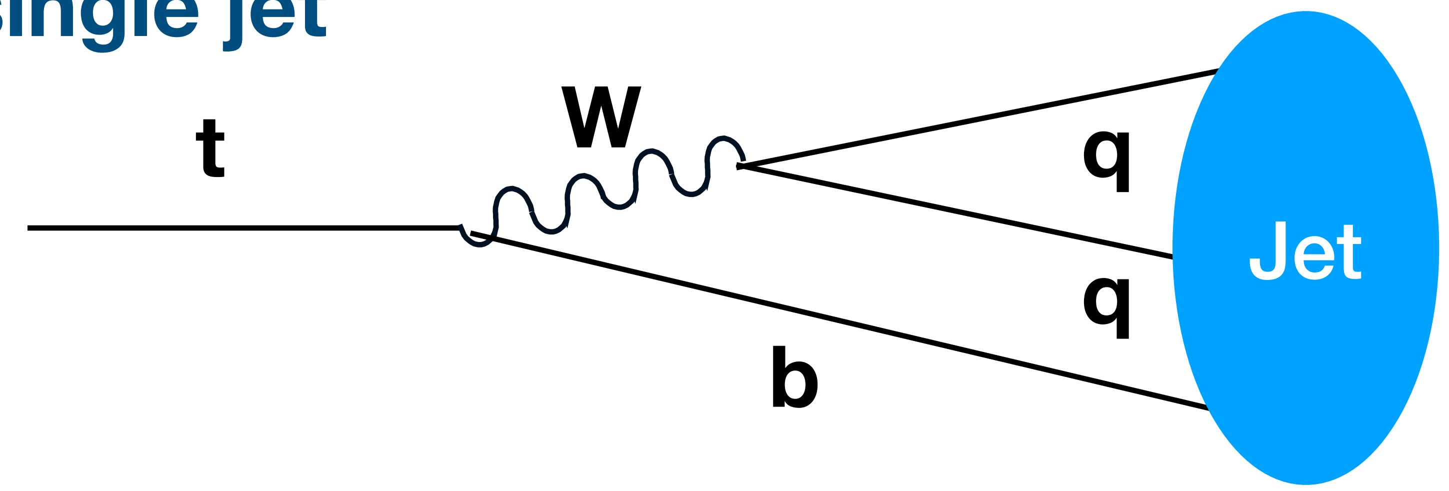
Even objects like highly-boosted H, W/Z, top will appear as a single jet



Can we learn something about the jet origin by looking at its inner features?

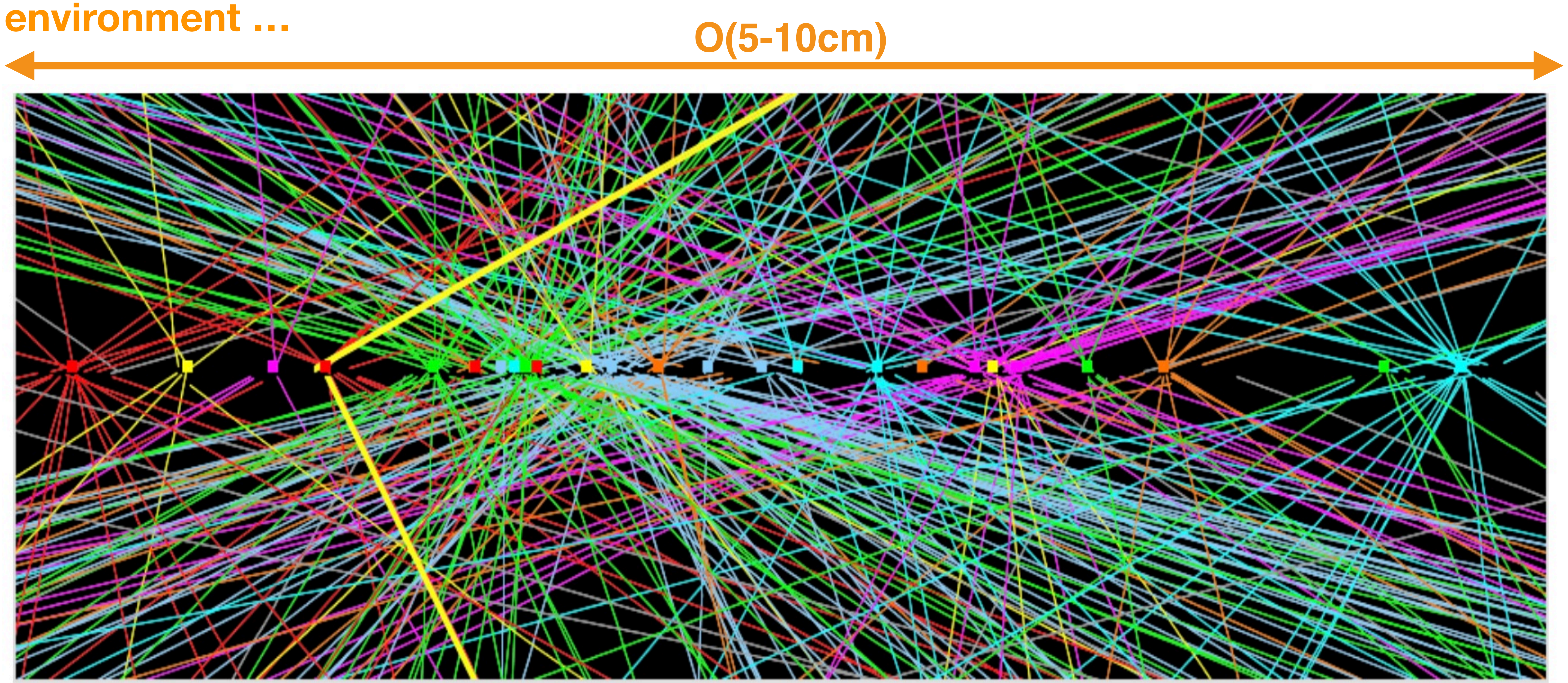
Can almost treat jets as individual particles

Even objects like highly-boosted H, W/Z, top will appear as a single jet



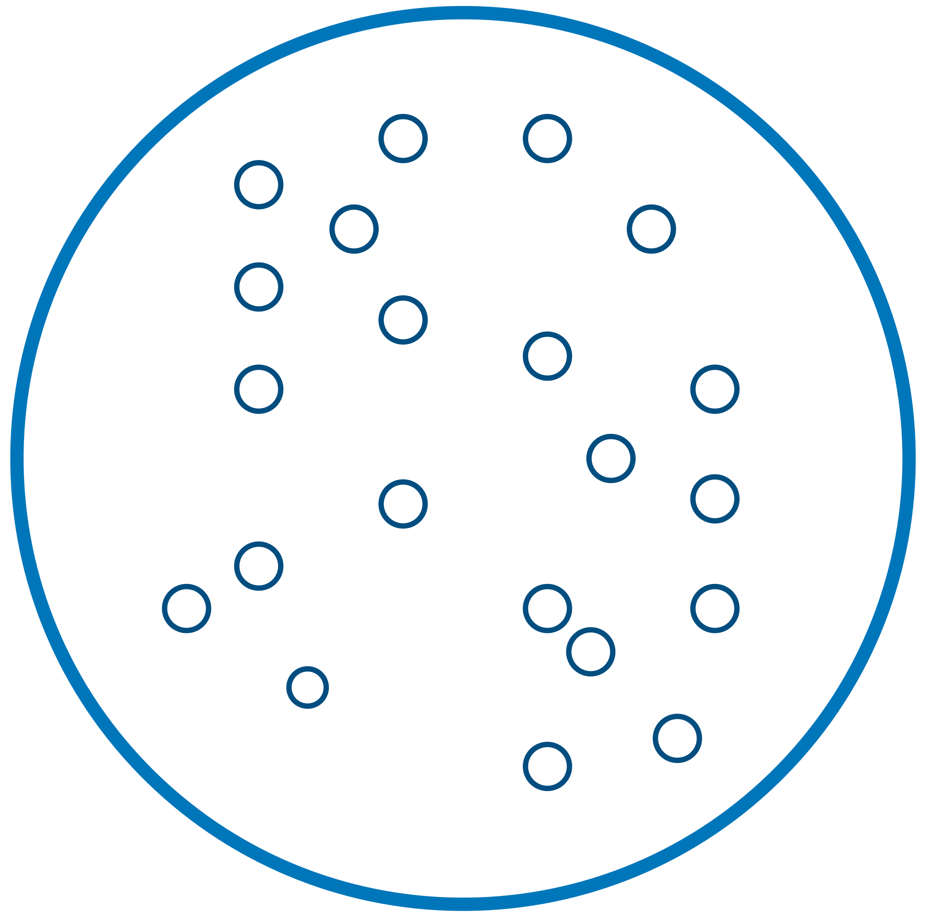
Can we learn something about the jet origin by looking at its inner features?

…. and in such as environment …

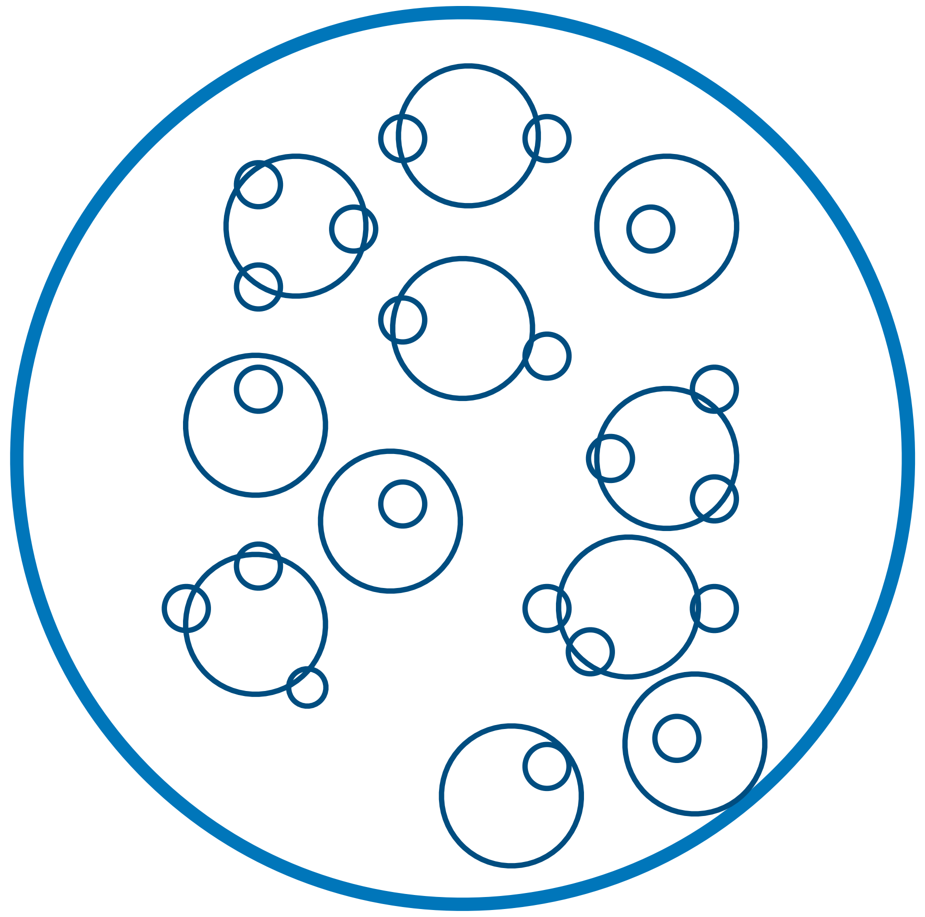


Jet substructure

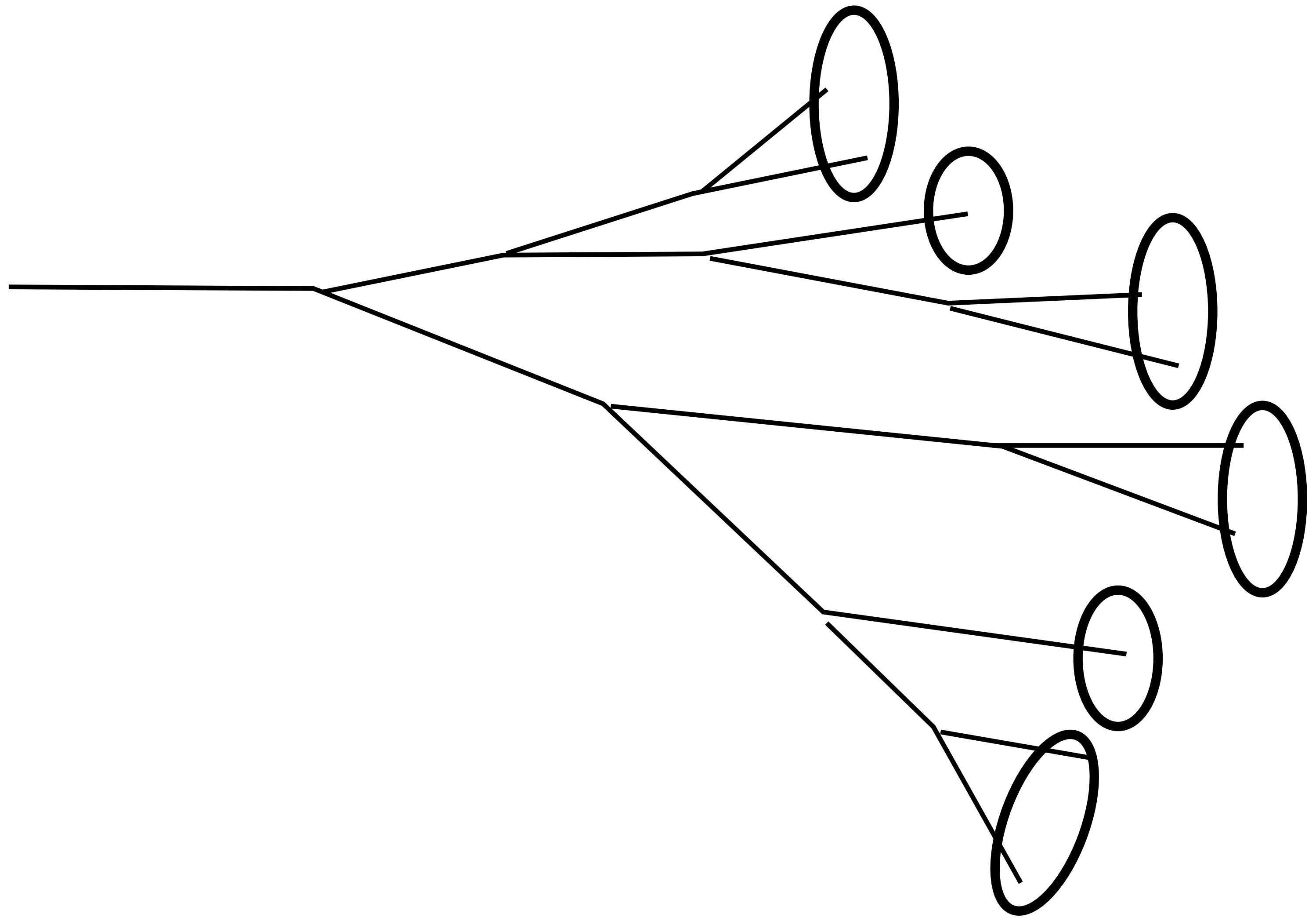
Large cone R=1 jet



Recluster in R=0.2 sub-jets ….



… and reconstruct a clustering history



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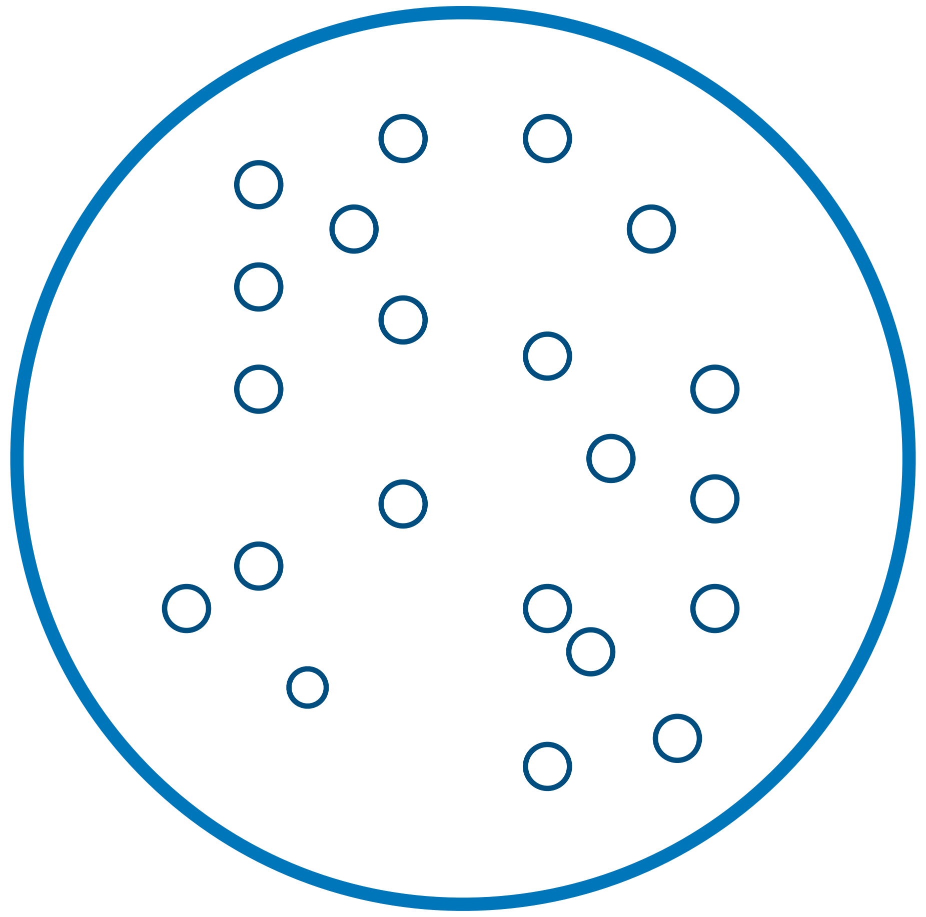

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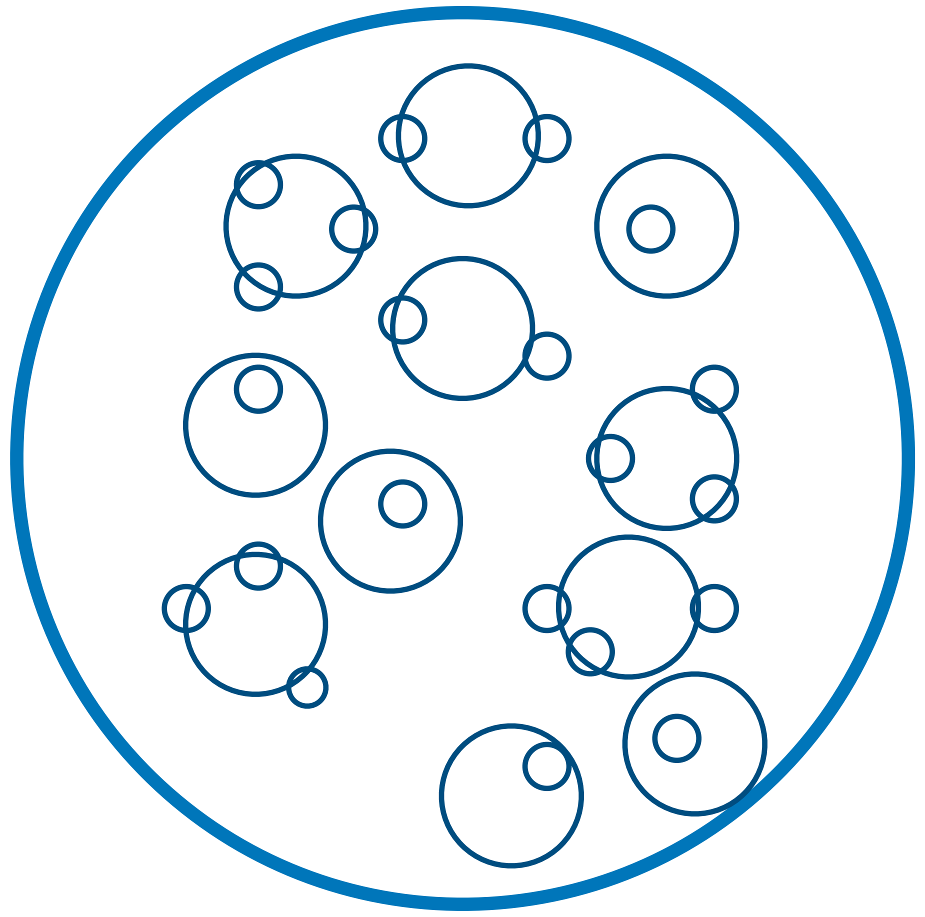

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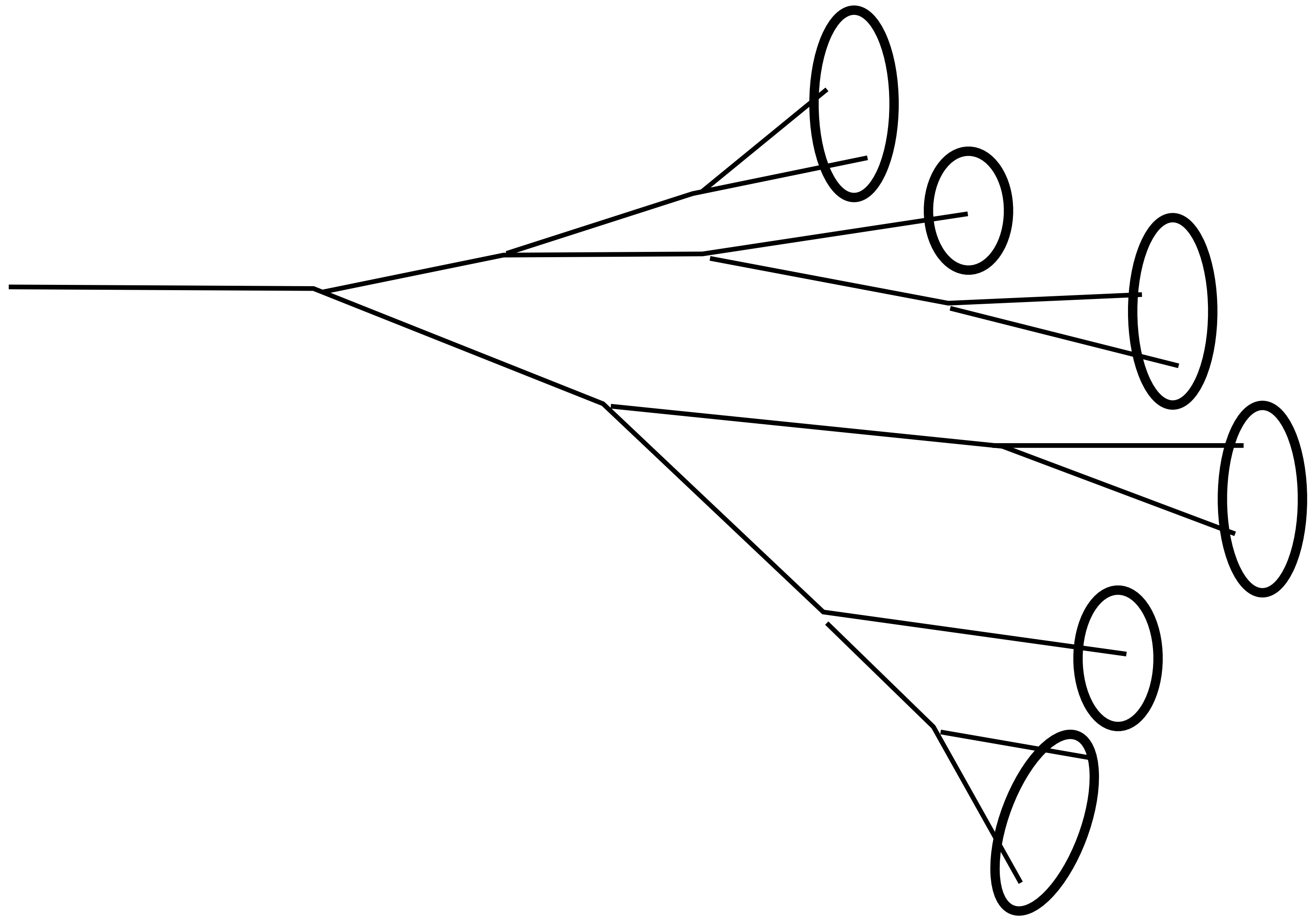
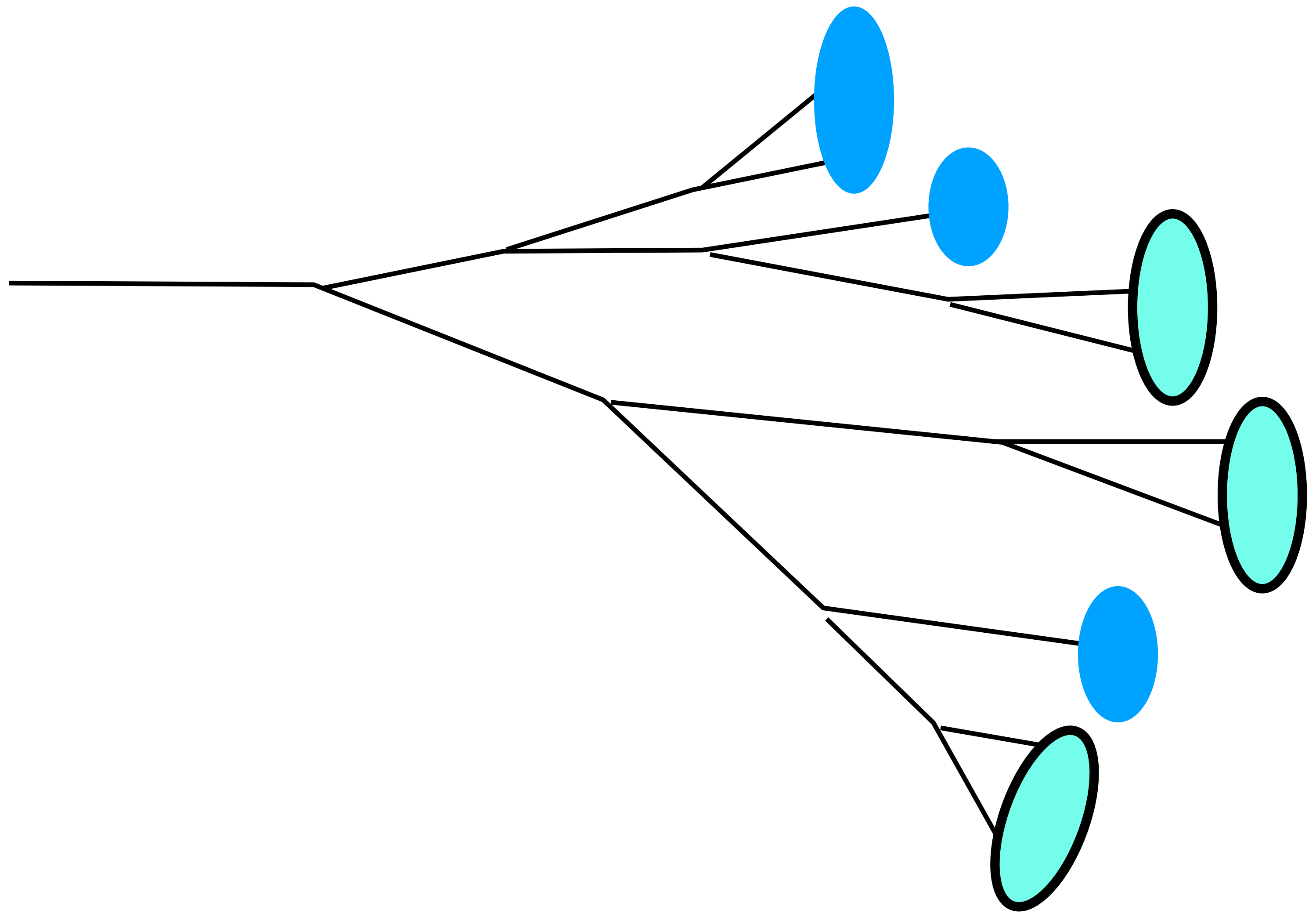
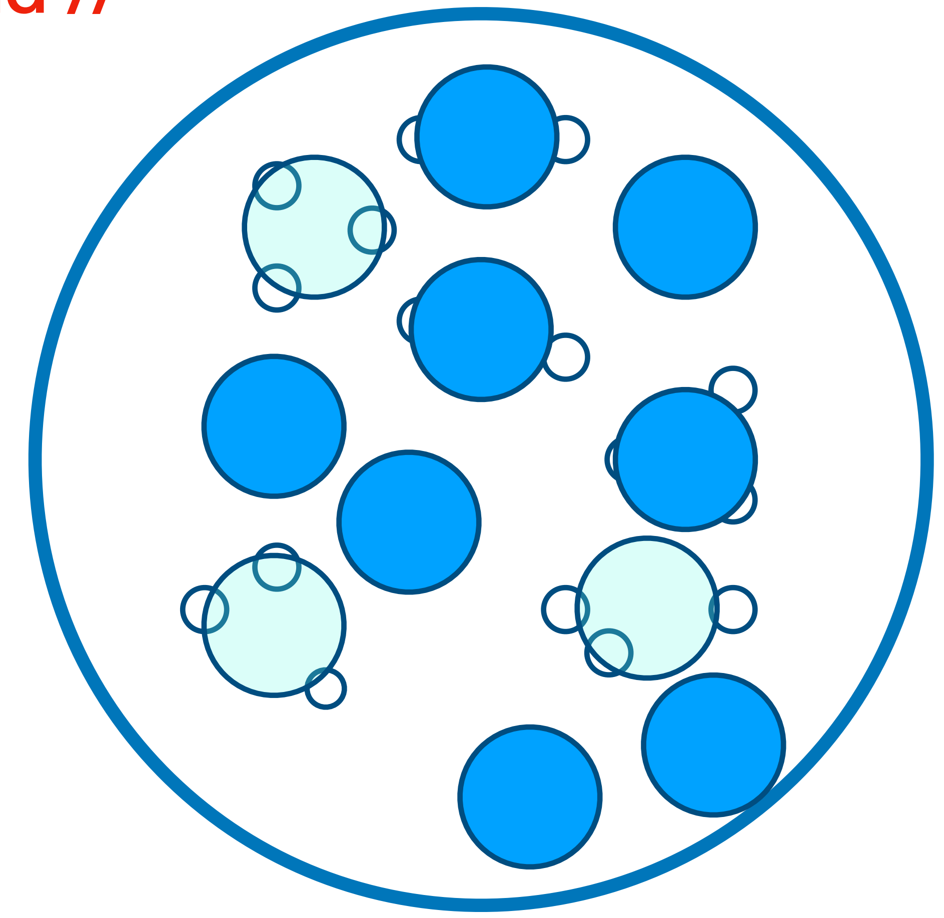
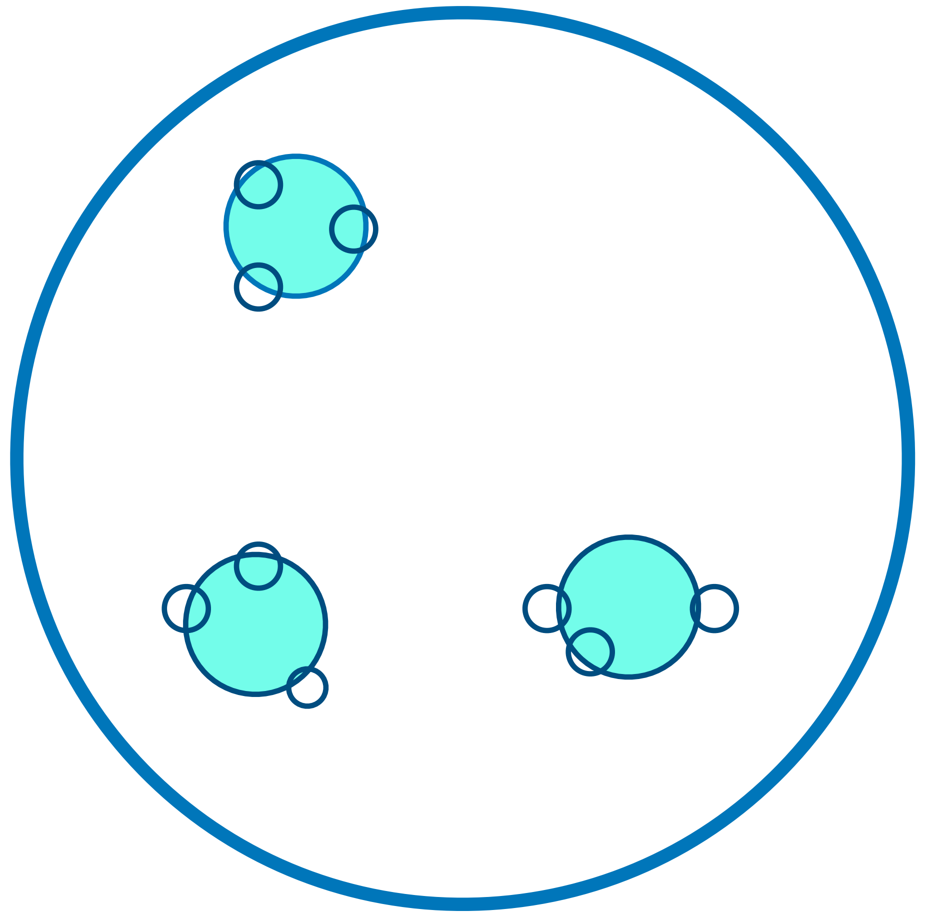


Sequentially prune, trim and drop soft components, more likely to come from the underlying event or pileup collisions, protecting the IR and // safety of the perturbative definition of the jet

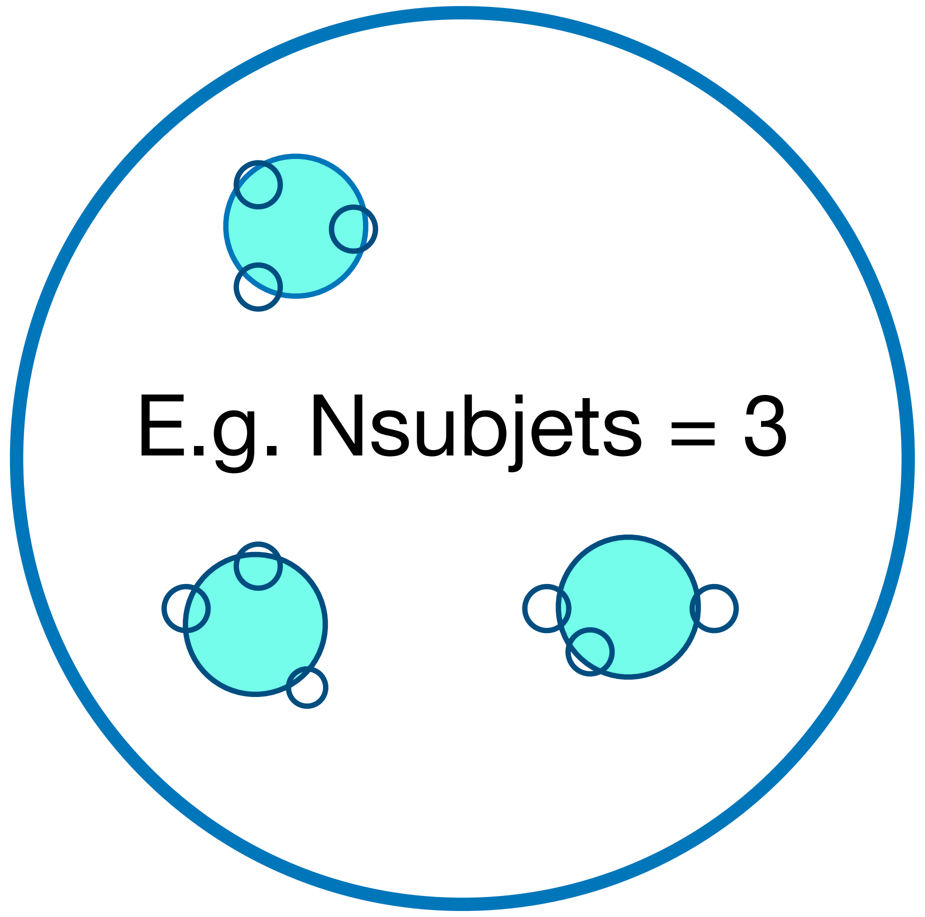


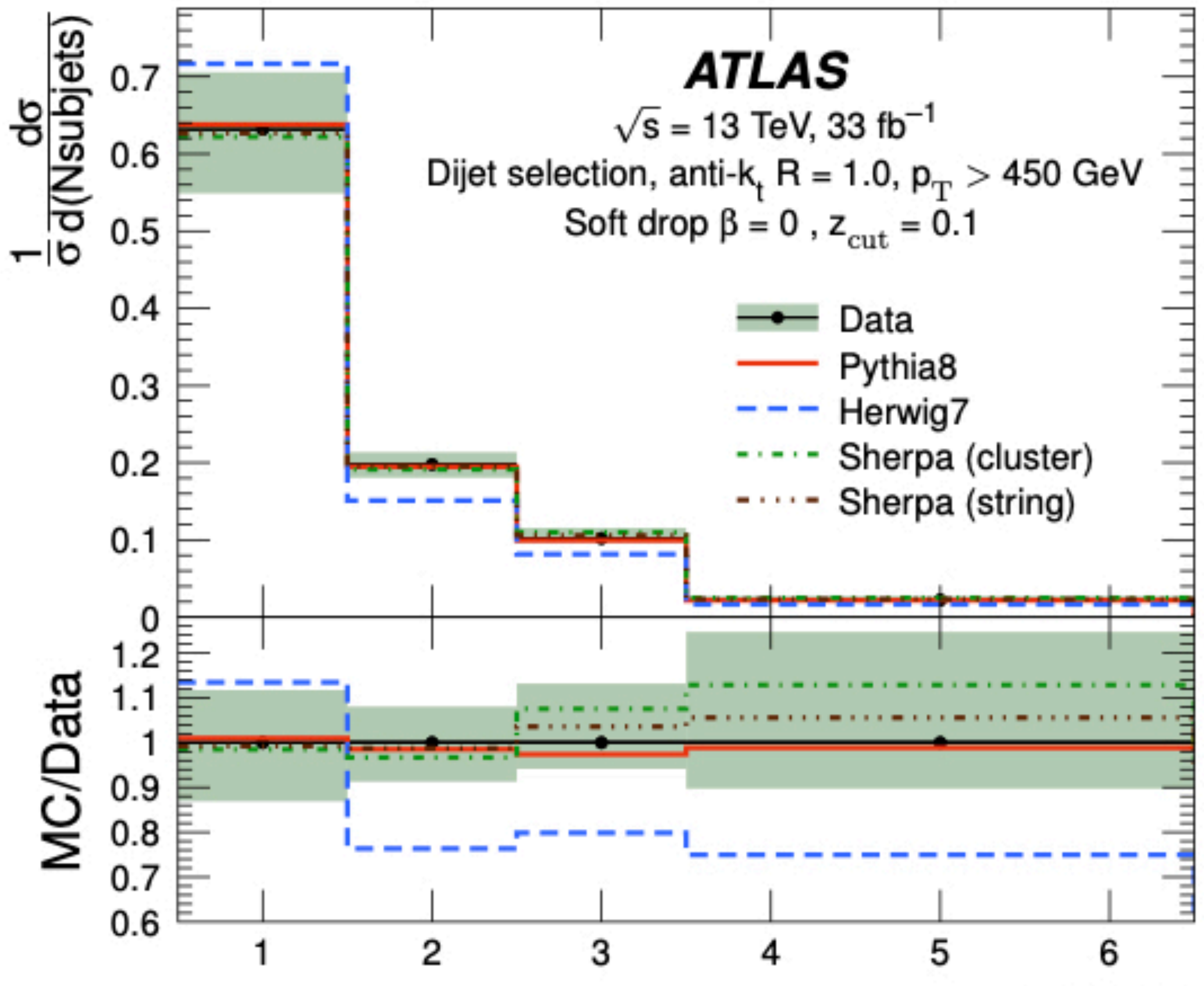




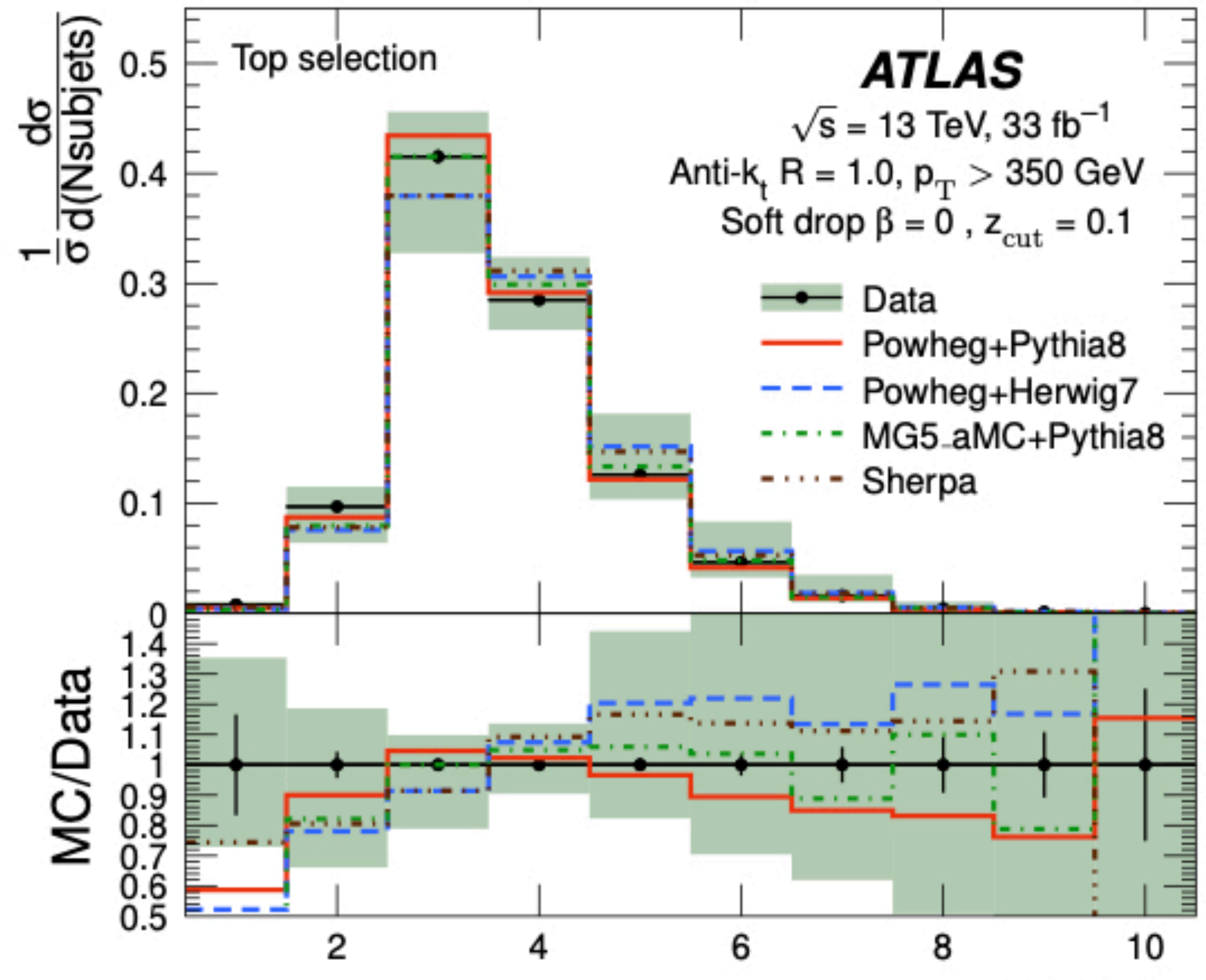
Example: light-jet, W and top jet discrimination

Nsubjets: # hard-core structures left inside a large-cone jet, after cleanup



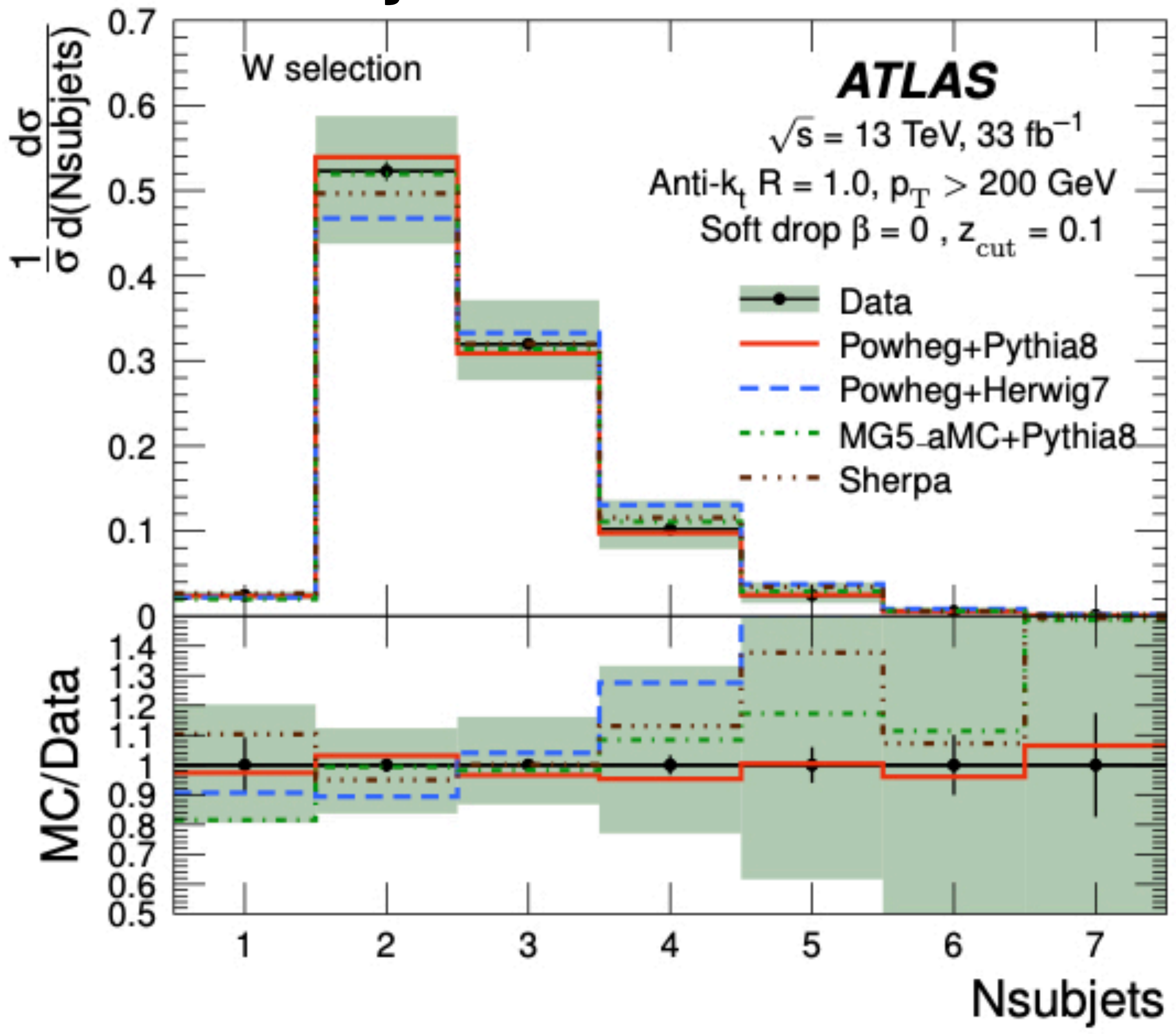


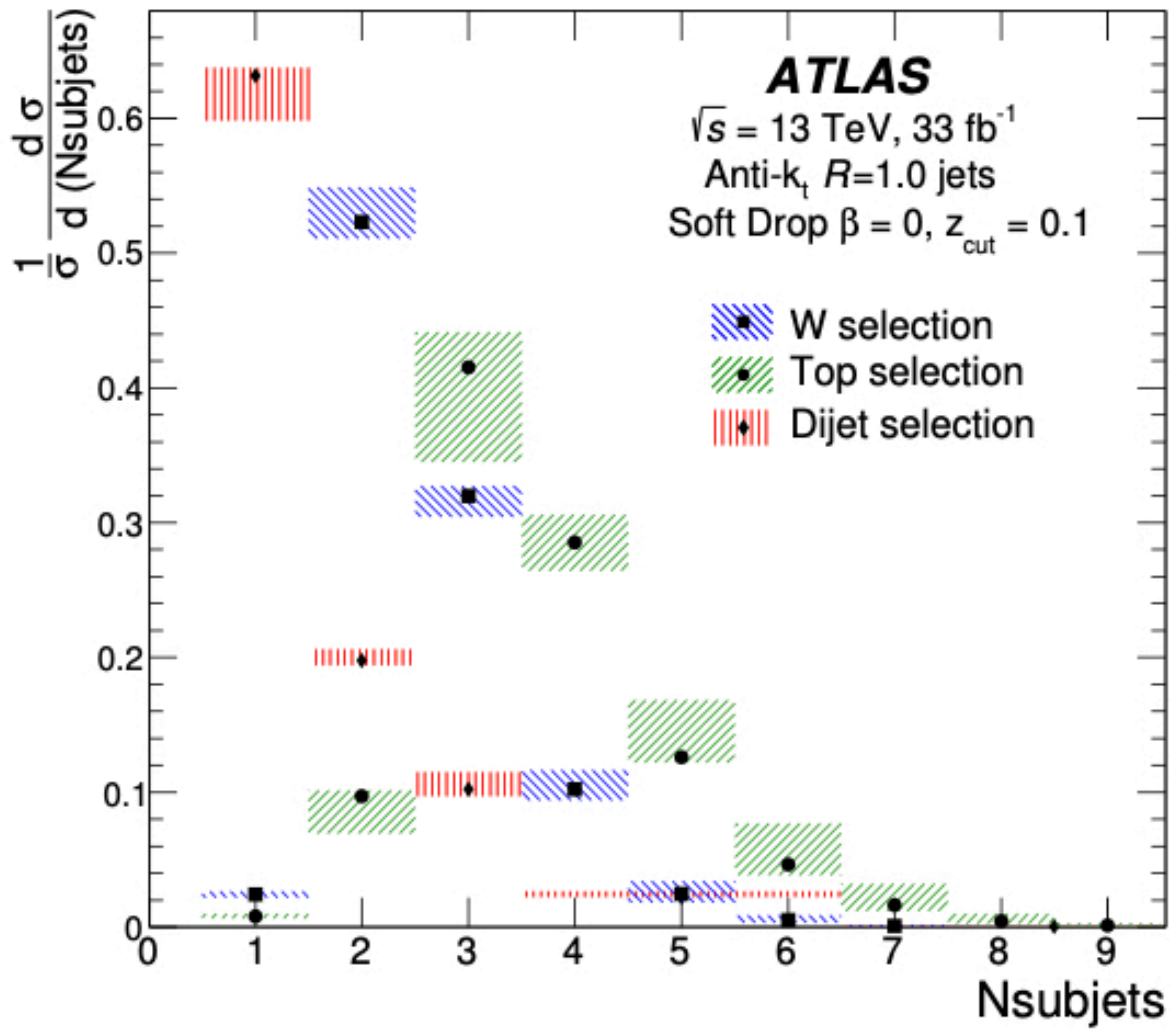
q jets



top jets

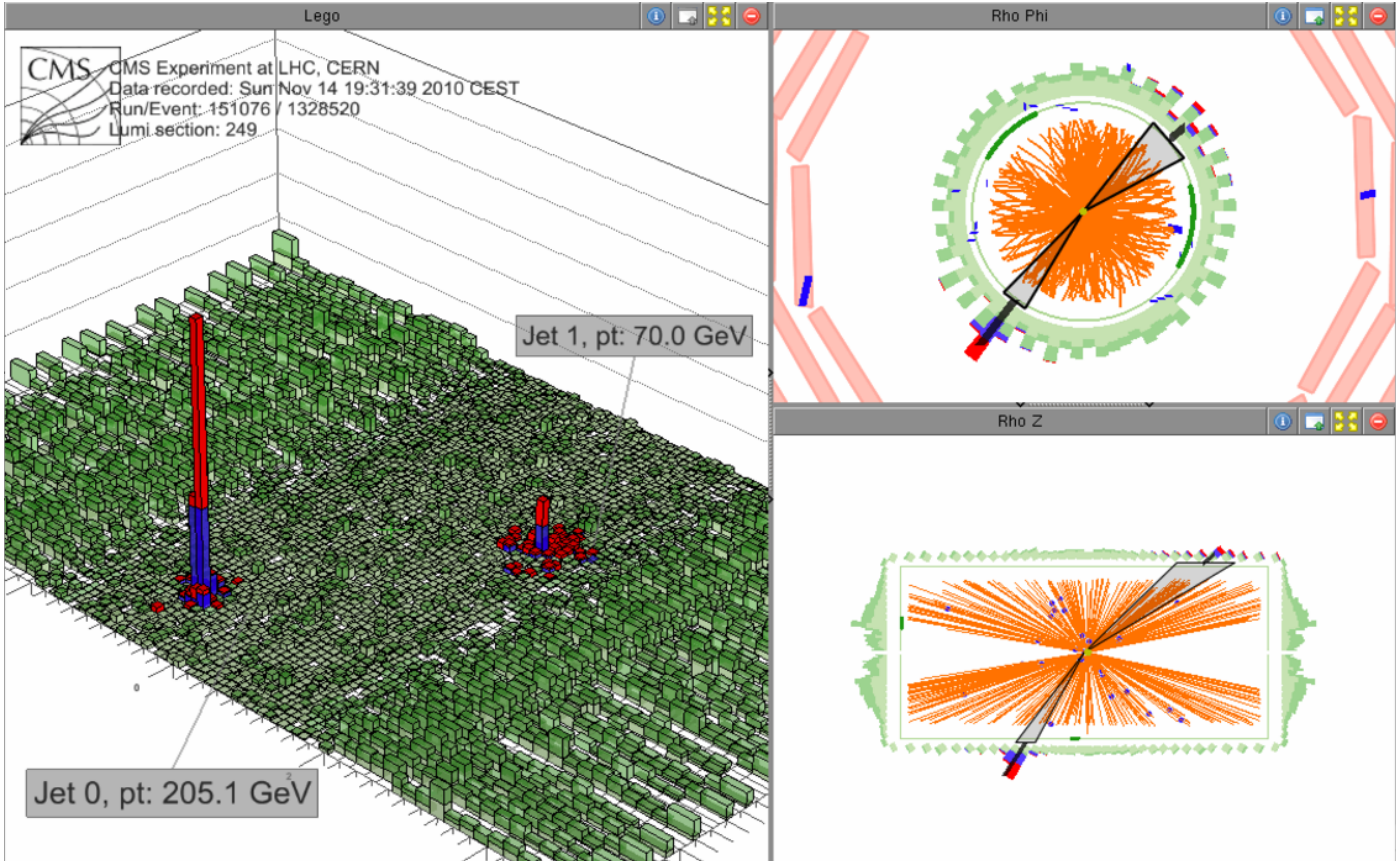
W jets





Jet quenching in a quark-gluon plasma

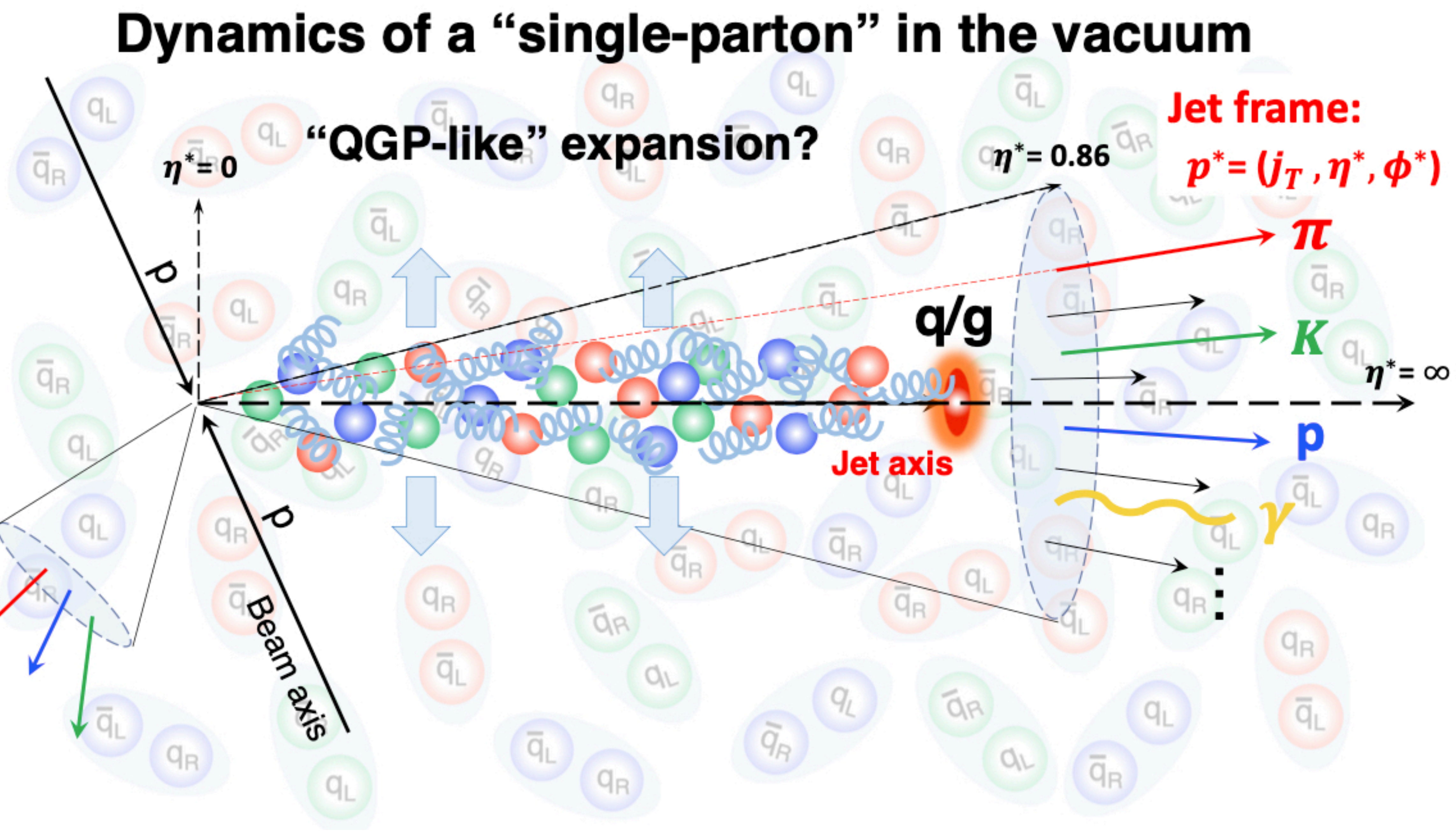
Pb Pb -> jet jet @ 5 TeV



On the inner structure of high-multiplicity jets in pp

CMS, PAS HIN-21-013

Can a high-multiplicity jet lead to correlations/coherent interactions beyond PT?



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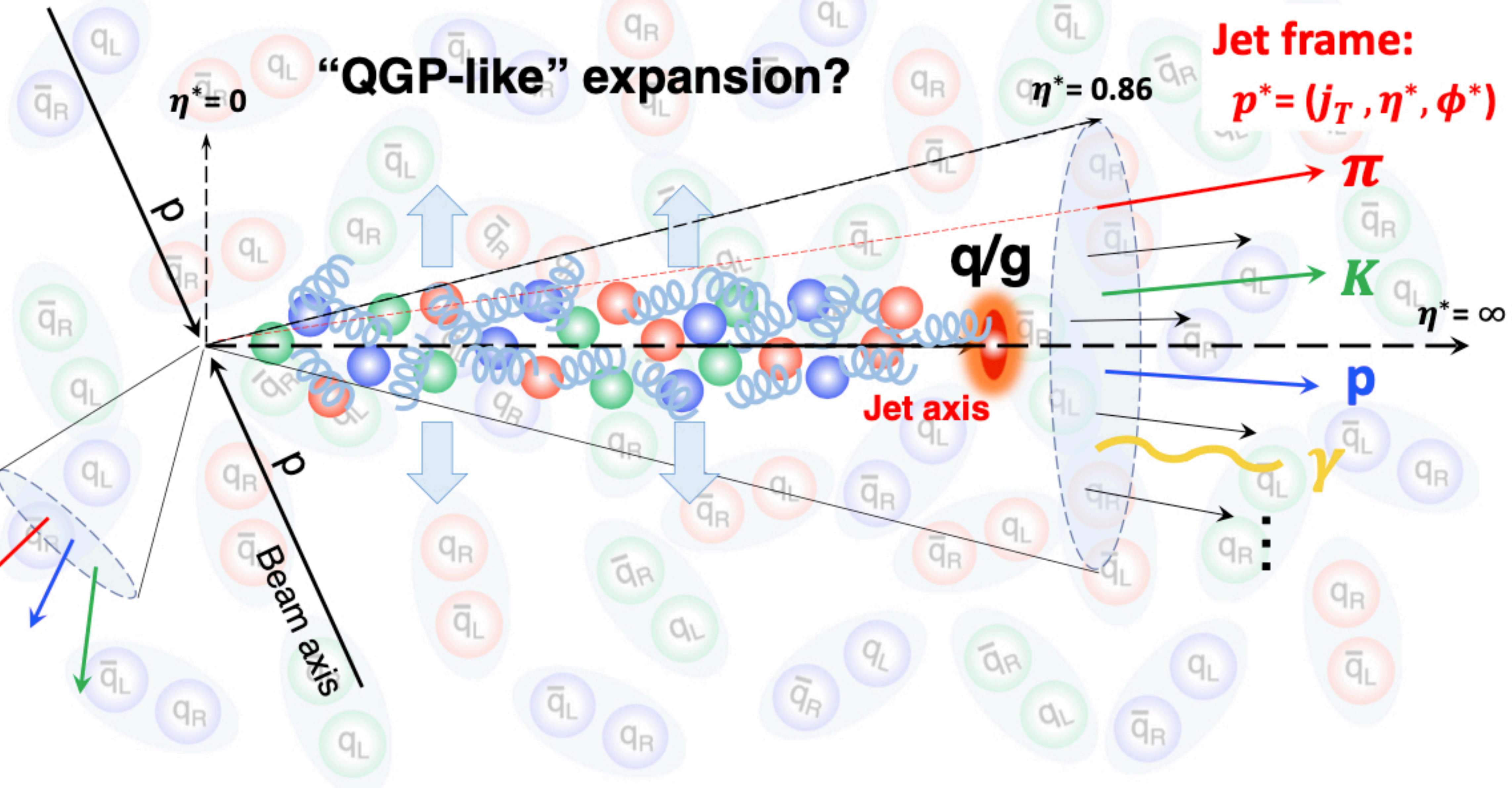
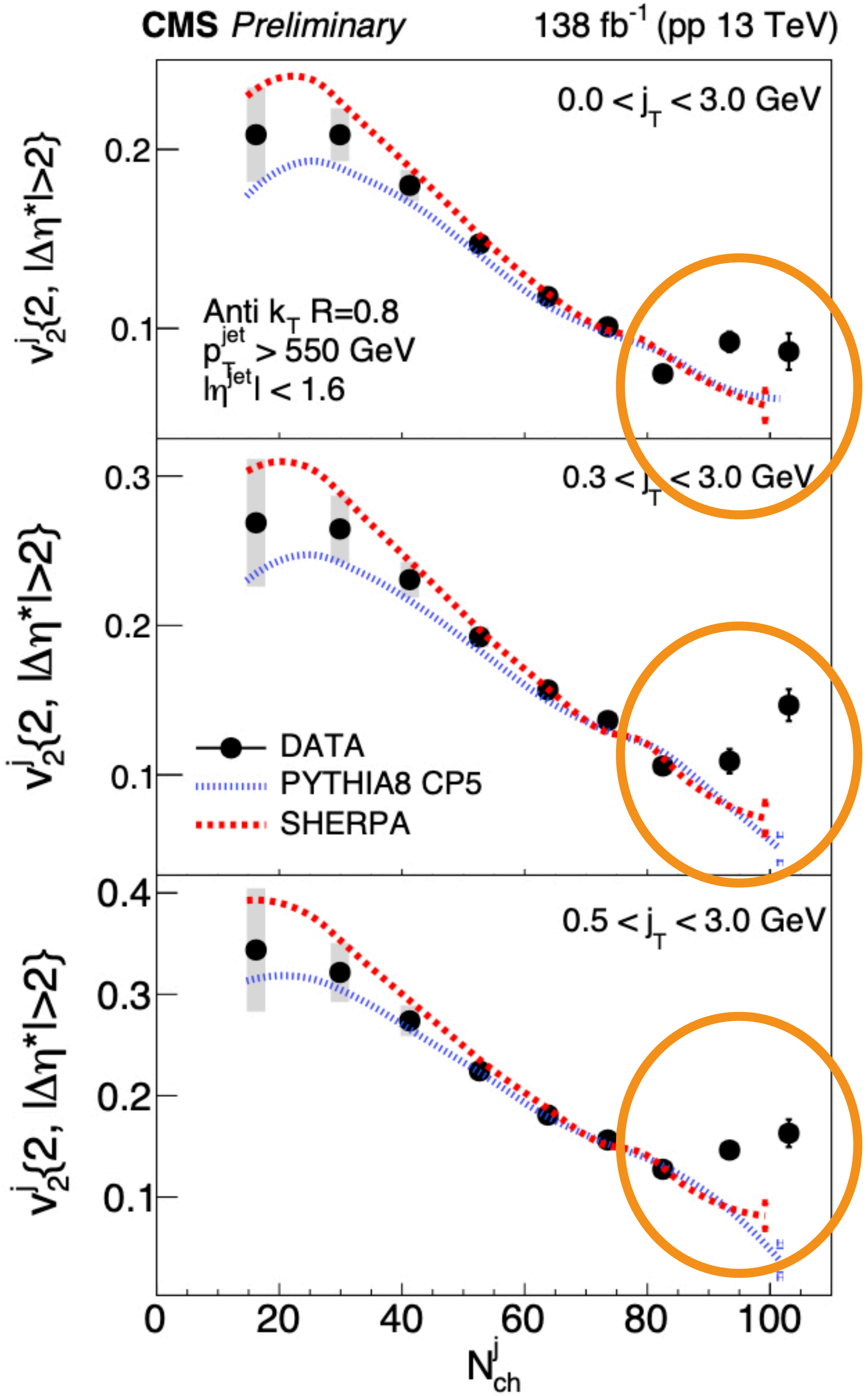
$$\frac{1}{N_{ch}^{trg}}\frac{dN^{pair}}{d\Delta\phi^*} \propto 1 + 2\sum_{n=1}^{\infty} V_{n\Delta}\cos(n\Delta\phi^*),$$



j_T = track p_T w.r.t the jet axis



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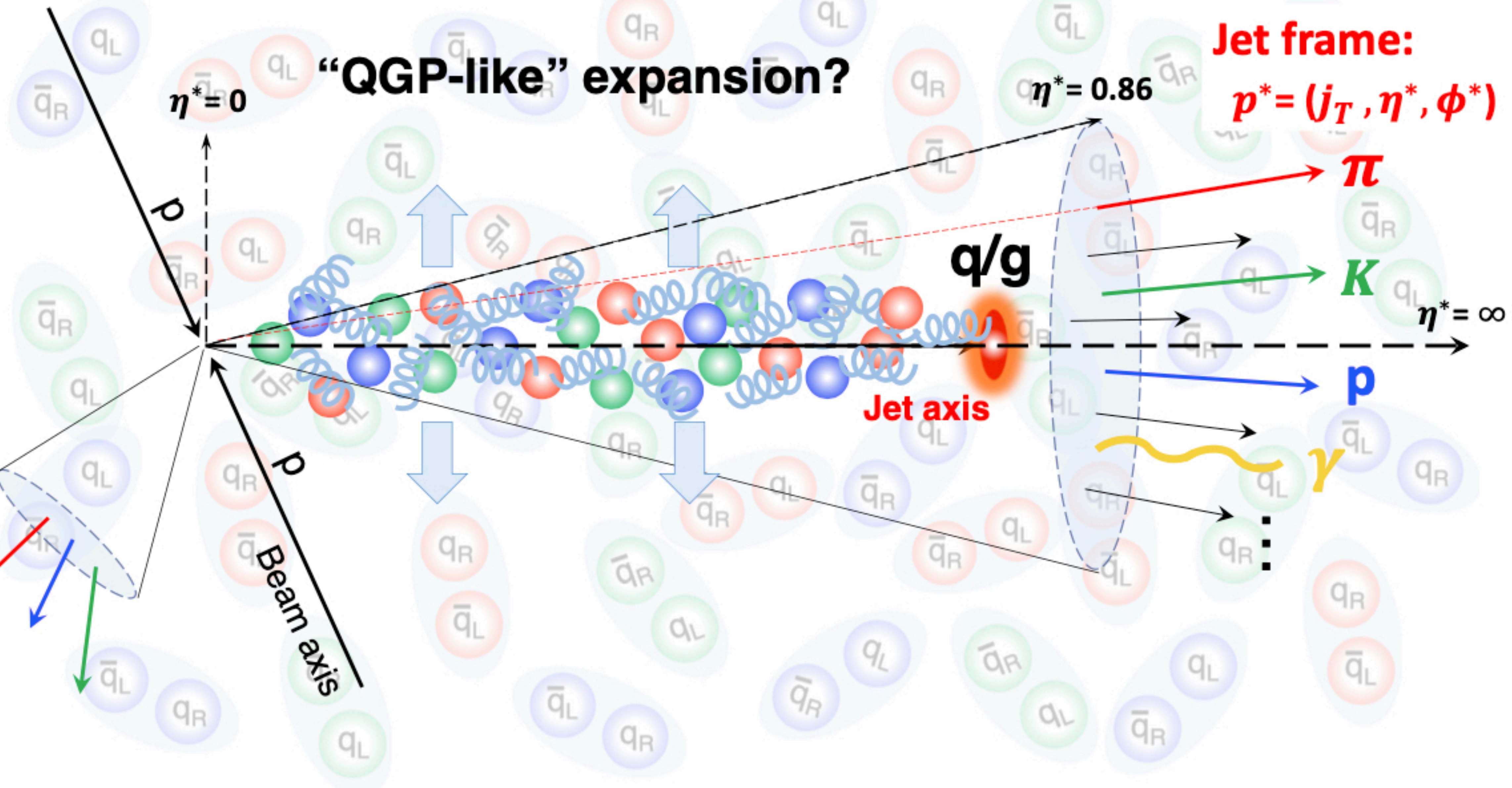
Dynamics of a "single-parton" in the vacuum



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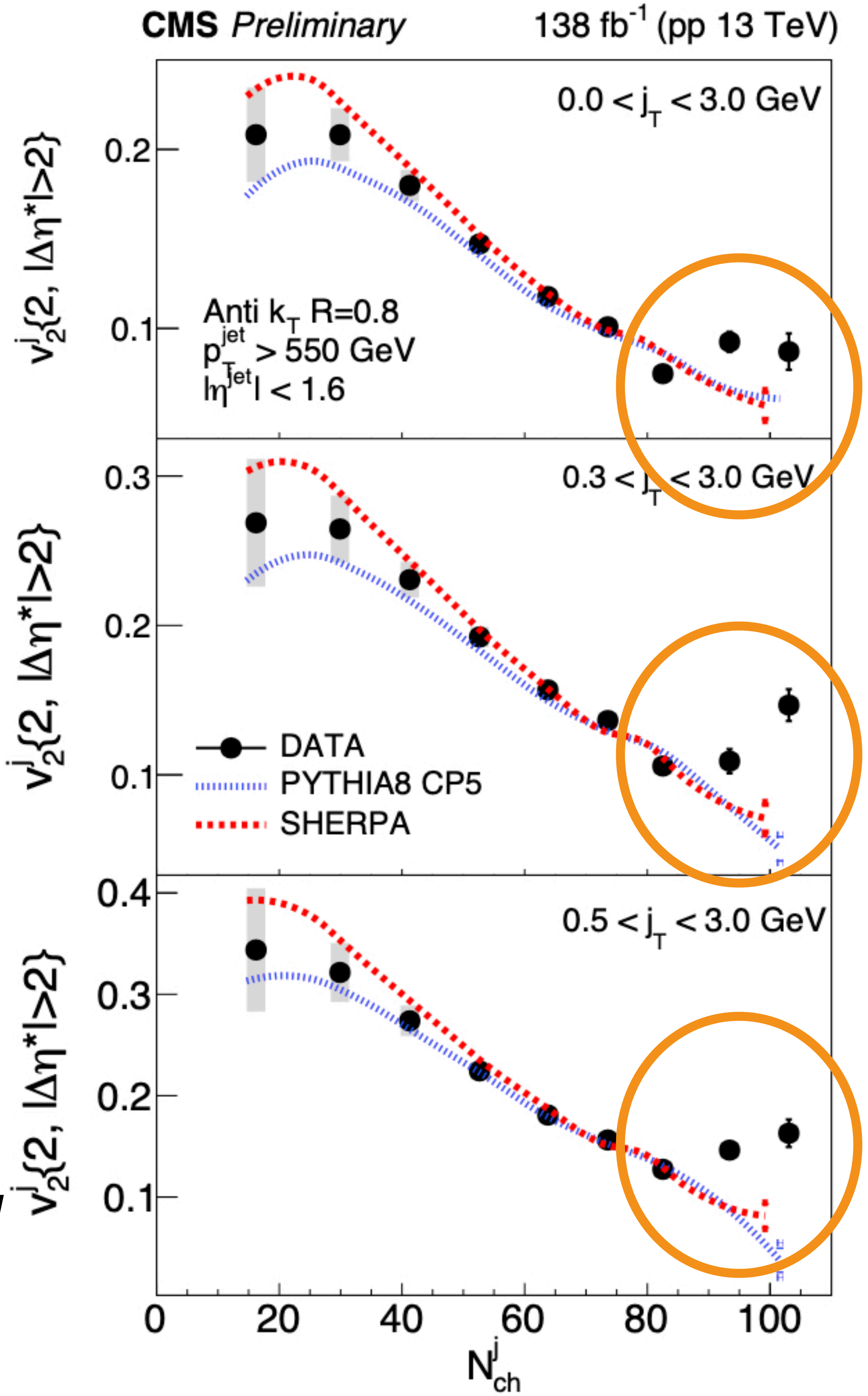

From the conclusions: *"While data and the MC samples are in good agreement for particle correlations inside low- and mid-Nj ch jets, the extracted long-range elliptic azimuthal anisotropy vj2{2} shows a distinct increase in data for Nj > 80. Such a feature is not observed in any of MC event generators that model the parton fragmentation process. Therefore,* ***results presented in this note may pave a new direction in uncovering novel effects related to nonperturbative QCD dynamics of parton fragmentation in the vacuum.*** *"*

Final words

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- Perturbative QCD predictions for jet properties in pp collisions have reached the O(%) level of precision
  - overall uncertainties often dominated by residual non=-perturbative inputs, like hadronization (at the low-energy end) and PDFs (at the high-x/high-energy end)

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- Jets have become a surgical tool for collider physics
  - perform precision measurements, both in the QCD and EW sectors
  - explore extreme dynamical regimes of strong interactions (eg in the context of the quark-gluon plasma)
  - search for new phenomena