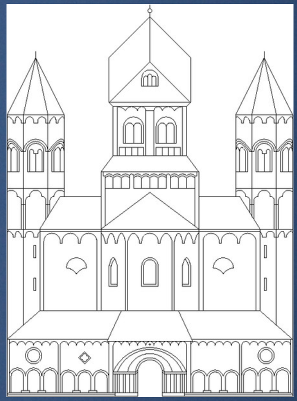
QCD and Jets at the LHC

V03 – From jet measurements to SM parameters (or new physics)

Herbstschule
Maria Laach



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Outline

- Inclusive jet measurement in details
- More on jets
  - Dijet cross section
  - Ratios & normalised distributions
- The strong coupling constant

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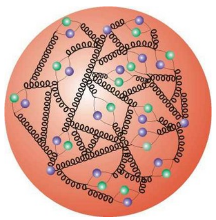
Hot topics I could not cover:

- Years of substructure analyses for q/g separation or boosted heavy particles
  - Lund jet plane analysis (C/A declustering)
- Flavor jets

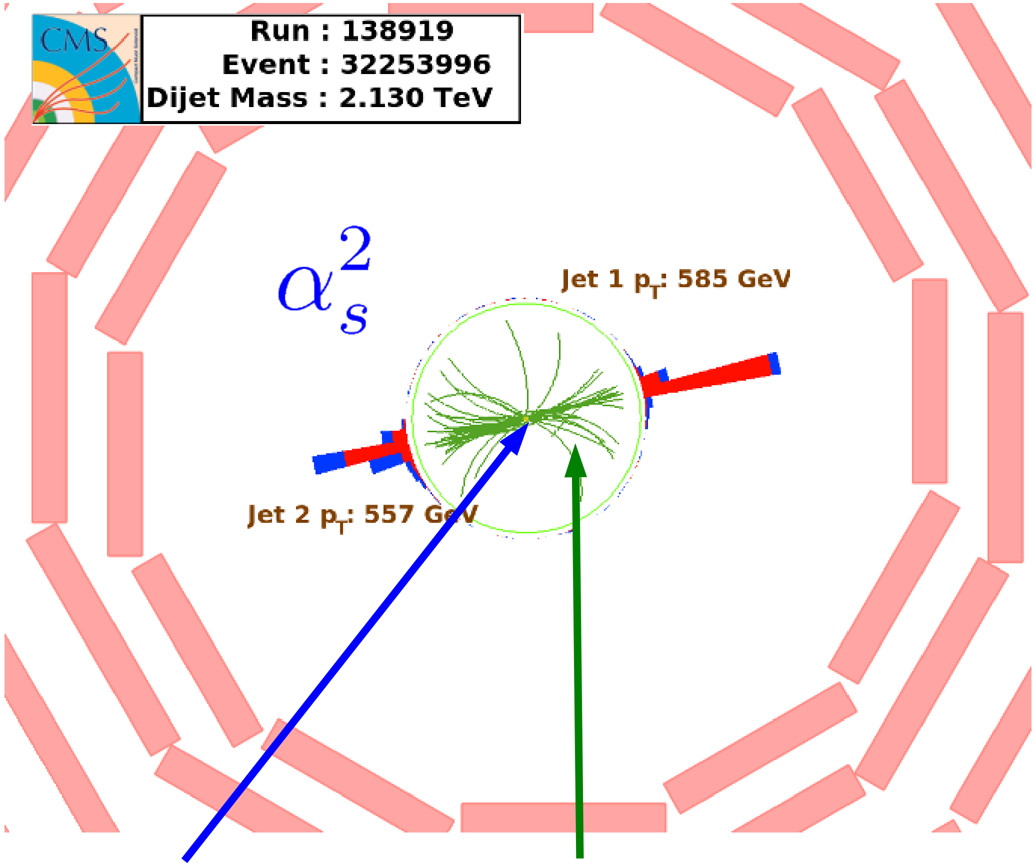
Jets at the LHC

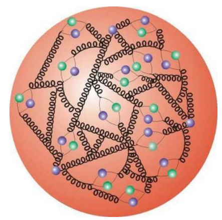
Abundant production of jets:

- Jets at hadron colliders provide the highest reach ever to determine the strong coupling constant at high scales Q
- Also learn about hard QCD, the proton structure, non-perturbative effects, and electroweak effects at high Q



Proton Structure (PDF)



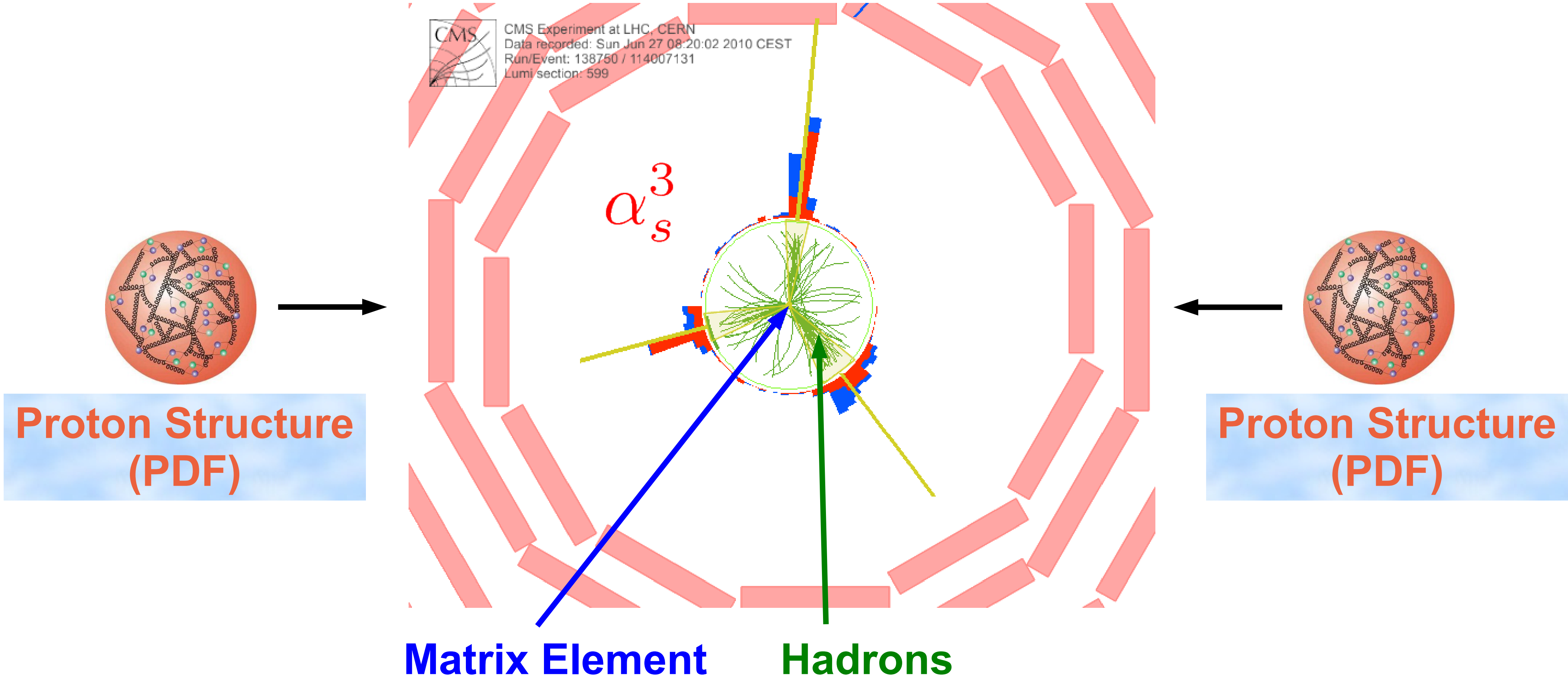


Proton Structure (PDF)

Matrix Element Hadrons

Abundant production of jets:

➜ **Extract $\alpha_s(M_Z)$, the least precisely known fundamental constant!**

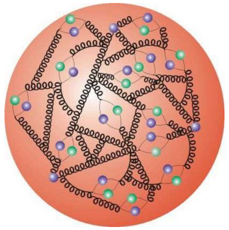


Jet cross sections ~ α_s^2

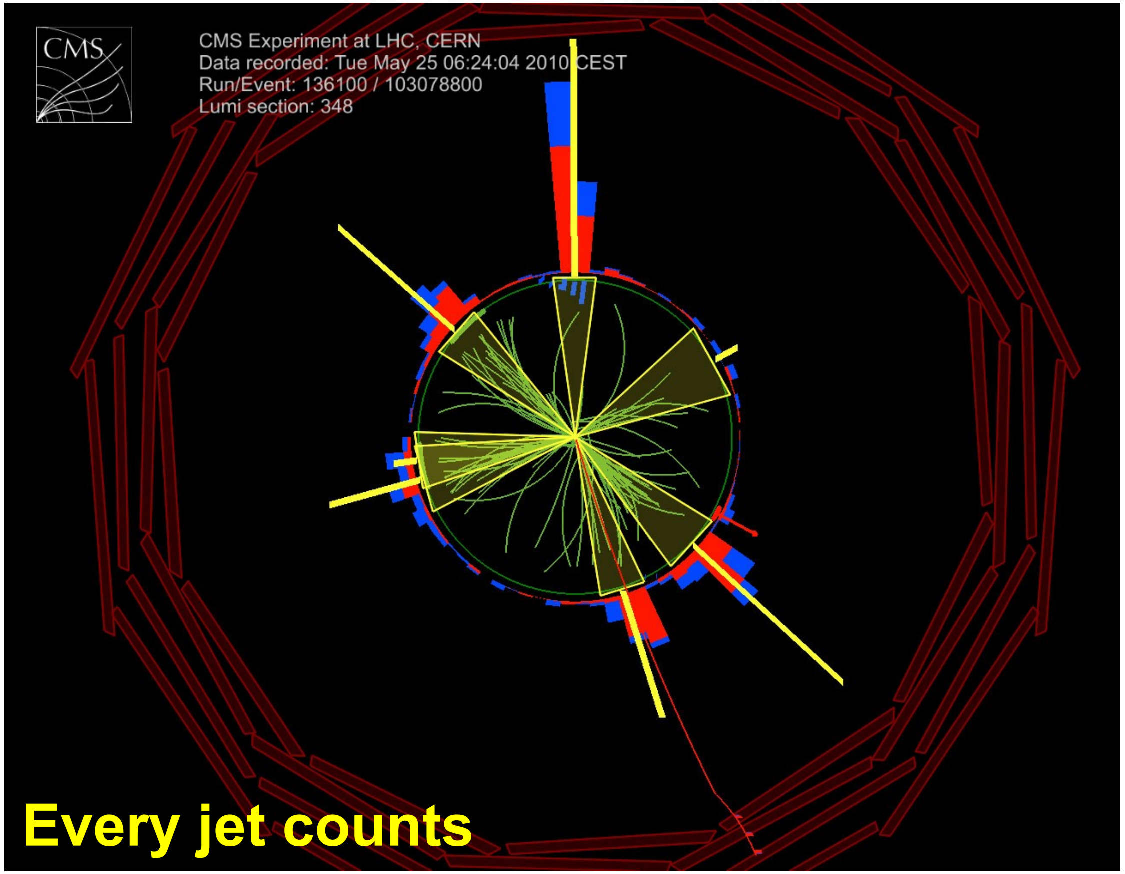
- Useful for i.a.:
  - Determination of $\alpha_s(M_Z)$ in single-parameter fit
  - Test consistency of running of $\alpha_s(Q)$
  - Multi-parameter fit of $\alpha_s(M_Z)$ & PDFs
  - Multi-parameter fit including EFT parameters
- Subject to all systematic uncertainties: JEC, JER, MHOU, luminosity, ...

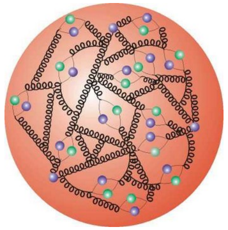
All inclusive

Large transverse momenta



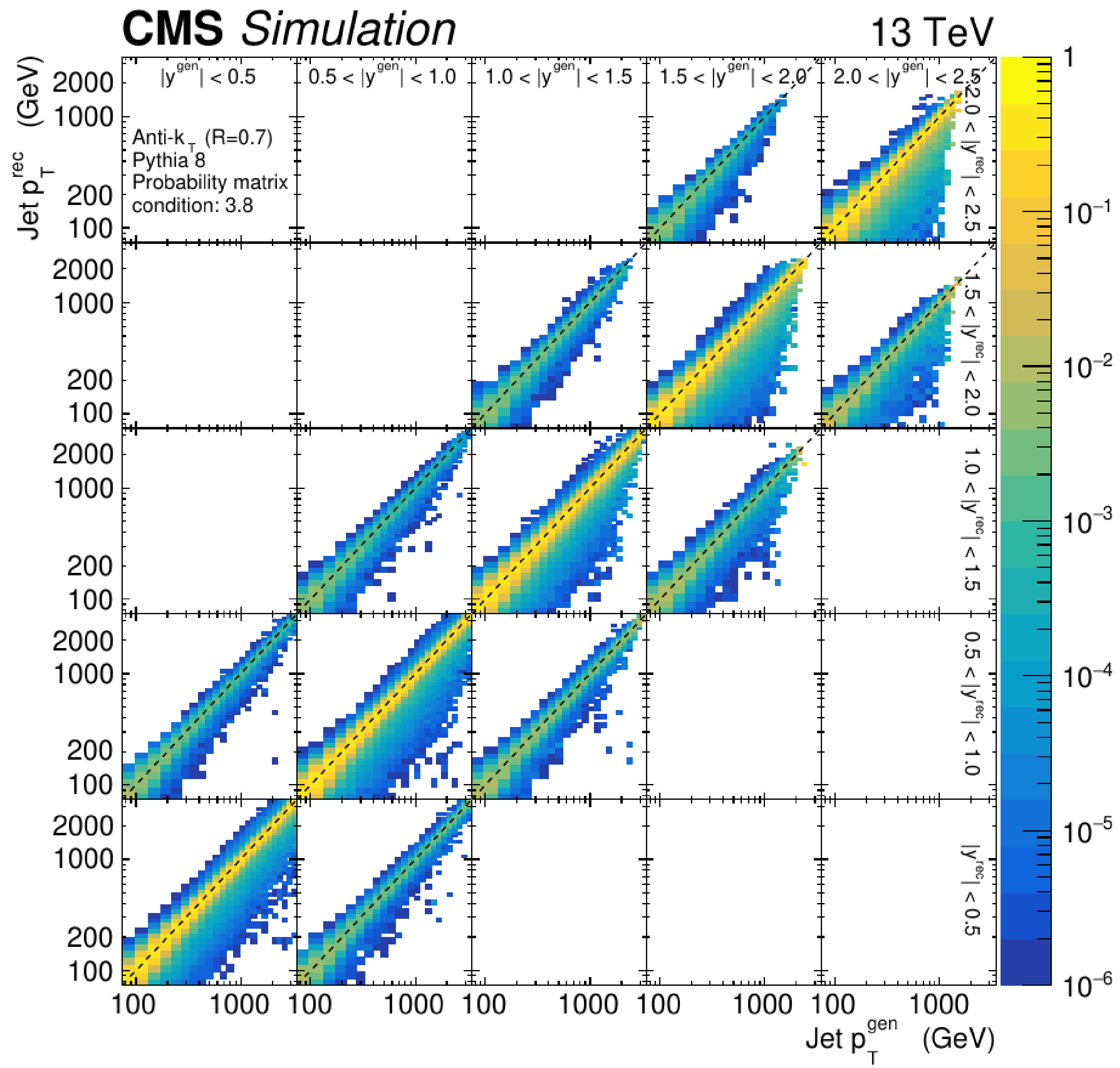
Proton



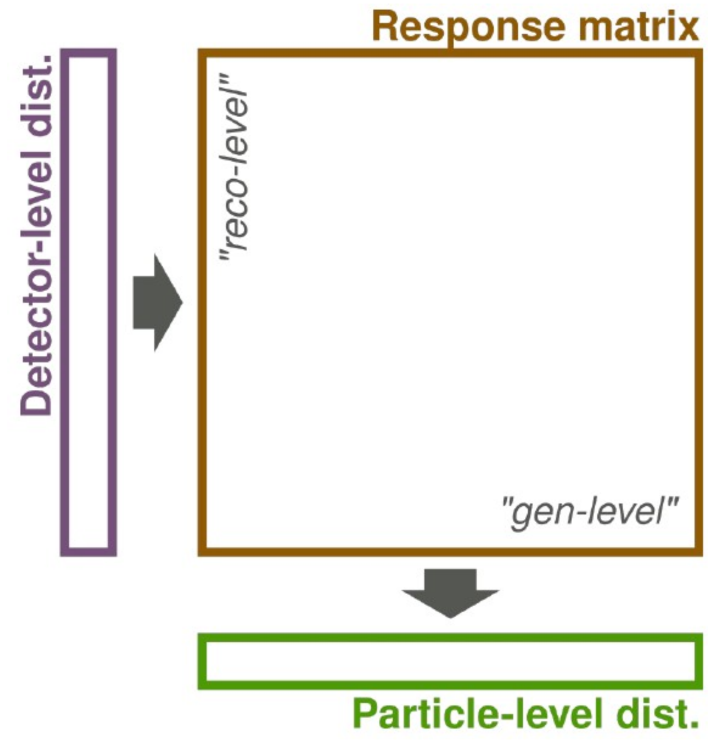


Proton

Response matrix



T unfold, S. Schmitt, JINST 7 (2012) T10003.



- Unfold effect of detector smearing
- Needs response from full simulation
- Sufficiently well-conditioned (3.8) / diagonal to allow matrix inversion

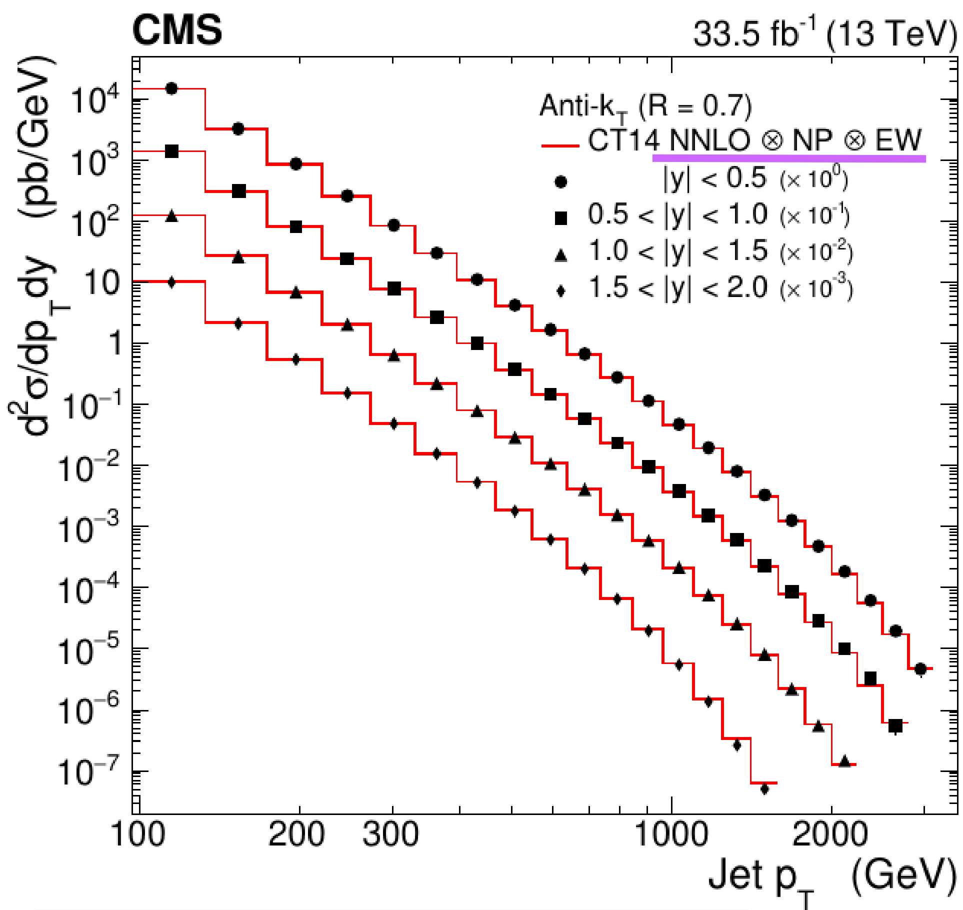
CMS JHEP02 (2022) 142, JHEP12 (2022) 035.

Inclusive jets: cross section

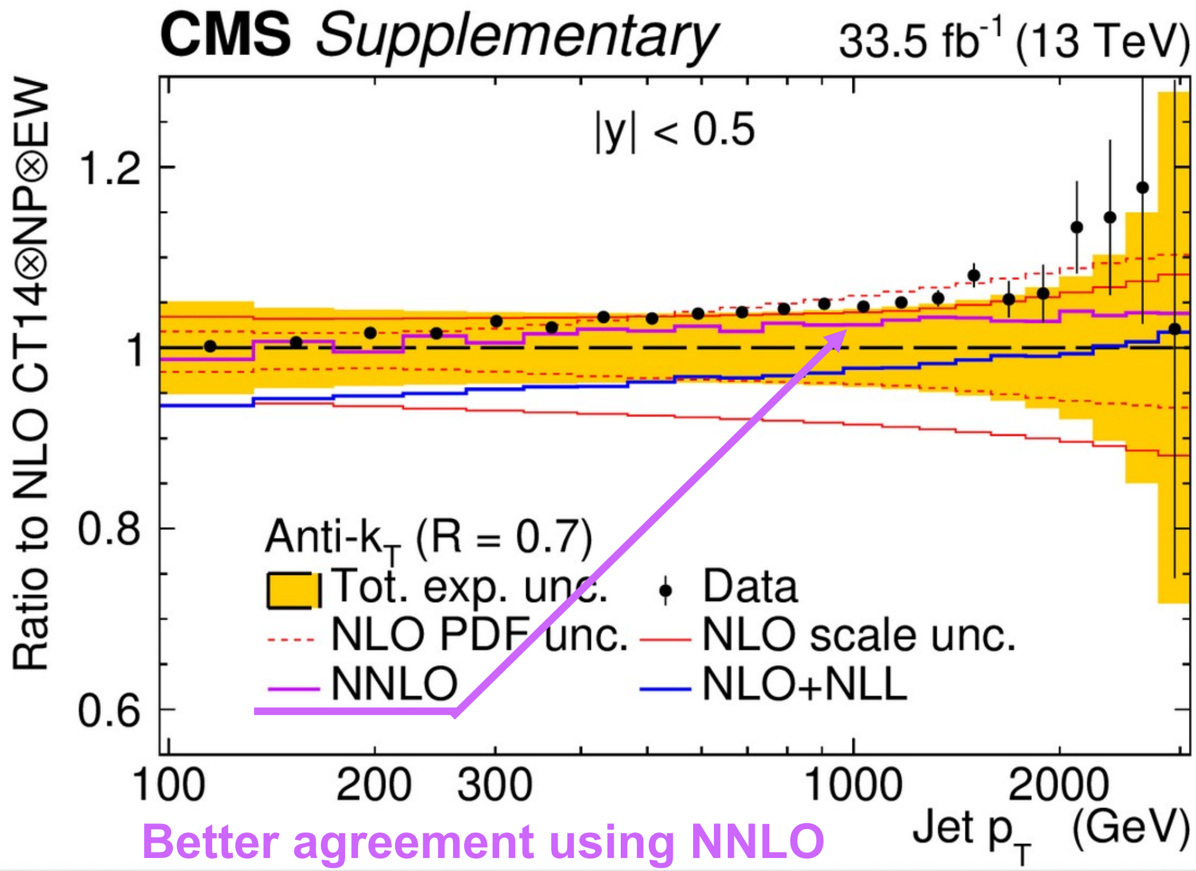
Overall agreement with NNLO x NP x EW
Over many orders of magnitude
Even beyond 2 TeV in jet p_T and for rapidities |y| up to 2

$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

anti-k_t, R=0.7, 13 TeV



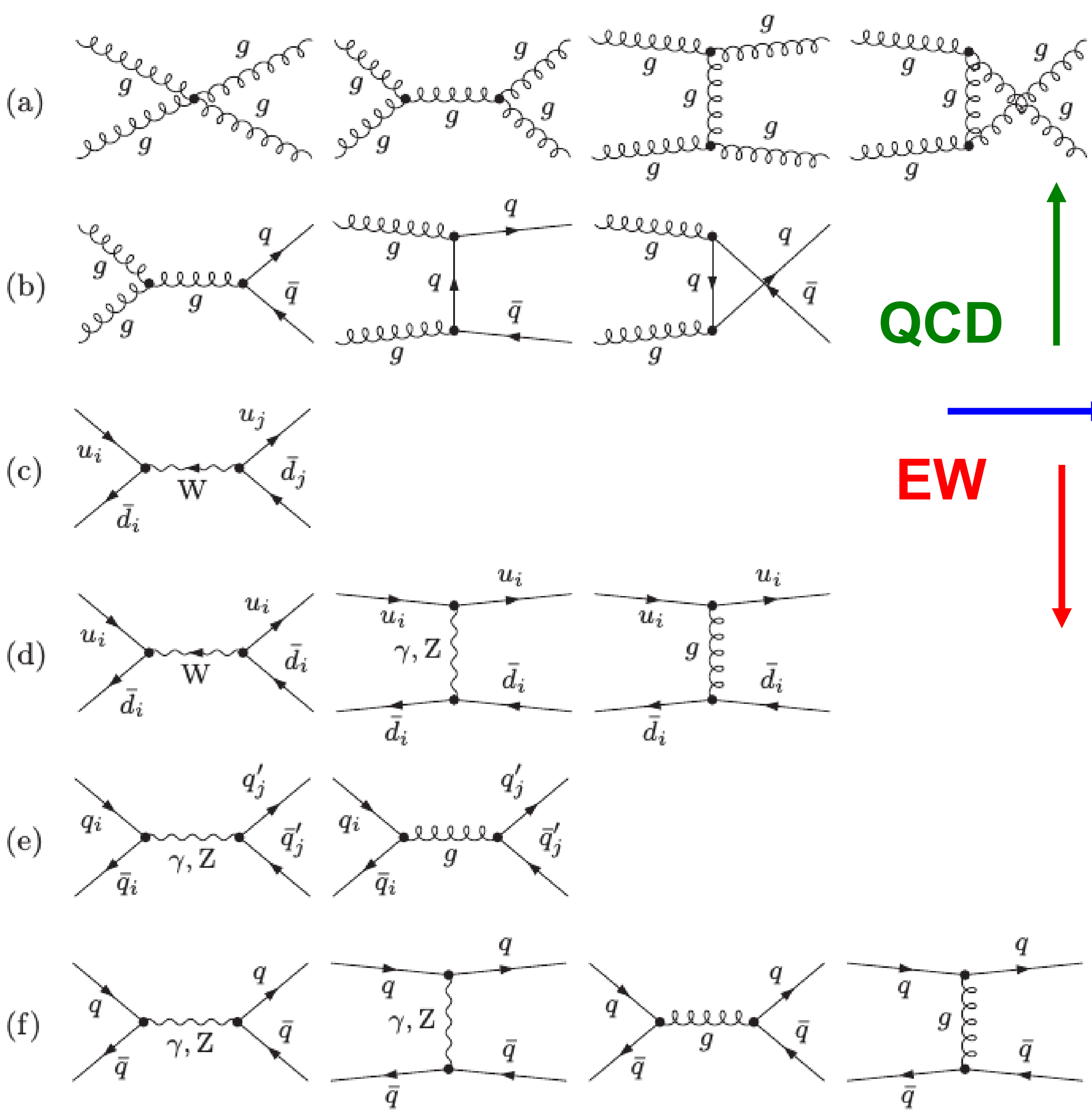
Ratio to NLO x NP x EW for |y| < 0.5



Better agreement using NNLO

CMS JHEP02 (2022) 142, JHEP12 (2022) 035.

NLOJet++: Nagy, PRD 68 (2003) 094002. NNLOJET: Currie et al., JHEP 10 (2018) 155.



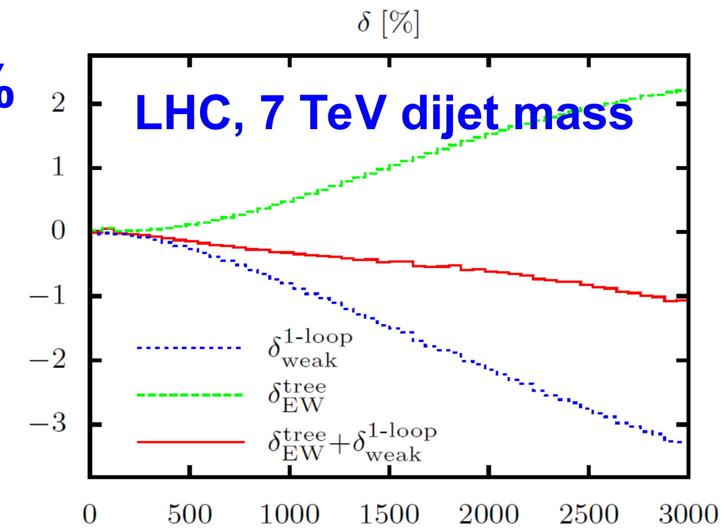
QCD ↑

EW ↓

→ jj

Elektroweak corrections $\propto \alpha\alpha_s^2$

%



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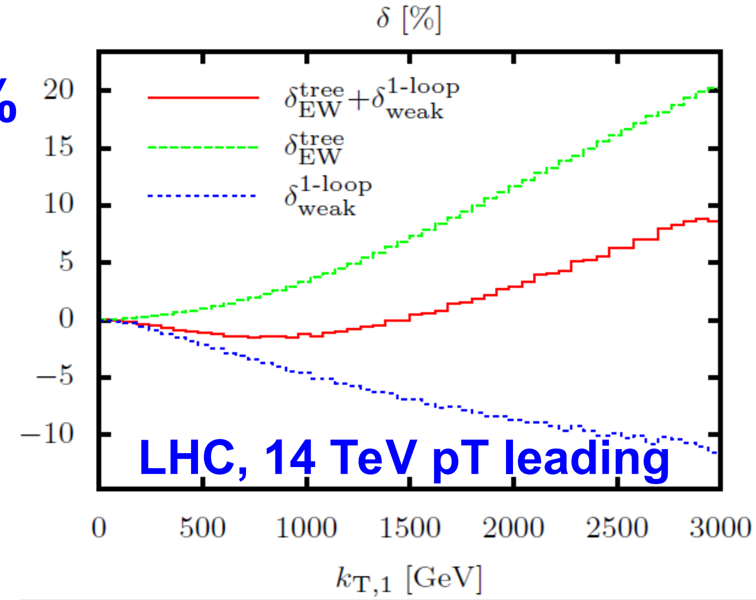
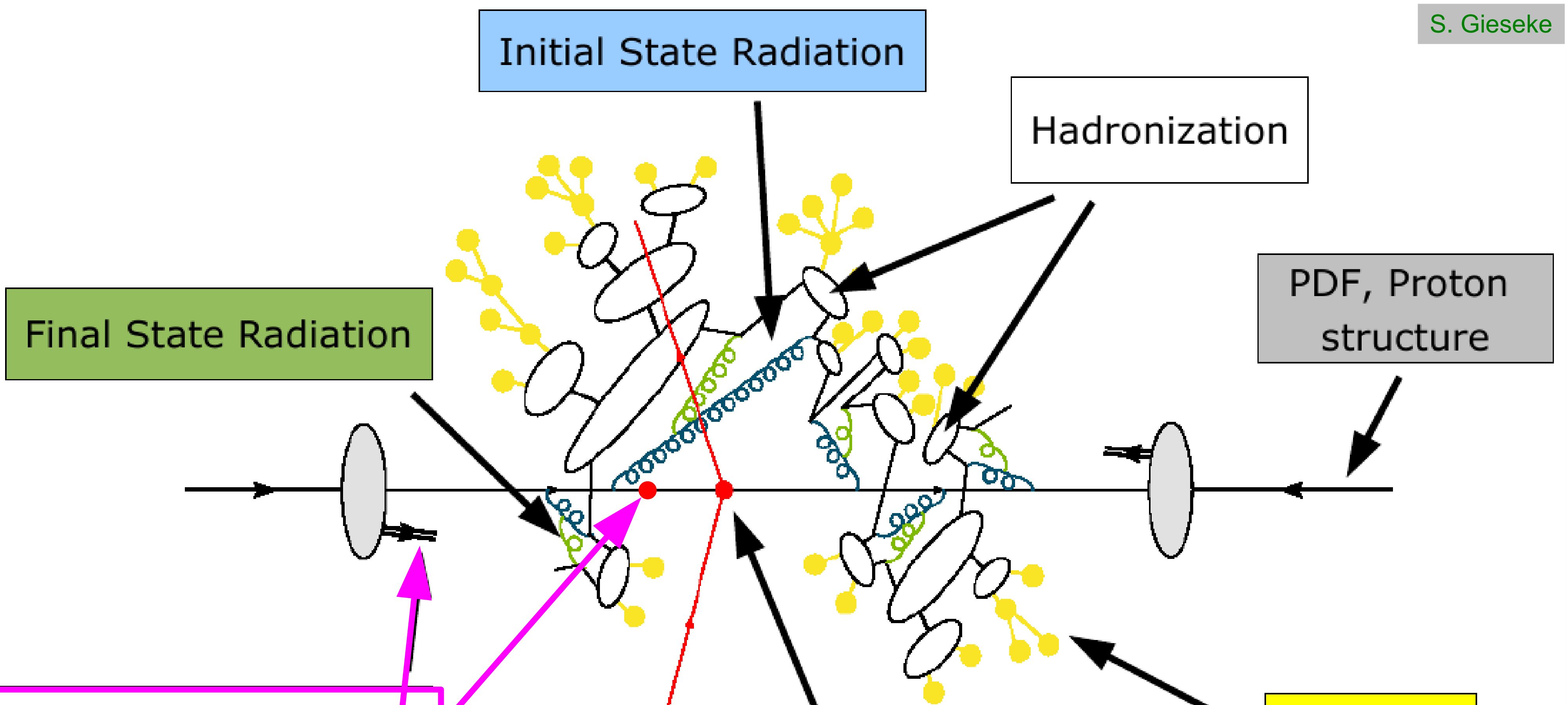


S. Dittmaier, A. Huss, C. Speckner, JHEP11 (2012);
R. Frederix et al., JHEP 04 (2017) 076.

Event display from MC generator



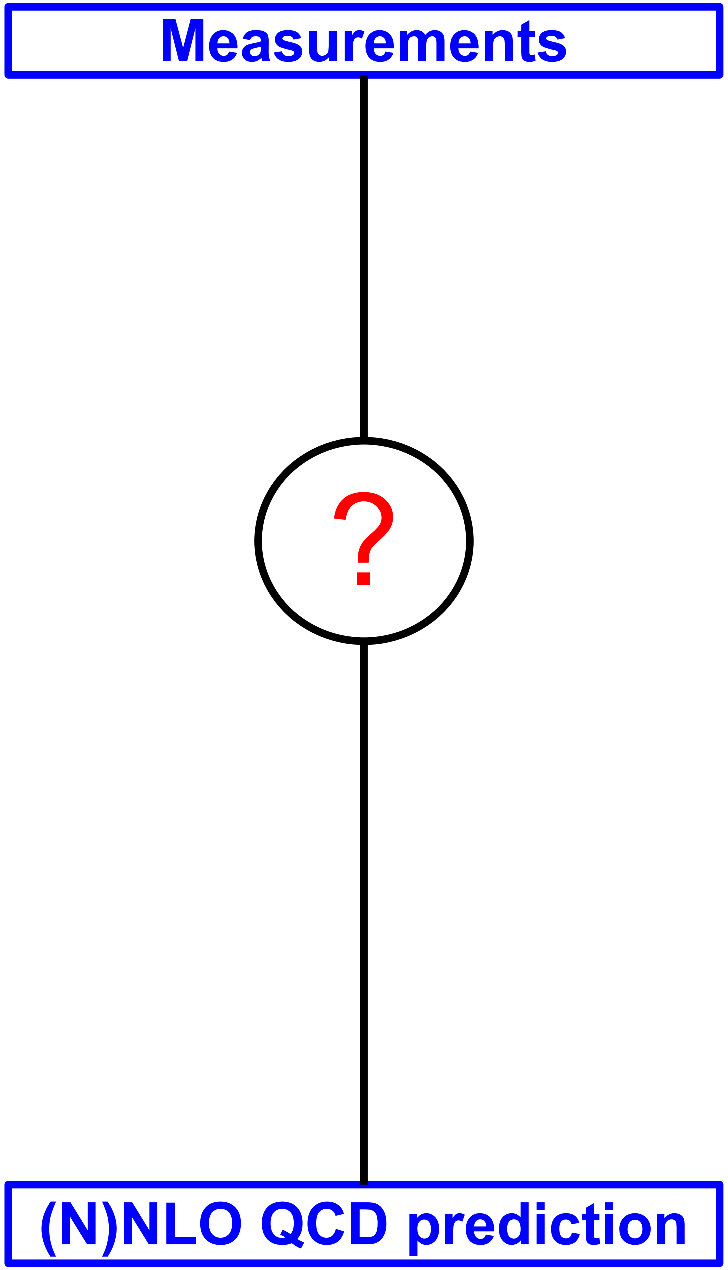
Not shown for simplicity:

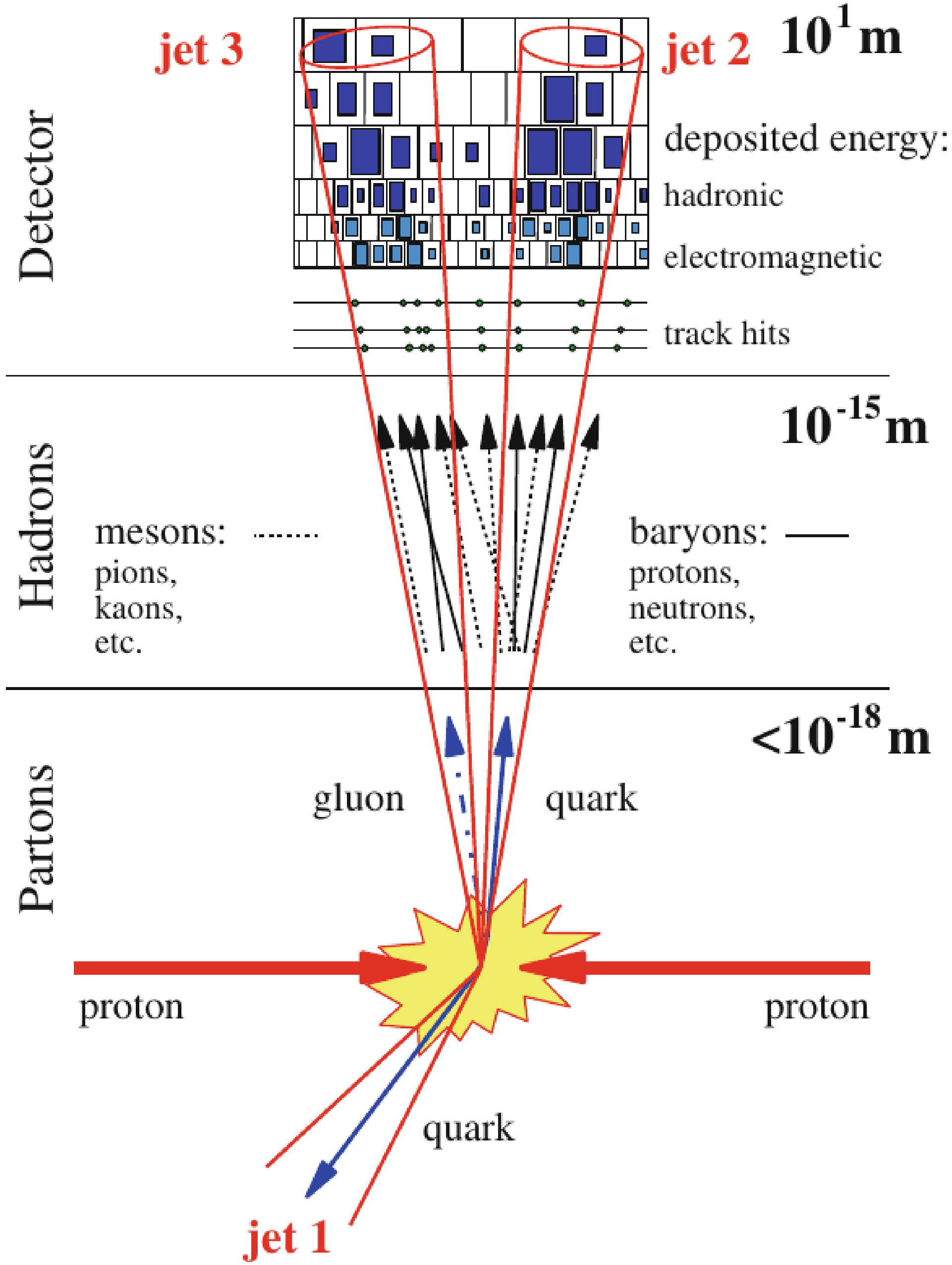
Beam Remnants

Multiple Interactions

FSR off the hard partons

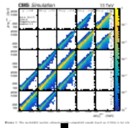
Comparison data-theory





Comparison data-theory

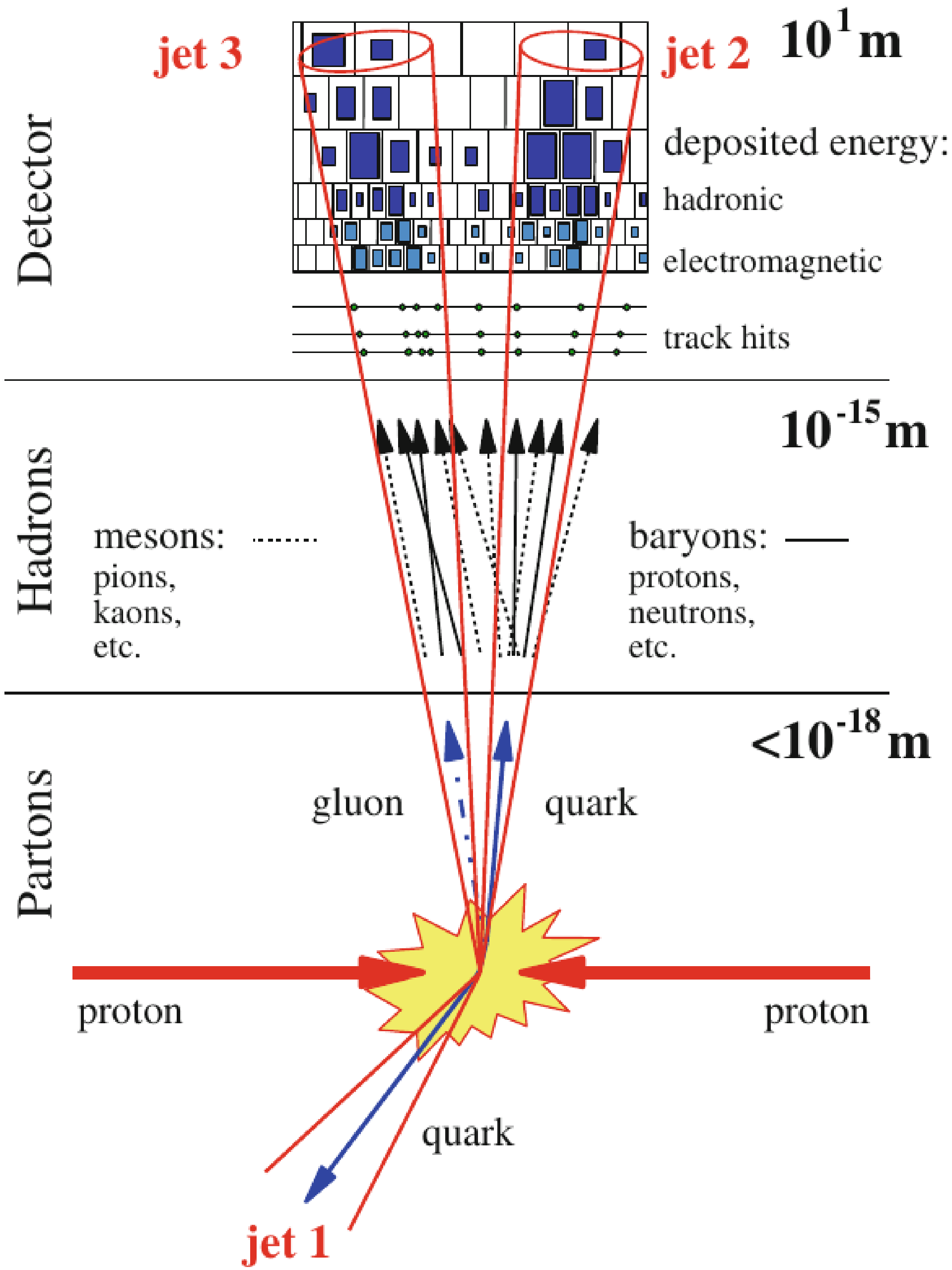
Measurements



Unfolded data

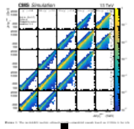
?

(N)NLO QCD prediction



Measurements

↓



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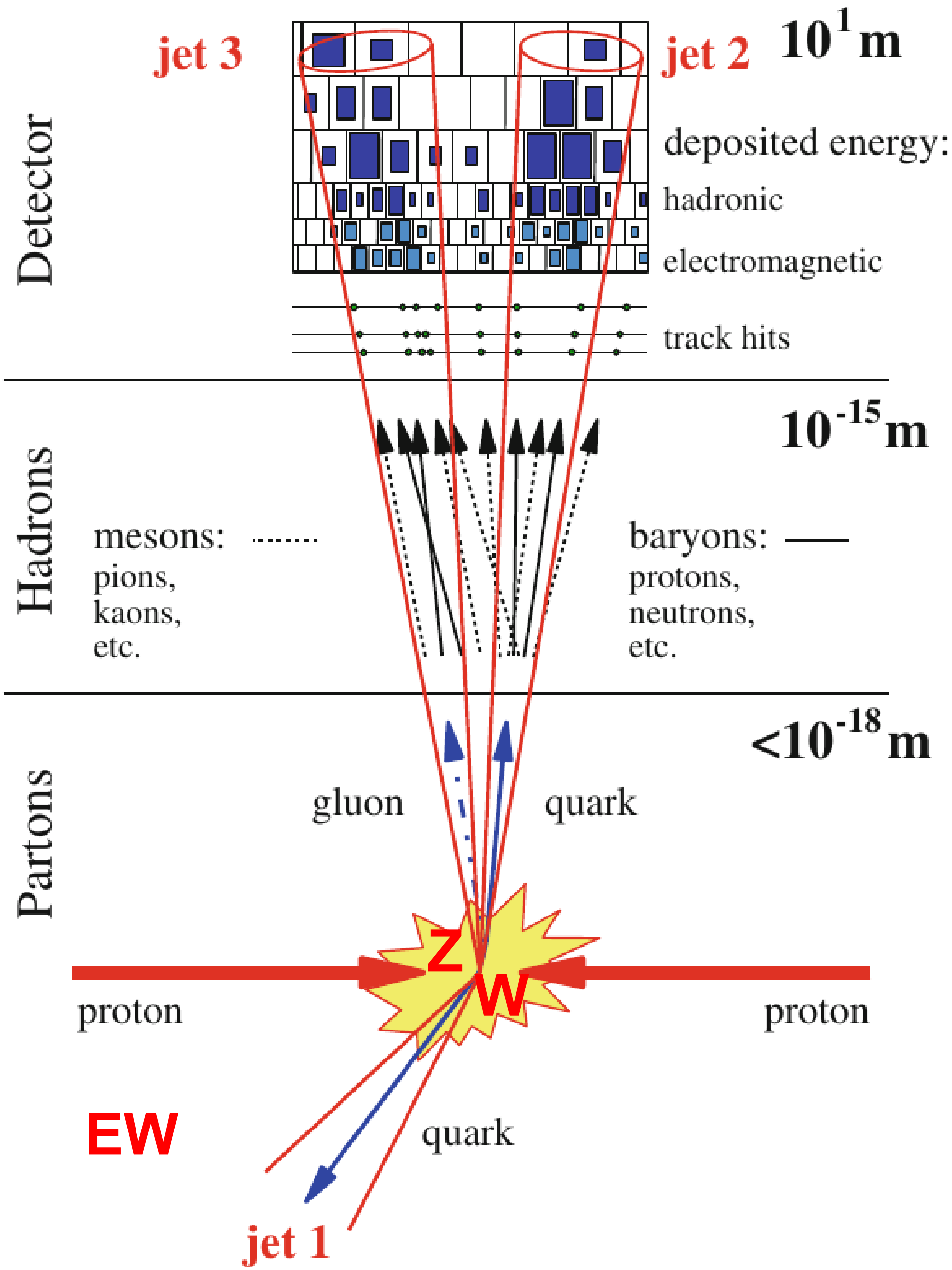
Unfolded data

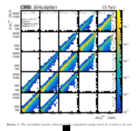
?

(N)NLO QCD prediction



Comparison data-theory

Measurements



Unfolded data

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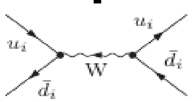
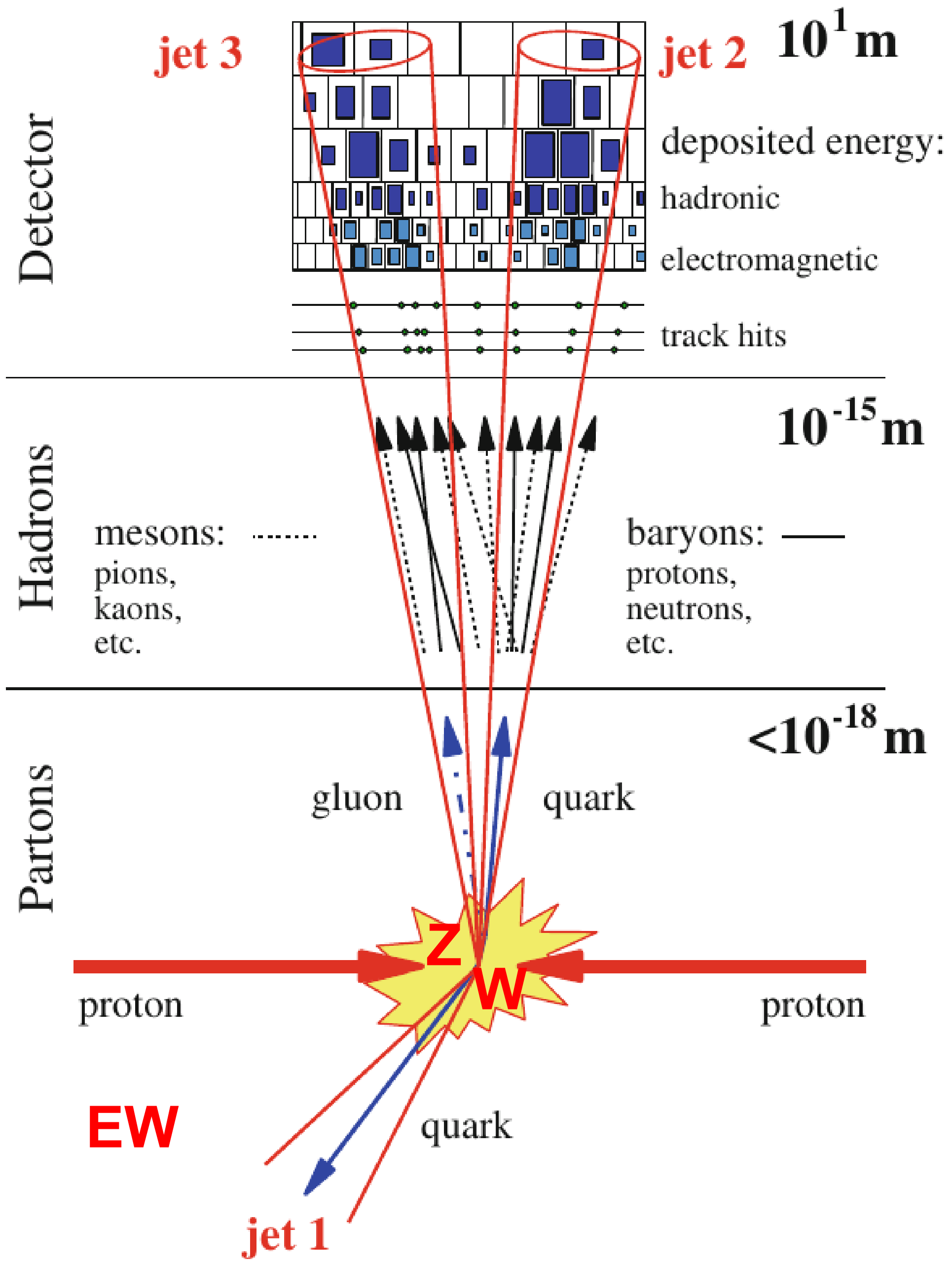
(N)NLO QCD x EW

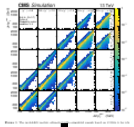


(N)NLO QCD prediction



Comparison data-theory

Measurements



Unfolded data

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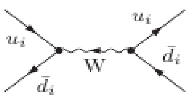
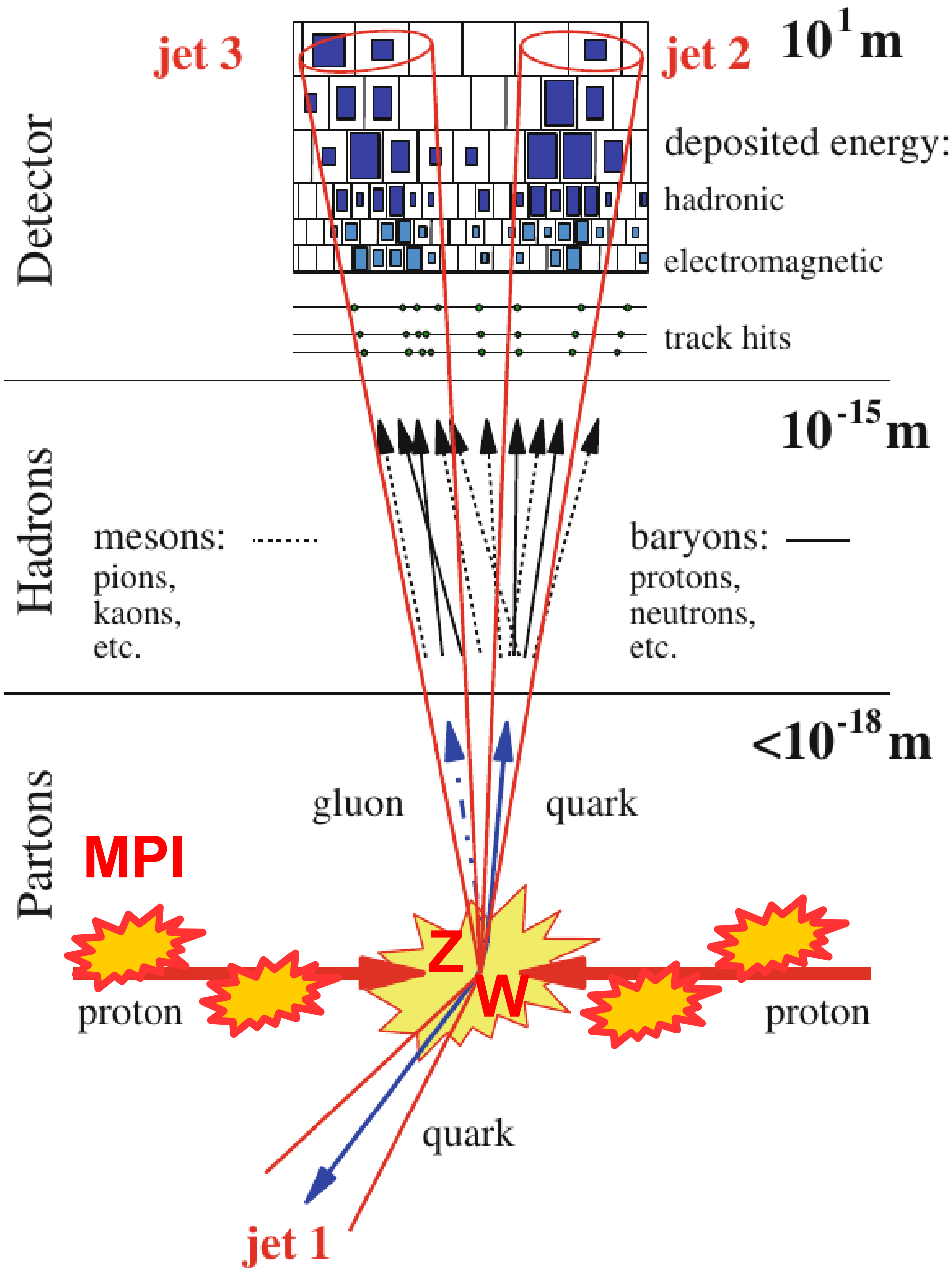
Multi parton interactions

(N)NLO QCD x EW

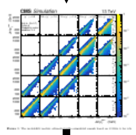


(N)NLO QCD prediction



Comparison data-theory

Measurements



Unfolded data

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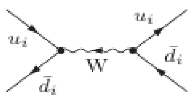
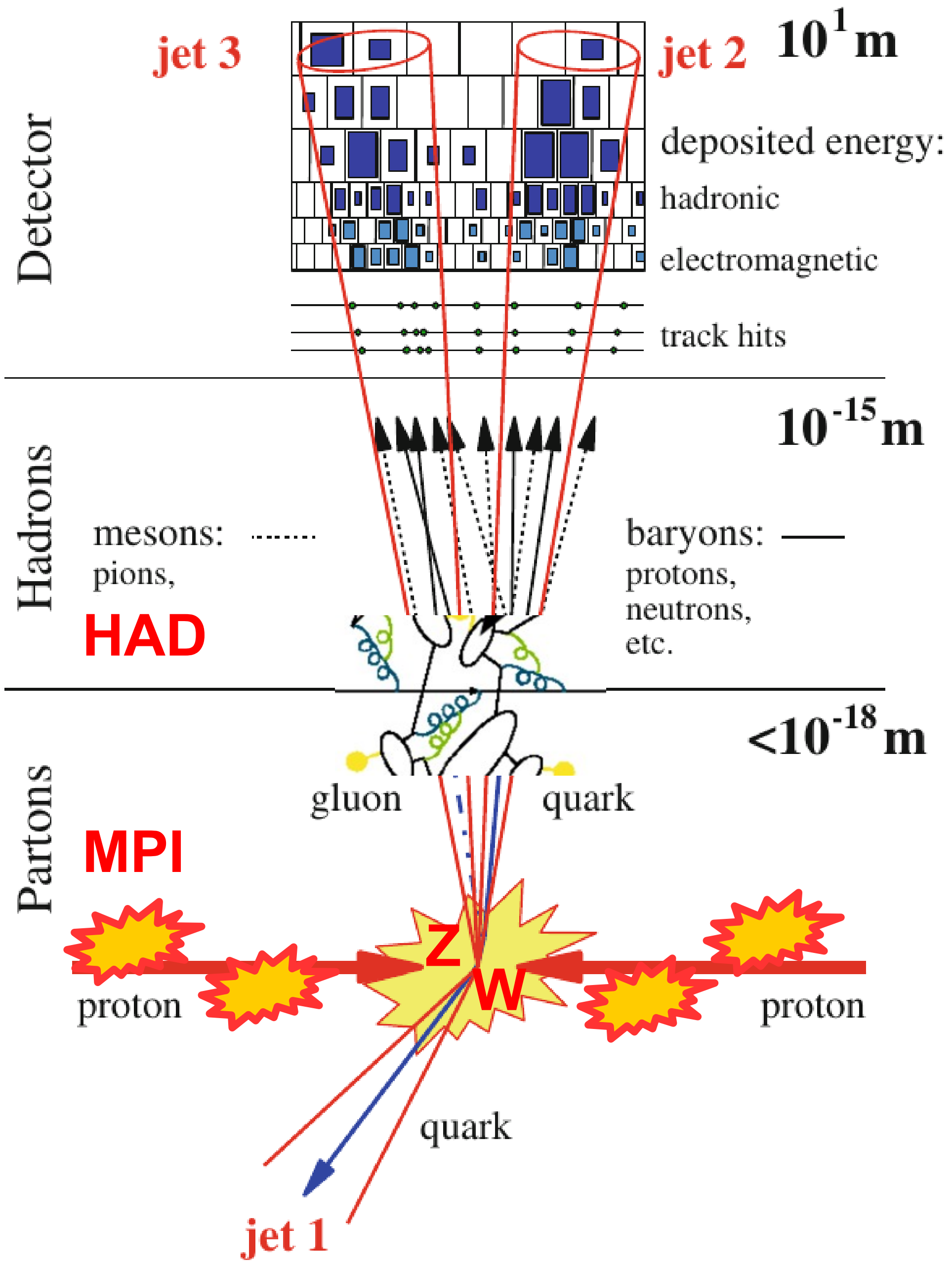
Hadronisation

Multi parton interactions

(N)NLO QCD x EW



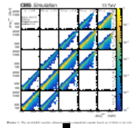
(N)NLO QCD prediction



Comparison data-theory

Measurements

↓



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Unfolded data

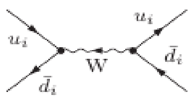
≈

(N)NLO QCD x EW x NP

↑

(N)NLO QCD x EW

↑



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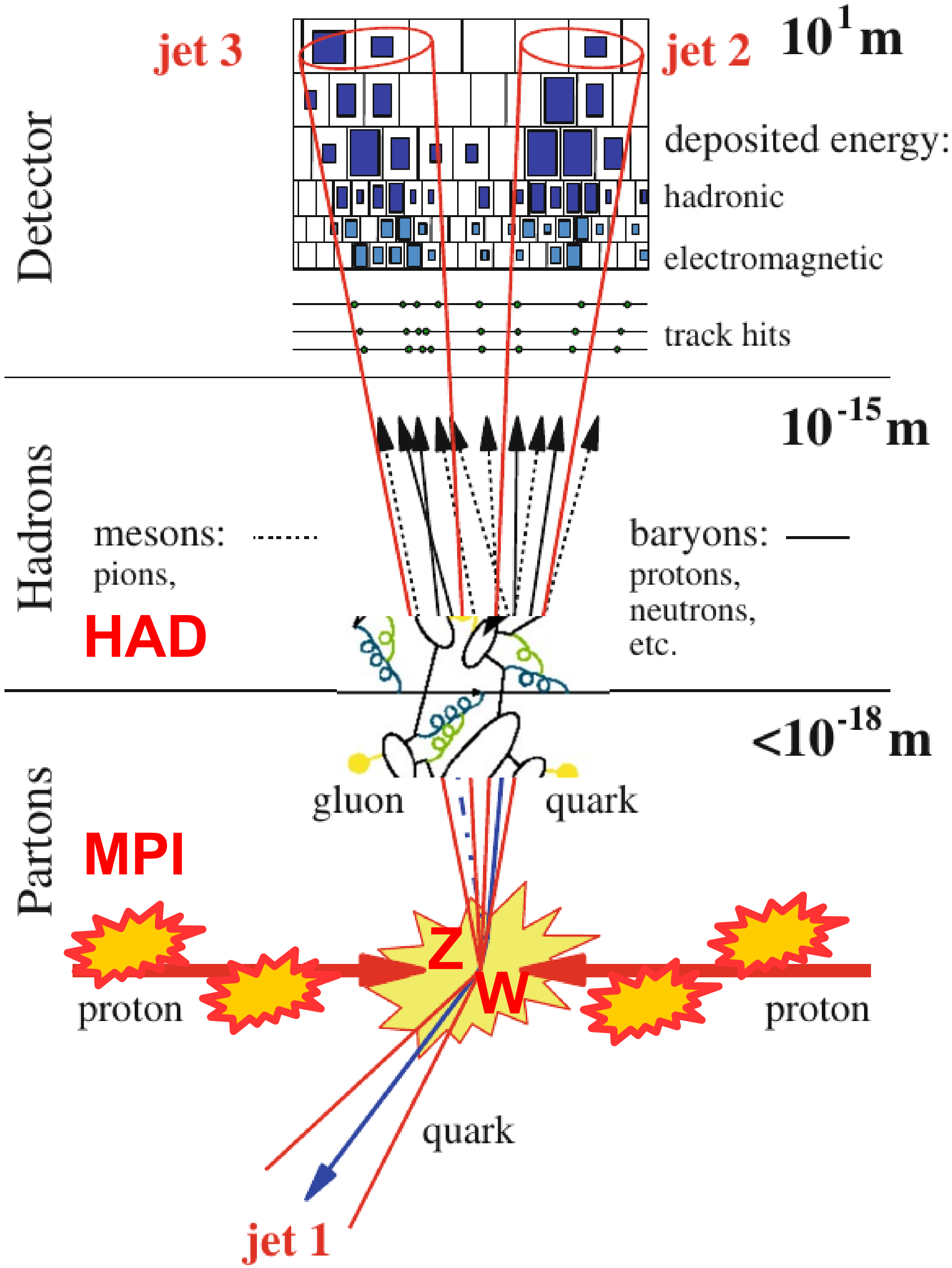
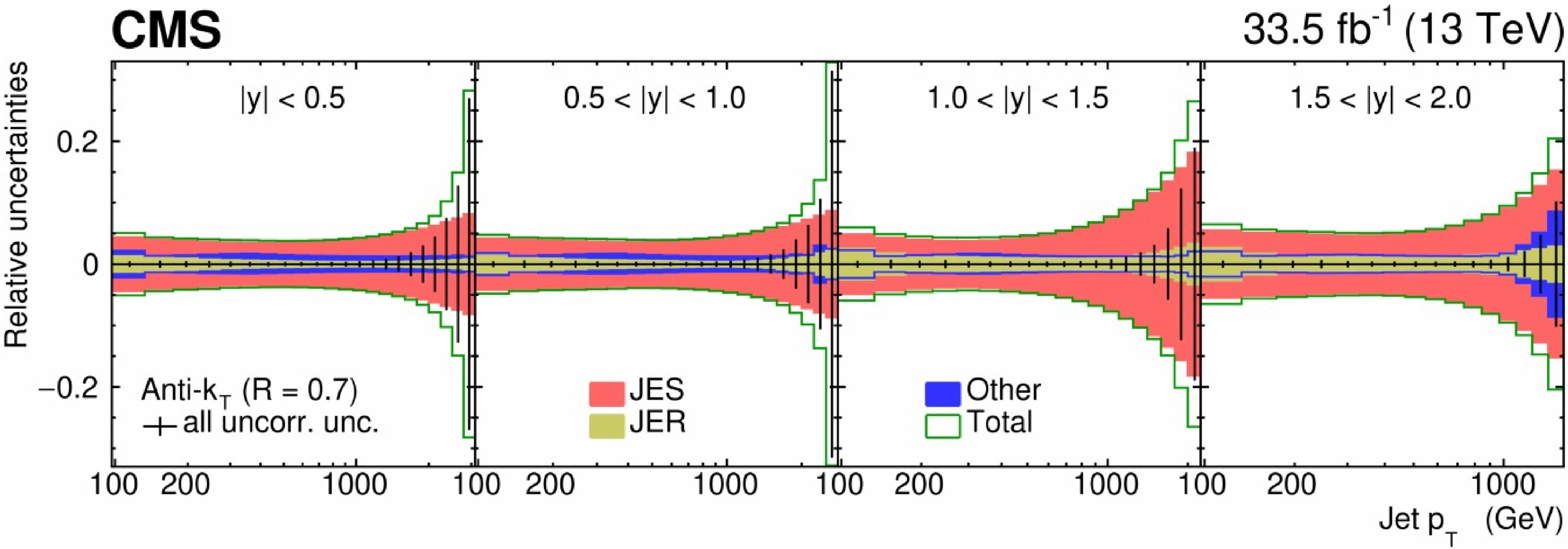
(N)NLO QCD prediction



Inclusive jets: exp. uncertainties

Of the order of 5%, larger at high y and p_T
Dominated by JES uncertainty (also JEC)
Except at highest p_T → statistical uncertainty

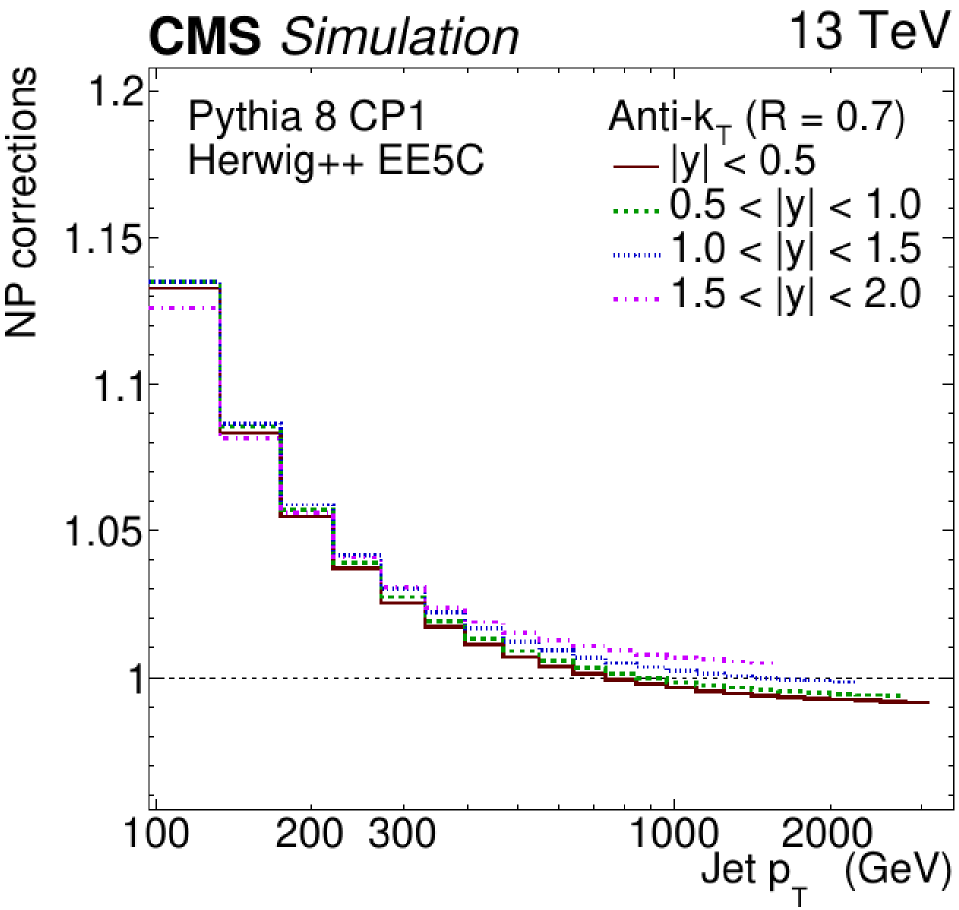


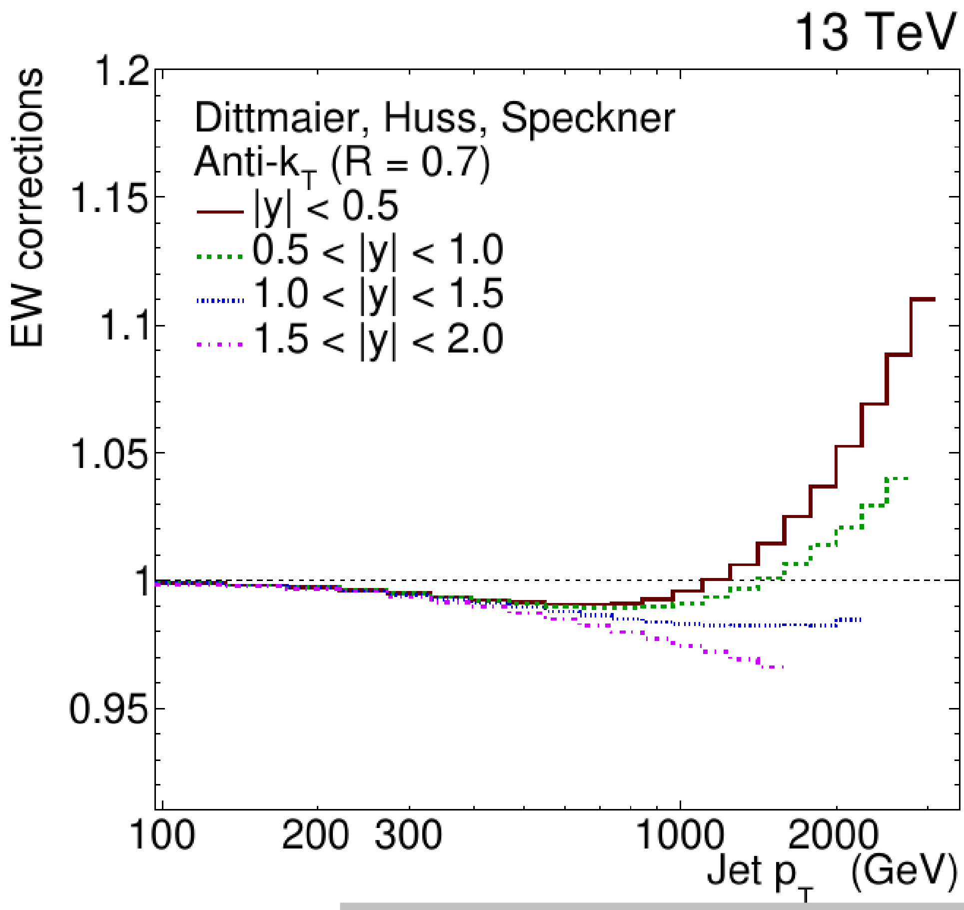
Inclusive jets: theory corrections

anti-kt, R=0.7, 13 TeV

Nonperturbative correction factors:
- estimated from tuned MC event generators
- strongly dependent on jet size R
- less important at high p_T

Electroweak correction factors:
- calculated perturbatively
- strongly dependent on jet rapidity y
- very important at high p_T





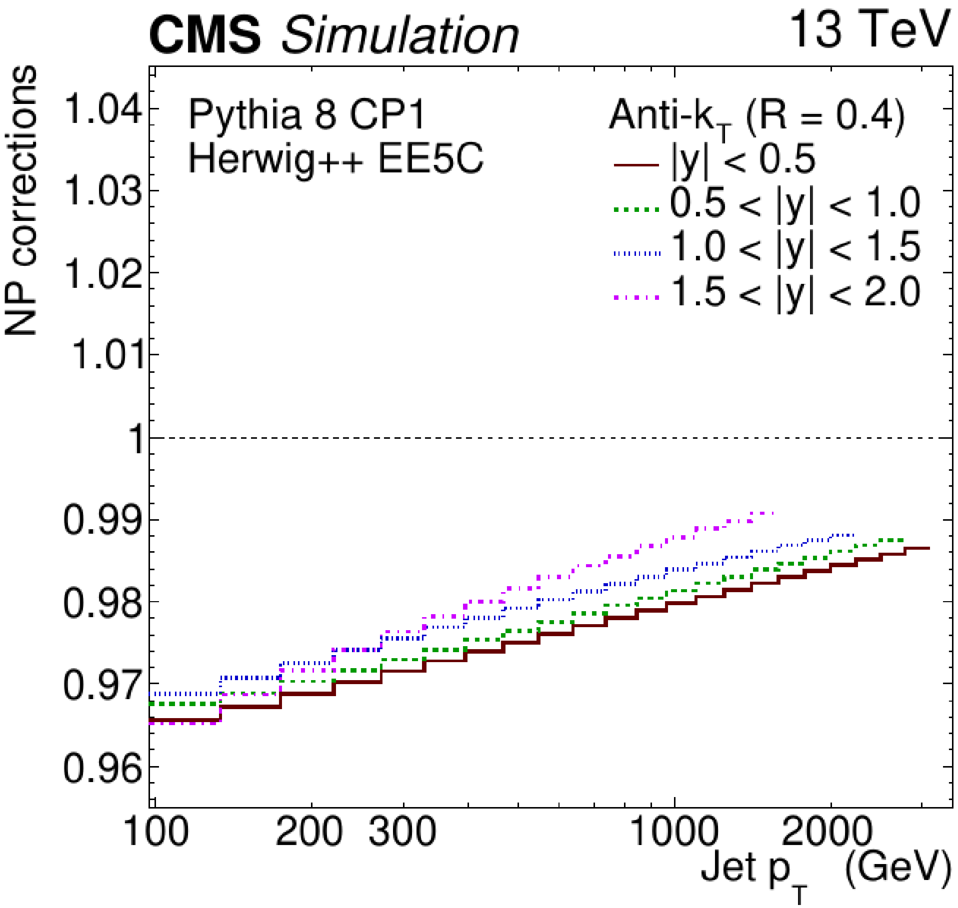
Dittmaier, Huss, Speckner, JHEP 11 (2012) 095.

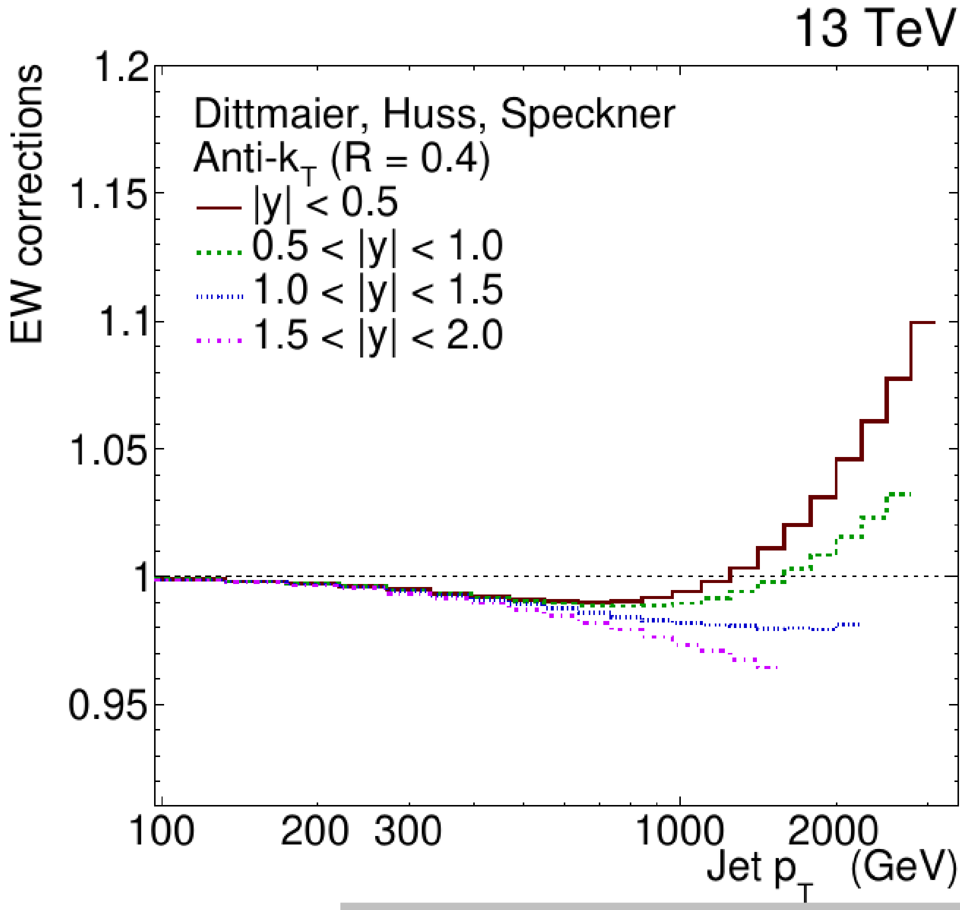
Inclusive jets: theory corrections

anti-kt, R=0.4, 13 TeV

Nonperturbative correction factors:
- estimated from tuned MC event generators
- strongly dependent on jet size R
- less important at high p_T

Electroweak correction factors:
- calculated perturbatively
- strongly dependent on jet rapidity y
- very important at high p_T



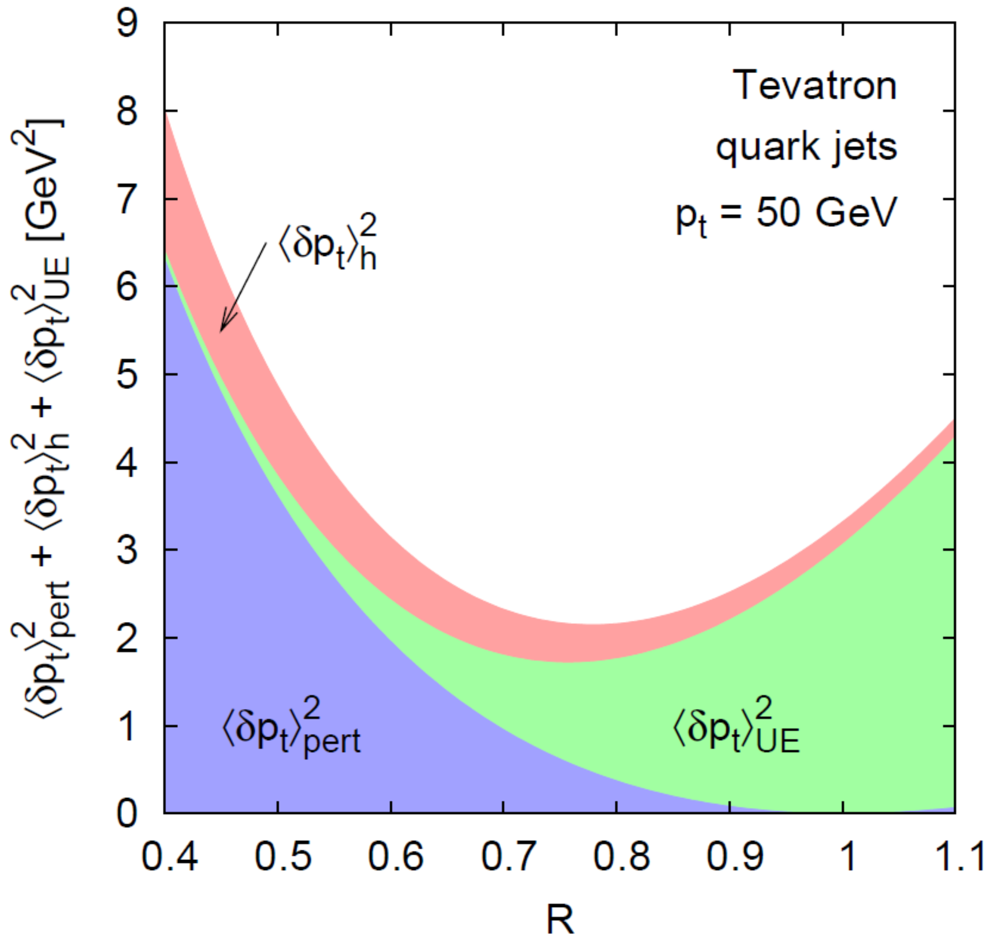


Dittmaier, Huss, Speckner, JHEP 11 (2012) 095.

Jet size dependence

Jet p_T shift as a function of R for several sources:

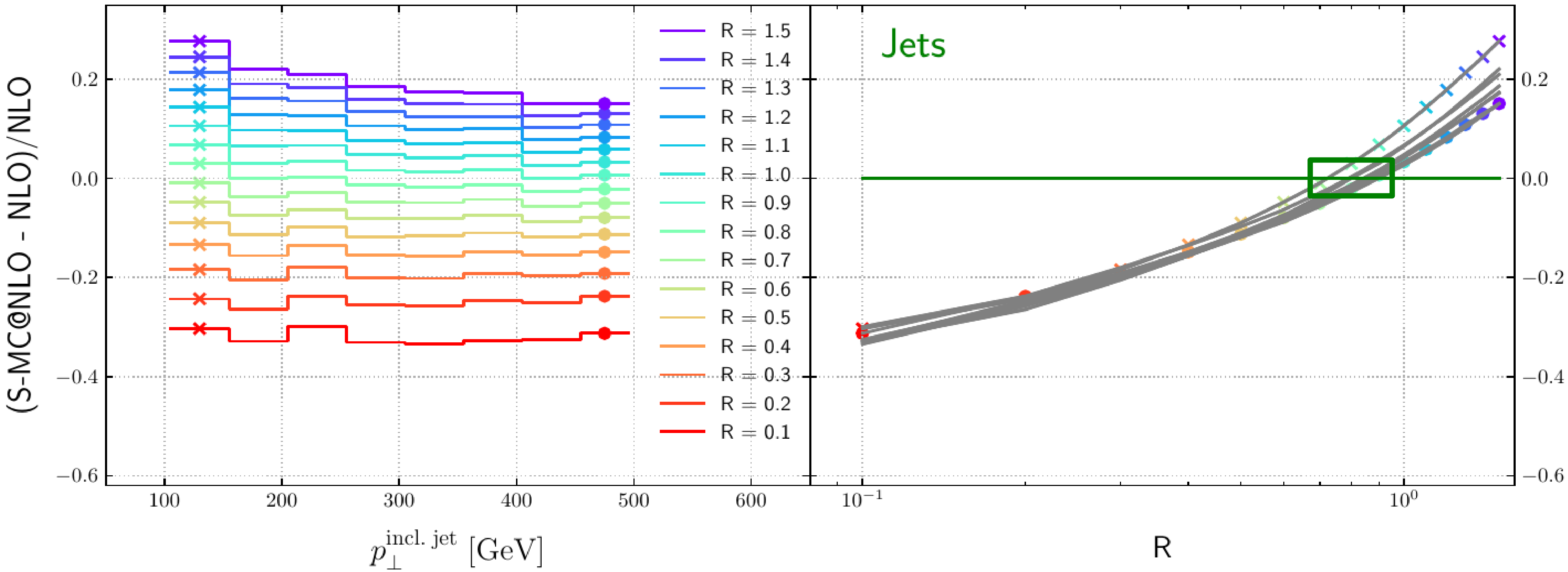
- **pert (Parton shower) scales with** $$\ln(R) + \mathcal{O}(1)$$
- **h (Hadronisation) scales with** $$-\frac{1}{R} + \mathcal{O}(R)$$
- **UE (Multiple Parton Interactions) scales with** $$R^2 + \mathcal{O}(R^4)$$



Dasgupta, Magnea, Salam, JHEP02 (2008) 055.

Recent investigation on R dep.

Relative difference between predictions of MC generator NLO+PS+MPI+HAD and NLO



Difference smallest for R around 0.7 – 1.0 → sweet spot!

Bellm et al., EPJC 80 (2020) 93.

Chi² Fit

Data points D_i

Theory prediction T_i

$$\chi^2 = \sum_{ij}^{N} (D_i - T_i)\, \mathrm{C}_{ij}^{-1}\, (D_j - T_j)$$

inverted covariance matrix C_{ij}

$$C = \mathrm{cov}_{\mathrm{unf+stat}} + \mathrm{cov}_{\mathrm{uncor}} + \left(\sum_{\mathrm{sources}} \mathrm{cov}_{\mathrm{JES}} \right) + \mathrm{cov}_{\mathrm{lumi}} + \mathrm{cov}_{\mathrm{PDF}}$$

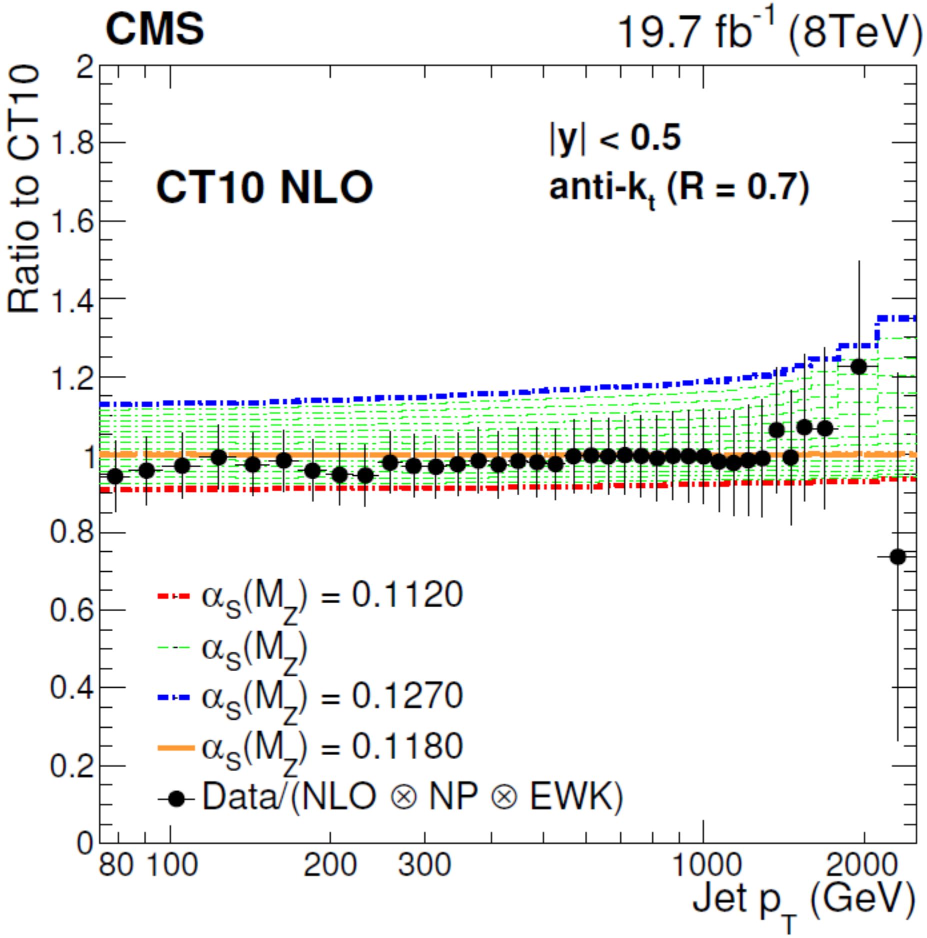
All uncertainty components in fit incl. correlations!

Scale and NP uncertainty via extra fits → offset method

Inclusive jets: α_s

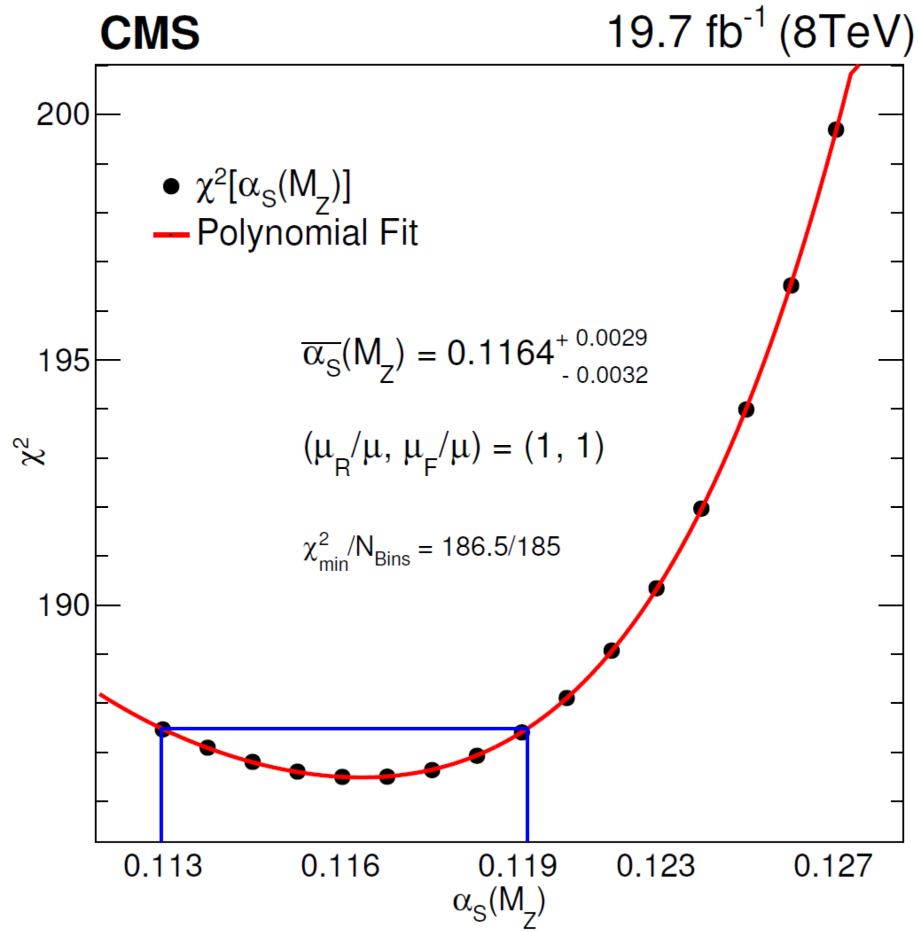
Sensitivity to $\alpha_s(M_Z)$ at NLO

- **CMS: anti-k_t R = 0.7 at $\sqrt{s}$ = 8 TeV**
- **QCD scale choice: $\mu_R = \mu_F = p_{T,jet}$**



χ^2 fit of $\alpha_s(M_Z)$ for all jet p_T and |y| bins

- **In fit: all exp. + PDF + NP uncertainties**
- **PDFs: CT10 NLO PDF sets for various $\alpha_s(M_Z)$**



Example from older analysis at 8 TeV!

Scale dependence

Jet cross section to all orders in perturbative QCD:

$$\sigma(pp \to jj + X) \propto \sum_{n=2}^{\infty} c_n(\mu_r)\alpha_s^n(\mu_r)$$

LO Coefficient, here c_2 independent of scale μ_r: $c_2(\mu_r) \equiv c_2$

Coefficients of higher orders depend on μ_r and renorm.- scheme, e.g.: $\overline{\mathrm{MS}}$

Infinite series independent of μ_r: $$\mu_r^2 \frac{d}{d\mu_r^2} \sum_{n=2}^{\infty} c_n(\mu_r)\alpha_s^n(\mu_r) = 0$$

Not so the truncated one!

$$\mu_r^2 \frac{d}{d\mu_r^2} \sum_{n=2}^{N} c_n(\mu_r)\alpha_s^n(\mu_r) \propto \mathcal{O}\left(\alpha_s^{N+1}(\mu_r)\right)$$

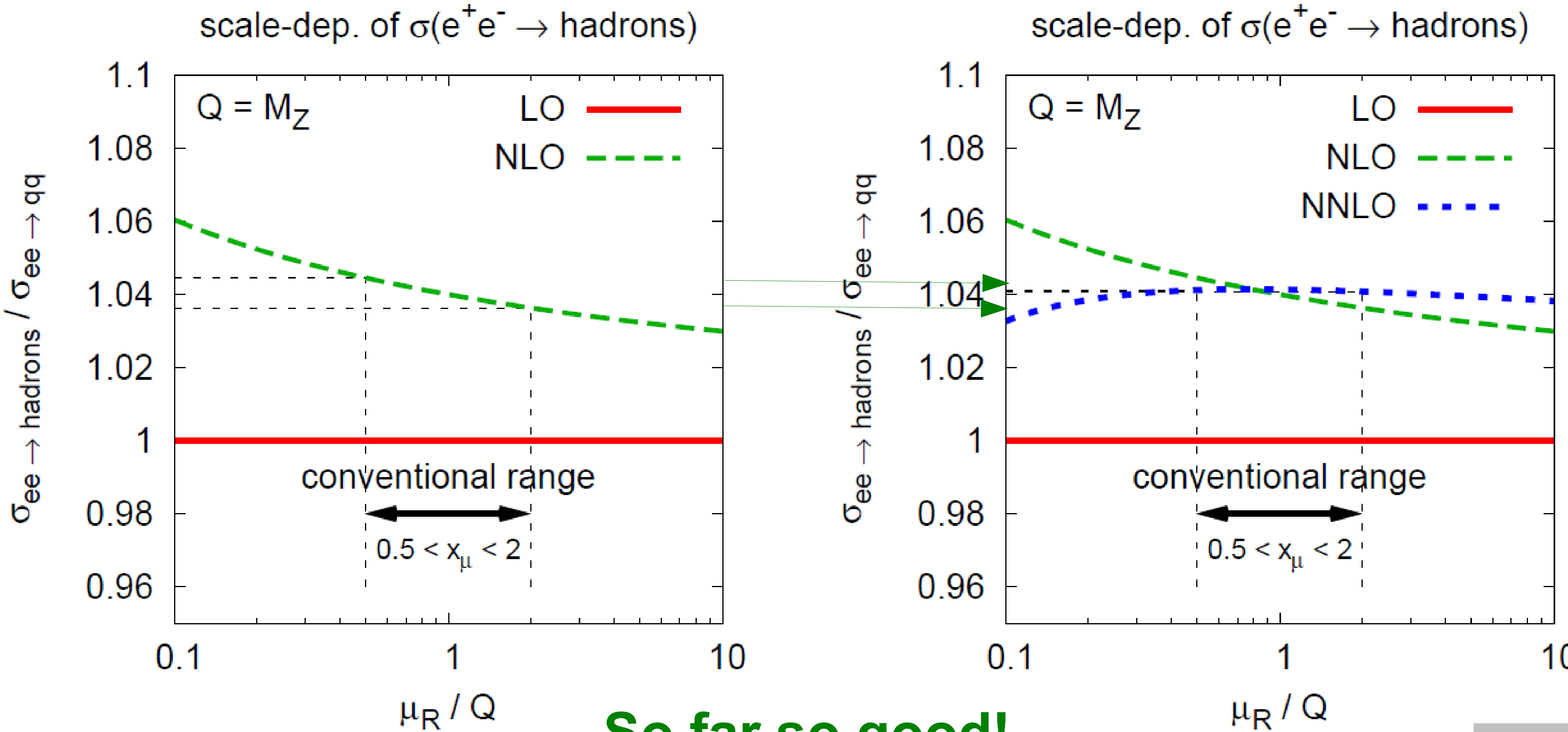
So for example: $$c_3(Q) = c_3(1) + \frac{\beta_0}{2\pi} \ln\left(\frac{\mu_r}{Q}\right) c_2$$

Conventional recipe

→ **Large LO scale dependence ~ $\alpha_s(\mu_r)$**

→ **Increasingly compensated by further terms**

→ **Recipe(!): Estimate impact of higher orders by μ_r variation**

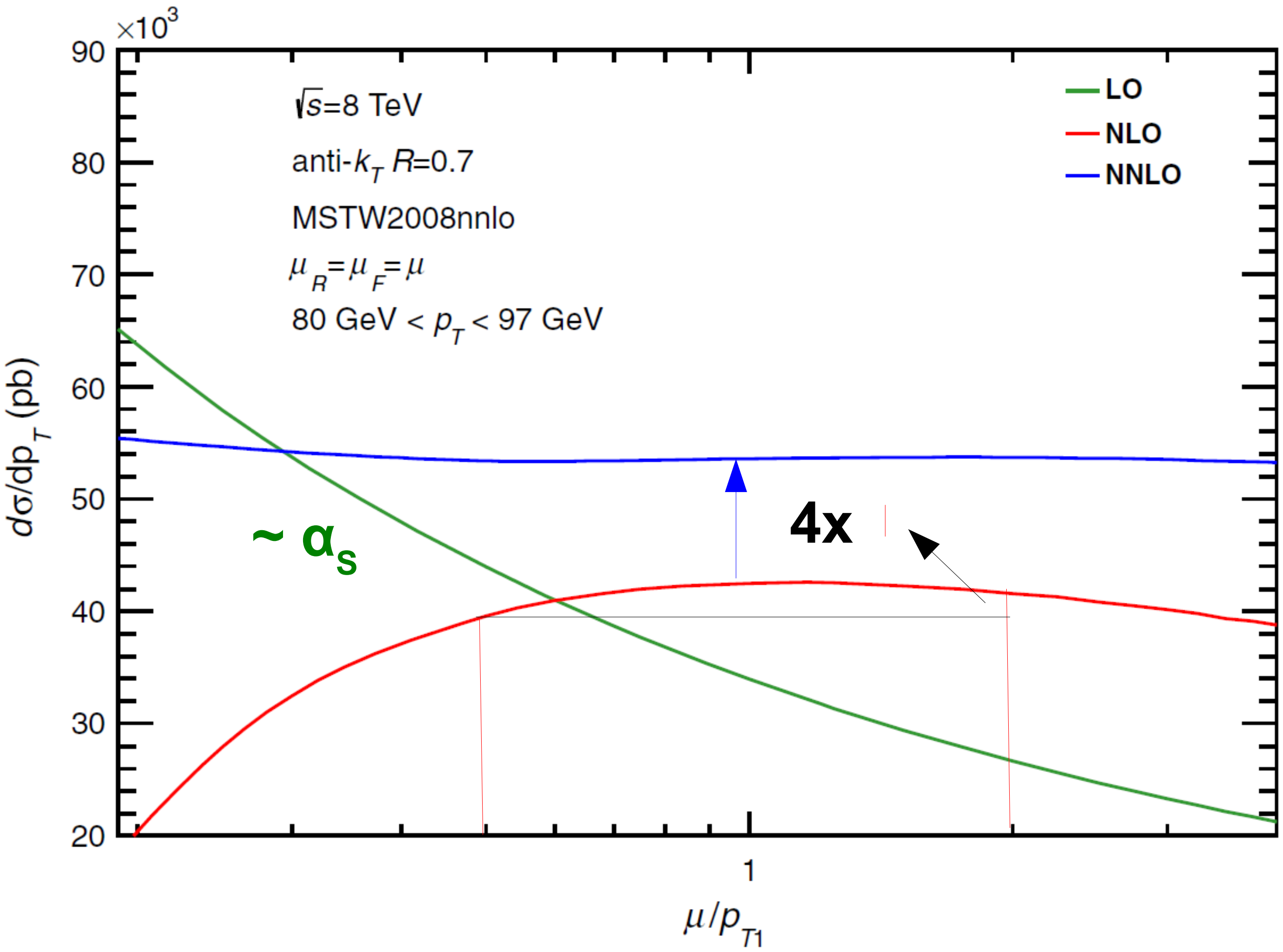


So far so good!

G. Salam, arxiv:1011.5131

Can go wrong, if e.g.:

1) Base scale badly chosen



Scale is:

p_T leading jet: p_{T1}

Looks much better, if respective jet pT is used!

Example plot of dep.: inklusive Jets, gg → jets

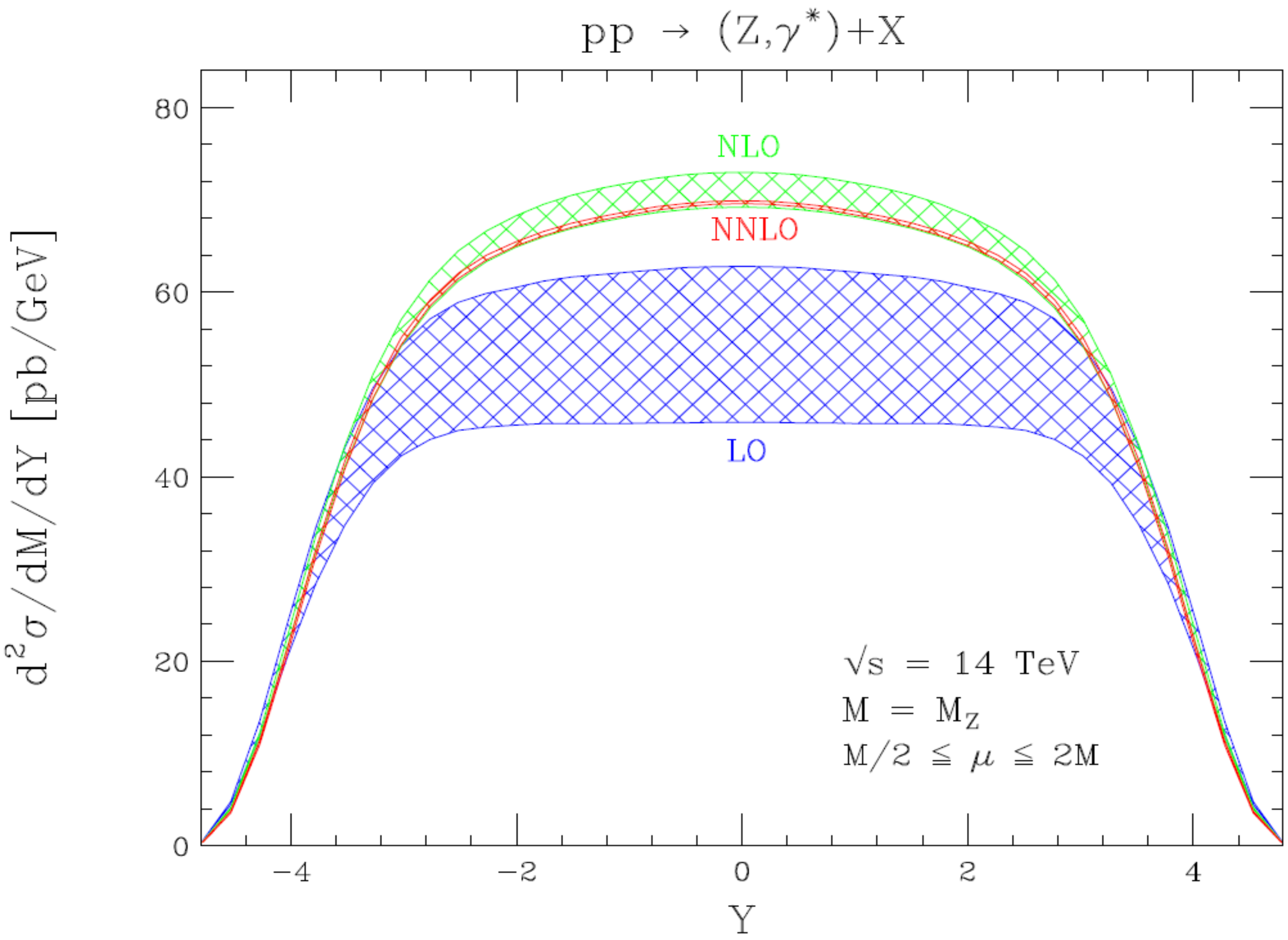
Gehrmann-De Ridder, Gehrmann, Glover, Pires, Phys. Rev. Lett., 2013, 110, 162003

Problems 2

Can go wrong, if e.g.:

1) Base scale badly chosen

2) In multi scale problems, e.g. Z+jet production



M_Z or $p_{T,jet}$ as scale?

Both can be sensible, depends on phase space.

Anastasiou, Dixon, Melnikov, Petriello, Phys. Rev. D, 2004, 69, 094008

Problems 3

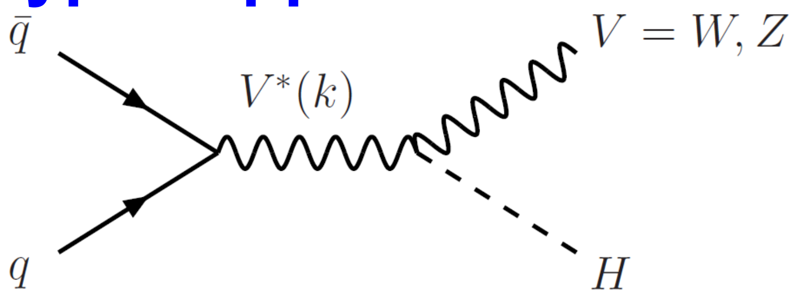
Can go wrong, if e.g.:

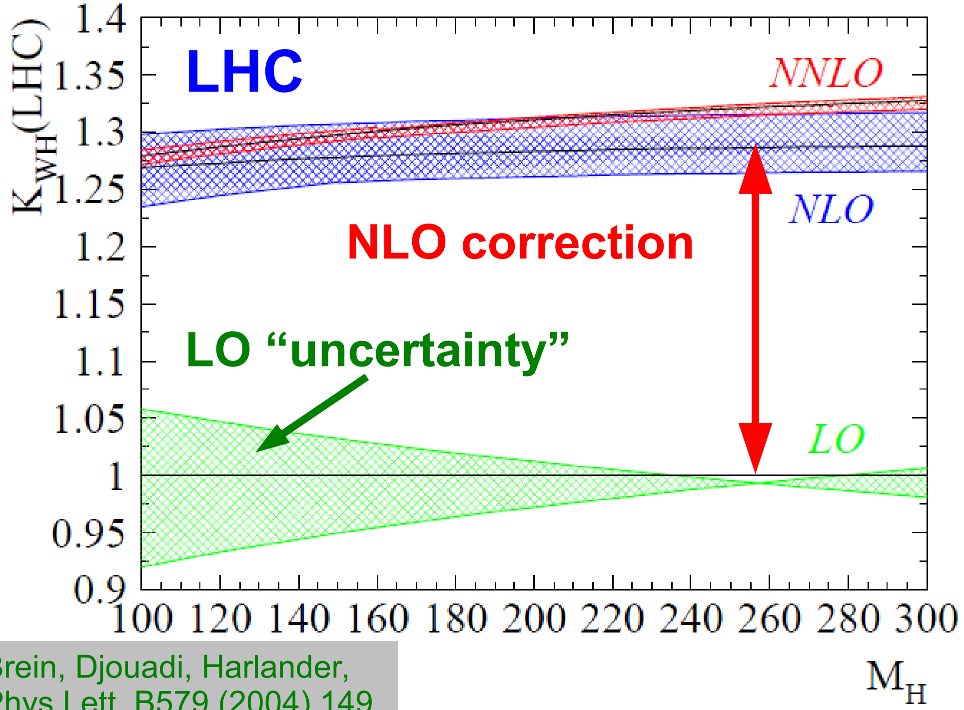
1) Base scale badly chosen
2) In multi scale problems, e.g. Z+jet production
3) New production channels or graph types appear

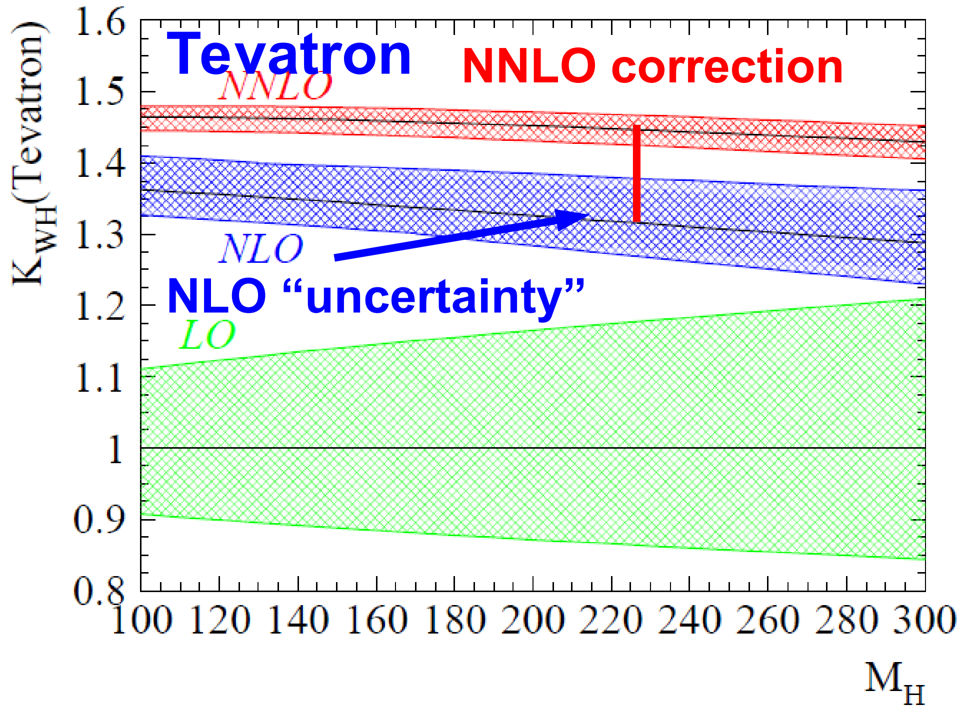
Process: Higgs radiation: pp → HV + X

Scale choice: M_{HV}

Scale variation $\mu_{r,f}/M_{HV}$**:** 1/3 … 3

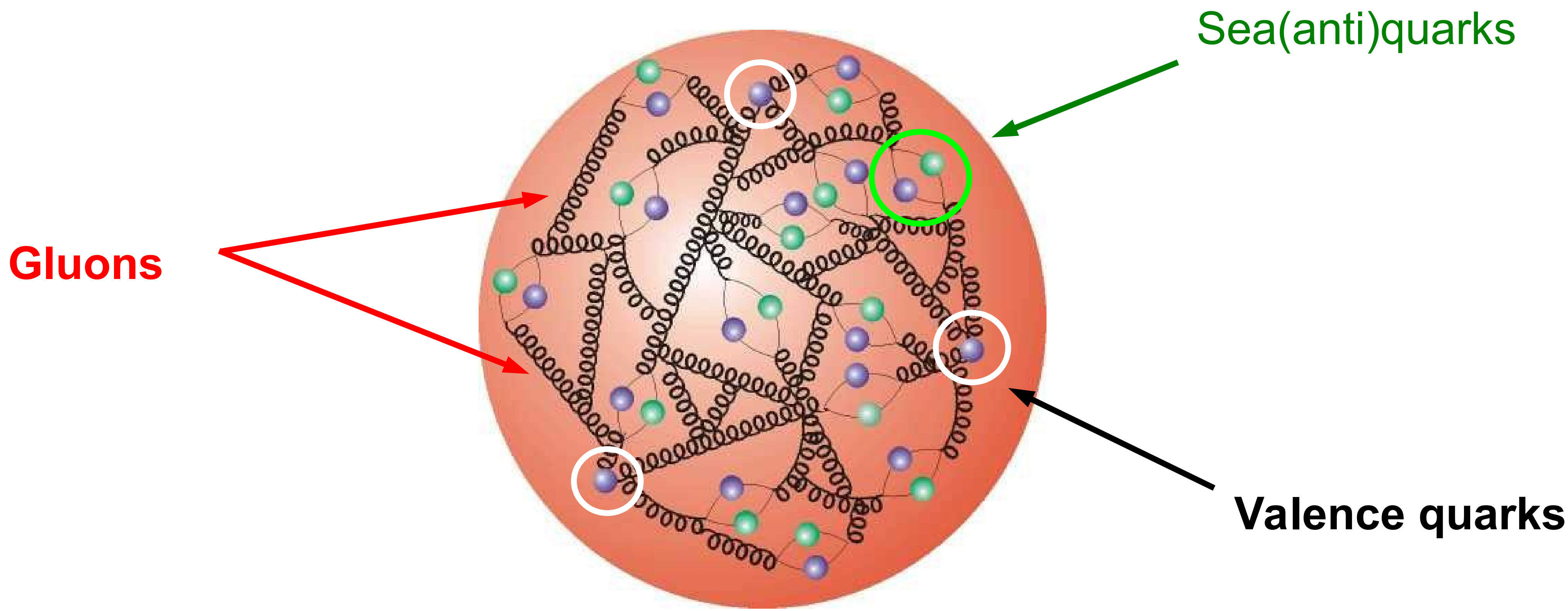






Brein, Djouadi, Harlander, Phys.Lett. B579 (2004) 149.

Constraining PDFs



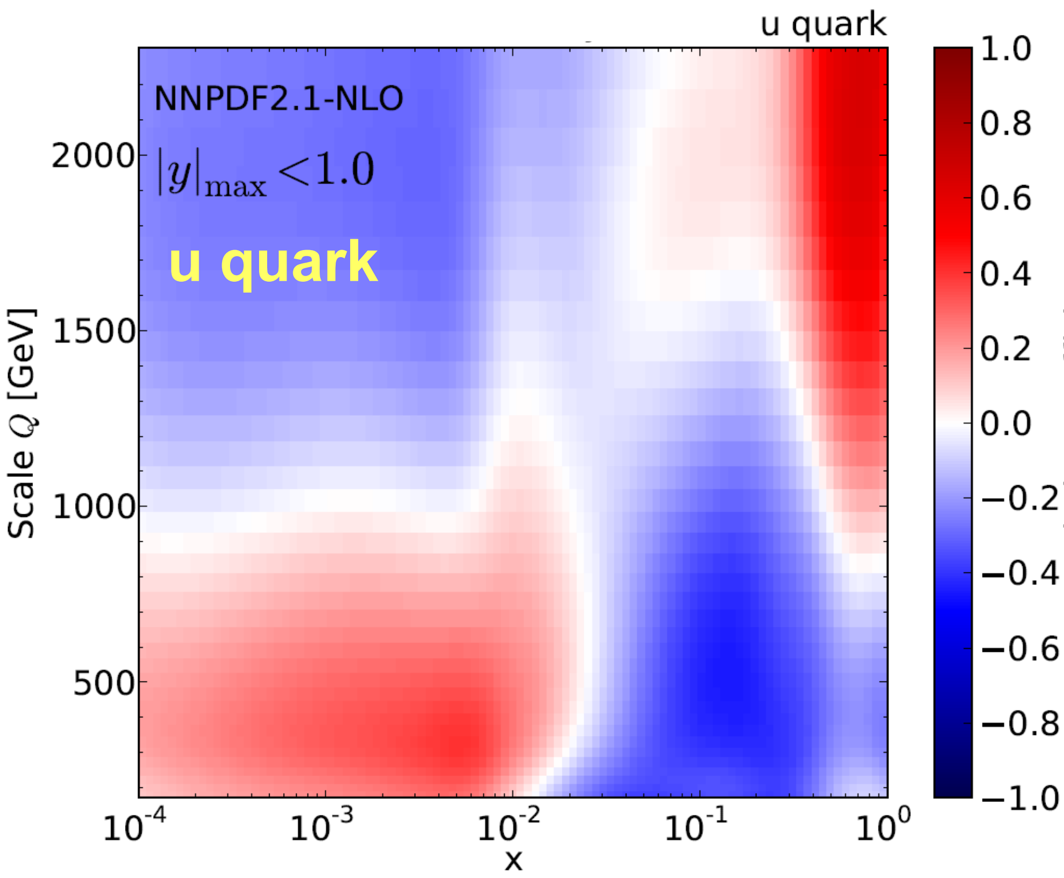
Correlation σ - PDF

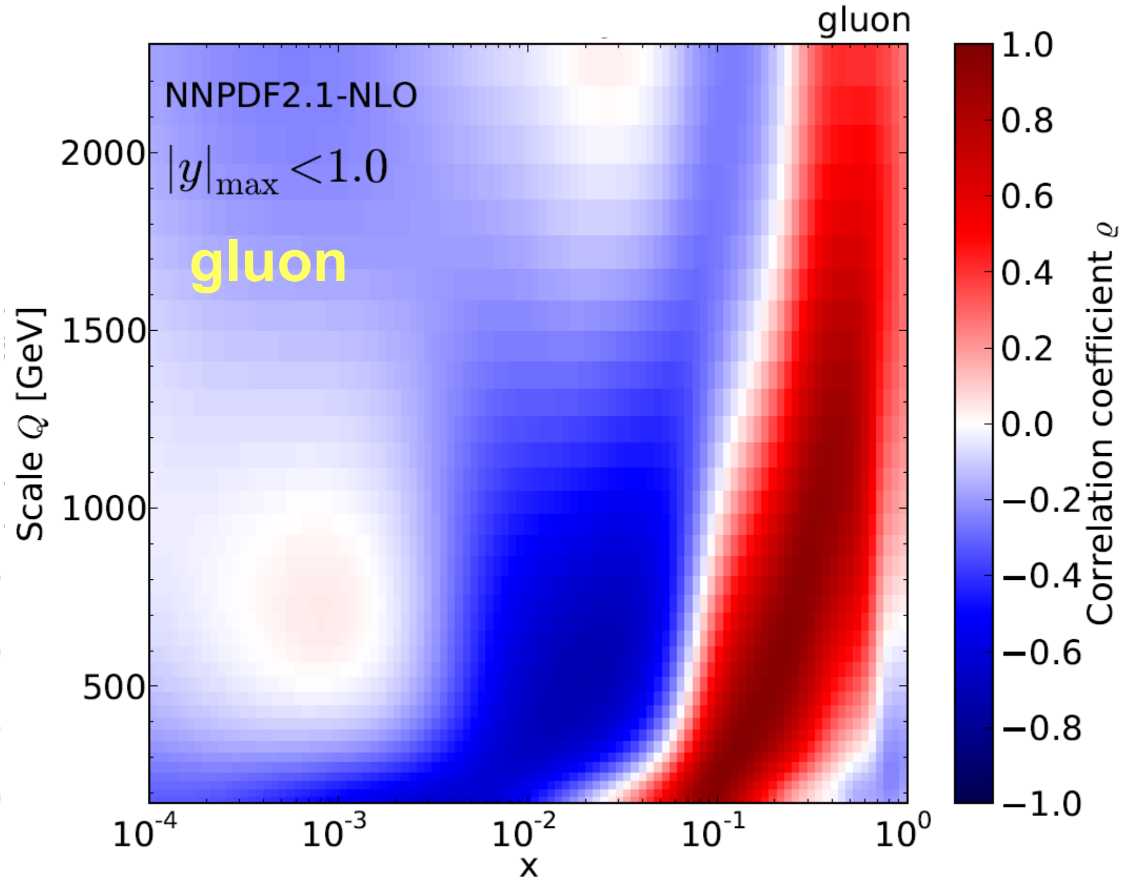
Measurement of inclusive jets at large pT impacts:

- Gluon density at large x (> 0.1)
- Quark density at large x (> 0.3)

Works nicely with statistical ensemble uncertainties of NNPDF!

$$\varrho_f(x,Q) = \frac{N}{(N-1)} \frac{\langle \sigma_{\text{jet}}(Q)_i \cdot xf(x,Q^2)_i \rangle - \langle \sigma_{\text{jet}}(Q)_i \rangle \cdot \langle xf(x,Q^2)_i \rangle}{\Delta_{\sigma_{\text{jet}}(Q)} \Delta_{xf(x,Q^2)}}.$$



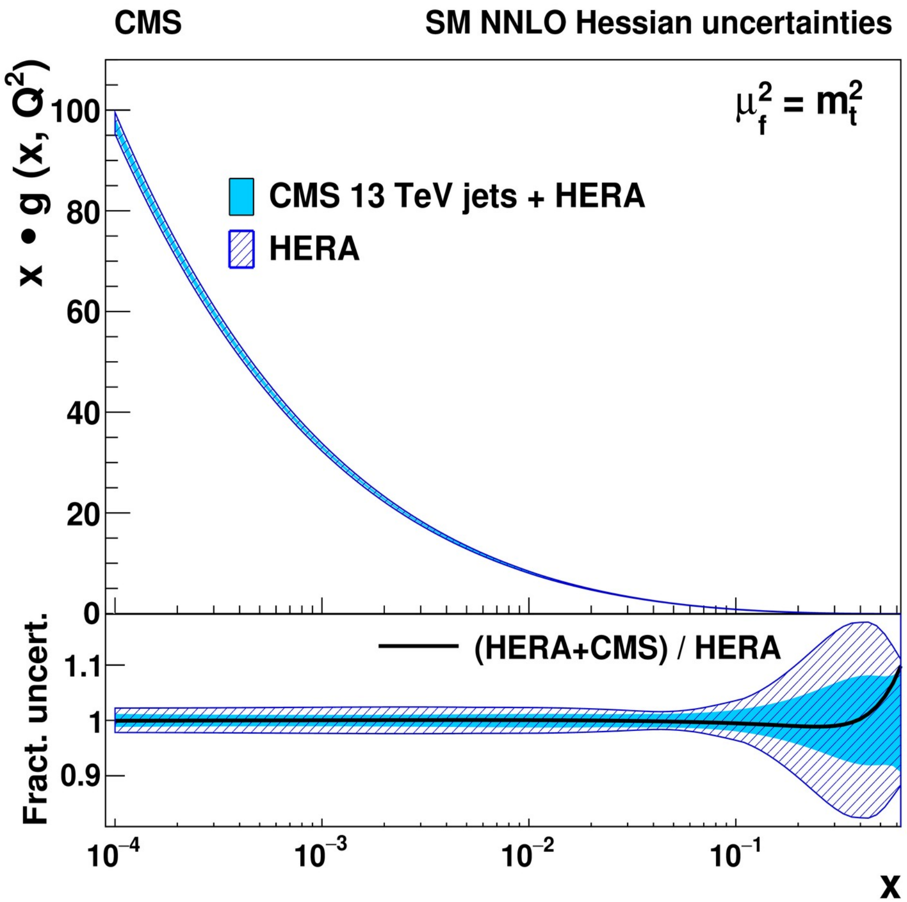


Inclusive jets: α_s & PDFs

Simultaneous fit of α_s & PDFs possible combining HERA DIS & CMS jet data using xFitter Tool

CMS result for $\alpha_s(M_Z)$ at NNLO: $\alpha_s(m_Z^2) = 0.1166 \pm 0.0016(\text{fitall}) \pm 0.0004(\text{scl})$

Reduced uncertainties of gluon PDF



xFitter (HERAFitter): Alekhin et al., EPJC 75 (2015) 304.

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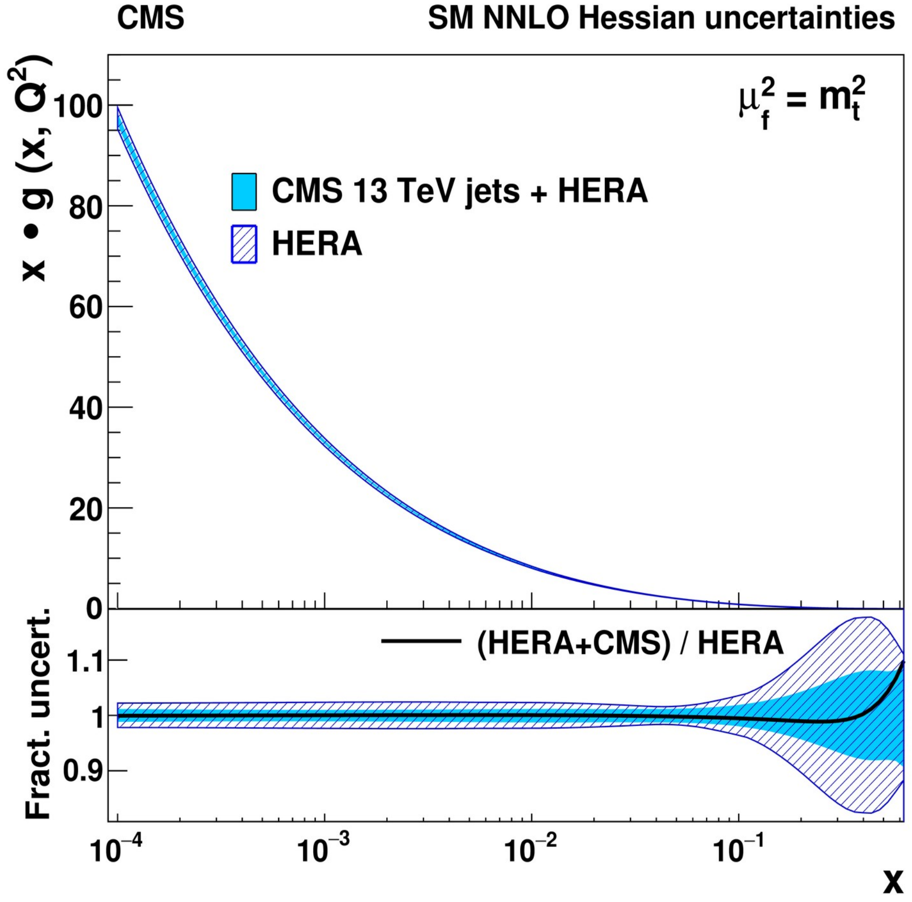


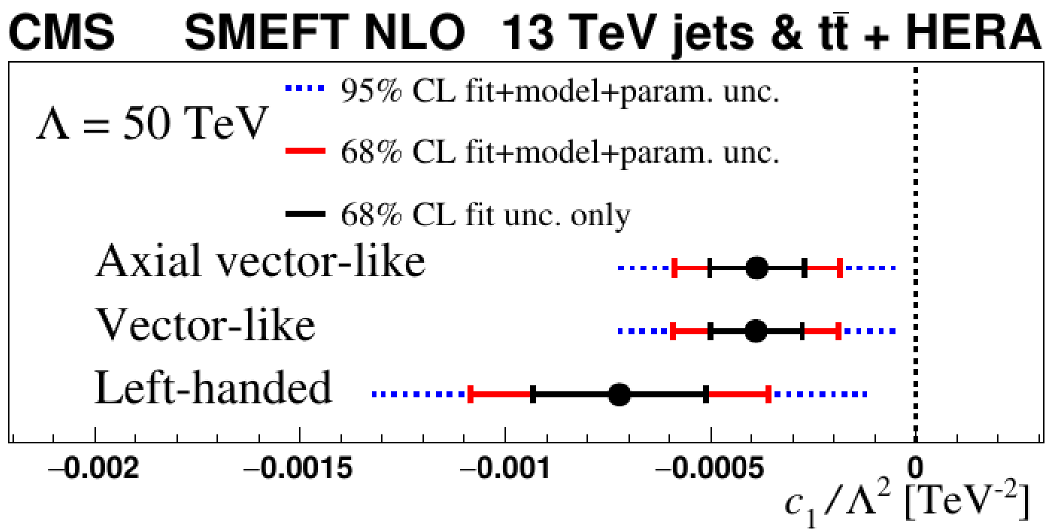
xFitter (HERAFitter): Alekhin et al., EPJC 75 (2015) 304.

Also NLO fit of α_s & PDFs & CI

Data compatible with SM → exclusion limits

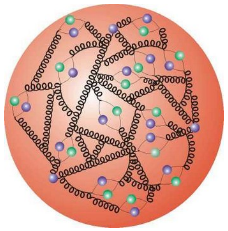
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{2\pi}{\Lambda^2} \sum_{n\in\{1,3,5\}} c_n O_n.$$

EFT

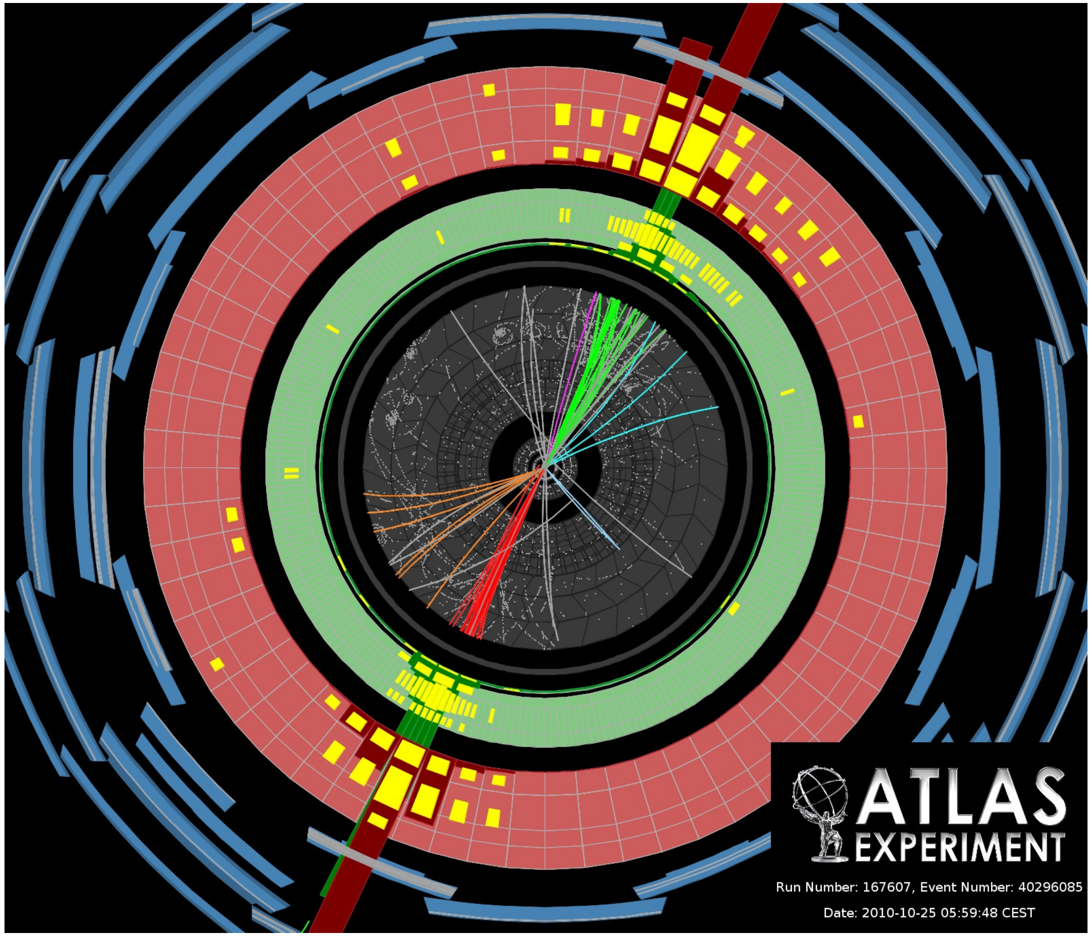


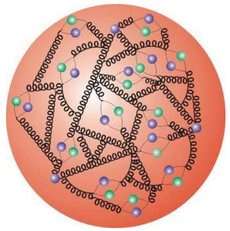
Dijets

Large masses



Proton





Proton

$$\frac{d^2\sigma}{dy_{max}dm_{1,2}} = \frac{1}{\varepsilon\,\mathcal{L}_{int}}\frac{N}{(2\,\Delta|y|_{max})\Delta m_{1,2}}.$$

$$\frac{d^3\sigma}{dy^* dy_b dx} = \frac{1}{\varepsilon\,\mathcal{L}_{int}}\frac{N}{\Delta y^* \Delta y_b \Delta x}.$$

Comparison to NNLO

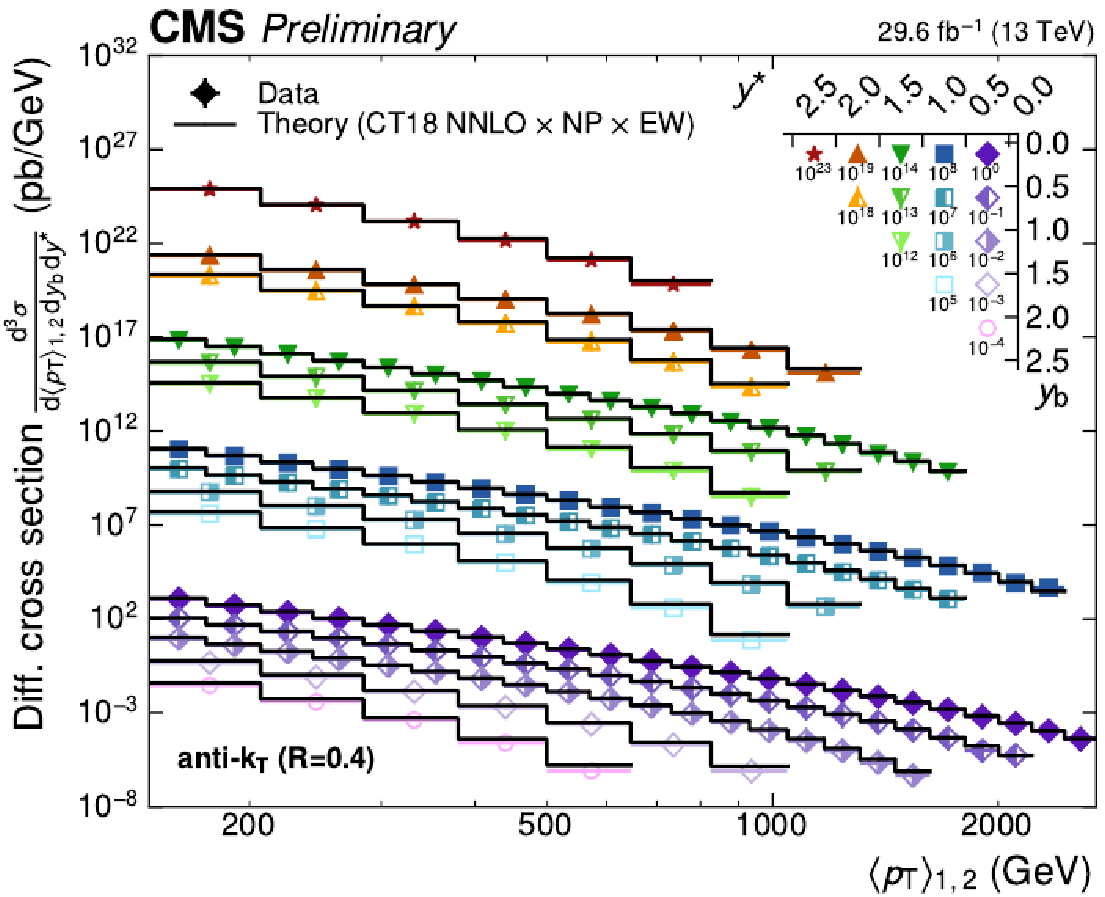
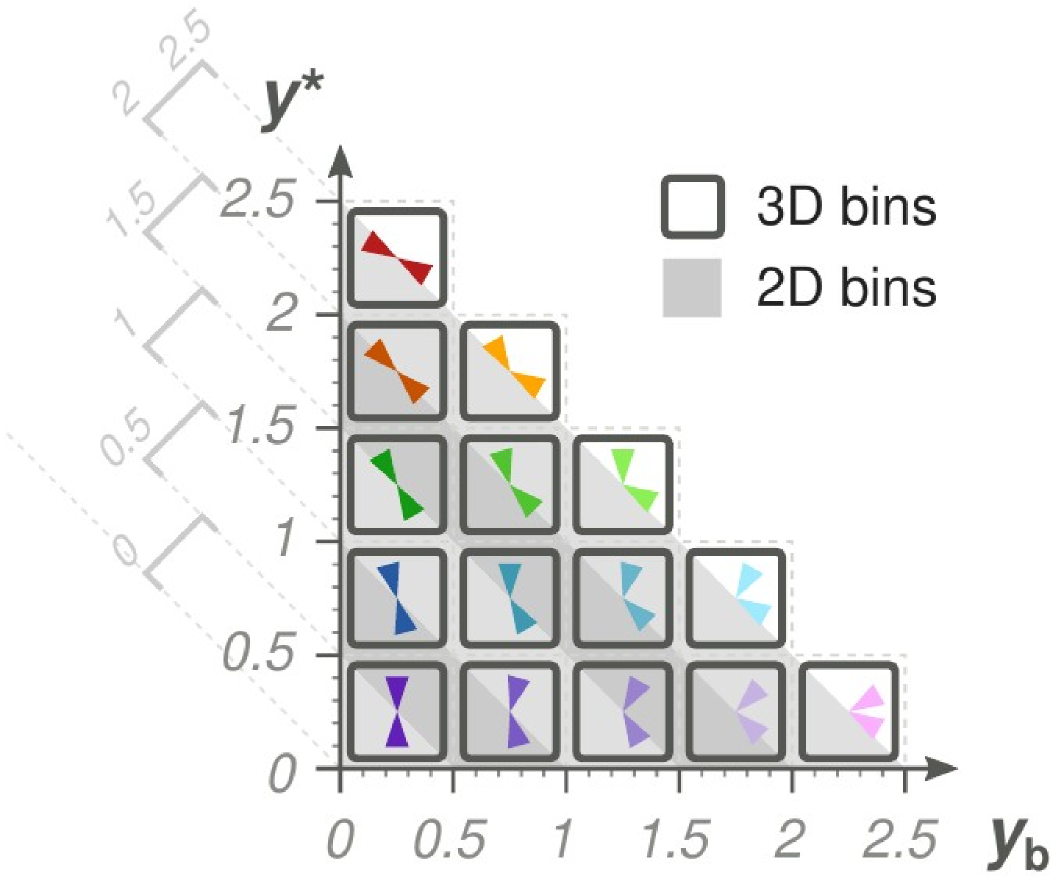


Illustration of dijet event topologies

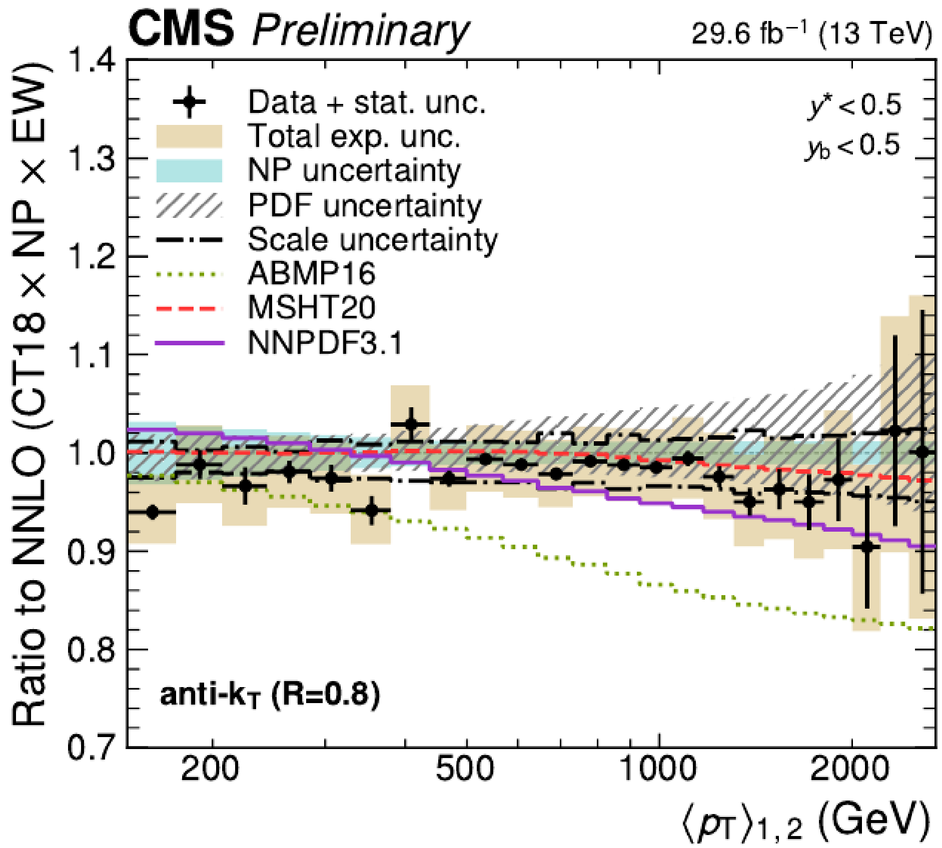


CMS, PAS-SMP-21-008 (2022).

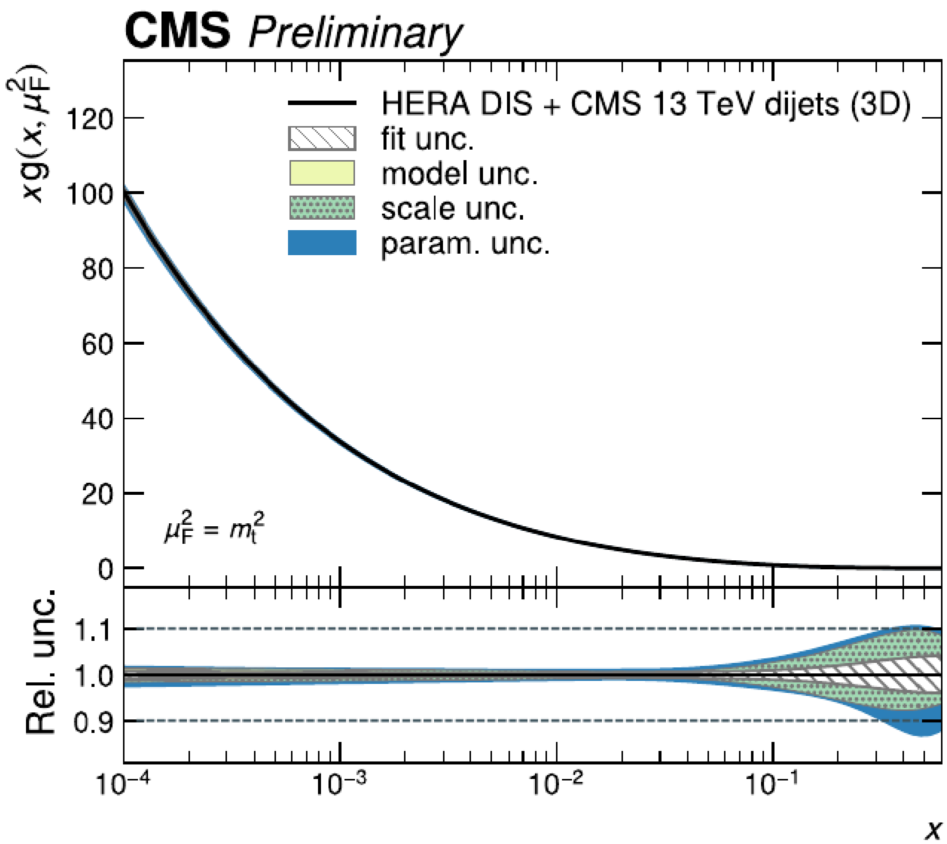
Double/Triple-differential dijets

Simultaneous fit of α_s & PDFs combining HERA DIS & CMS djet data using xFitter Tool

Data over NNLO pQCD x NP x EW corrections →



Determine gluon PDF



Determine strong coupling

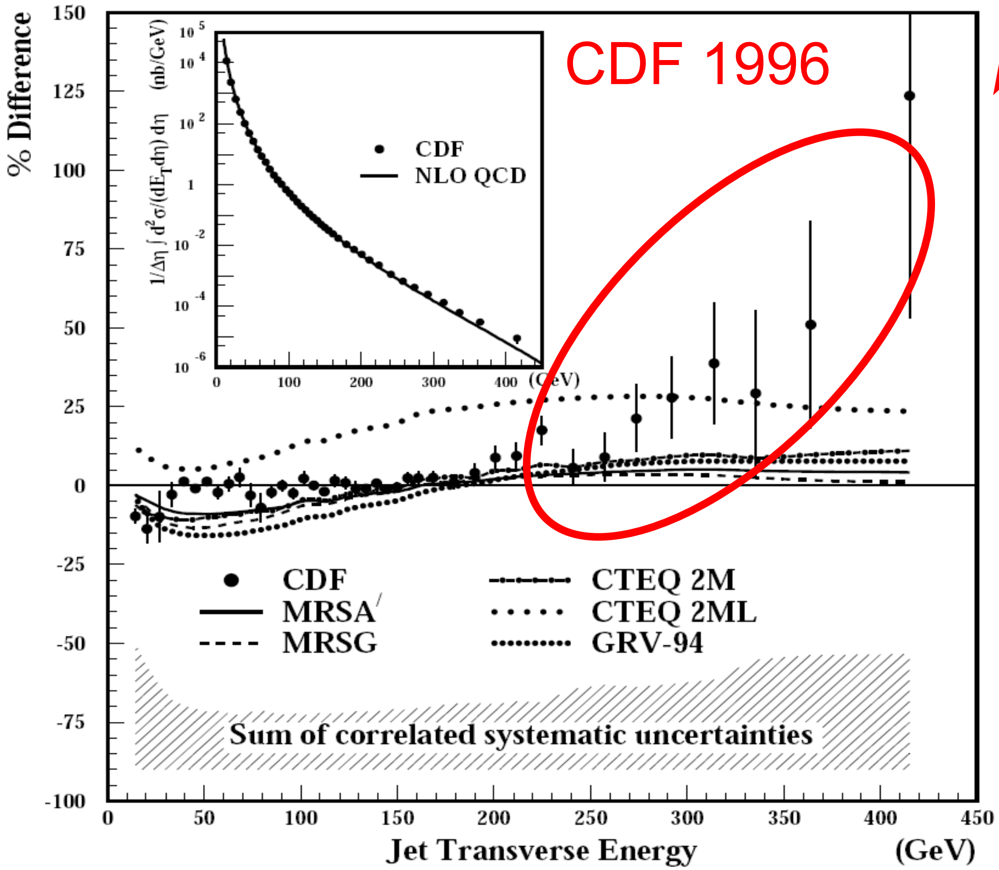
2D $\alpha_s(m_Z)$ = **0.1201** (12)$_{fit}$ (8)$_{scale}$ (8)$_{model}$ (5)$_{param}$

3D $\alpha_s(m_Z)$ = **0.1201** (10)$_{fit}$ (5)$_{scale}$ (8)$_{model}$ (6)$_{param}$

New physics ?

"The data are compared with QCD predictions for various sets of parton distribution functions.
The cross section for jets with E_T>200 GeV is significantly higher than current predictions based on $O(\alpha_S^3)$ perturbative QCD calculations. ..."

Explained by better adaptation of gluon density in proton! → $g(x,Q^2)$



CDF Run 1: Phys.Rev.Lett. 77 (1996)

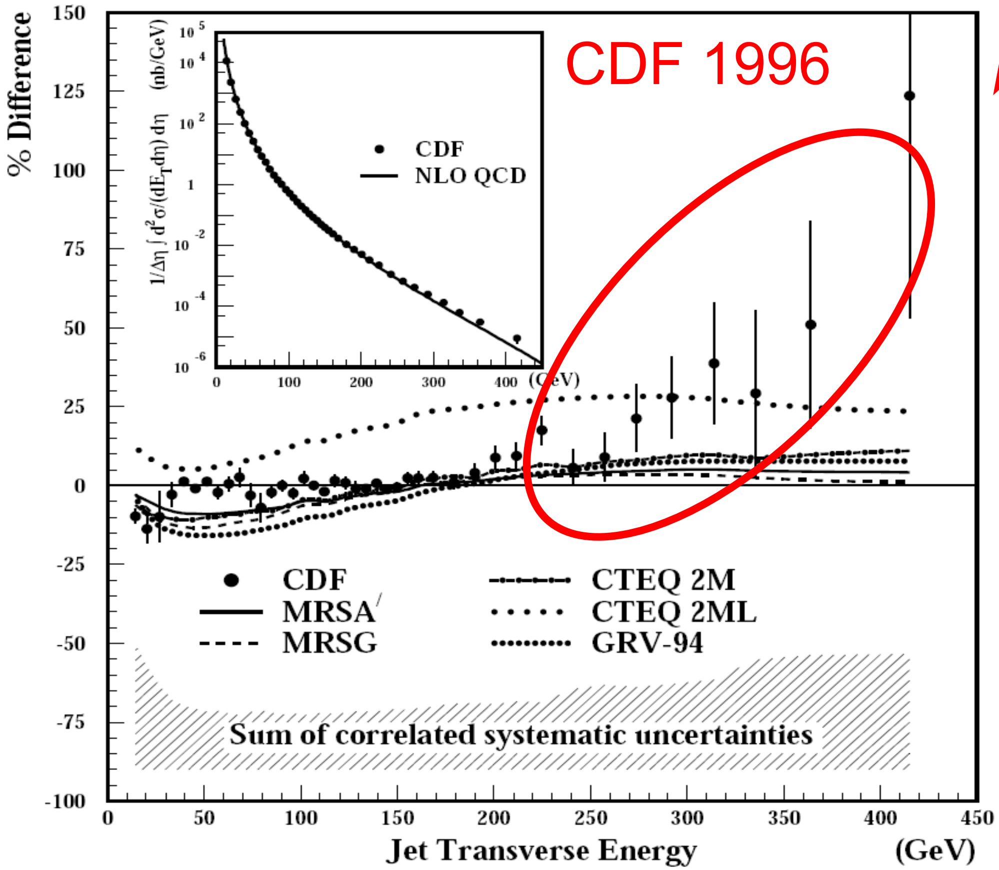
New physics ? Not yet.

"The data are compared with QCD predictions for various sets of parton distribution functions.
The cross section for jets with E_T>200 GeV is significantly higher than current predictions based on $O(\alpha_S^3)$ perturbative QCD calculations. ..."

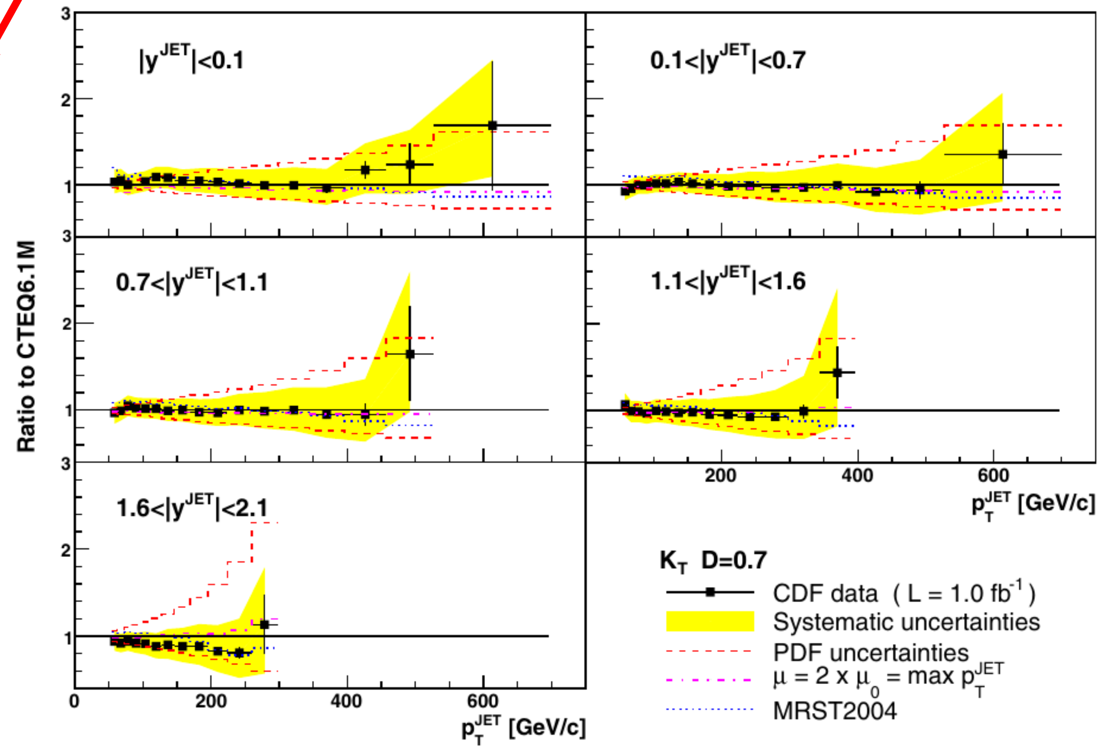
Explained by better adaptation of gluon density in proton! → $g(x,Q^2)$

Today:

Significantly improved determination of uncertainties

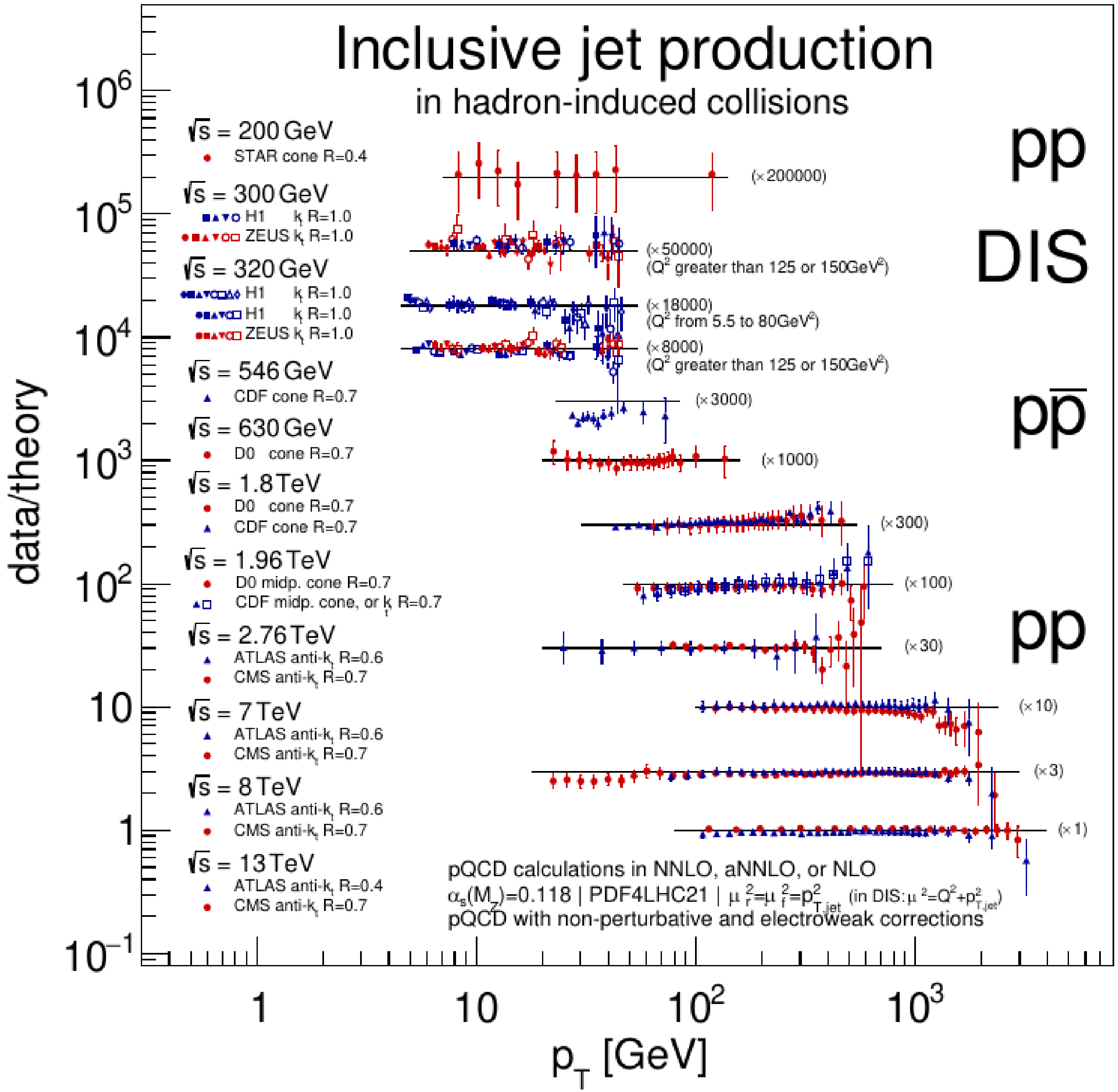


CDF Run 1: Phys.Rev.Lett. 77 (1996)



CDF Run 2: PRD 75 (2007) 092006

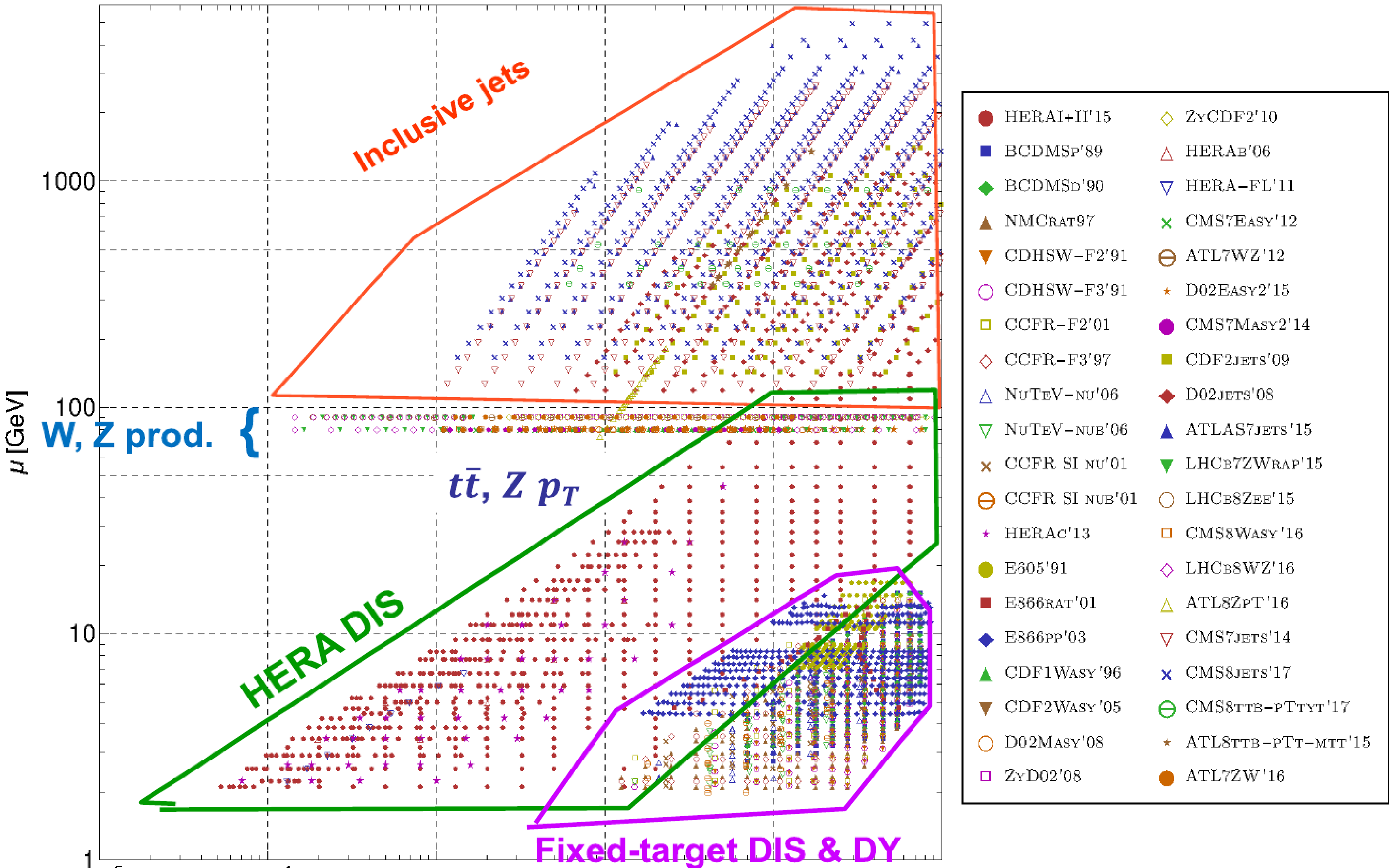
No sign of new physics so far



Ratio of data over theory for a large number of inclusive jet datasets

50 years of QCD, arXiv:2212.11107.

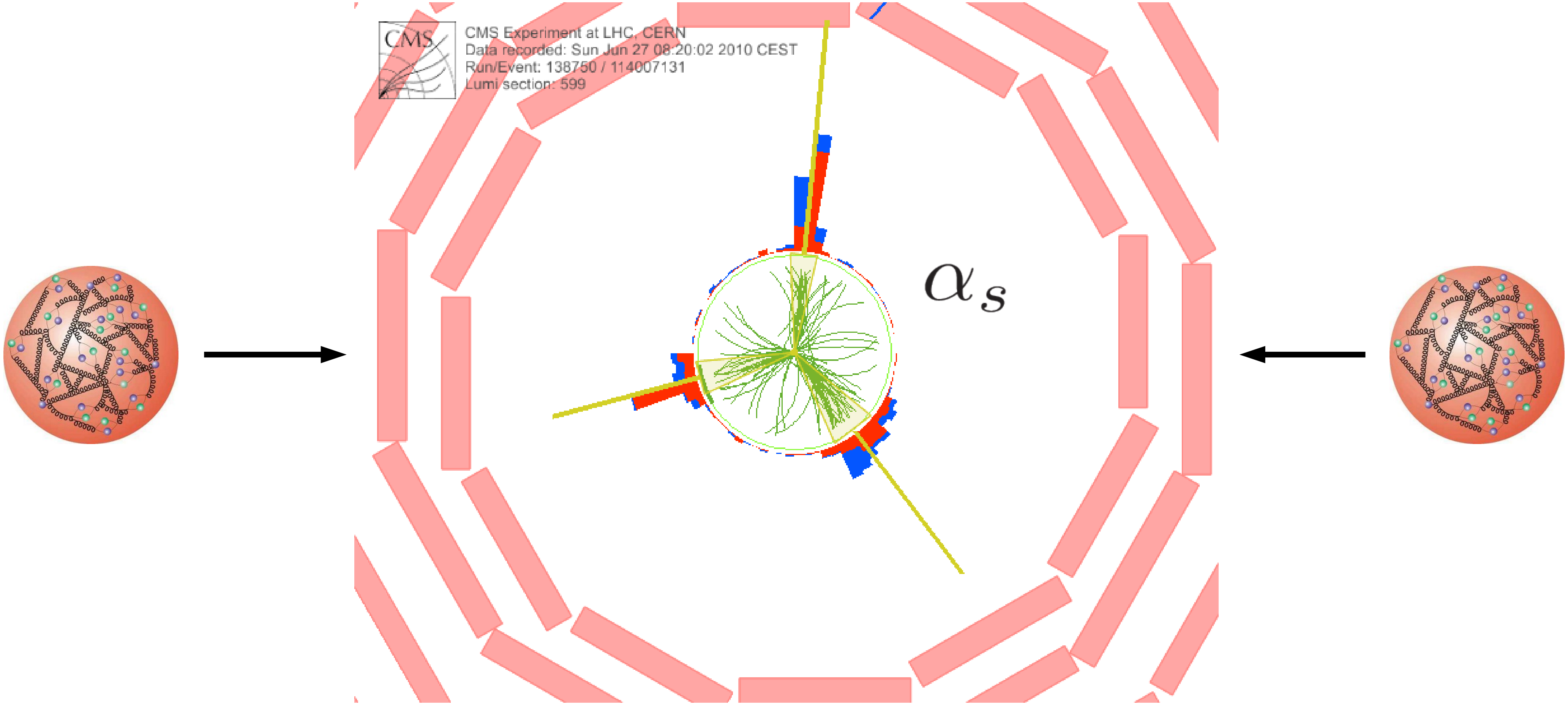
Experimental data in CT18 PDFs



From P. Nadolsky (CTEQ), 17.05.2020.

Multi-jets

Higher multiplicity



Jet cross section ratios

- Determination of $\alpha_s(M_Z)$ in single-parameter fit
- Test running of $\alpha_s(Q)$ (reduced PDF dependence)
- Some reduction in sensitivity
- But cancellation of many systematic effects
- More scale choices

Jet-radius ratios

- Examine radius dependence of jet cross section:
  - "LO" – two partons in opposite directions
  - → Always two jets, independently of algorithm → ratio trivially unity
  - First non-trivial order needs THREE partons
  - → 3-jet observable, LO corresponds to NLO dijet production → NLOJet++
- Definition:

$$\left(\frac{\mathrm{d}\sigma^{\mathrm{alt}}}{\mathrm{d}p_{\mathrm{T}}}-\frac{\mathrm{d}\sigma^{\mathrm{ref}}}{\mathrm{d}p_{\mathrm{T}}}\right)\Big/\left(\frac{\mathrm{d}\sigma^{\mathrm{ref}}}{\mathrm{d}p_{\mathrm{T}}}\right)=\mathscr{R}(\mathrm{alt},\mathrm{ref})-1$$

3-Jet NLO 2-Jet NLO

- "alt" and "ref" could be two different jet algorithms
  - ZEUS e.g. investigated kT, anti-kT and SISCone
  - ALICE + CMS: Two different jet radii for anti-kT

ZEUS, PLB691 (2010) 127.

Jet radius ratios

Cross-section ratio for R = 0.5/0.7

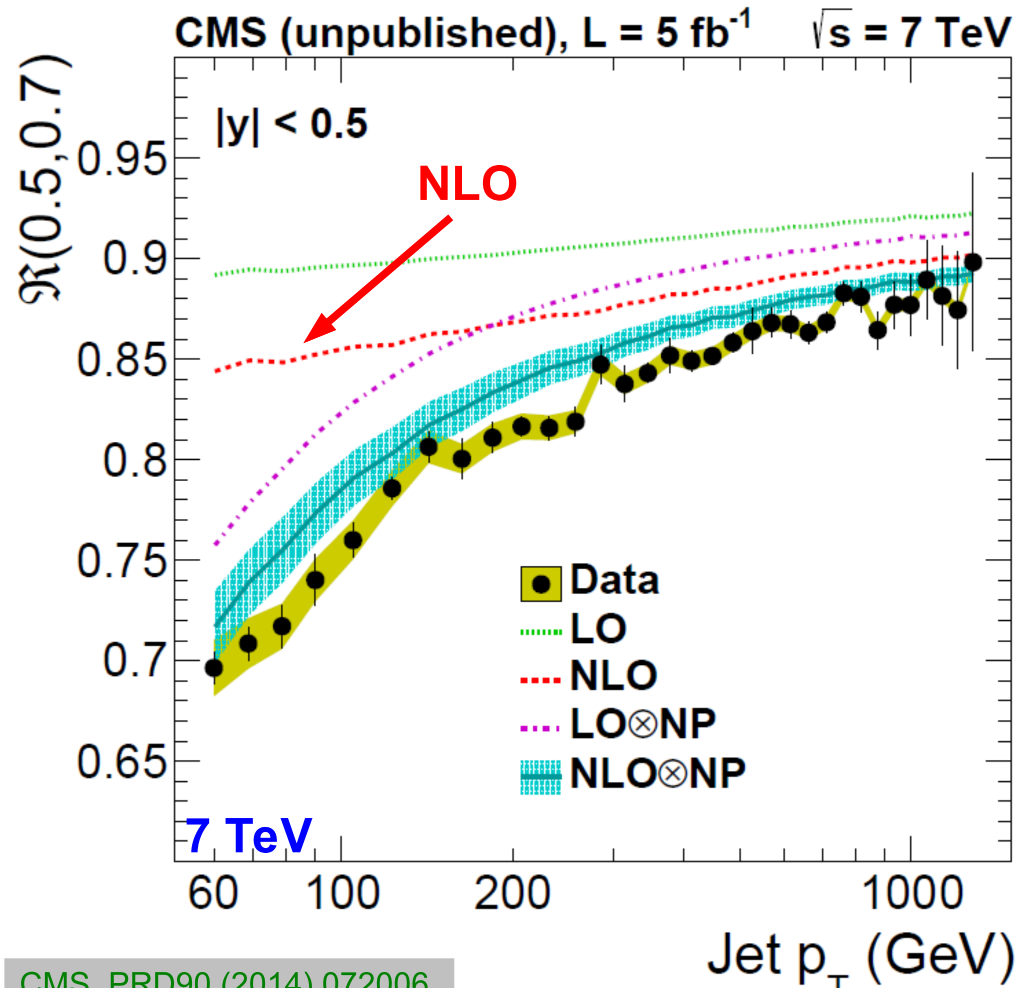
Emphasizes effect of parton shower and hadronisation
→ NLO 3-jet not sufficient!

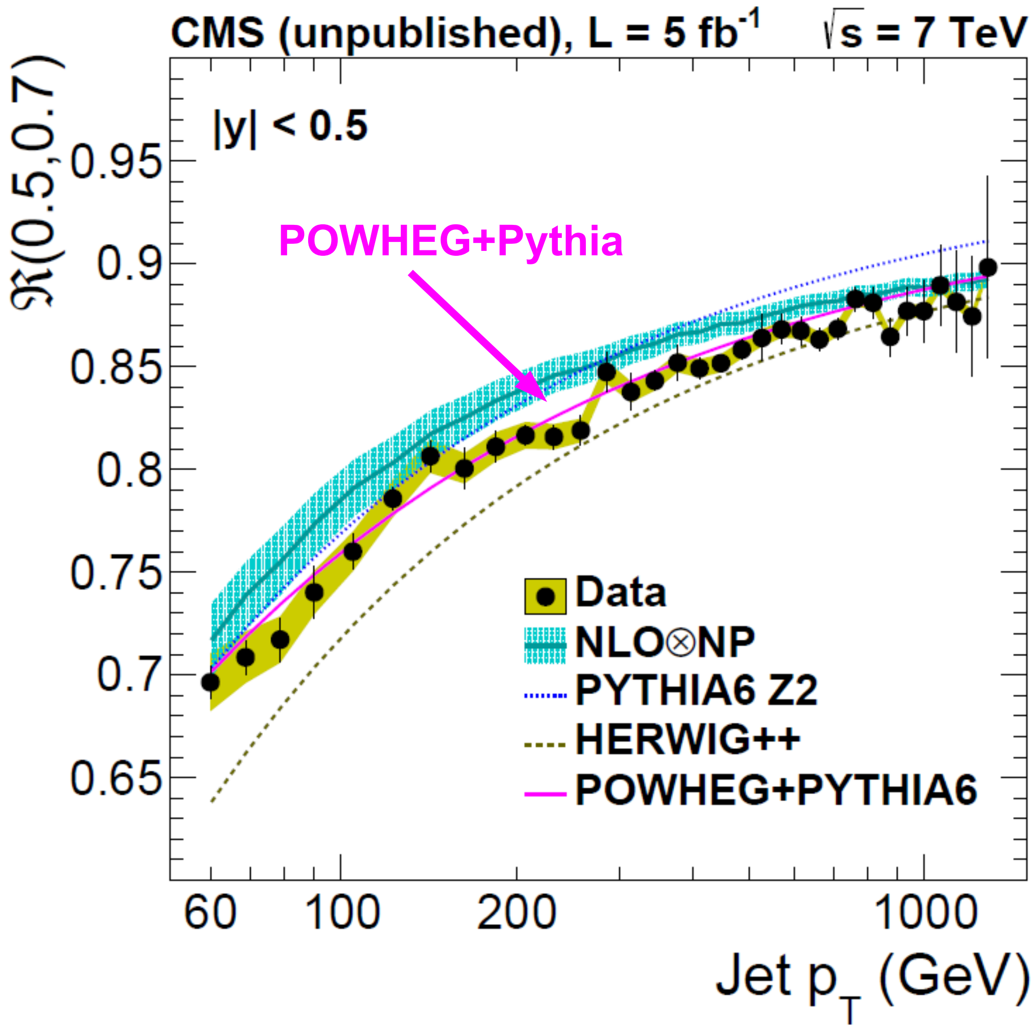
Needs event generators:
LO+PS+HAD → better (Pythia6,Herwig++)
NLO+PS+HAD → best (POWHEG+Pythia)

G. Soyez, PLB698 (2011).

ALICE study R=0.2 / R=0.4

ALICE, PLB722 (2013).





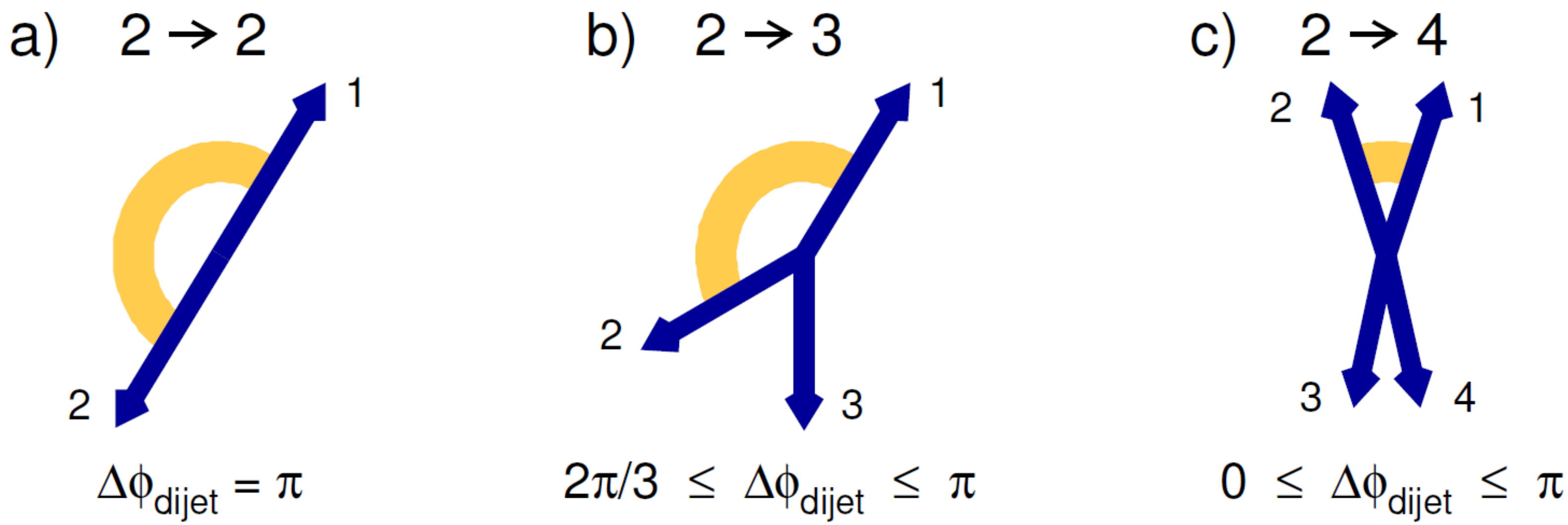
CMS, PRD90 (2014) 072006.

Dijet azimuthal decorrelation

Determine $\alpha_s(Q)$ from additonal parton branchings separated in Φ around the two leading jets. Binning in sum of scalar transverse momentum H_T and rapidity separation y^*.

$$R_{\Delta\phi}(H_T, y^*; \Delta\phi_{\max}) = \frac{\dfrac{d^2\sigma_{\text{dijet}}(\Delta\phi_{\text{dijet}} < \Delta\phi_{\max})}{dH_T dy^*}}{\dfrac{d^2\sigma_{\text{dijet}}(\text{inclusive})}{dH_T dy^*}}$$

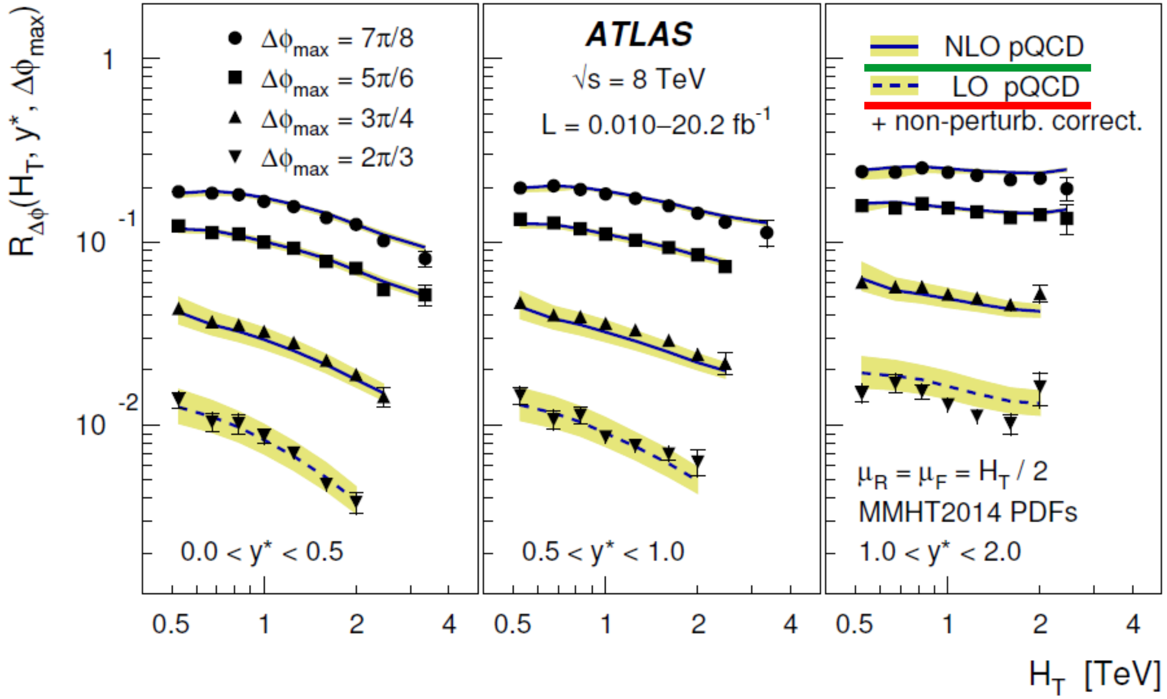
$$R_{\Delta\phi} \propto \alpha_s$$



If $\Delta\varphi_{max}$ in 3-jet region

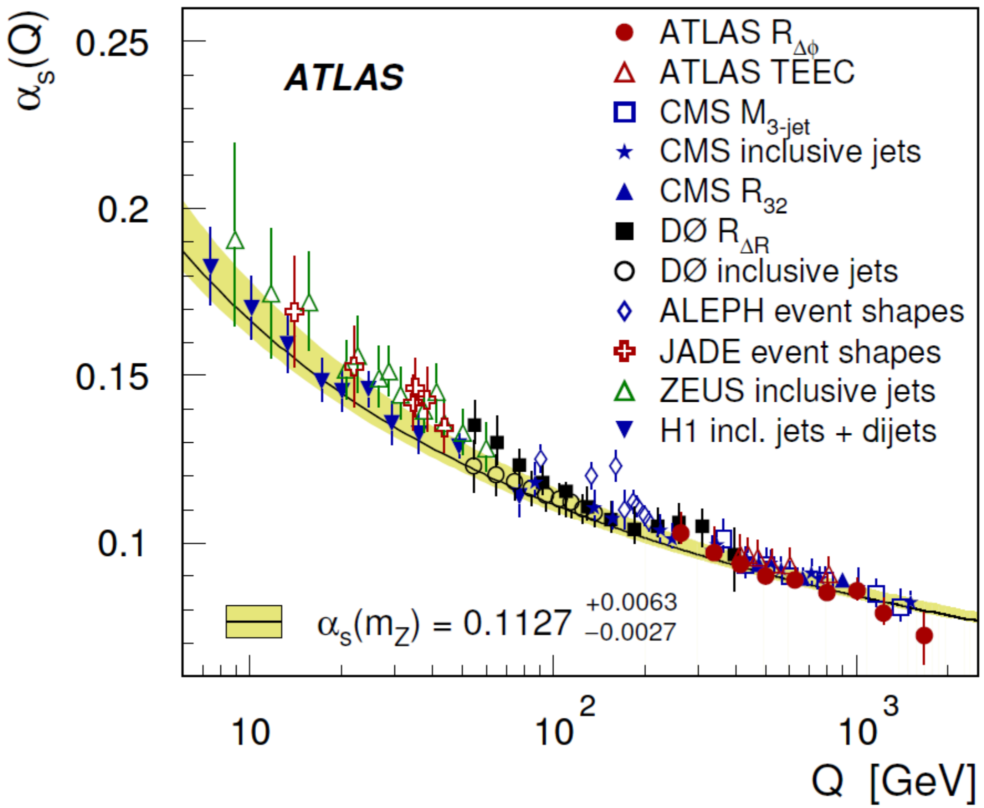
Wobisch et al., JHEP 01 (2013) 172;
KR, M. Wobisch, JHEP 12 (2015) 024.

$R_{\Delta\Phi}$ in bins of $Q = H_T/2$



Theory:
3-jet NLOJet++

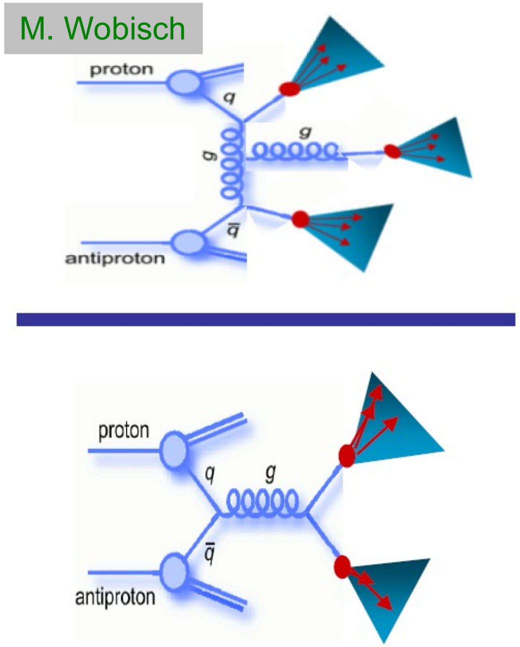
Scale choice: $\mu_R = \mu_F = H_T/2$



From more precise results with
$\Delta\varphi_{max} = 7\pi/8$ in the two y* regions below 1.0:

$$\alpha_S(m_Z) = 0.1127^{+0.0063}_{-0.0027}$$

M. Wobisch

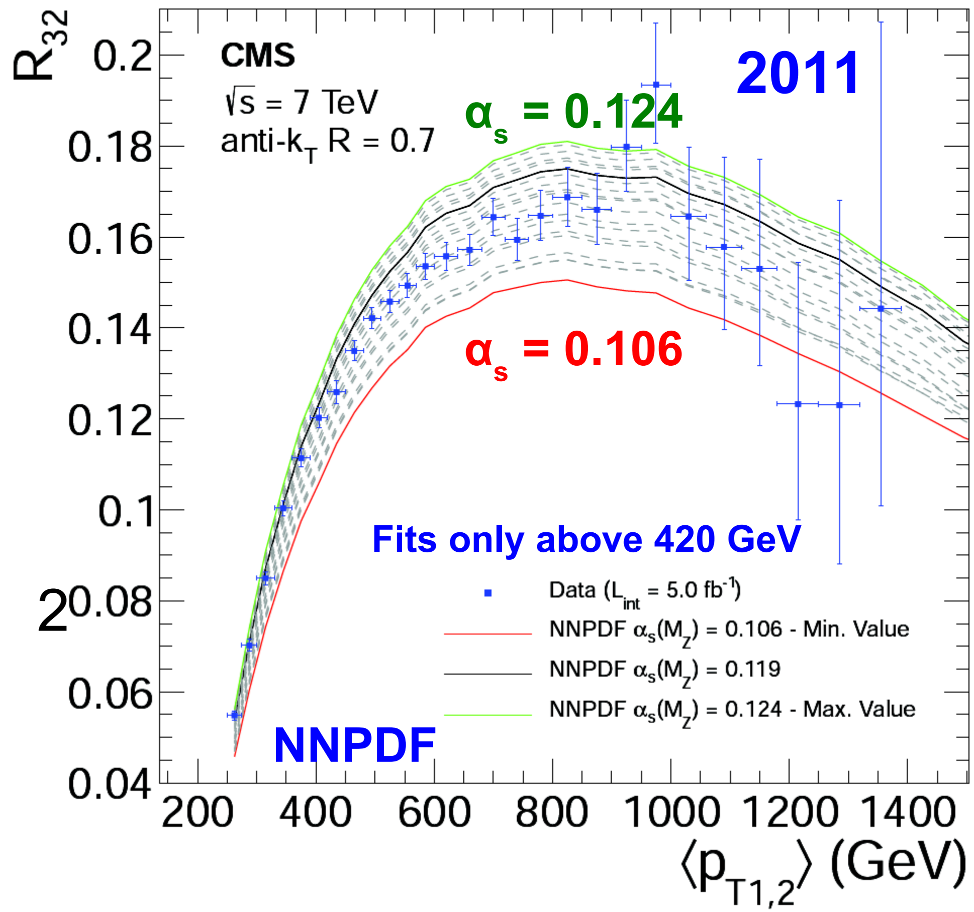


R$_{3/2}$

$\Leftrightarrow$ α_s

$$\frac{\sigma_{3+\text{jet}}}{\sigma_{2+\text{jet}}} \propto \alpha_s^1$$

$$Q = \langle p_{T1,2} \rangle$$



CMS: R$_{3/2}$
- **Ratio of inclusive 3- to inclusive 2-jet events**
- **anti-kT R=0.7**
- **Min. jet pT: 150 GeV**
- **Max. rap.: |y| < 2.5**
- **Data 2011 7 TeV, and 2012 8 TeV prel.**

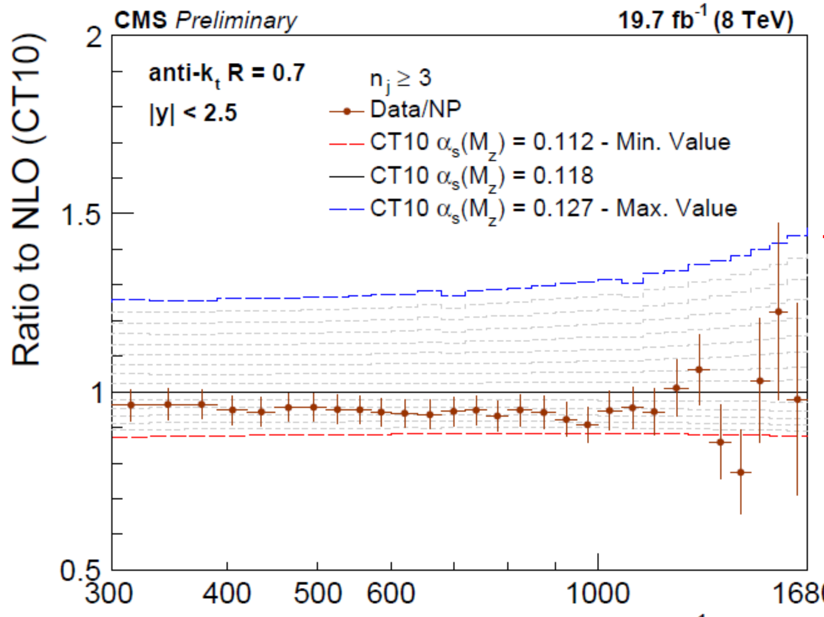
$$\alpha_S(M_Z) = 0.1148 \pm 0.0014\ (\text{exp.}) \pm 0.0018\ (\text{PDF}) \pm 0.0050\ (\text{theory}),$$

BUT do we gain from taking ratios?

Sensitivity vs. systematic effects

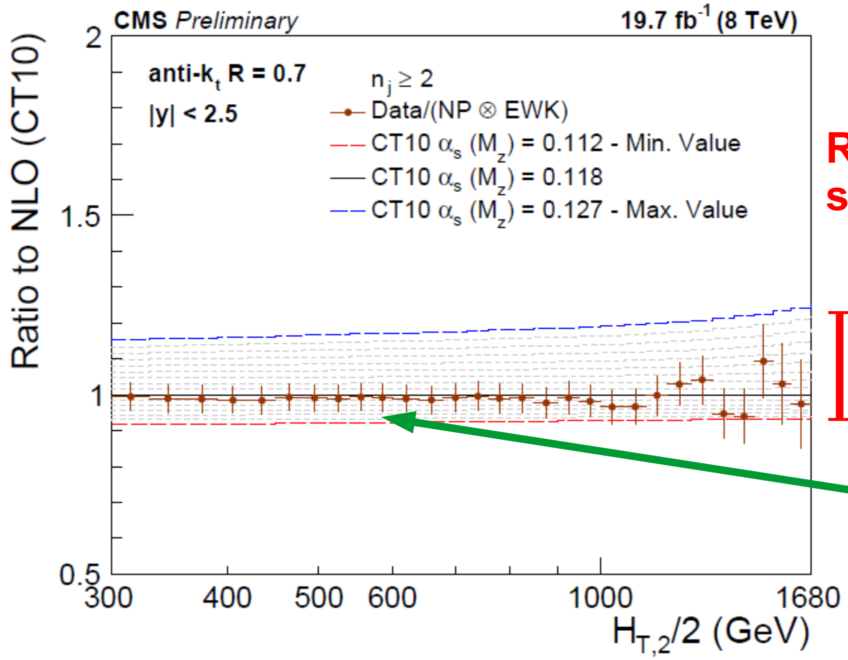
Inclusive 3-jet cross section

$$\sigma_{3j} \propto \alpha_s^3$$



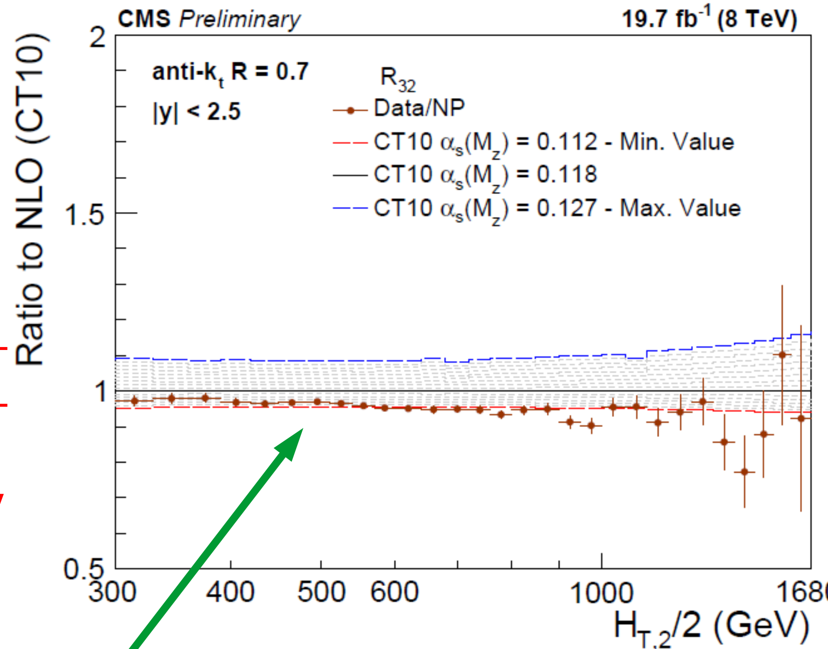
Inclusive 2-jet cross section

$$\sigma_{2j} \propto \alpha_s^2$$



Inclusive 3-jet to inclusive 2-jet cross section ratio

$$R_{3/2} \propto \alpha_s$$



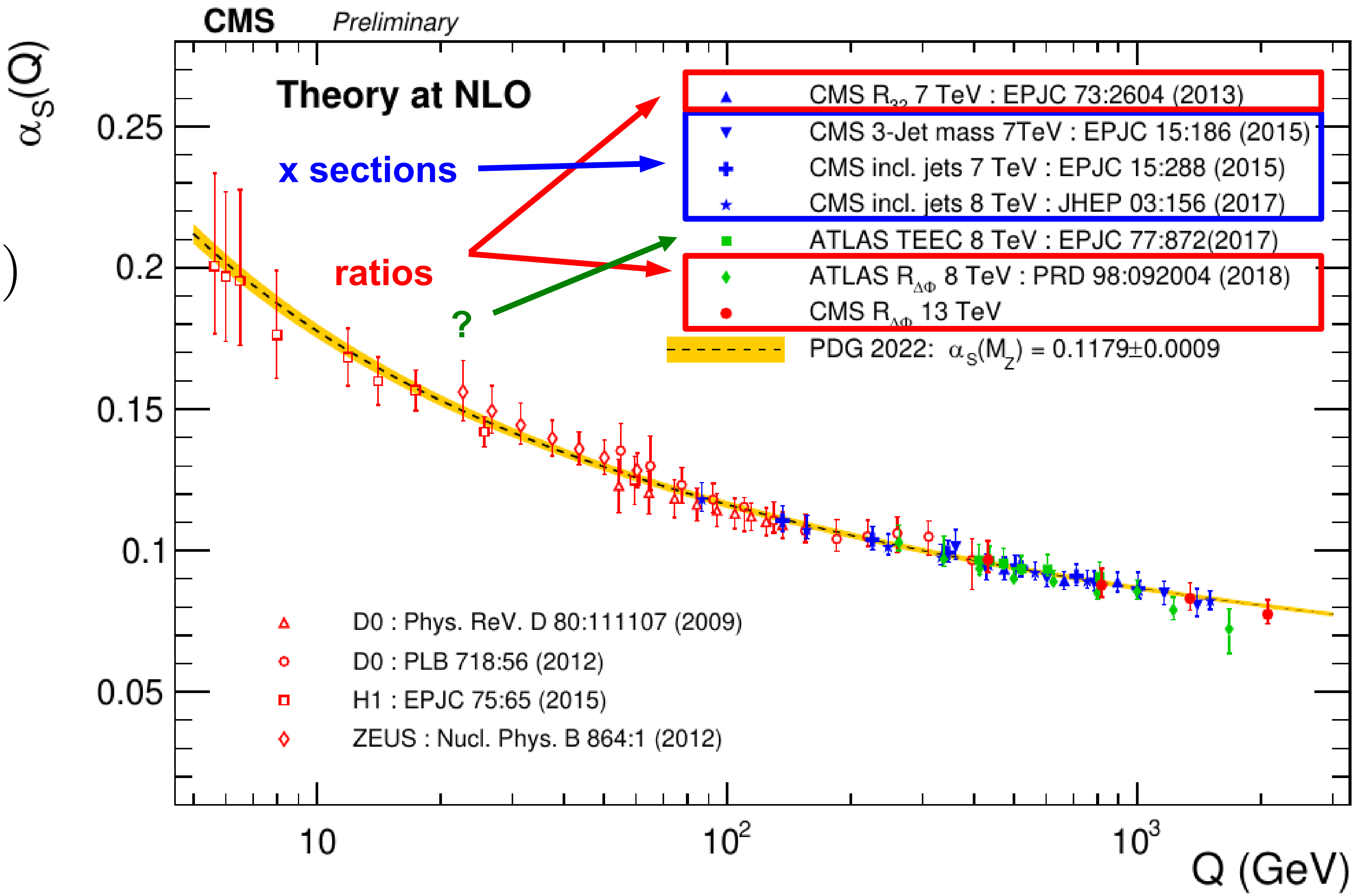
Reduced sensitivity

Much reduced systematic uncertainty

Running of $\alpha_s(Q)$ (CMS style)

Perform fits in fixed intervals of the chosen scale Q

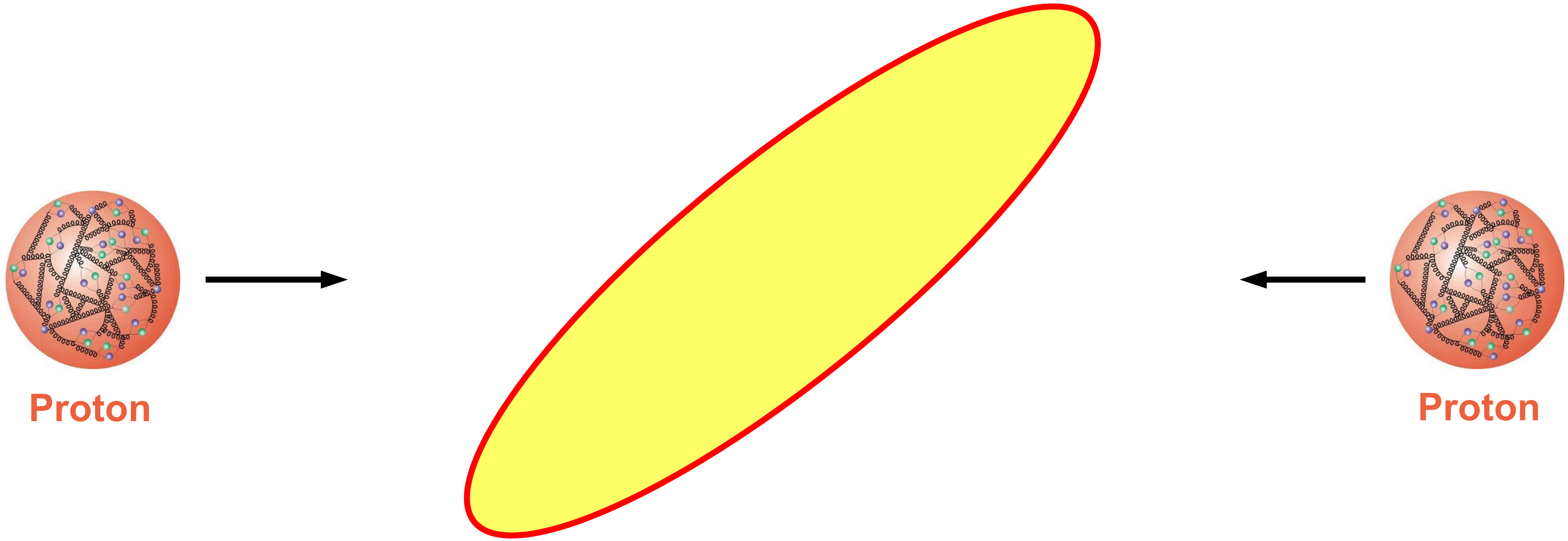
$\rightarrow$ $\alpha_s(Q)$



New range explored at LHC $\rightarrow$

Normalised distributions

Event shapes



Normalised distributions

Pros & cons similar as for cross section ratios ...

- Determination of $\alpha_s(M_Z)$ in single-parameter fit
- Test running of $\alpha_s(Q)$ (reduced PDF dependence)
- Some reduction in sensitivity
- But cancellation of many systematic effects
- More scale choices

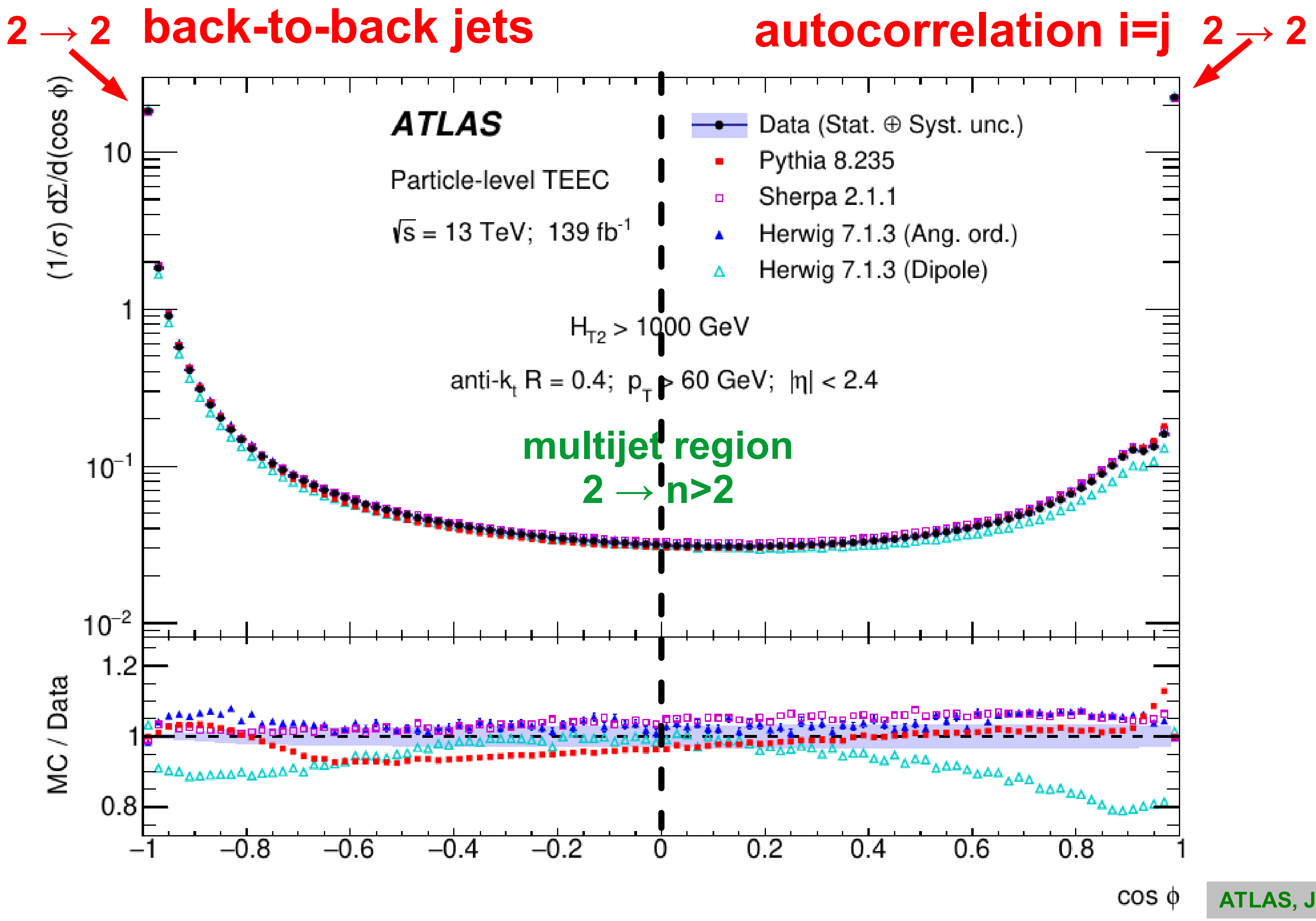
Transverse energy-energy correlation

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\mathrm{T}i}E^A_{\mathrm{T}j}}{\left(\sum_k E^A_{\mathrm{T}k}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

$\mathrm{TEEC} \propto \alpha_s$

Normalised

Multiple bins in H_T



ATLAS, JHEP 07 (2023) 085.

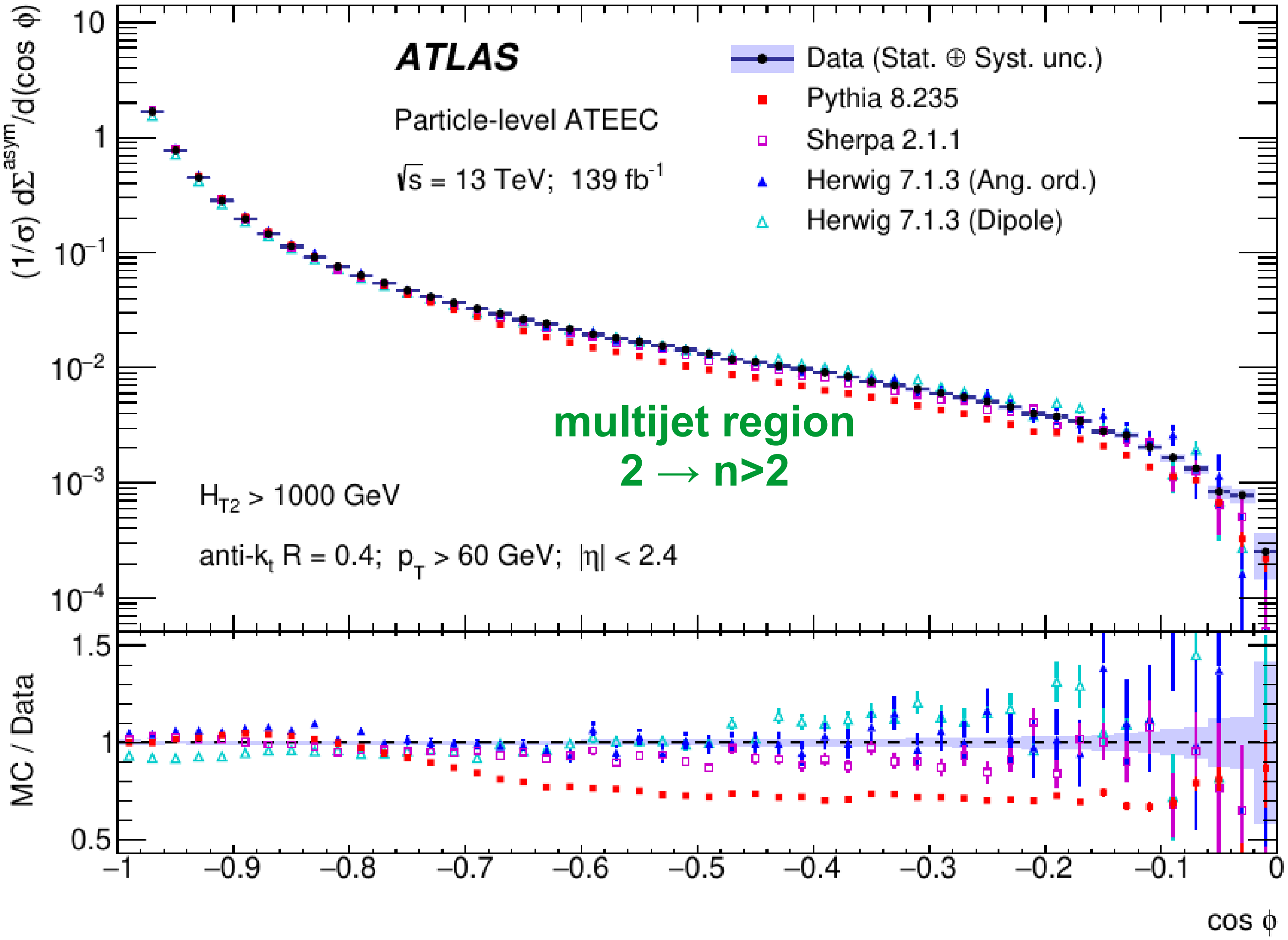
Transverse energy-energy correlation

$$\frac{1}{\sigma}\frac{d\Sigma^{\mathrm{asym}}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

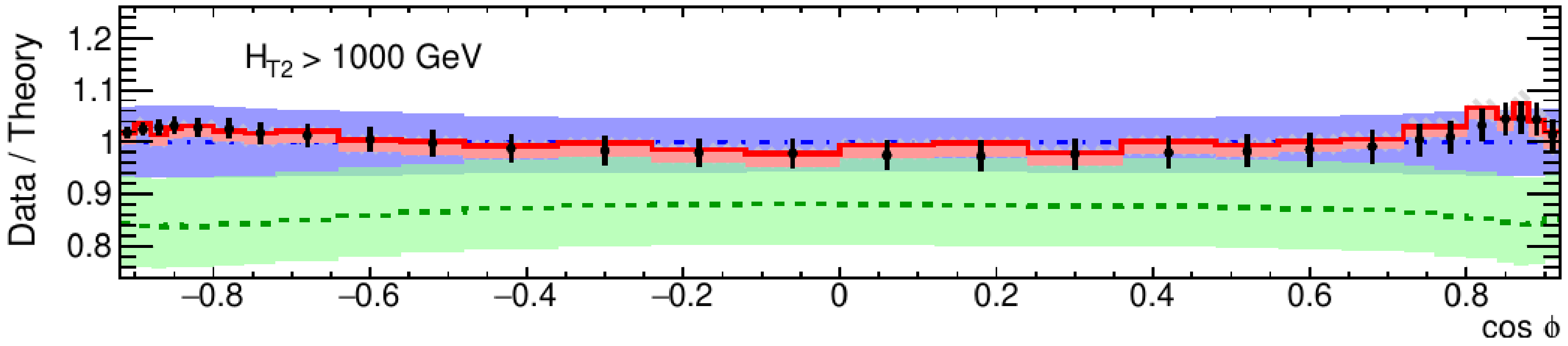
Asymmtry

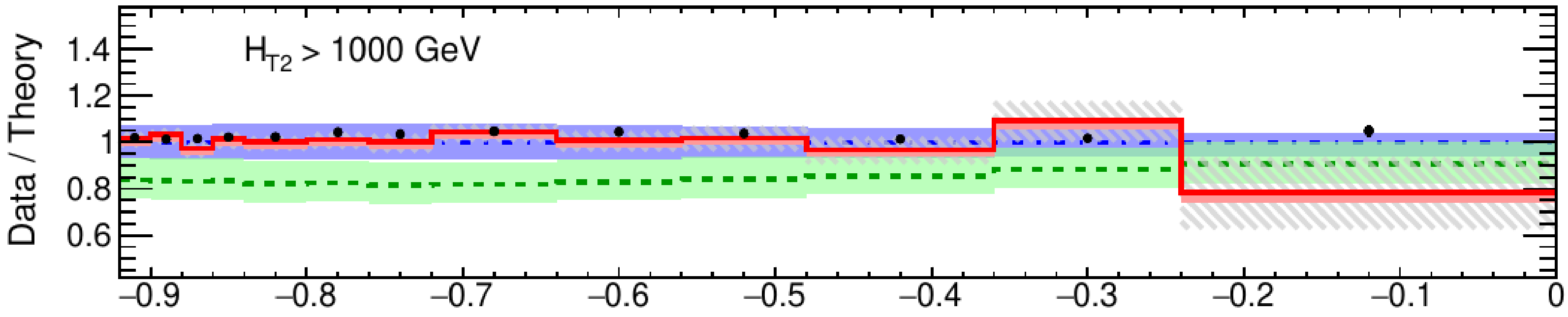
$$\mathrm{ATEEC} \propto \alpha_s$$

Normalised



ATLAS, JHEP 07 (2023) 085.





$$\alpha_s(m_Z) = 0.1175 \pm 0.0006\ (\text{exp.})^{+0.0034}_{-0.0017}\ (\text{theo.})\ \text{and}$$

$$\alpha_s(m_Z) = 0.1185 \pm 0.0009\ (\text{exp.})^{+0.0025}_{-0.0012}\ (\text{theo.}).$$

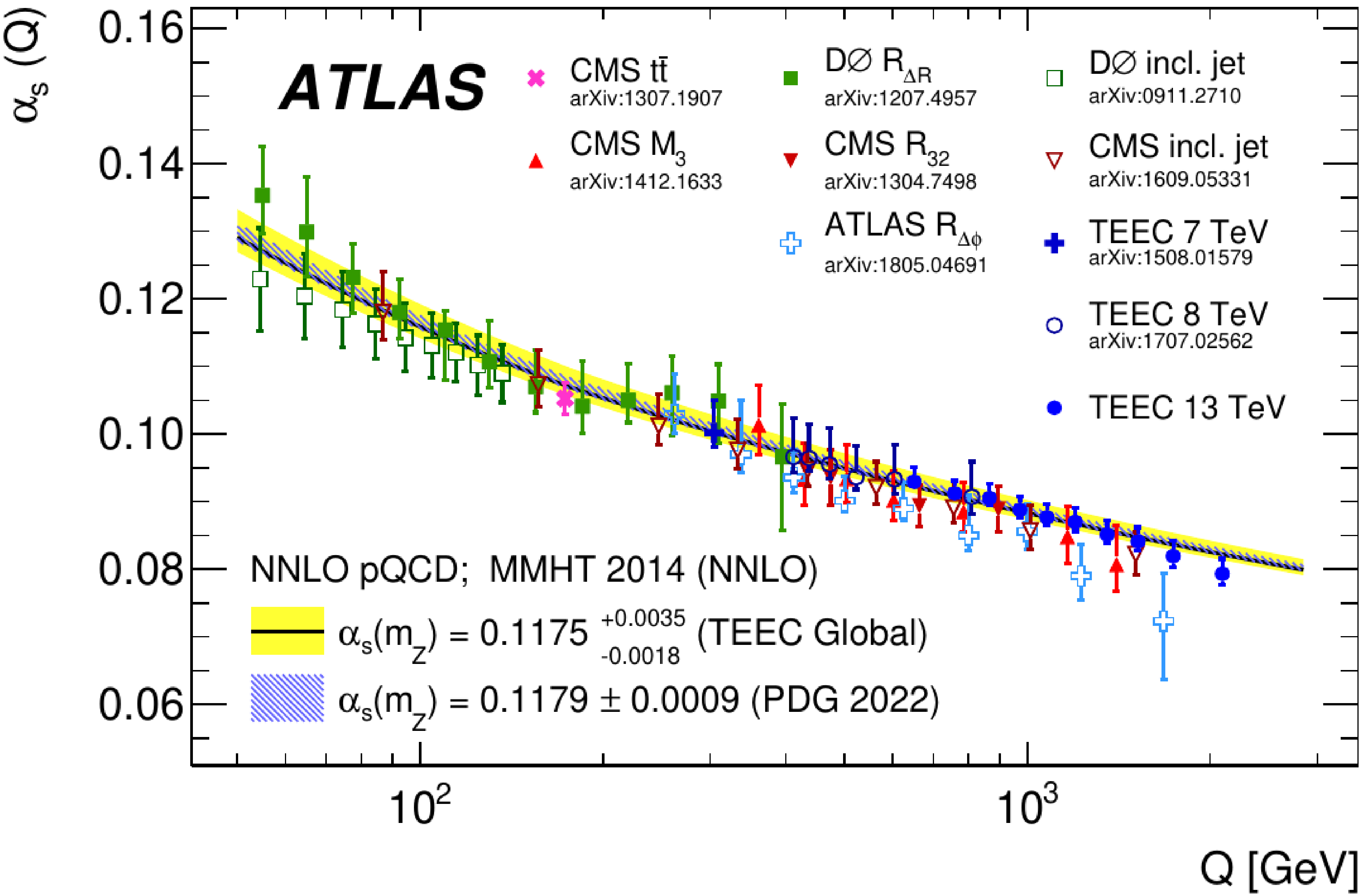
3.jet NNLO:
Czakon, Mitov, Poncelet, PRL 127 (2021) 152001.

Running of $\alpha_s(Q)$ (ATLAS style)

Theory:
3-jet NNLO

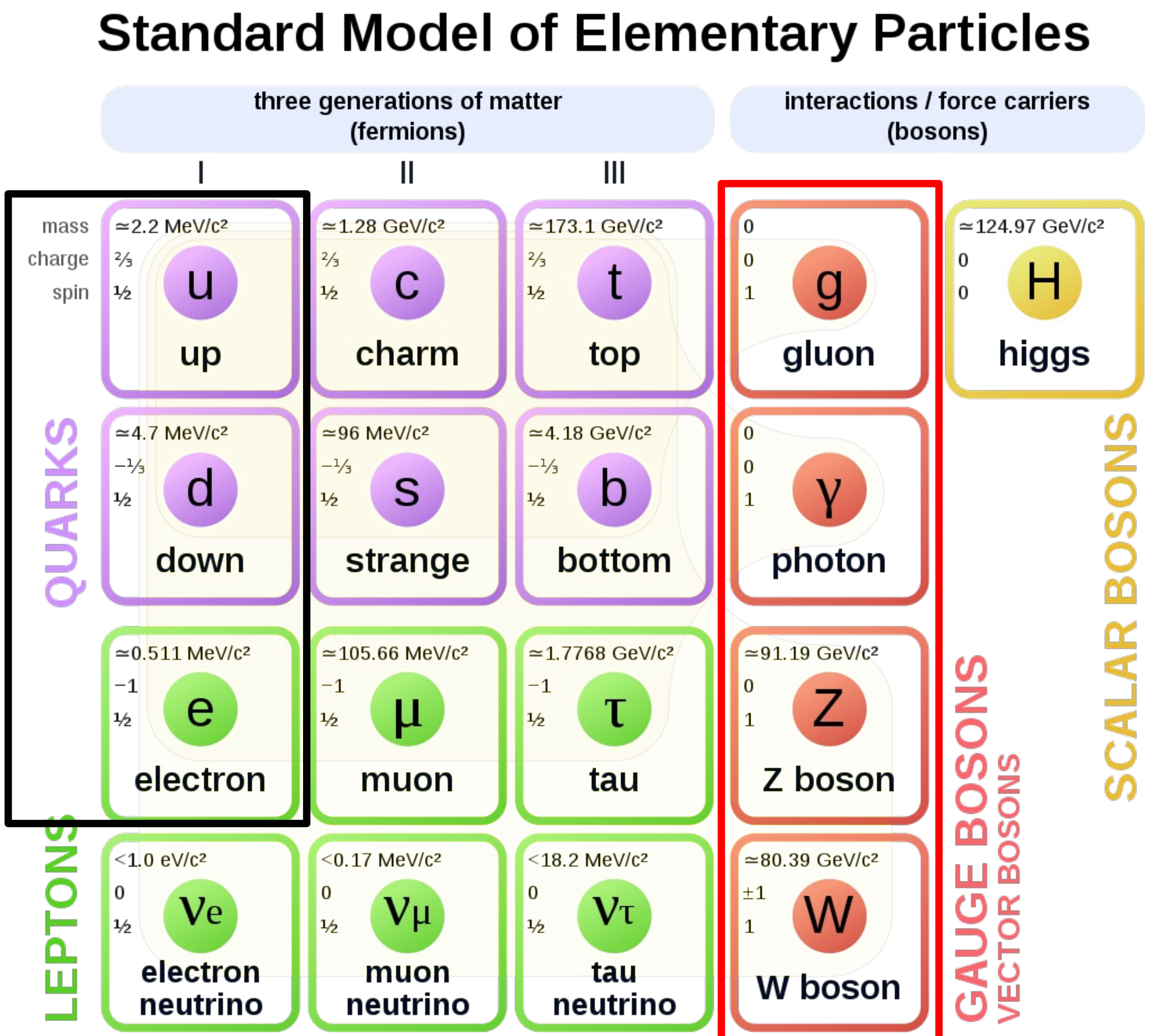
Scale choice:

Run2 13 TeV:
$\mu_R = \mu_F = H_T/2$



Solid matter

...

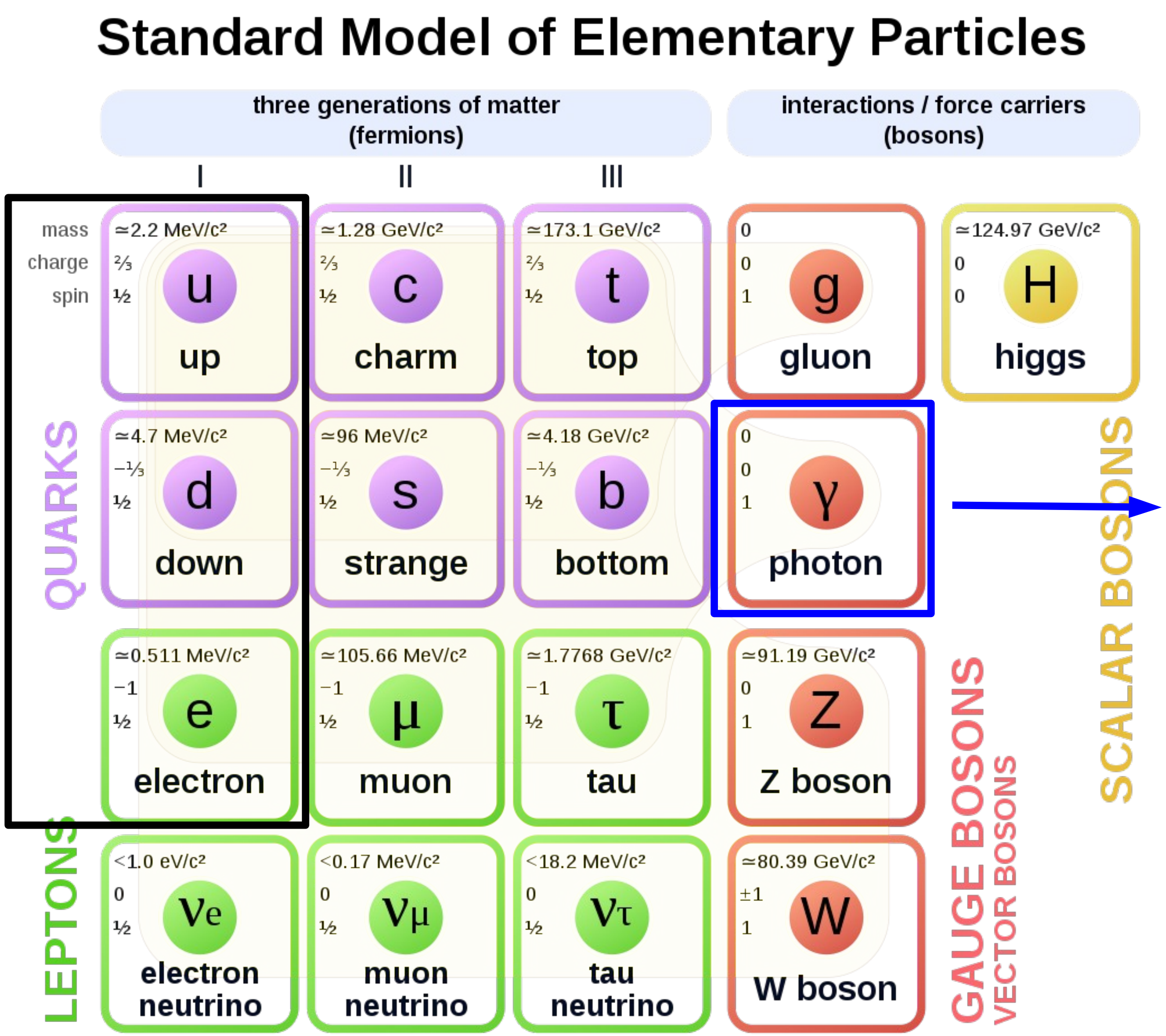


Cush, Wikipedia.

… and three fundamental interactions.
(no gravity)

Standard Model of Particle Physics

Solid matter ...



Cush, Wikipedia.

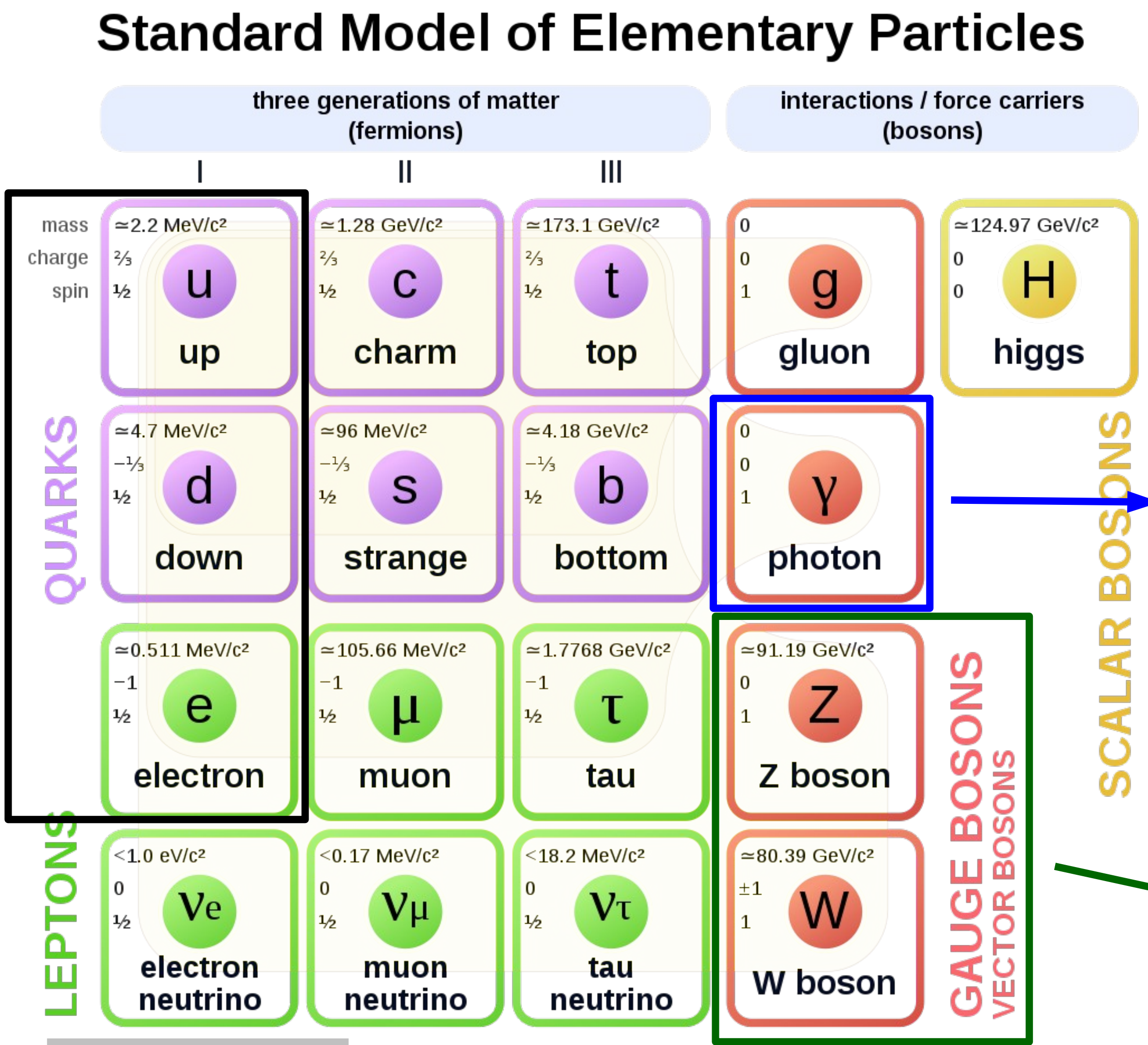
Electromagnetic interaction (magnets, electricity, ...)

$\alpha \approx 1/137$

$\Delta\alpha/\alpha = 0.15 \cdot 10^{-9}$

… and three fundamental interactions. (no gravity)

Solid matter ...



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Weak interaction (β decays, sun, ...)

$G_F \approx 1.17 \cdot 10^{-5}/\mathrm{GeV}^2$

$\Delta G_F/G_F = 0.51 \cdot 10^{-6}$

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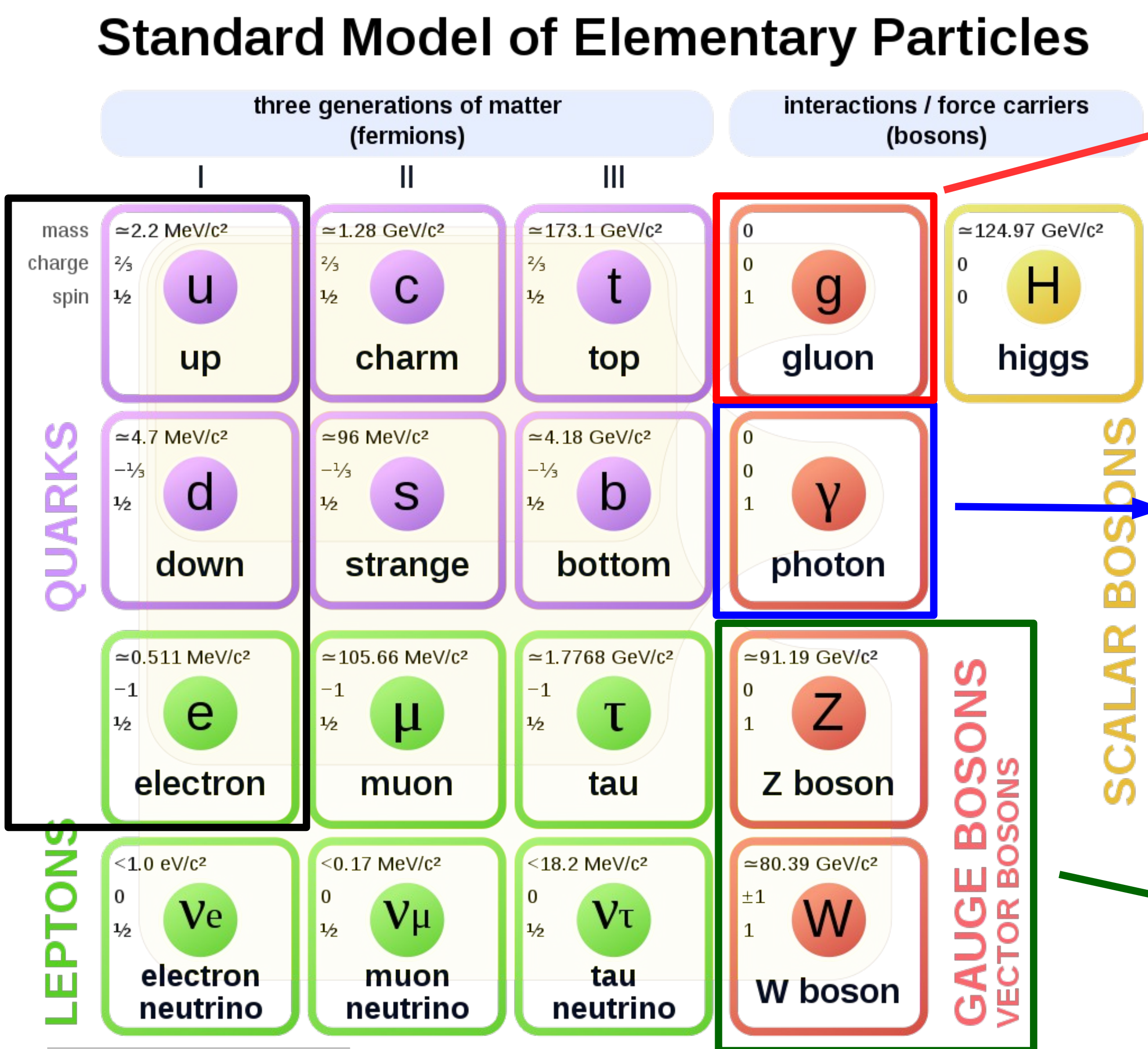
Standard Model of Particle Physics

Solid matter ...



Cush, Wikipedia.

Strong interaction (nuclear forces, ...)

$\alpha_s \approx 0.118$

$\Delta\alpha_s/\alpha_s = 8.5 \cdot 10^{-3}$

Electromagnetic interaction (magnets, electricity, ...)

$\alpha \approx 1/137$

$\Delta\alpha/\alpha = 0.15 \cdot 10^{-9}$

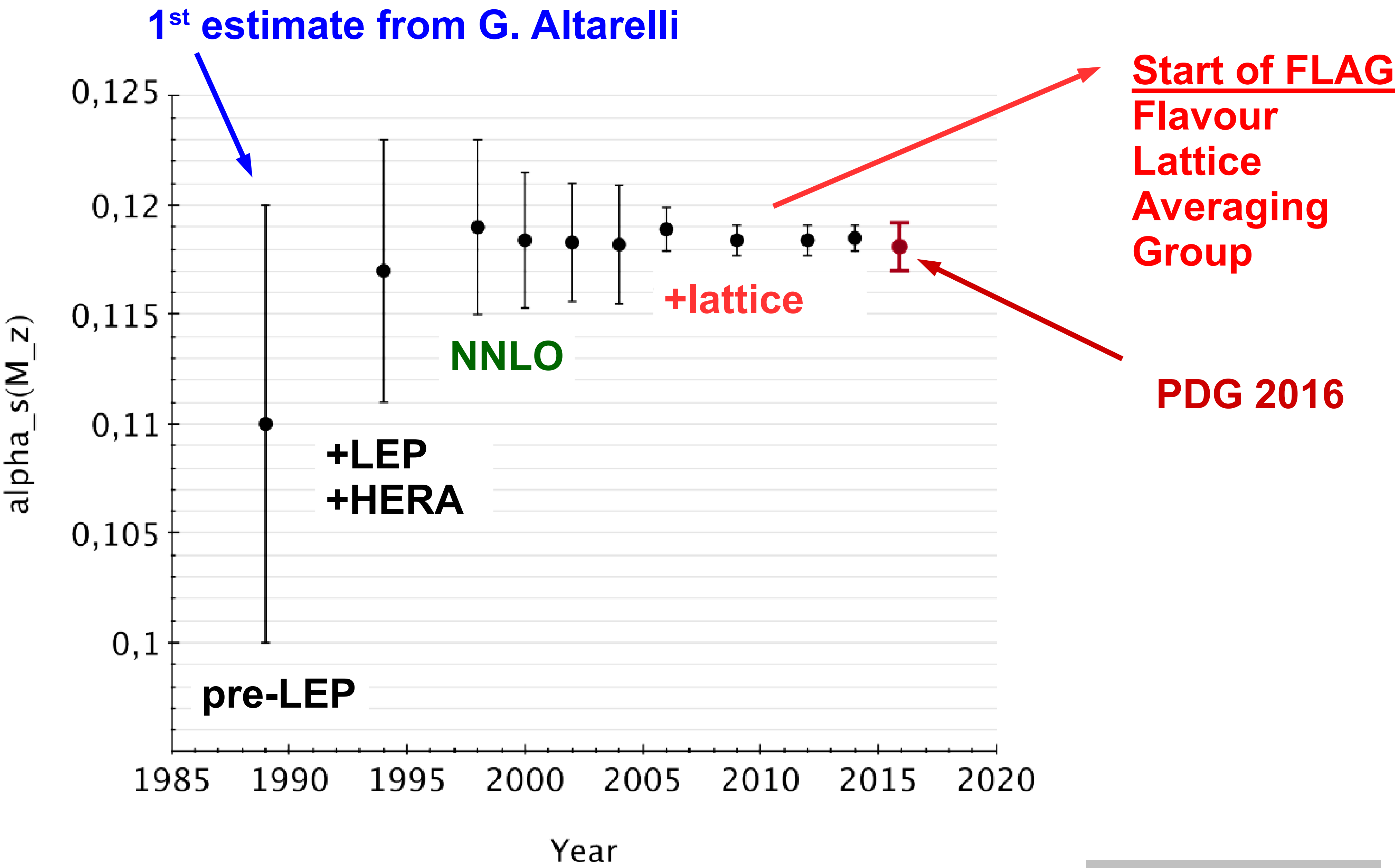
Weak interaction (β decays, sun, ...)

$G_F \approx 1.17 \cdot 10^{-5}/\mathrm{GeV}^2$

$\Delta G_F/G_F = 0.51 \cdot 10^{-6}$

… and three fundamental interactions. (no gravity)

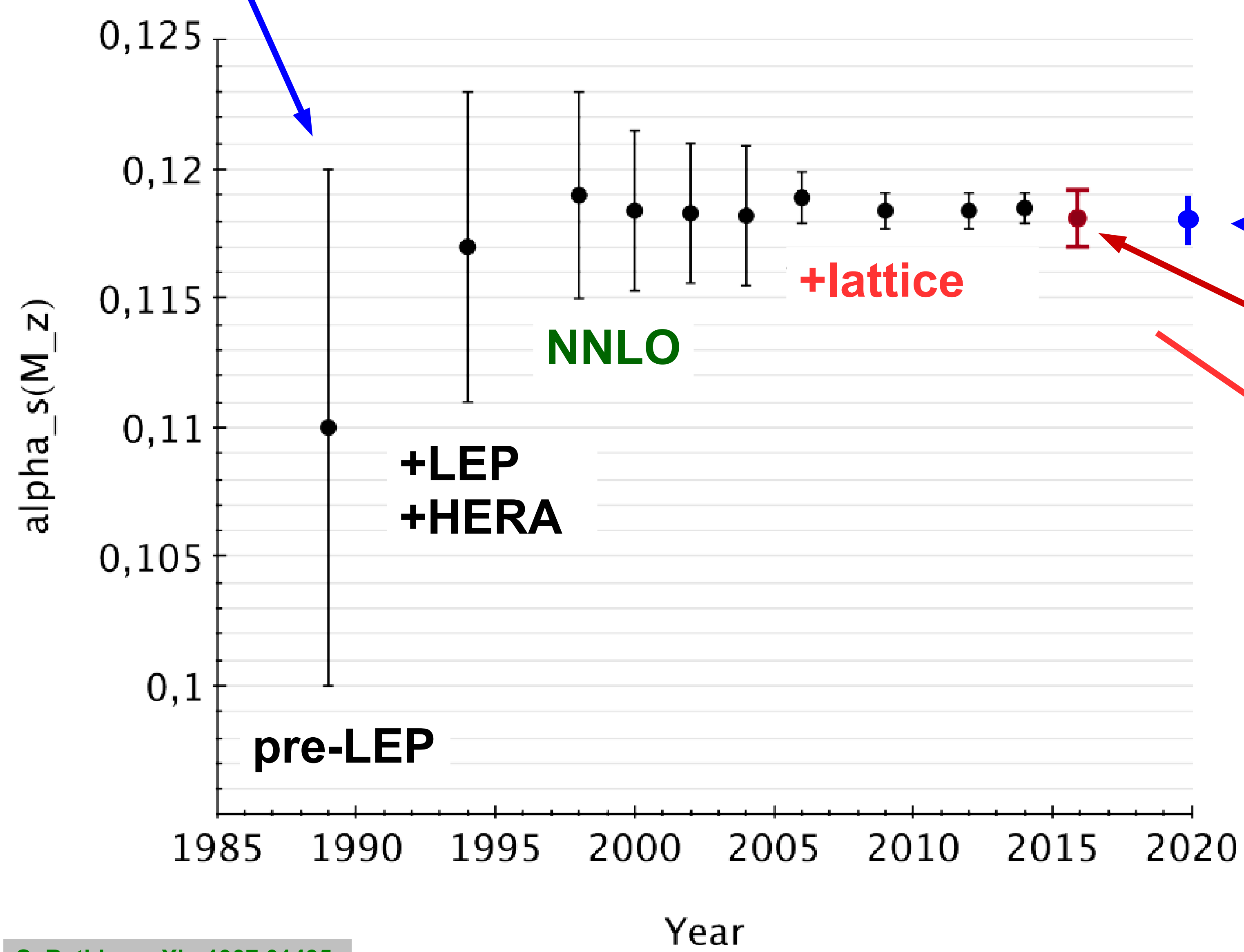
$\alpha_s(M_Z)$ world average versus time



S. Bethke, arXiv:1907.01435.

$\alpha_s(M_Z)$ world average versus time

1st estimate from G. Altarelli



PDG 2020

PDG 2016

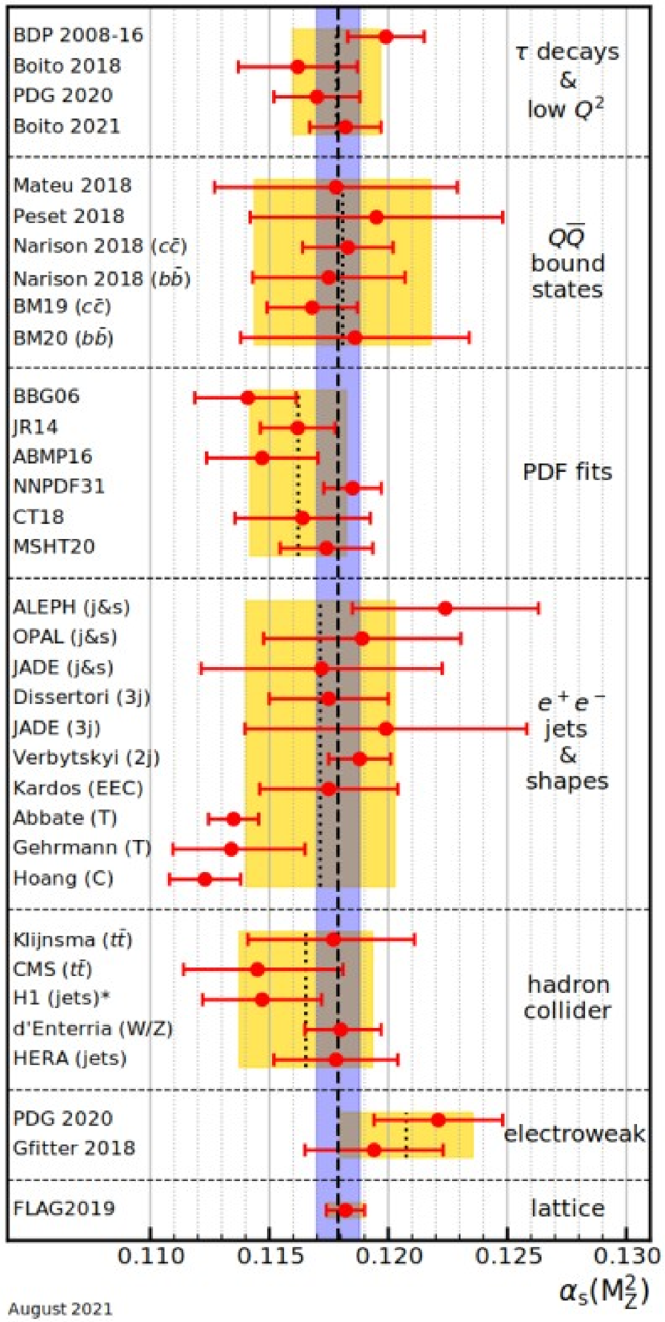
Large theoretical uncertainty from (PDF + α_s) on Higgs x sections

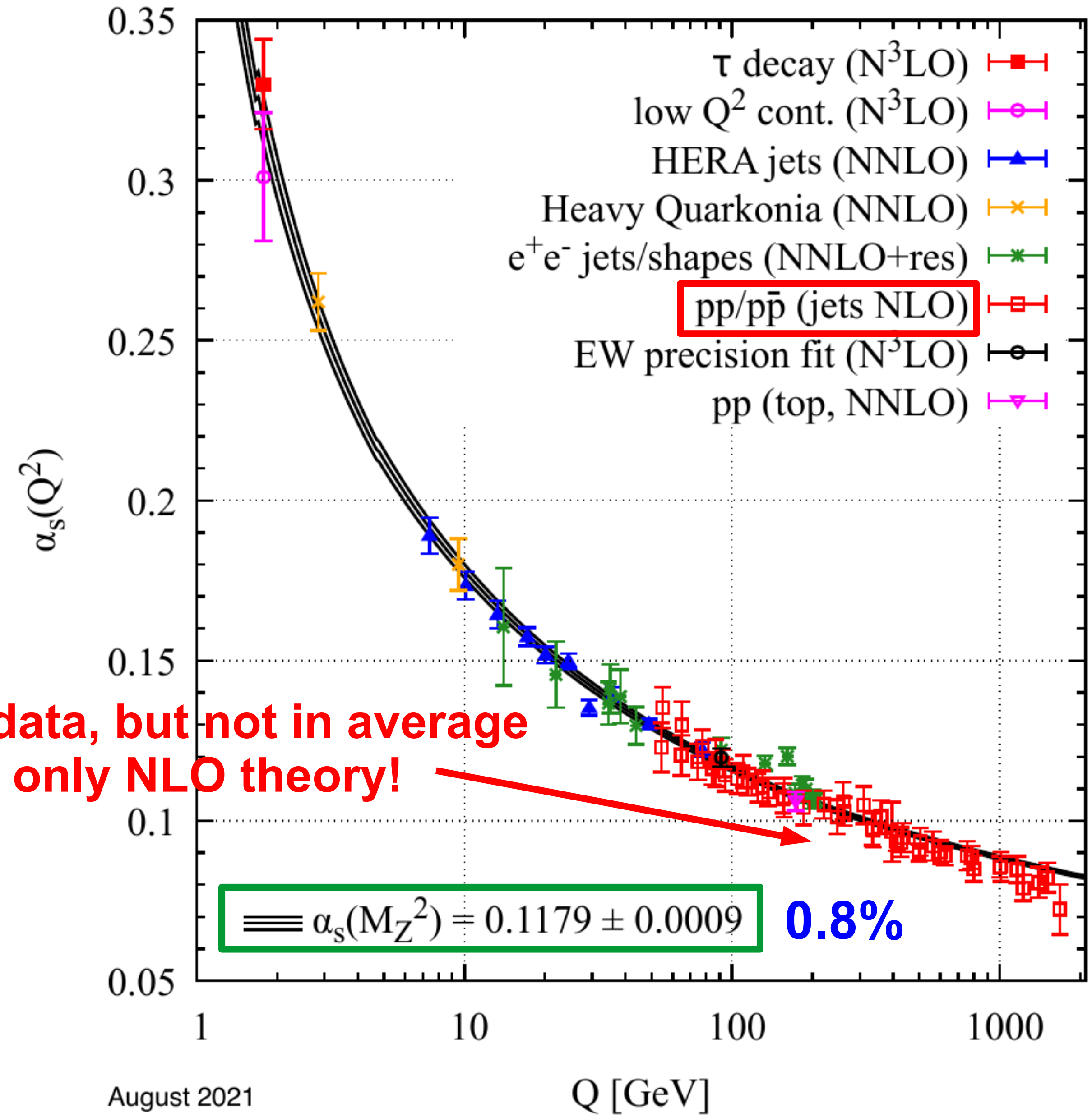
In particular tTH & gg-Fusion: 7-13%

S. Bethke, arXiv:1907.01435.

CERN YR, LHC Higgs xs WG.

PDG α_s average 2022





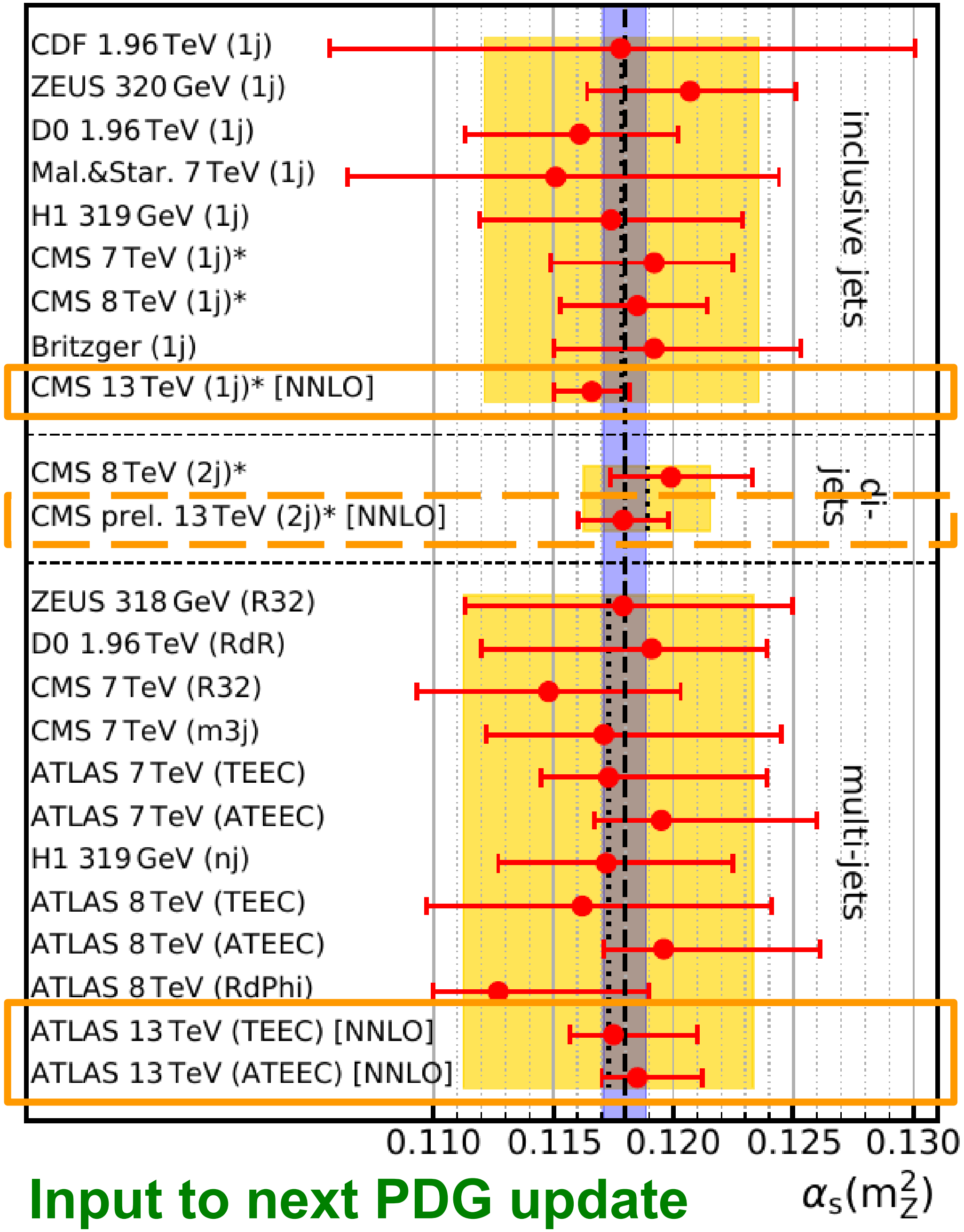
LHC data, but not in average since only NLO theory!

0.8%

PDG, PTEP (2022) 083C01.

PDG´92: 2.4%

$\alpha_s(m^2_Z)$ from jet data



2023: new at NNLO!

Input to next PDG update

Thank you for your attention!

Thank you very much to the organisers for the invitation to this very special place