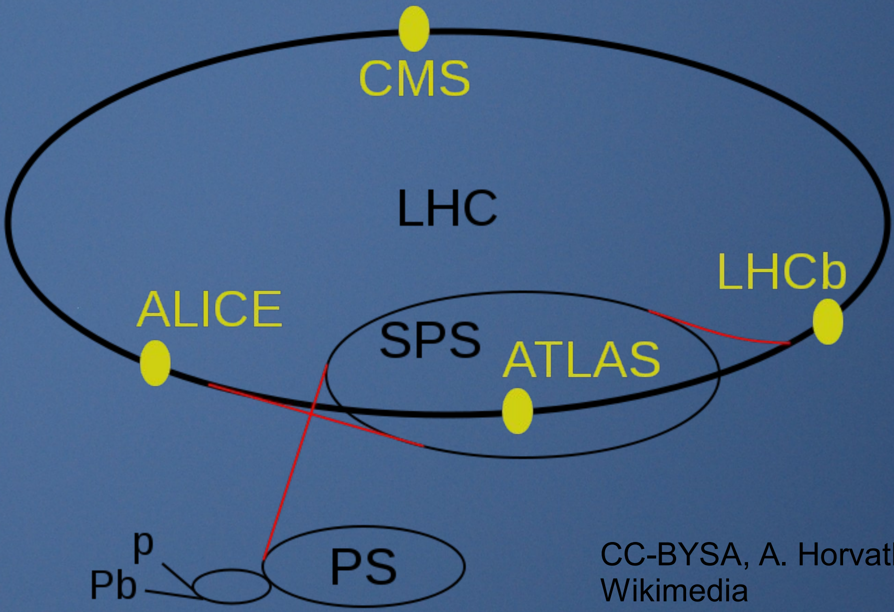
Physikalisches Kolloquium **29.04.2016**

Jet physics and the strong coupling constant at the LHC



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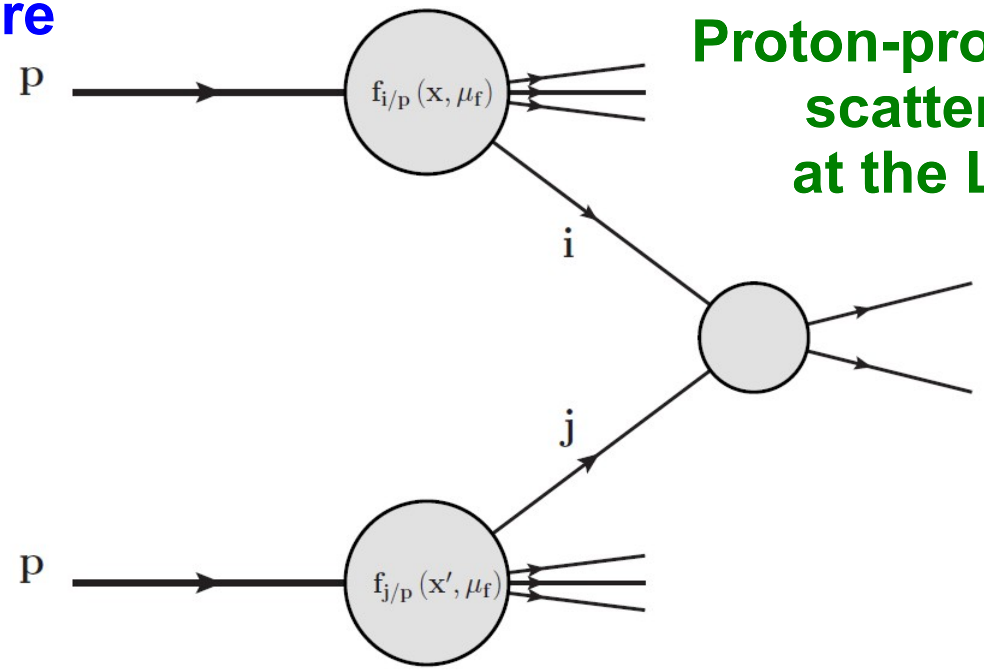
K. Rabbertz

Karlsruhe Institute of Technology

Outline

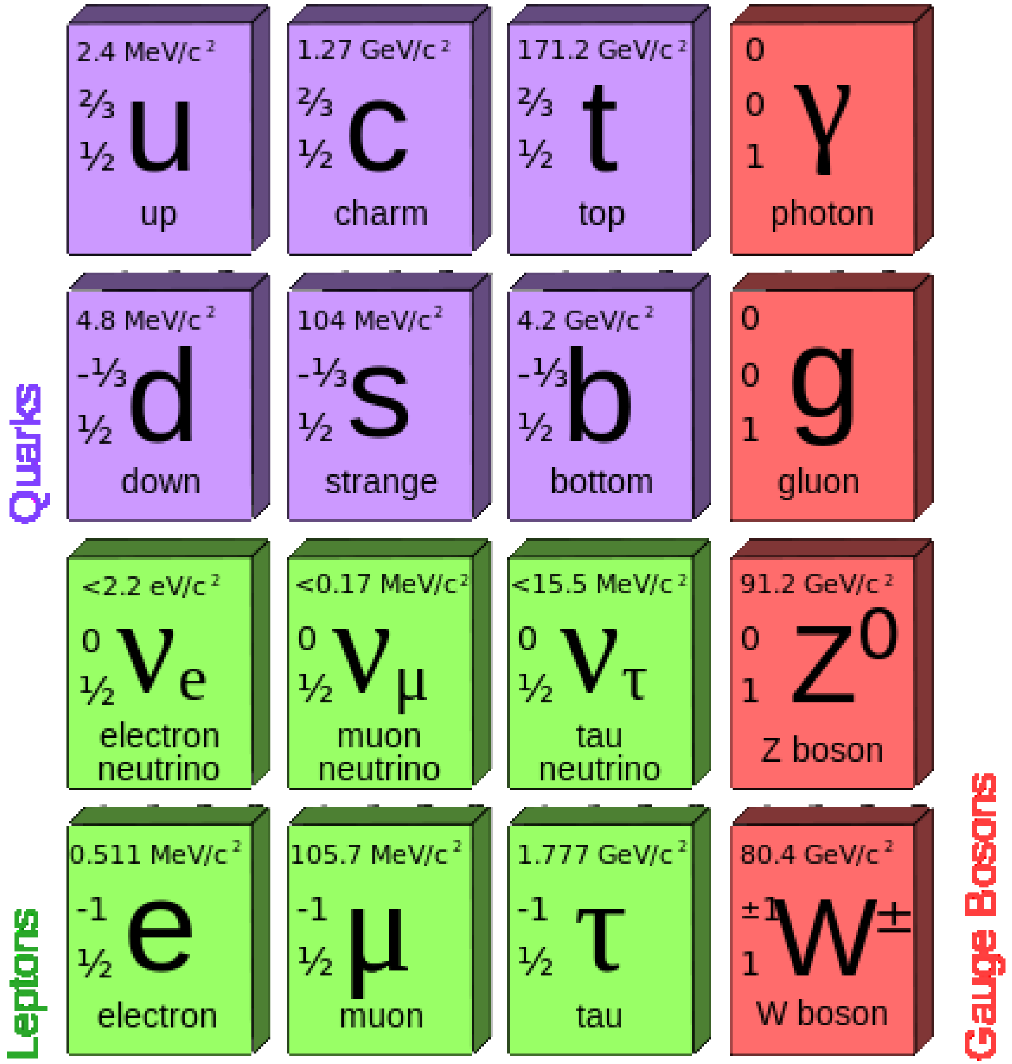
- Motivation
  - From QCD to quarks to jets
- Experimental & theoretical setup
- Details on selected jet measurements
  - Dijet angular distributions and new phenomena
  - Inclusive jets and proton structure
  - Multijets and α_s
- The strong coupling constant α_s
  - α_s at the LHC
  - α_s at hadron colliders
  - α_s in the global context
- Perspectives & Summary



Proton-proton scattering at the LHC

May contain traces of Higgs!

Standard Model of Particle Physics

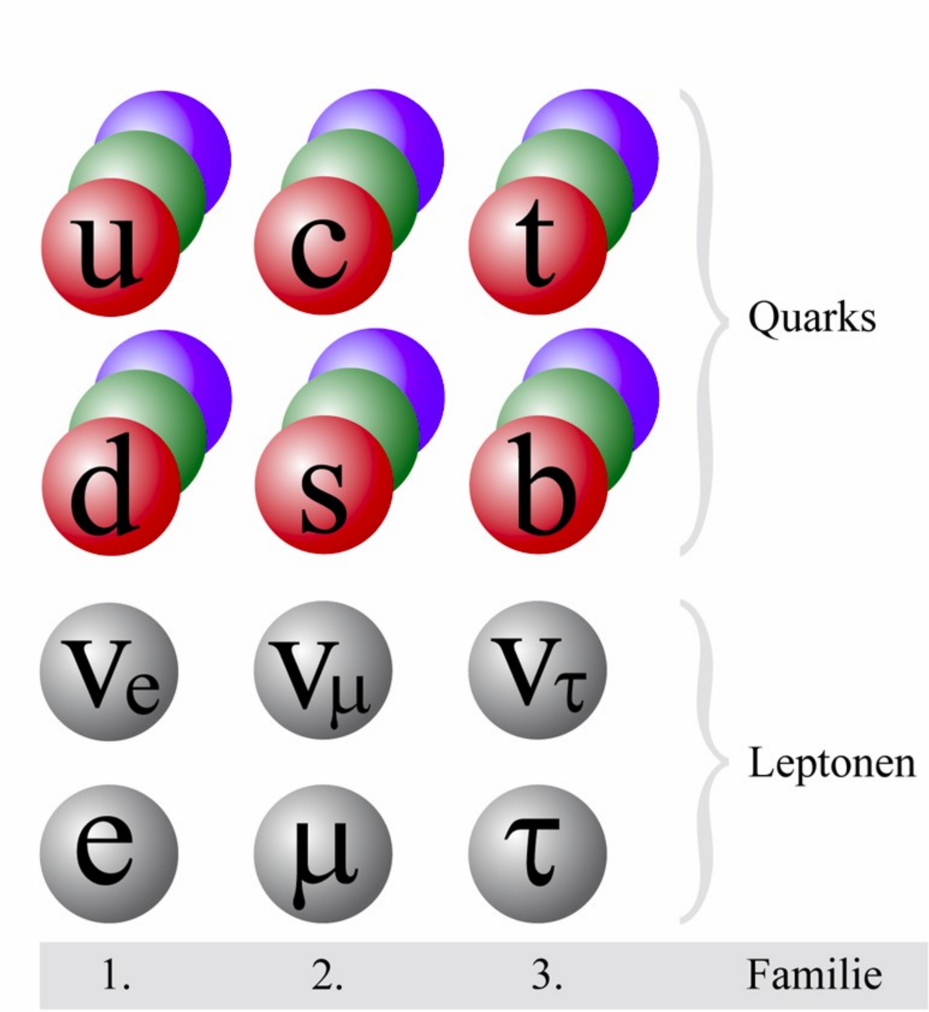


Quarks	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon
	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon
Leptons	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson
	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson

Gauge Bosons

Wikipedia

Quarks with color!

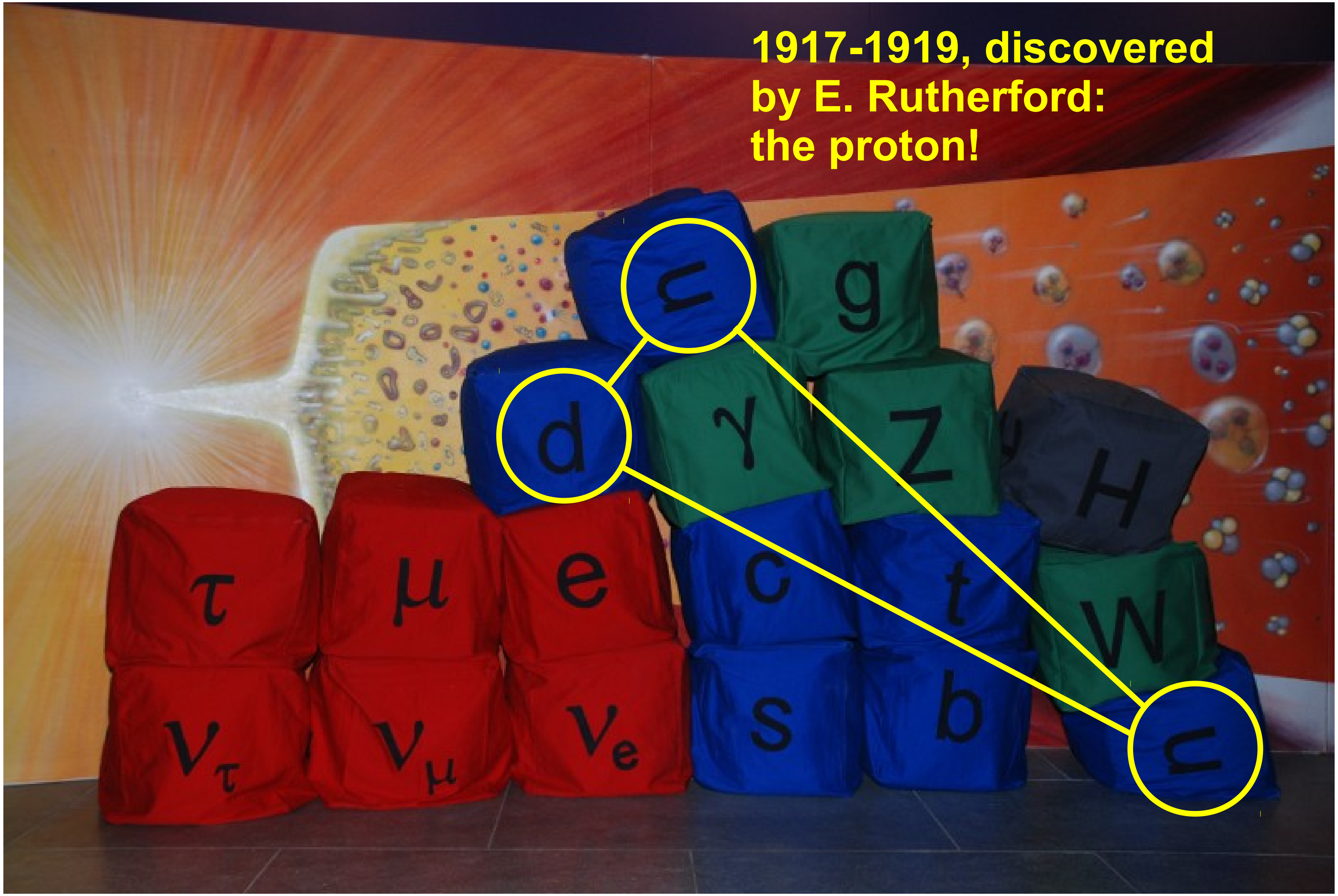


DESY

Everything?

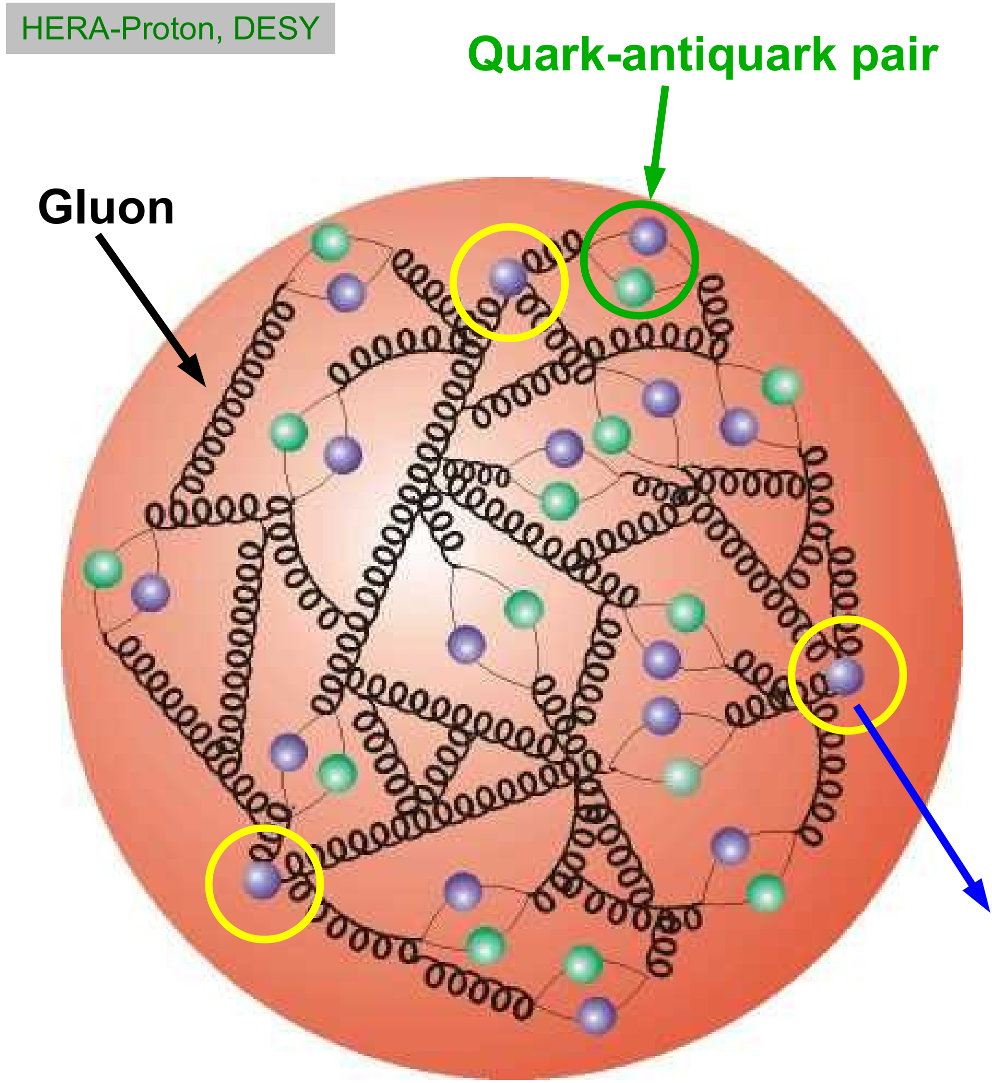
July 2012 at the LHC
Well hidden, but uncovered:
the Higgs boson!

Oops, two up quarks …



1917-1919, discovered
by E. Rutherford:
the proton!

Mass matters ...



- **> 99% of visible matter in the universe: protons and neutrons**
- **~ 95% of proton mass: from QCD**
- **Negligible share from quark masses through Brout-Englert-Higgs mechanism**

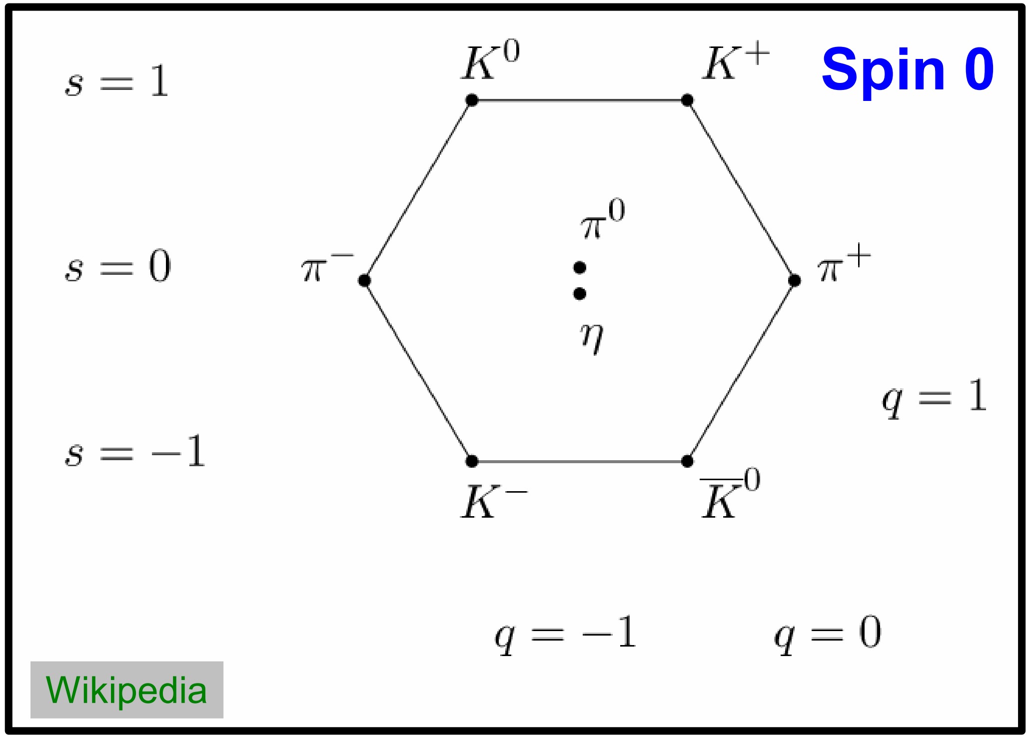
Proton:
mass ~1000 MeV

→ Physikalisches Kolloquium, 27.05.2016:
"The Origin of Mass in the visible Universe",
Z. Fodor, Uni Wuppertal, 27.05.2016

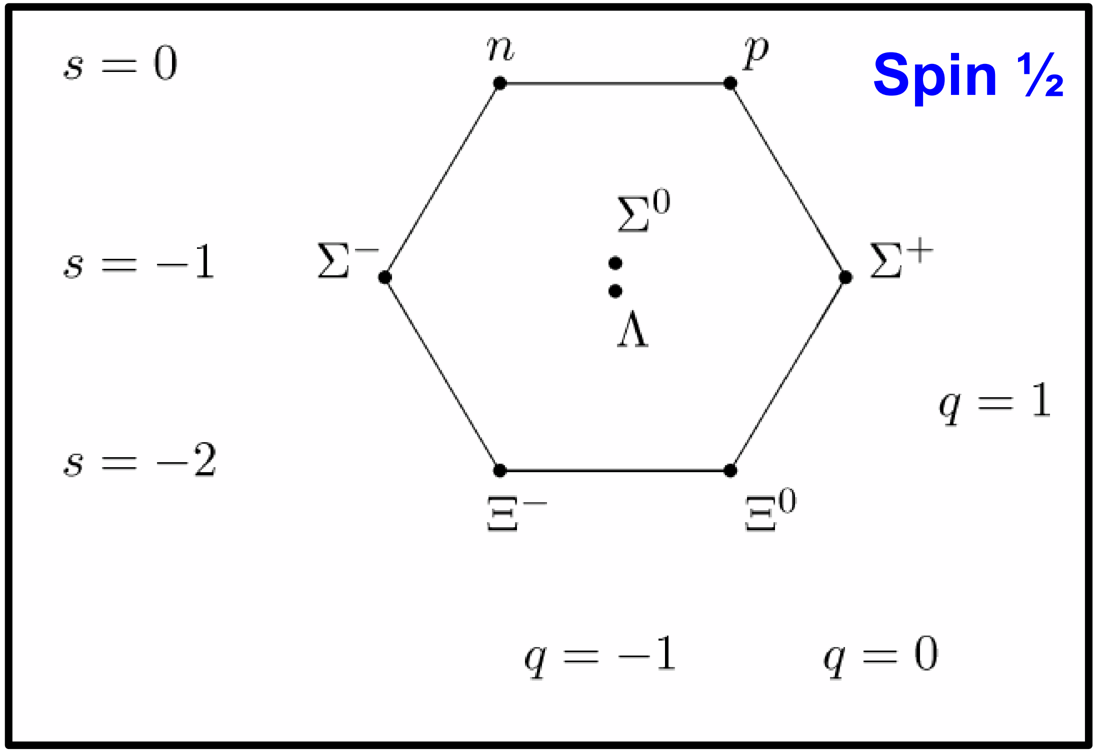
Origin of Quarks: The Particle Zoo

- **Cosmic rays and first accelerators → plethora of new "elementary" particles!**
  - **M. Gell-Mann, 1964, the "Eightfold Way":**
    mesons and baryons ordered according to charge q and "strangeness" s

M. Gell-Mann
nobelprize.org



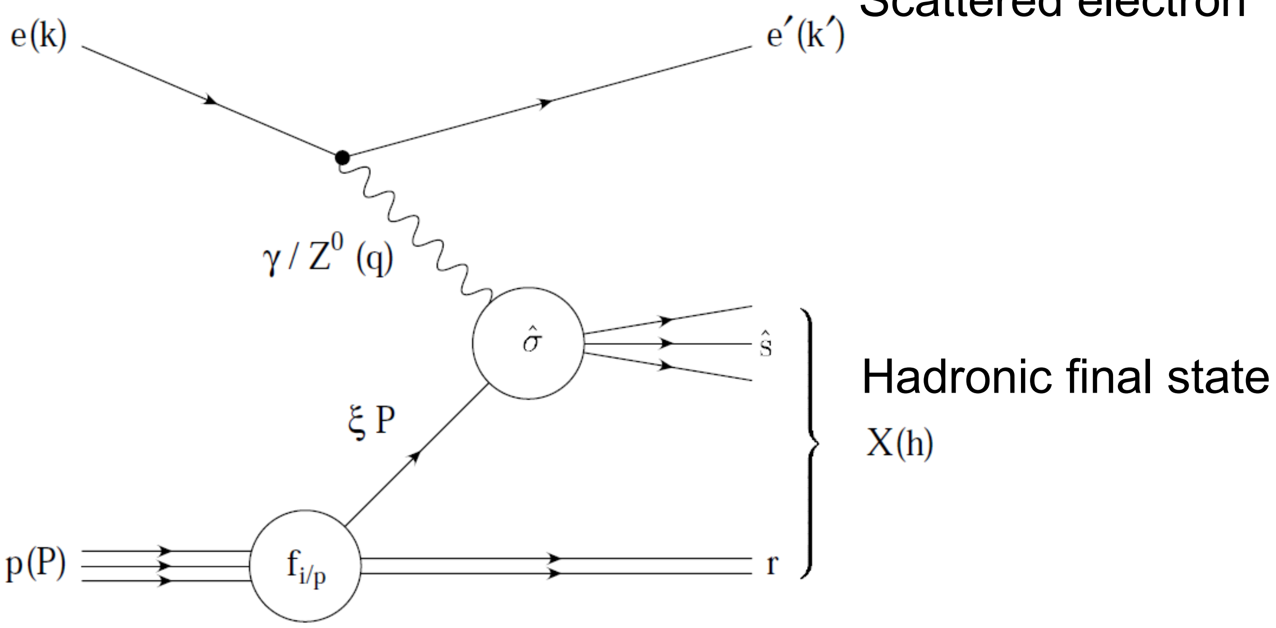
Wikipedia



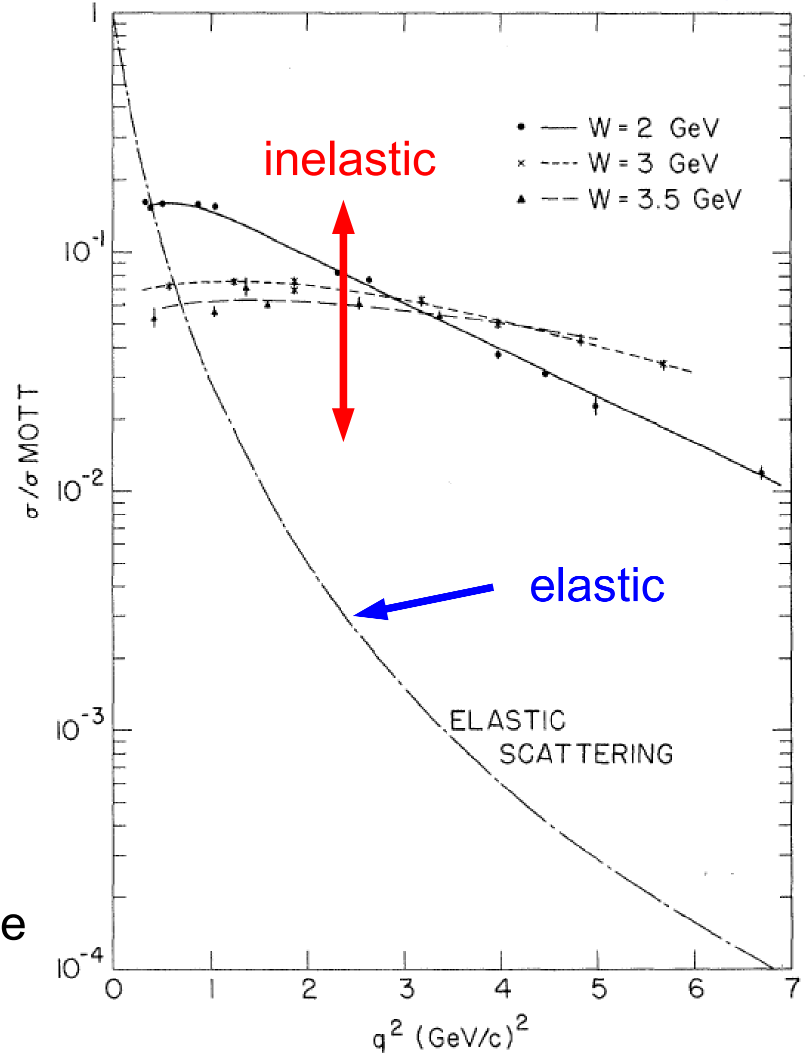
Origin of Quarks: Scale Invariance

- **Inelastic >> elastic cross section**
- **Inelastic ~ Mott cross section**
  - **independent of resolution ~ q^2**
  - **scale invariant = no natural length scale**
  - **like scattering on point-like objects**

Deep-inelastic scattering (DIS)



electron proton scattering



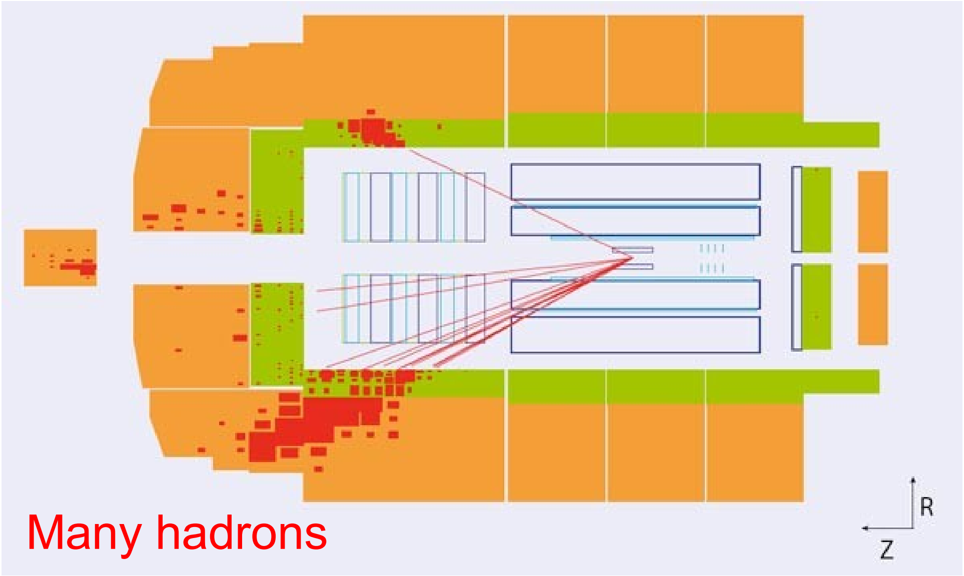
PRL 23 (1969) 935.

Origin of Quarks: Scale Invariance

- Inelastic >> elastic cross section
- Inelastic ~ Mott cross section
  - independent of resolution ~ q^2
  - scale invariant = no natural length scale
  - like scattering on point-like objects

DIS: Modern Version at HERA

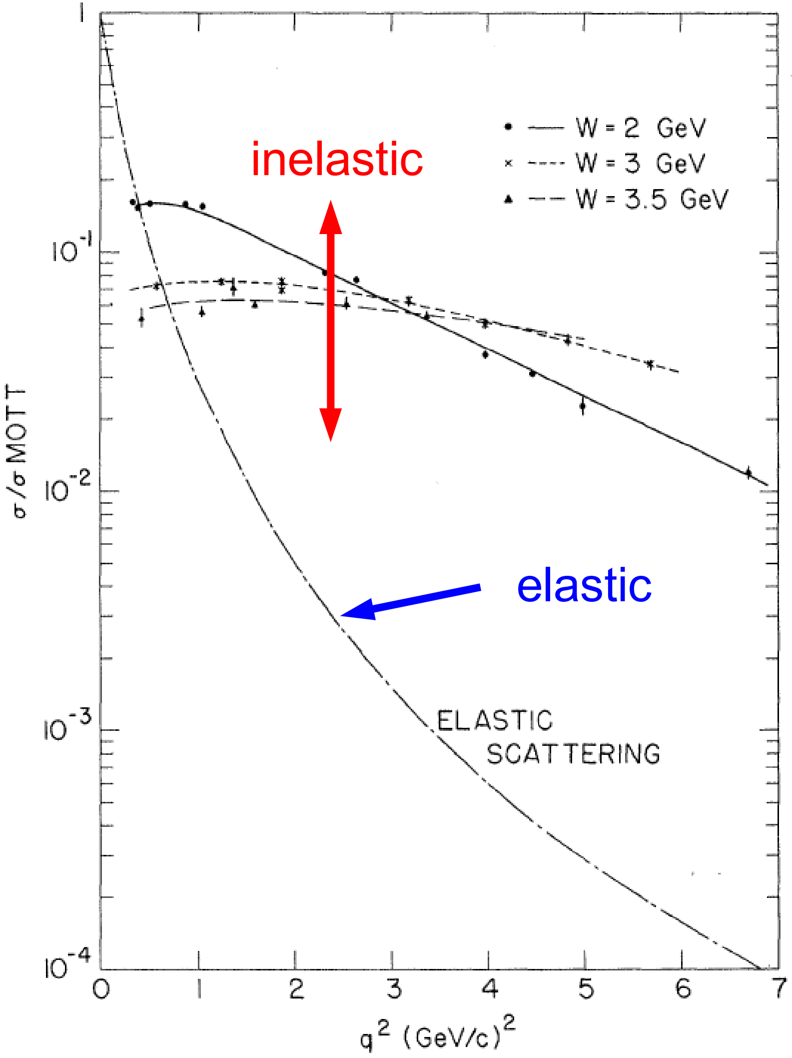
Scattered electron



Many hadrons

H1/DESY.

electron proton scattering



PRL 23 (1969) 935.

First Steps towards Understanding

- **M. Gell-Mann:** mesons ~ quark-antiquark pair (color-anticolor)
  baryons ~ 3 quarks (complementary colors)
  Named after J. Joyce “Finnegan's Wake”:
  “Three quarks for Muster Mark.”

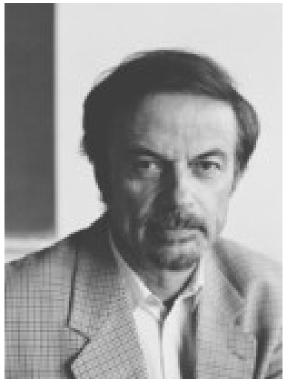
- **G. Zweig:** Same concept, his name of “aces” not retained.
  - Quarks/Aces require charges in thirds, never observed!

G. Zweig
Scienceworld

- **R. Feynman:** Scaling of DIS in SLAC-MIT experiment
  → point-like scattering inside proton: partons
  - Later: partons = (anti-)quarks and gluons

R. Feynman
nobelprize.org

- **M. Veltman, G. 't Hooft:** Renormalizability of SU(N) non-Abelian quantum field theories
  - SU(3) suggested by **H. Fritzsch, M. Gell-Mann,**
    → QCD

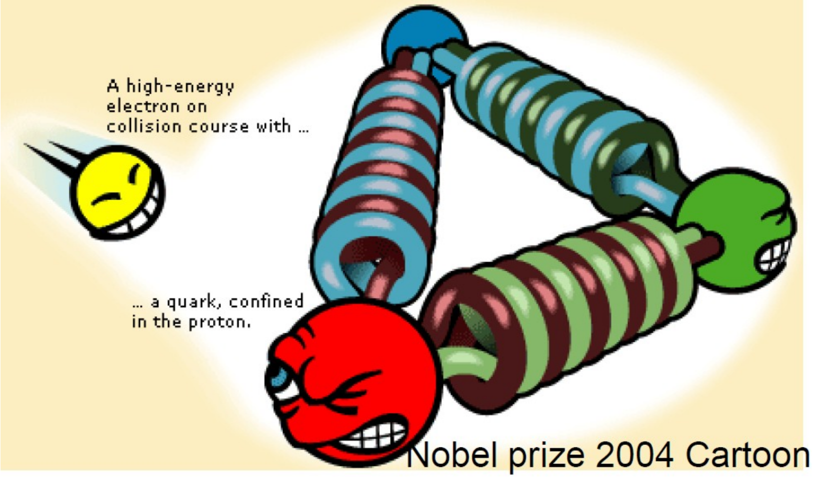


H. Fritzsch
LMU

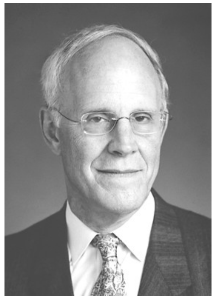
M. Veltman, G. 't Hooft
nobelprize.org

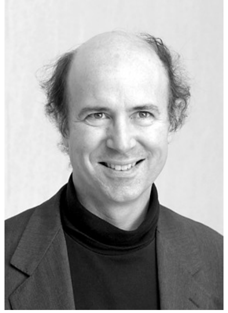
Asymptotic Freedom & Confinement

- **Renormalization of QCD:**
  - **Running coupling constant**
  - **'Strong' coupling weak for $Q^2 \to \infty$, i.e. small distances**
  - **Perturbative; asymptotic freedom**



Nobel prize 2004 Cartoon





D. Gross
D. Politzer
F. Wilczek
nobelprize.org

- **What happens at large distances?**
  - **$Q^2 \to 0$?**
  - **Cannot be answered, since perturbative formulae not applicable anymore!**
  - **Non-perturbative; confinement**

$$\beta_0 = \frac{33 - 2 \cdot N_f}{12\pi} > 0$$

See also article: Physik Journal 3 (2004) Nr. 12

Running Coupling Constant

$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln\left(\frac{Q^2}{\Lambda^2}\right)}$$

with **Λ** typically ≈ **200 – 300 MeV**

QCD Potential grows linearly with distance:

$$V = \sigma \cdot r \approx 1\mathrm{GeV/fm} \cdot r$$

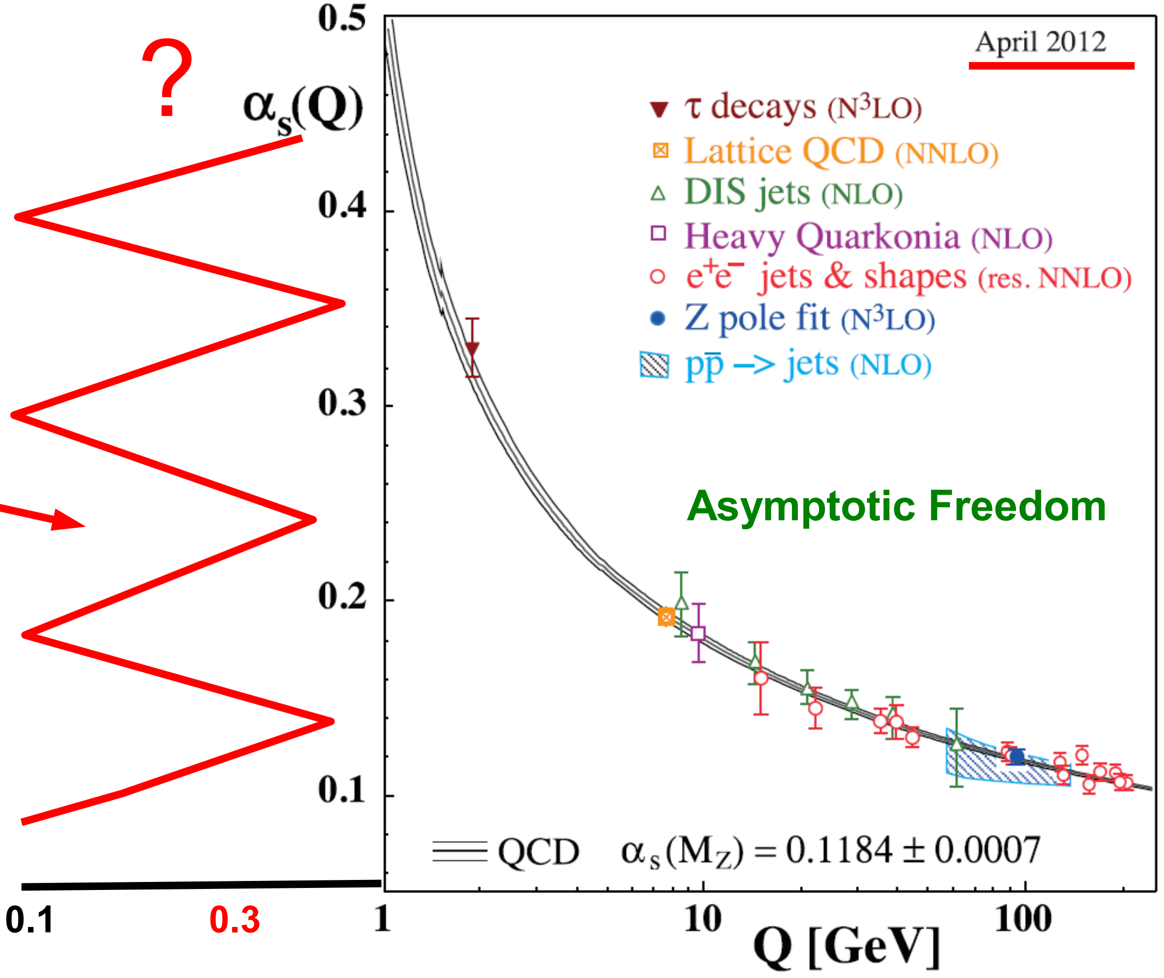
→ **No free quarks (or gluons)**

→ **Confinement**

2012: No LHC results yet **~250 GeV**

?

Non-perturbative regime



Asymptotic Freedom

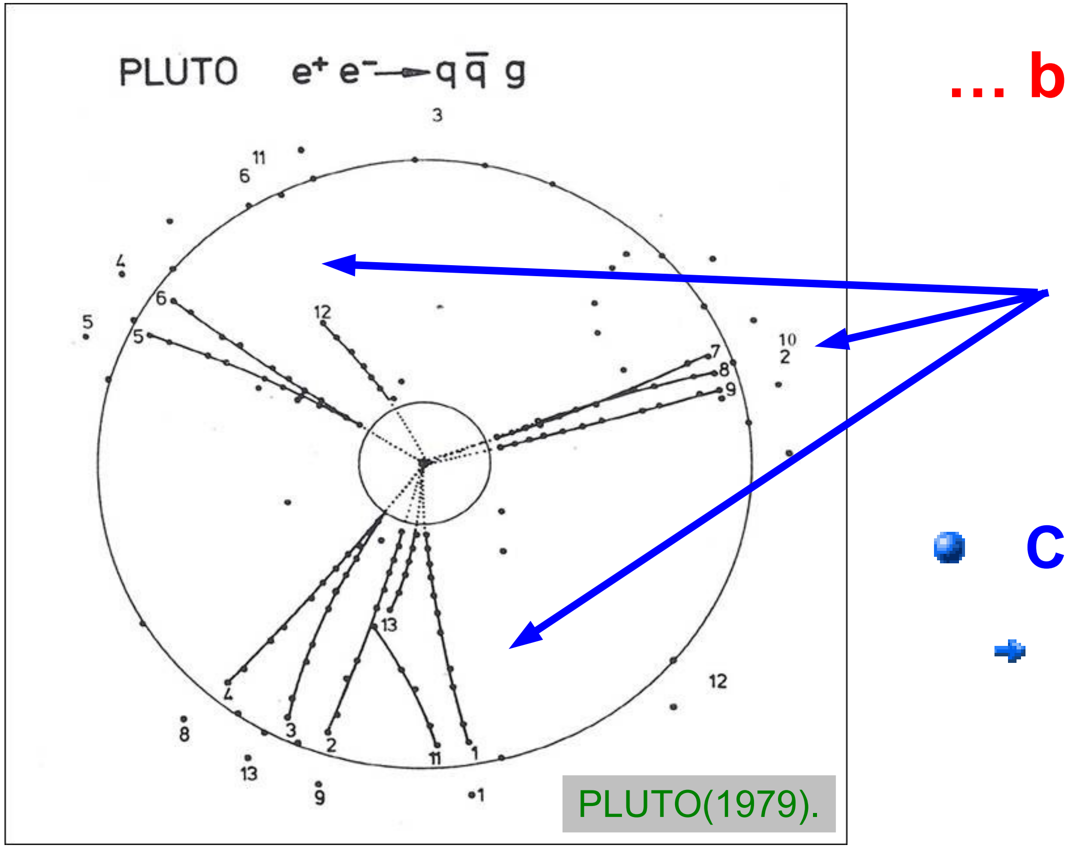
PDG2012

What about Gluons?

First indications of “gluon” production ...

PLUTO @ PETRA,1979
e^+e^-, $\sqrt{s}$ = 30 GeV
Multiplicity ~ 10

$$e^+e^- \rightarrow qqg$$



PLUTO(1979).

… but not as a free particle

and which one is it?

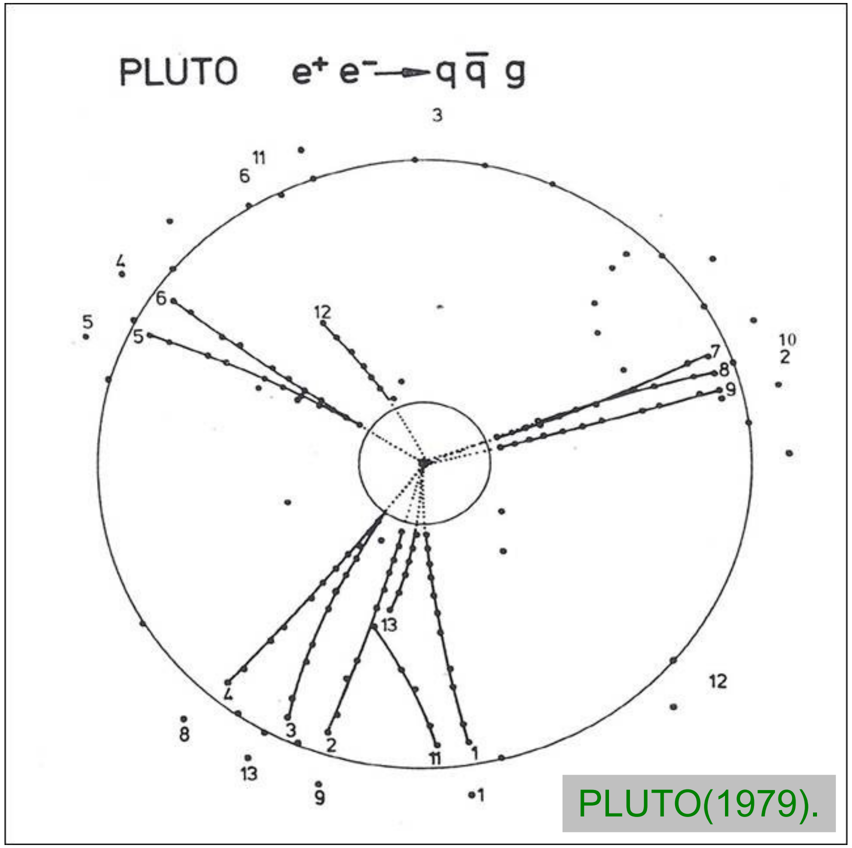
- **Collimated bundles of particles with**
  - **Small transverse momenta (~ Λ)**

3-Jet Events 1979 → 2010

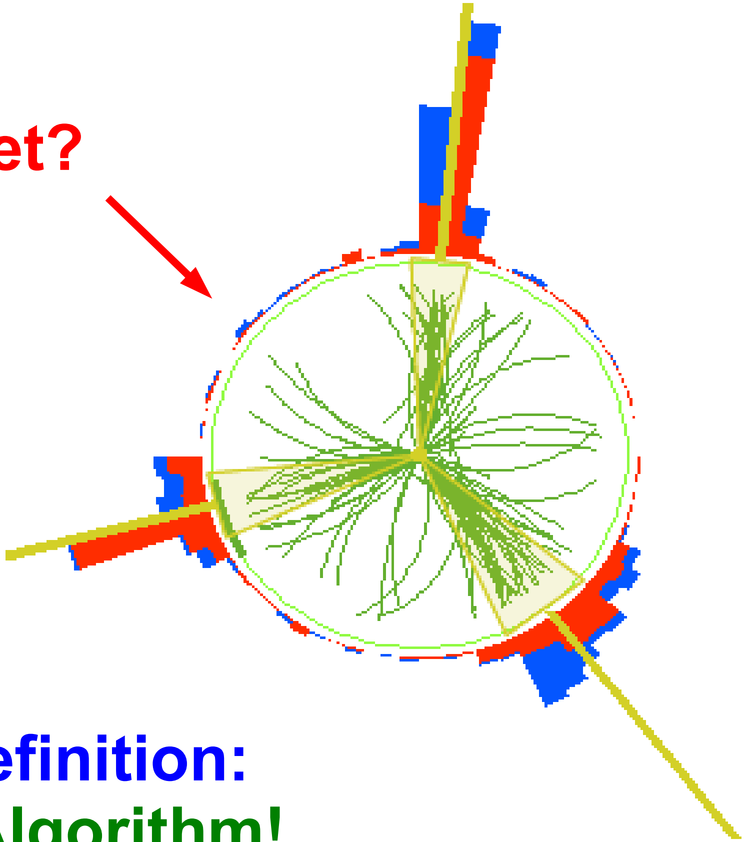
Jets clearer visible … but what belongs where?

PLUTO @ PETRA,1979
e^+e^-, $\sqrt{s}$ = 30 GeV
Multiplicity ~ 10

CMS @ LHC, 2010
pp, $\sqrt{s}$ = 7000 GeV
Multiplicity ~ 100



PLUTO(1979).



Which Jet?

Need definition:
→ Jet-Algorithm!

Jet Algorithms

Primary Goal:

Establish correspondence between:

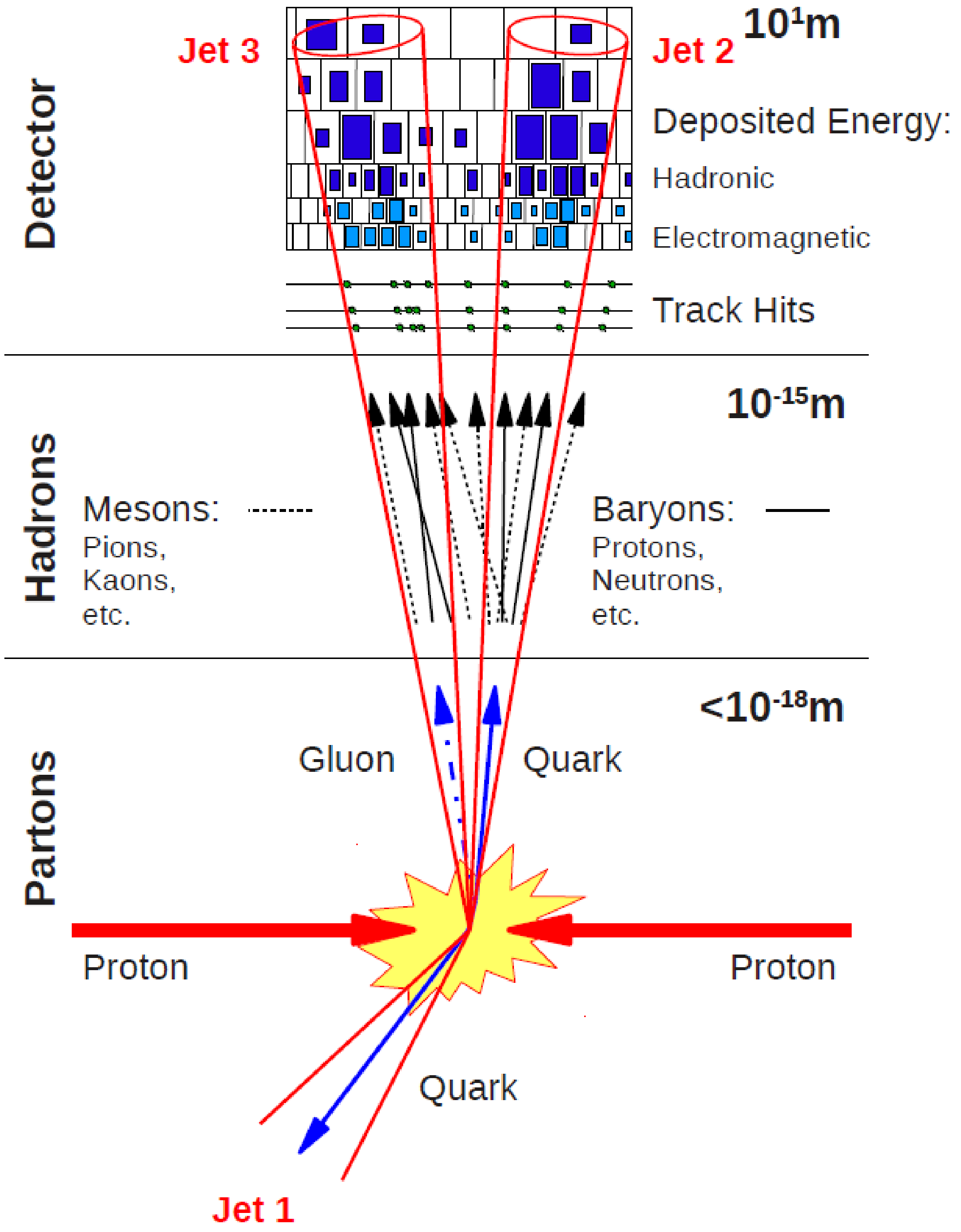
- **detector measurements**
- **final-state particles and**
- **high-p_T partons**

Two classes of algorithms:

1. **Cone algorithms:**
   Geometrical assignment
   (preferred at hadron colliders)

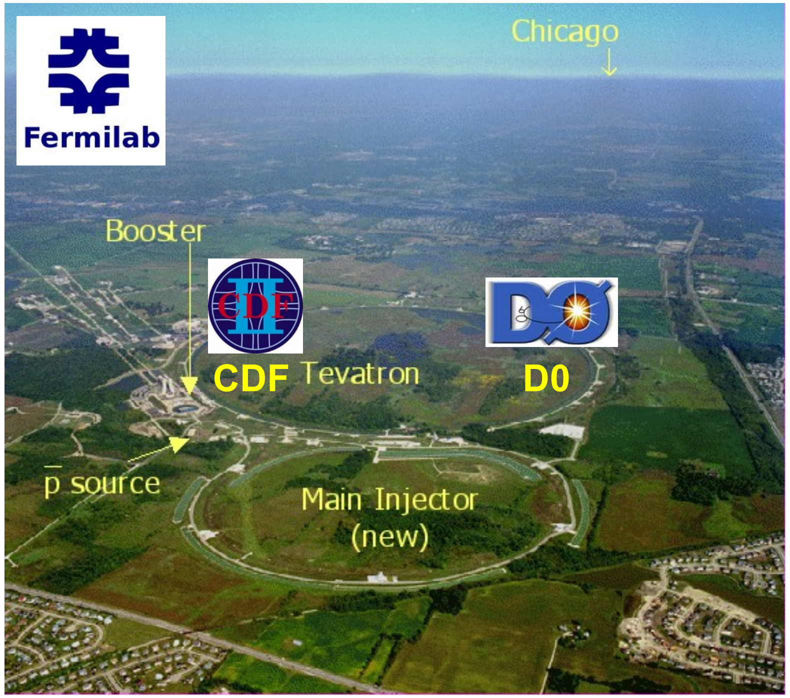
2. **Sequential recombination:**
   Iterative merging of nearest neighbours
   (preferred at e^+e^- & ep colliders)

Standard at LHC: anti-kT
Type 2 algorithm that looks like a cone!



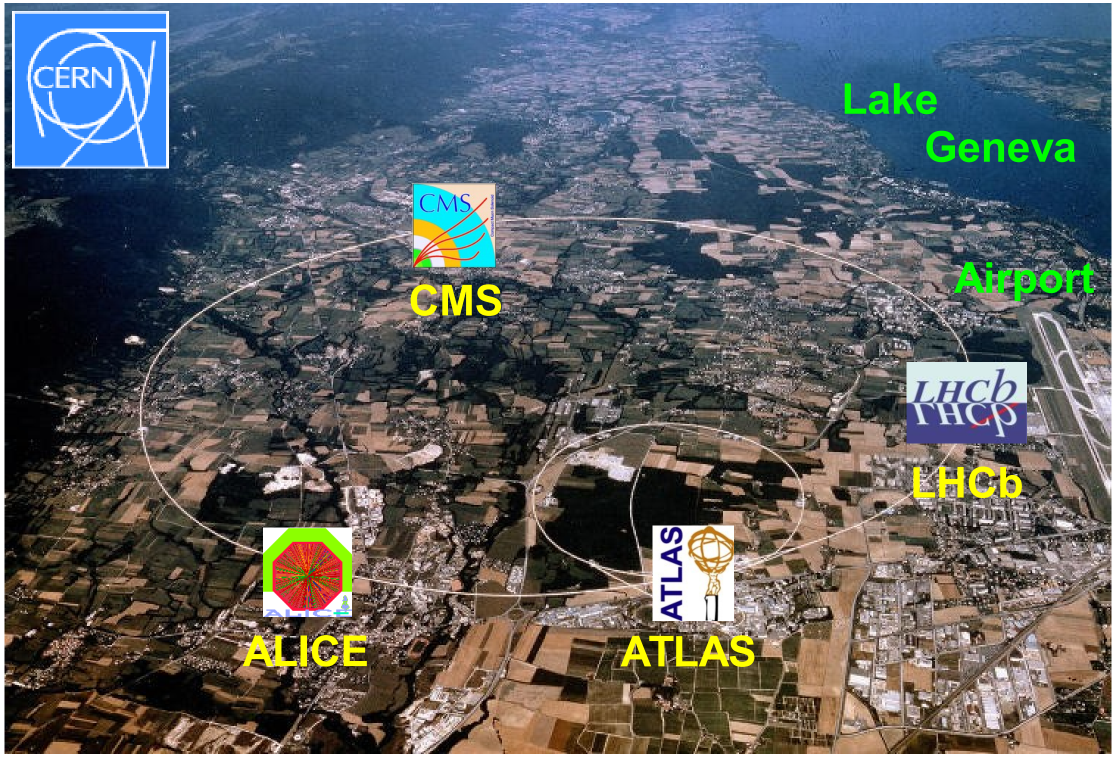
The latest Colliders

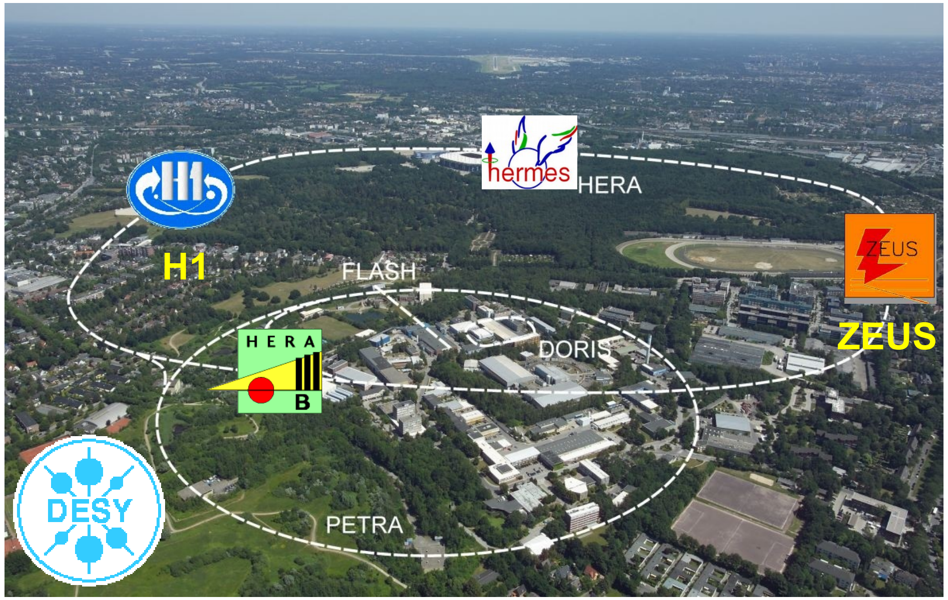
Tevatron: 1986 – 2011
Collisions of p anti-p
Run II: E_{cms} =1.96 TeV
Run II: Record luminosity: 4.3 x 10^{32} $cm^{-2}s^{-1}$



LHC: 2009 – present
Collisions of p-p, Pb-Pb, and p-Pb
E_{cms} = 0.9, … , 8, 13 TeV
Peak inst. Luminosity: ~ 8 x 10^{33} $cm^{-2}s^{-1}$

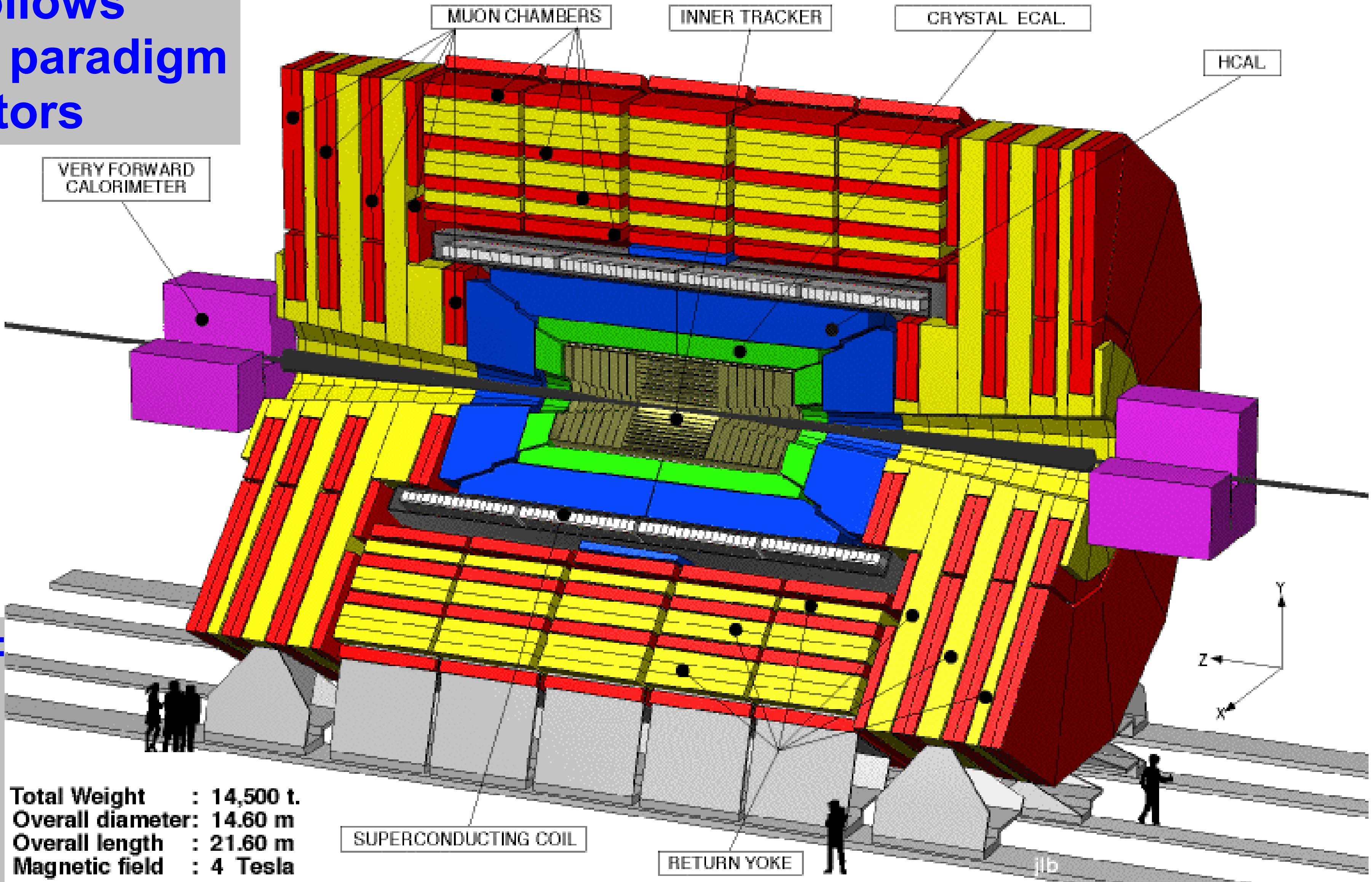
HERA: 1992 – 2007
Collisions of e^+-p, e^--p
HERA II: E_{cms} = 319 GeV





CMS Detector

Structure follows the "onion" paradigm of 4π detectors



Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

Silicon trackers:
Up to |η| = 2.5

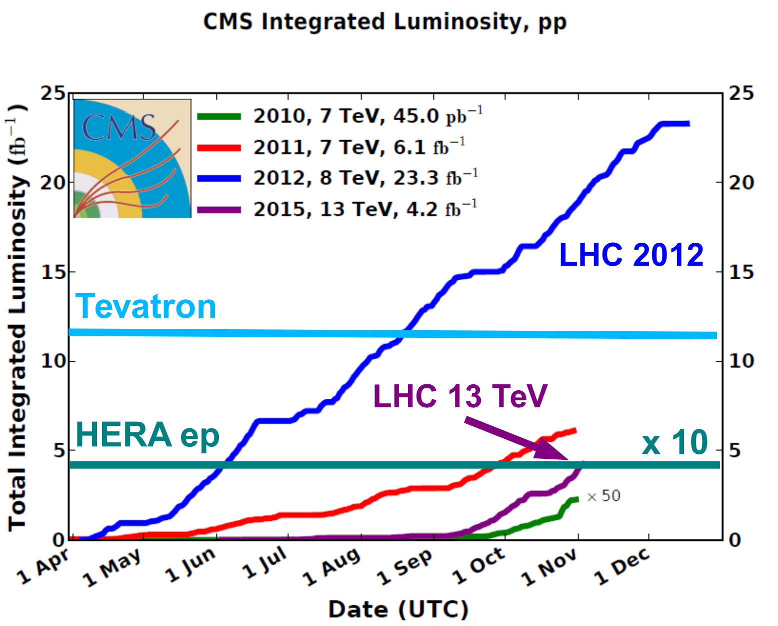
Calorimetry:
Up to |η| ~ 5.0

Muon chambers
Up to |η| ~2.7

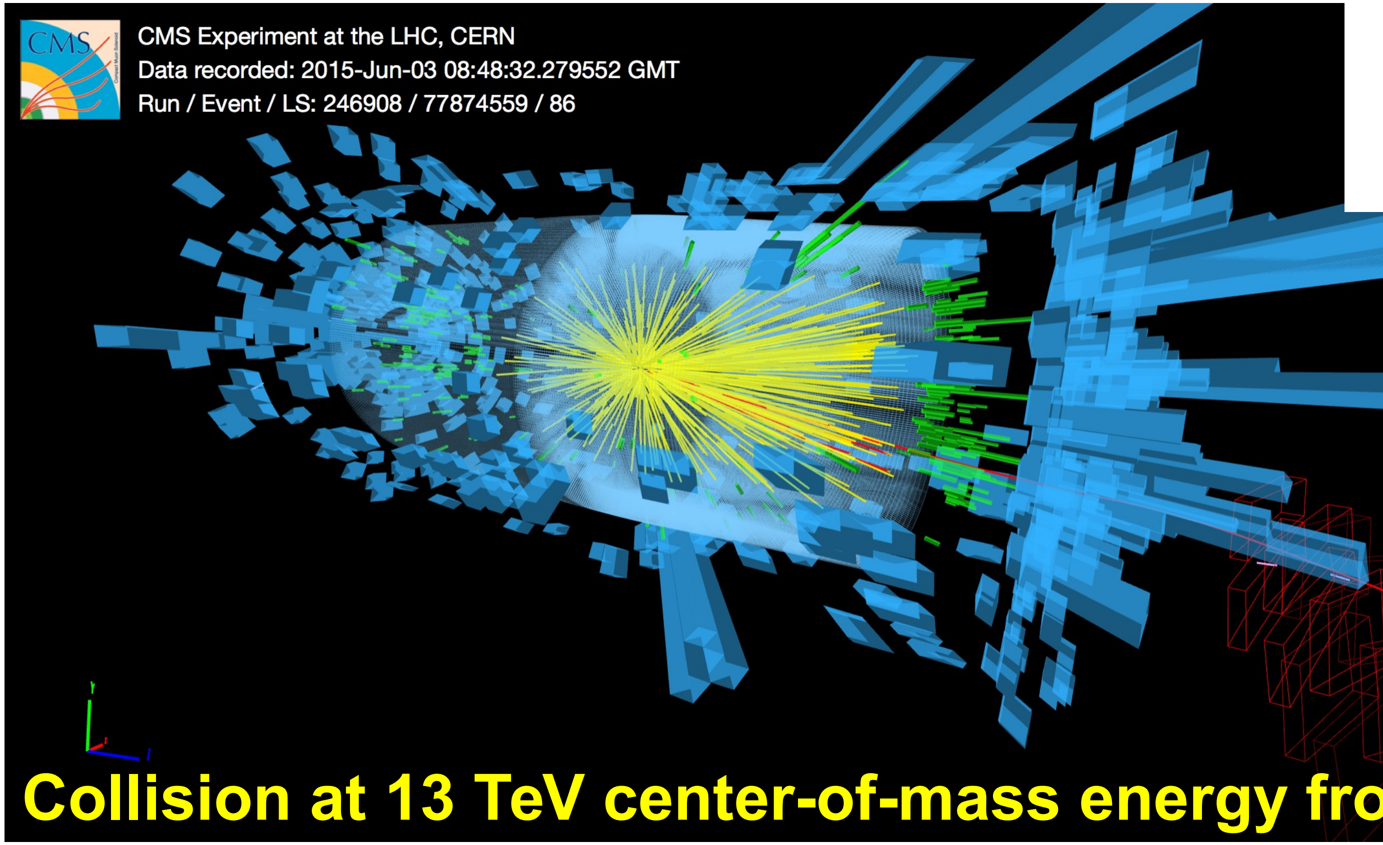
LHC Start of Run II

23. April 2016!

LHC: p-p collisions 13 TeV:
2015: 4.22 fb^{-1}
2016: just started



03. Juni 2015



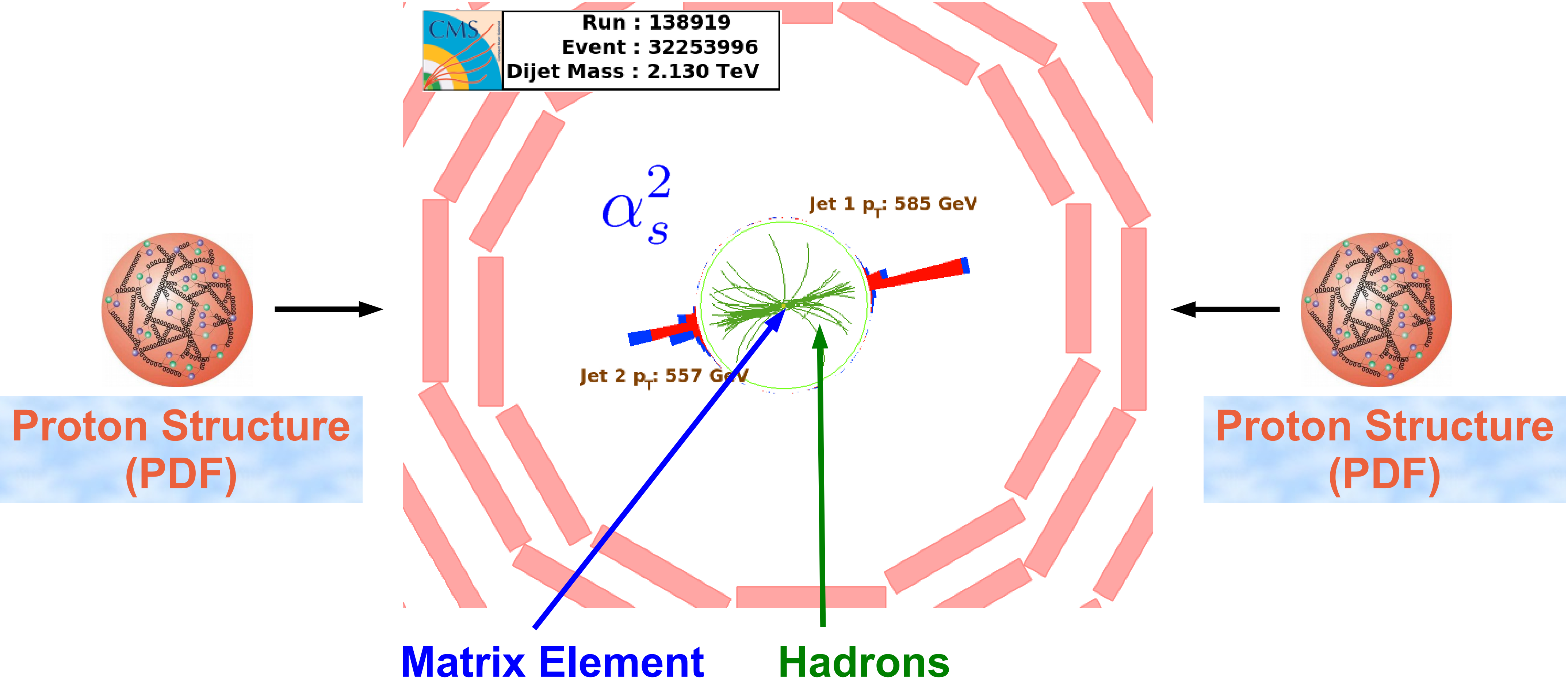
Collision at 13 TeV center-of-mass energy from CMS

$$N_{\text{event}} = \mathcal{L}_{\text{int}} \cdot \sigma$$

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)

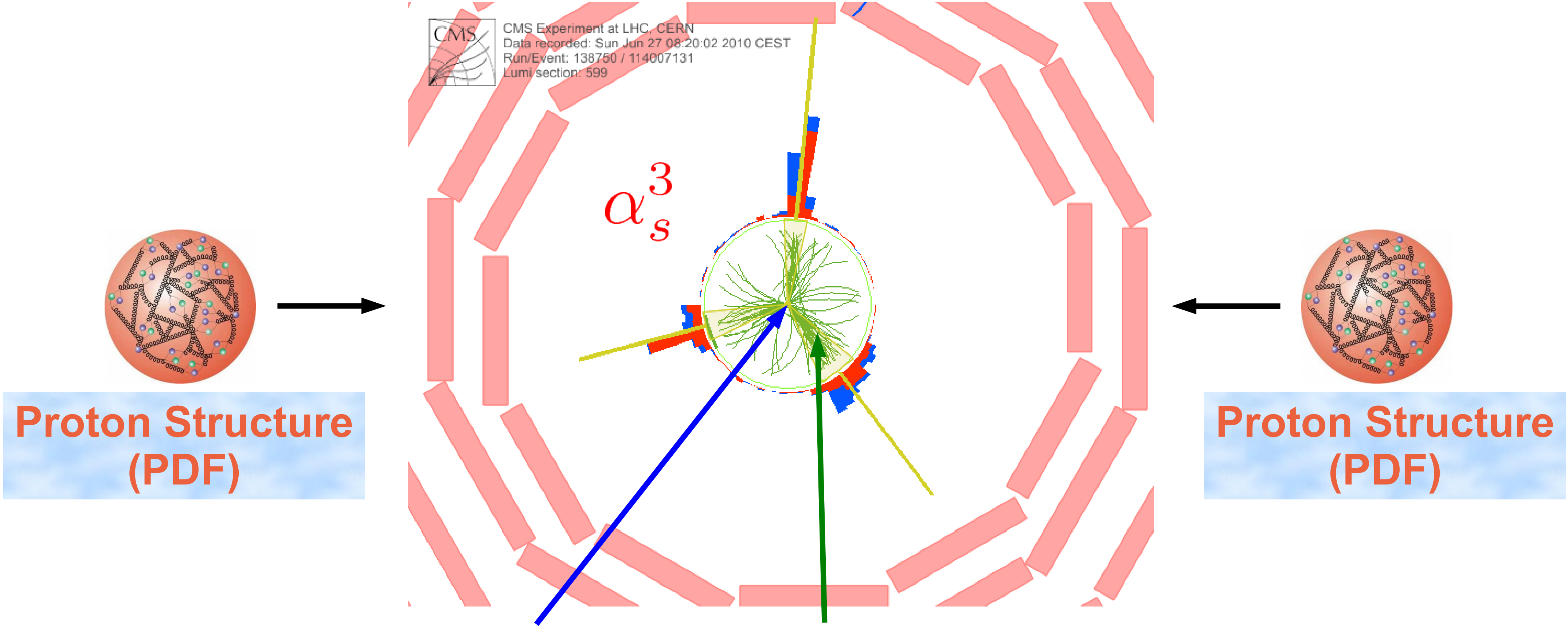
Matrix Element

Hadrons

Jets at the LHC

Abundant production of jets:

- **Extract $\alpha_s(M_Z)$, the least precisely known fundamental constant!**
  $\Delta\alpha/\alpha \sim 3\cdot10^{-10}$, $\Delta G_F/G_F \sim 5\cdot10^{-8}$, $\Delta G/G \sim 10^{-5}$, $\Delta\alpha_s/\alpha_s \sim 10^{-2}$



Proton Structure (PDF)

Proton Structure (PDF)

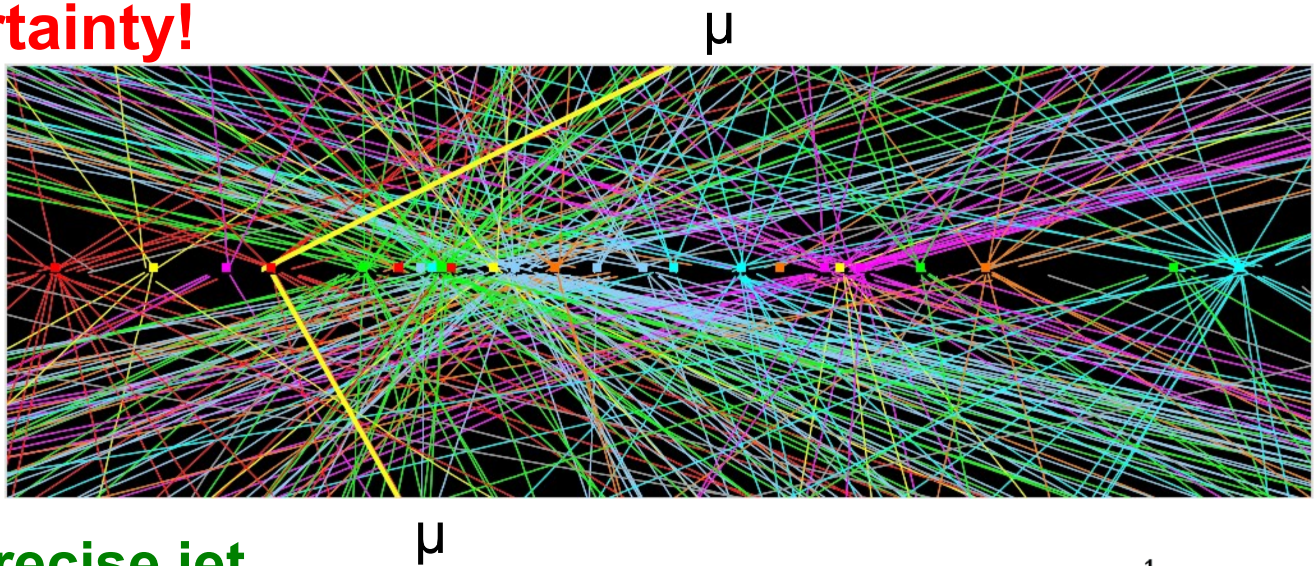
Matrix Element **Hadrons**

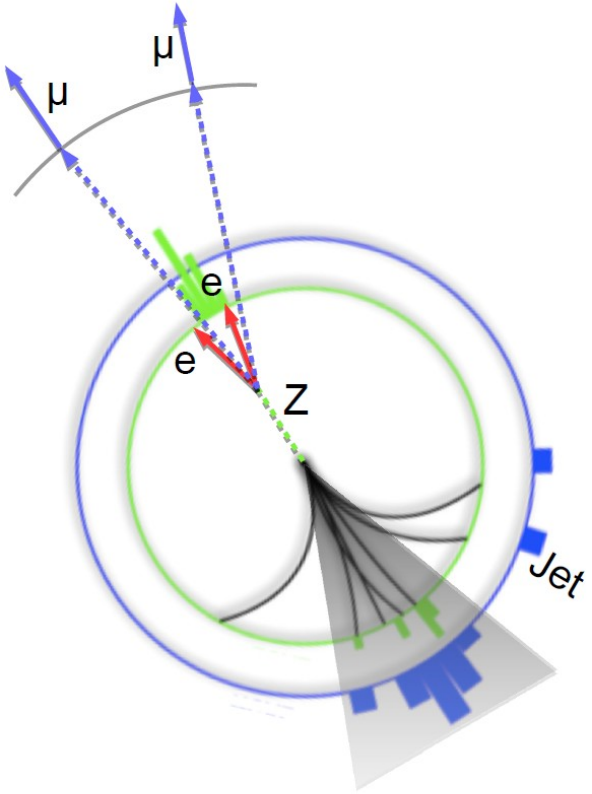
Jet Energy Scale

Dominant experimental uncertainty!

Recurring issue:
Multiple pp collisions (pile-up)
2012: ~20 collisions
→ worse at high lumi 13 TeV!

ATLAS Z → μμ candidate event
25 primary vertices:
(Record beyond 70!)

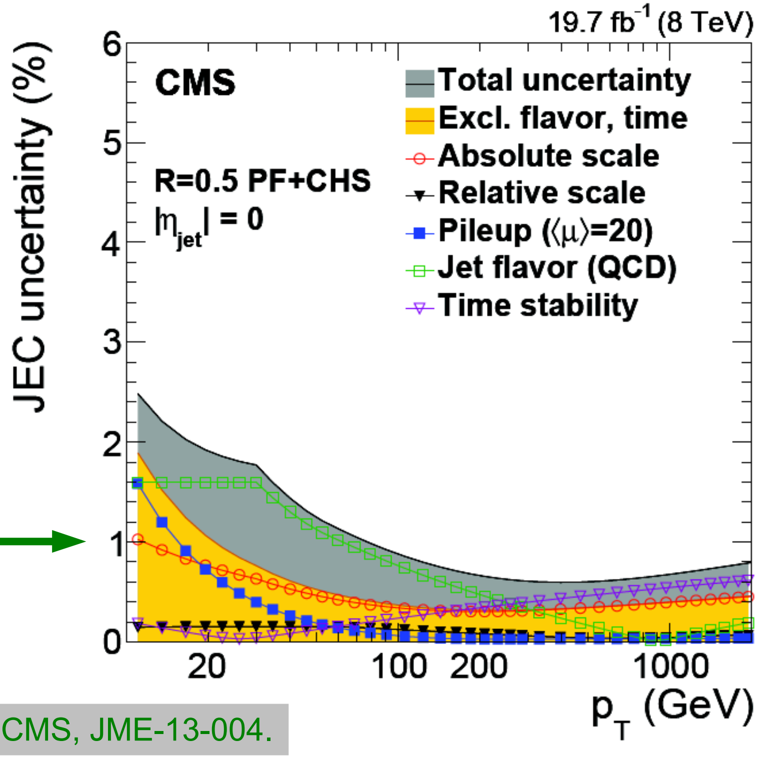




Most precise jet calibration channel: Z(--> μμ,ee) + jet

Potential for improvements:
- flavour dep. MC corrections
- time dep. in calo calibration
→ grey band

Beyond 100 GeV p_T accuracy better than 1%! →



CMS, JME-13-004.

Factorized Cross Section

Dominant theoretical uncertainties: missing higher orders (NLO), PDFs

hadron-hadron cross section:

PDFs describing initial state hadrons

$$\sigma_{pp\to X} = \sum_{ijk} \int \mathrm{d}x_1 \mathrm{d}x_2 \mathrm{d}z \, f_i(x_1,\mu)\, f_j(x_2,\mu)$$

Final state: fragmentation function or jets

$$\times\, \hat{\sigma}_{ij\to k}\left(x_1, x_2, z, Q^2, \alpha_s(\mu), \mu\right) D_{k\to X}(z,\mu)$$

Perturbative cross section:

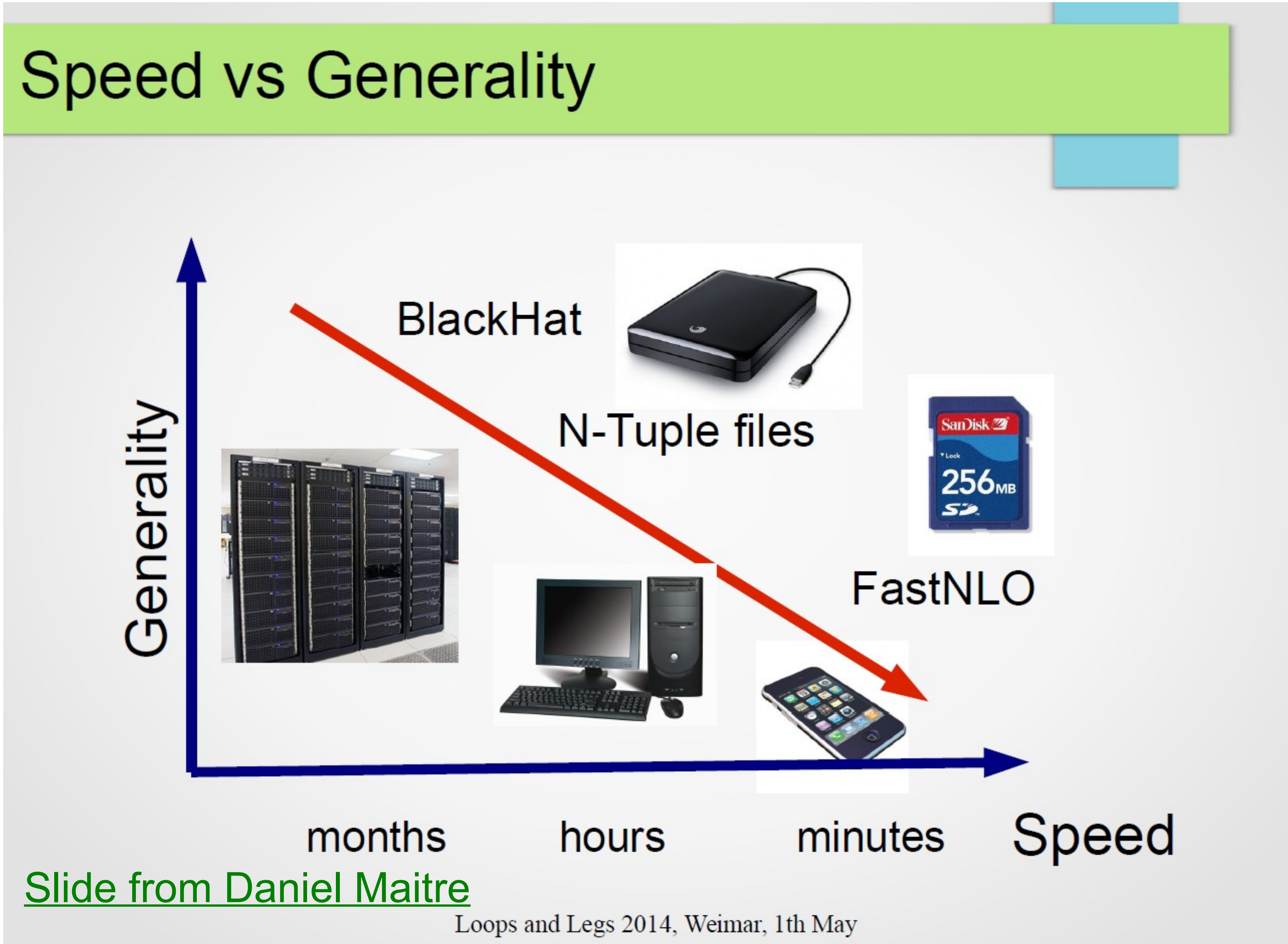
- **huge amount of “human” time to calculate**
- **huge amount of CPU time for num. integrations**

CPU time:

LO: O(<< 10^0h)
NLO: O(~ 10^3h)
NNLO: O(~ 10^5h)
→ Not usable in fits!

Solution: Interpolation techniques
Change PDFs, μ_r, μ_f, $\alpha_s(M_Z)$, α_s evolution without recalculation.
→ Run once, then gain > O(10^9) in speed!

Use with BlackHat N-Tuples



Speed vs Generality

Generality

BlackHat

N-Tuple files

FastNLO

months

hours

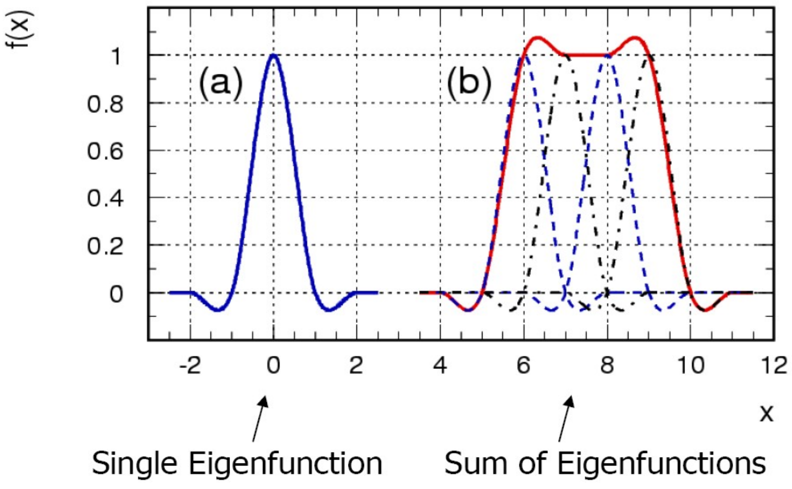
minutes

Speed

Slide from Daniel Maitre

Loops and Legs 2014, Weimar, 1th May

The fastNLO Concept



Single Eigenfunction

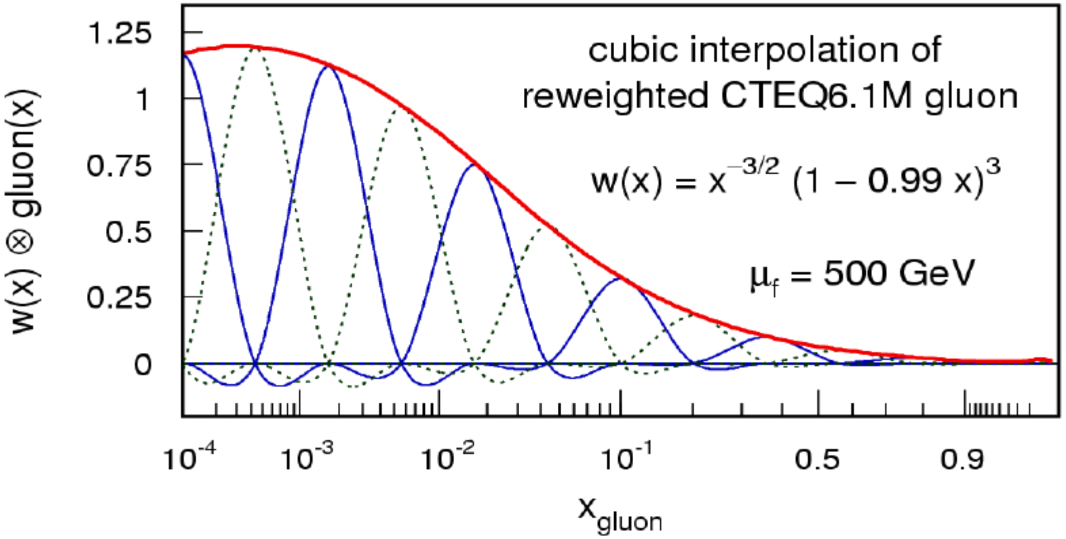
Sum of Eigenfunctions

Choose interpolation kernel

(Our 1st version: Catmull-Rom splines
as used by Pixar Animation Studios)

- Set of n discrete **x-nodes** x_i
- Set of **Eigenfunctions** $E_i(x)$ around nodes x_i
  - → Single PDF is replaced by a linear combination of interpolation kernels

$$f_a(x) \cong \sum_i f_a(x_i) \cdot E^{(i)}(x)$$



→ Do integrals once

→ Afterwards:
Change prefactors in summation
to change PDF (or scales, …)

→ milliseconds

Store tabulated perturbative coefficients convoluted with interpolation kernels

→ use jet cross sections in fits!

C. Pascaud, F. Zomer (Orsay, LAL), LAL-94-42..
fastNLO, T. Kluge, KR, M. Wobisch, arxiv:0609285

Event Rates at the LHC

Total cross section

Jets: $\sigma_{jet}(E_T^{jet} > 100\,\mathrm{GeV})$

~ 2000 / s

W & Z bosons: σ_W, σ_Z

~ 200 / s, 50 / s

Top quarks (σ_{tt})

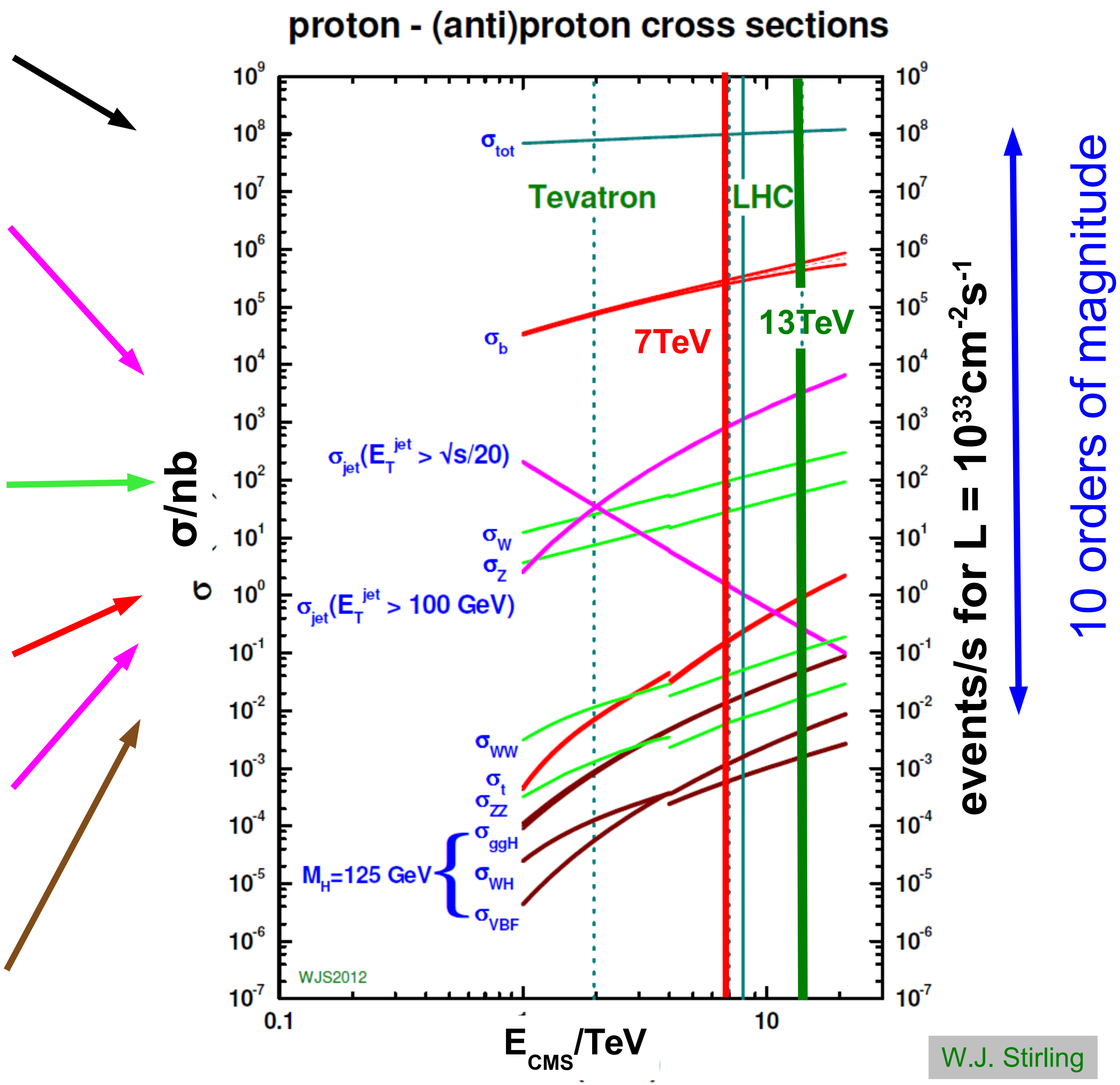
~ 1 / s

Jets: $\sigma_{jet}(E_T^{jet} > 650\,\mathrm{GeV})$

~ 18 / min

Higgs bosons (σ_{ggH}, σ_{WH}, σ_{VBF})

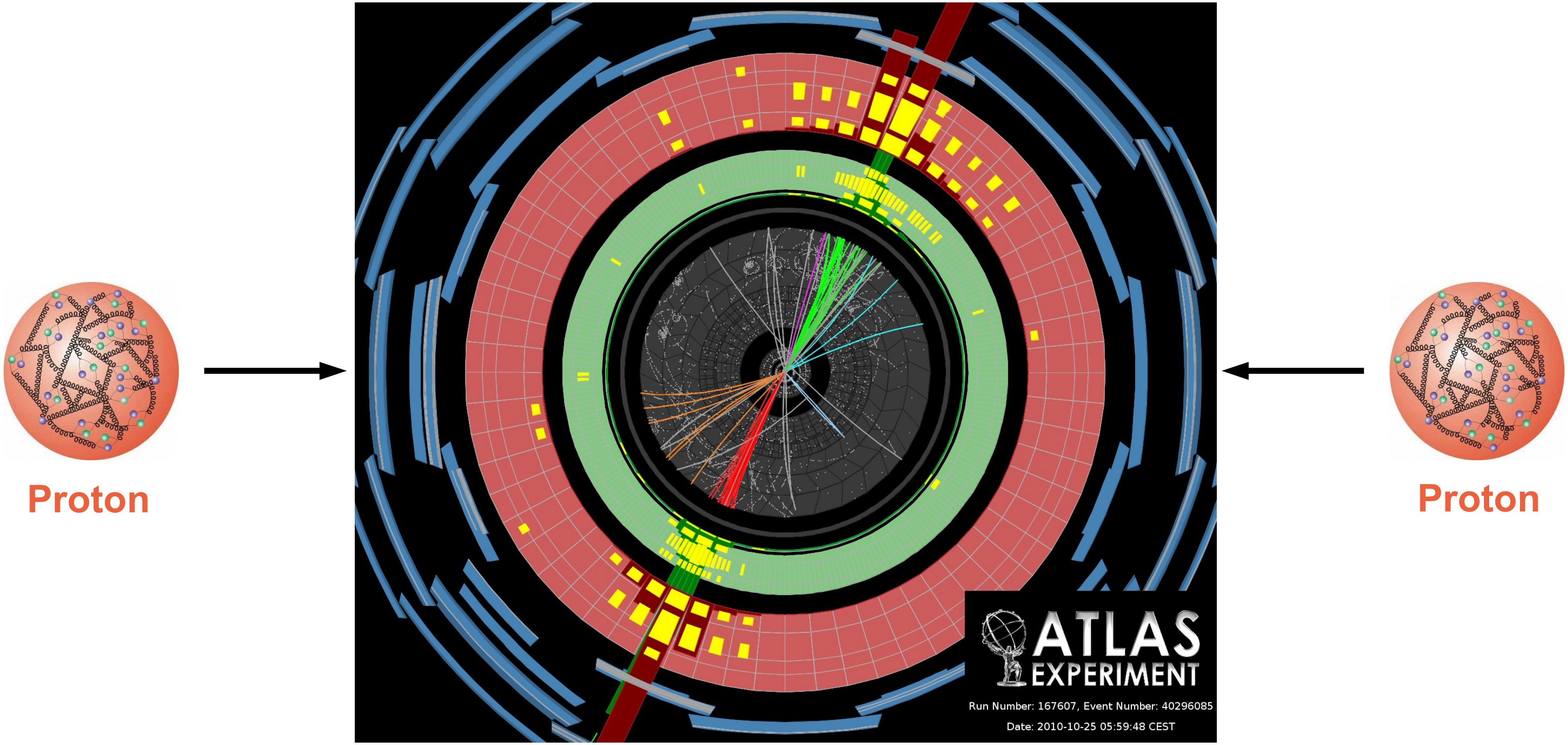
~ 150 / h



W.J. Stirling

Dijets

High Masses



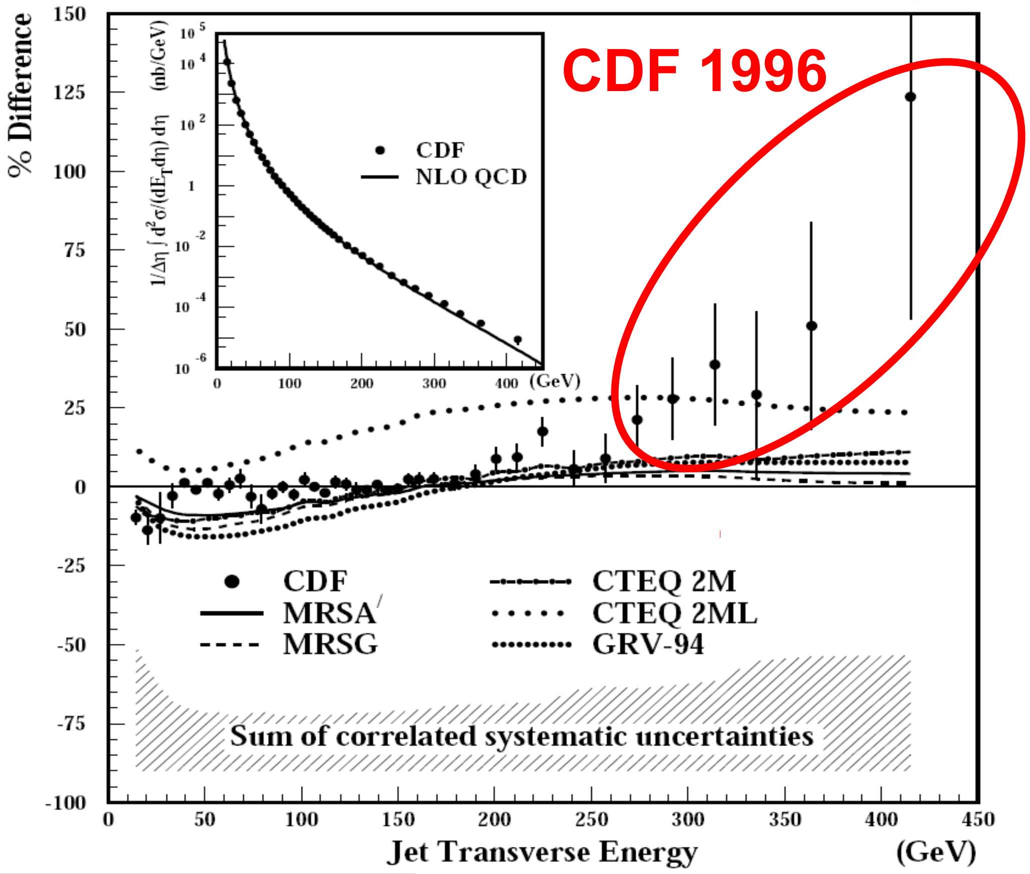
New Phenomenon?

CDF derived a preferred contact interaction scale of Λ = 1.6 TeV!

Explainable through adaptation of gluon density → $g(x,Q^2)$

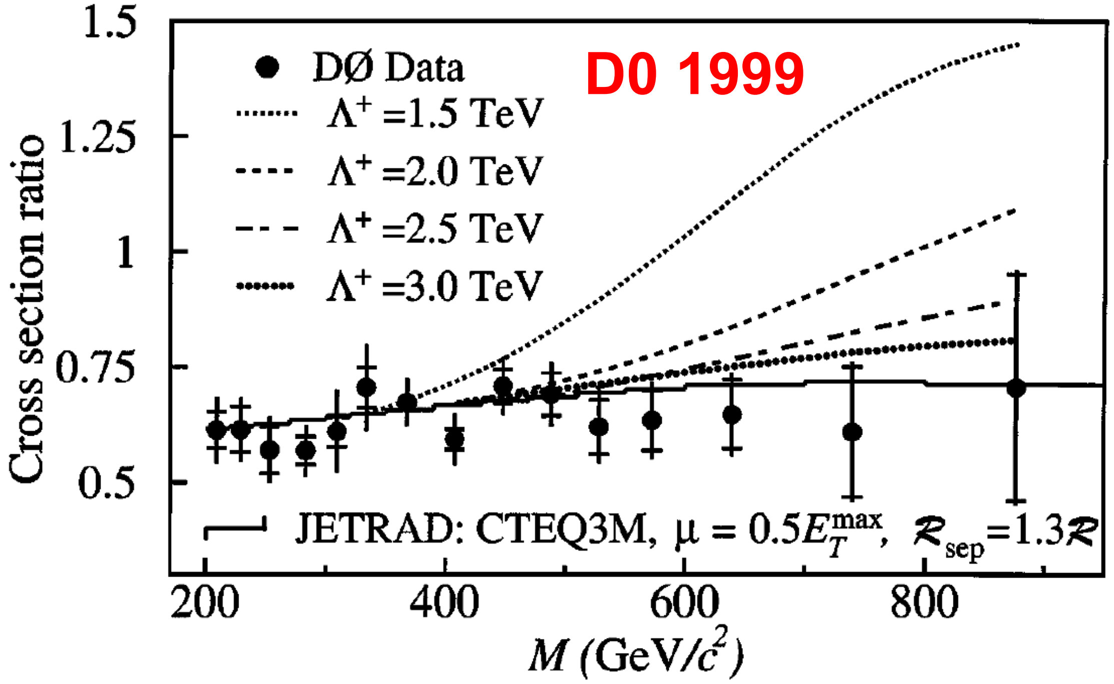
Later D0 analysis:
no significant Deviations!

Inclusive jet p_T



Phys.Rev.Lett. 77 (1996)

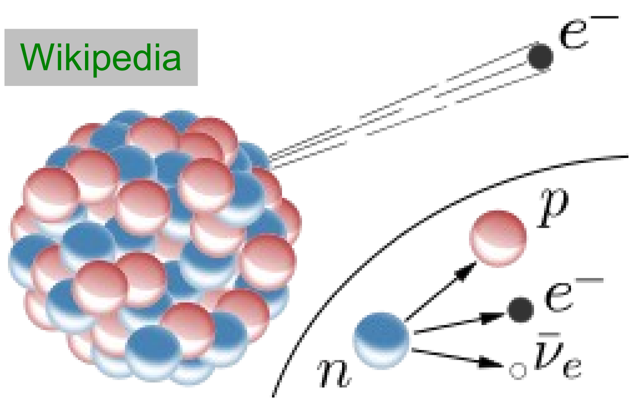
$$\eta\text{-ratio} = \frac{N(|\eta_{1,2}|<0.5)}{N(0.5<|\eta_{1,2}|<1)}$$



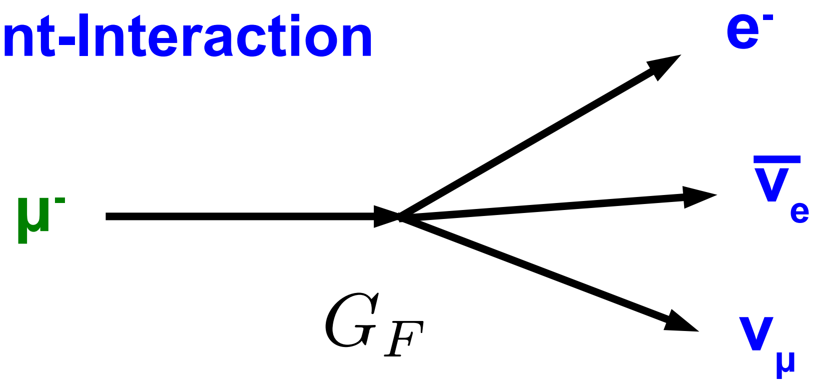
D0, PRL82 (1999) 2457.

Fermi's Four-Fermion-Coupling

β Decay

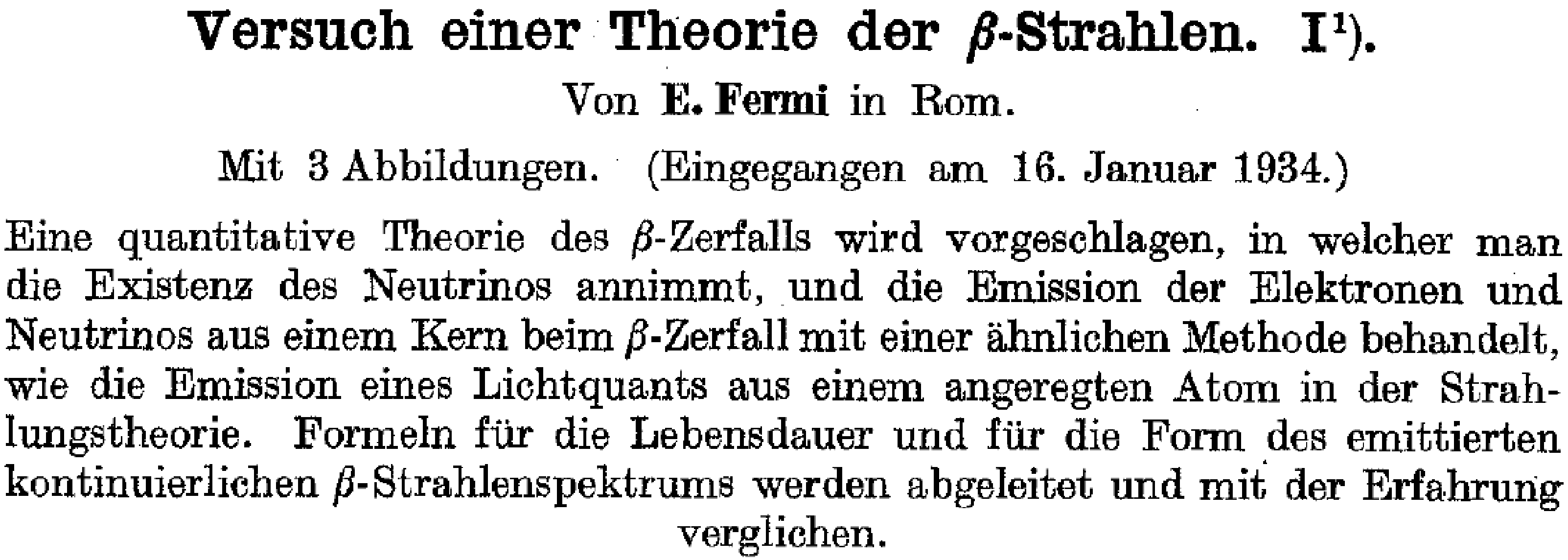

Wikipedia

μ Decay Point-Interaction



Publication refused by “Nature” as too speculative.

→ First appeared in German and Italian!



Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

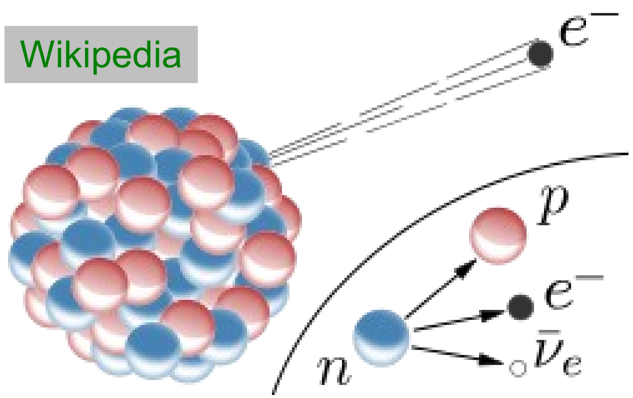
Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

Eine quantitative Theorie des β-Zerfalls wird vorgeschlagen, in welcher man die Existenz des Neutrinos annimmt, und die Emission der Elektronen und Neutrinos aus einem Kern beim β-Zerfall mit einer ähnlichen Methode behandelt, wie die Emission eines Lichtquants aus einem angeregten Atom in der Strahlungstheorie. Formeln für die Lebensdauer und für die Form des emittierten kontinuierlichen β-Strahlenspektrums werden abgeleitet und mit der Erfahrung verglichen.

Fermi, Z. Phys., 1934, 88, 16; Nuovo Cim., 1934, 11, 1

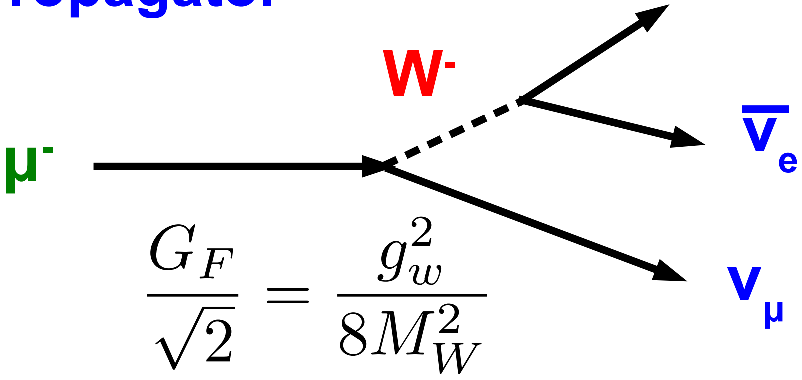
Fermi's Four-Fermion-Coupling

β Decay



Wikipedia

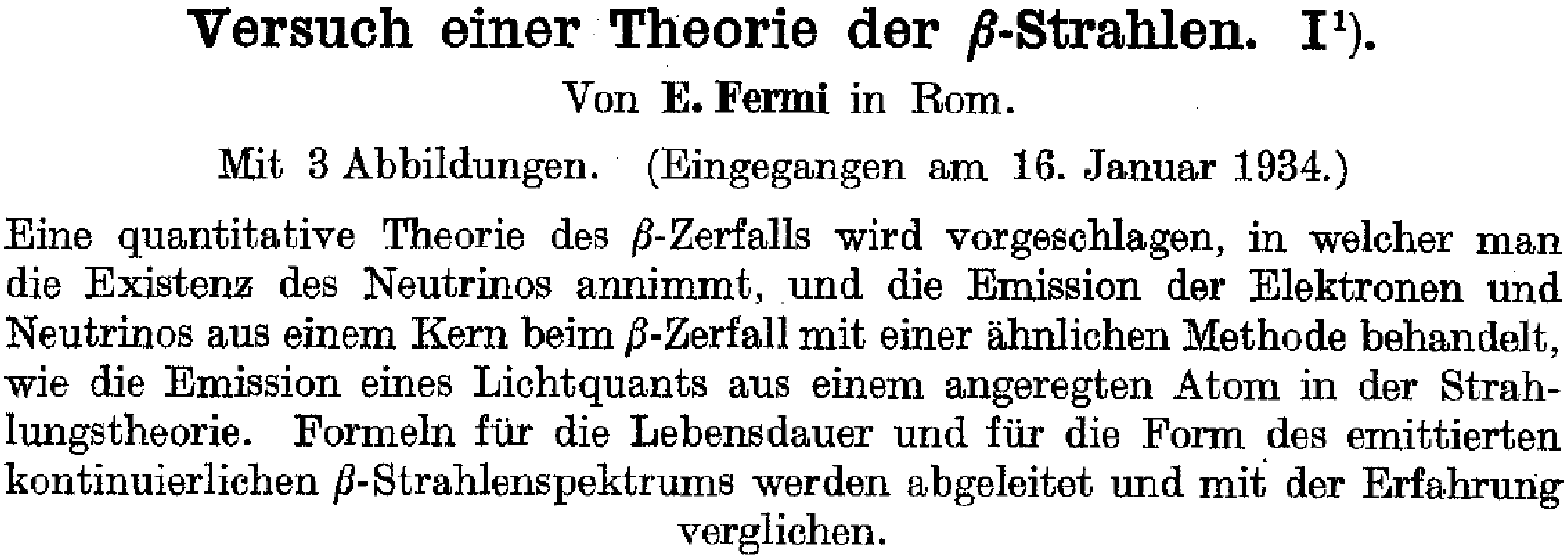
μ Decay W Propagator



$$\frac{G_F}{\sqrt{2}} = \frac{g_w^2}{8M_W^2}$$

Publication refused by “Nature” as too speculative.

→ First appeared in German and Italian!



Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

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Fermi, Z. Phys., 1934, 88, 16; Nuovo Cim., 1934, 11, 1

Contact Interactions (CI)

Numerous models: i.a.
composite "elementary particles"

Terazawa, Phys. Rev. D, 1980, 22, 184.
Eichten, Lane, Peskin, Phys. Rev. Lett., 1983, 50, 811,
Eichten, Hinchcliffe, Lane, Quigg, Rev. Mod. Phys., 1984, 56, 579.
Baur, Hinchcliffe, Zeppenfeld, Int. J. Mod. Phys. A, 1987, 2, 1285.
Hewett, Rizzo, Phys. Rept., 1989, 183, 193.
Frampton, Glashow, Phys. Lett. B, 1987, 190, 157.
Simmons, Phys. Rev. D, 1997, 55, 1678.
Randall, Sundrum, Phys. Rev. Lett., 1999, 83, 3370.

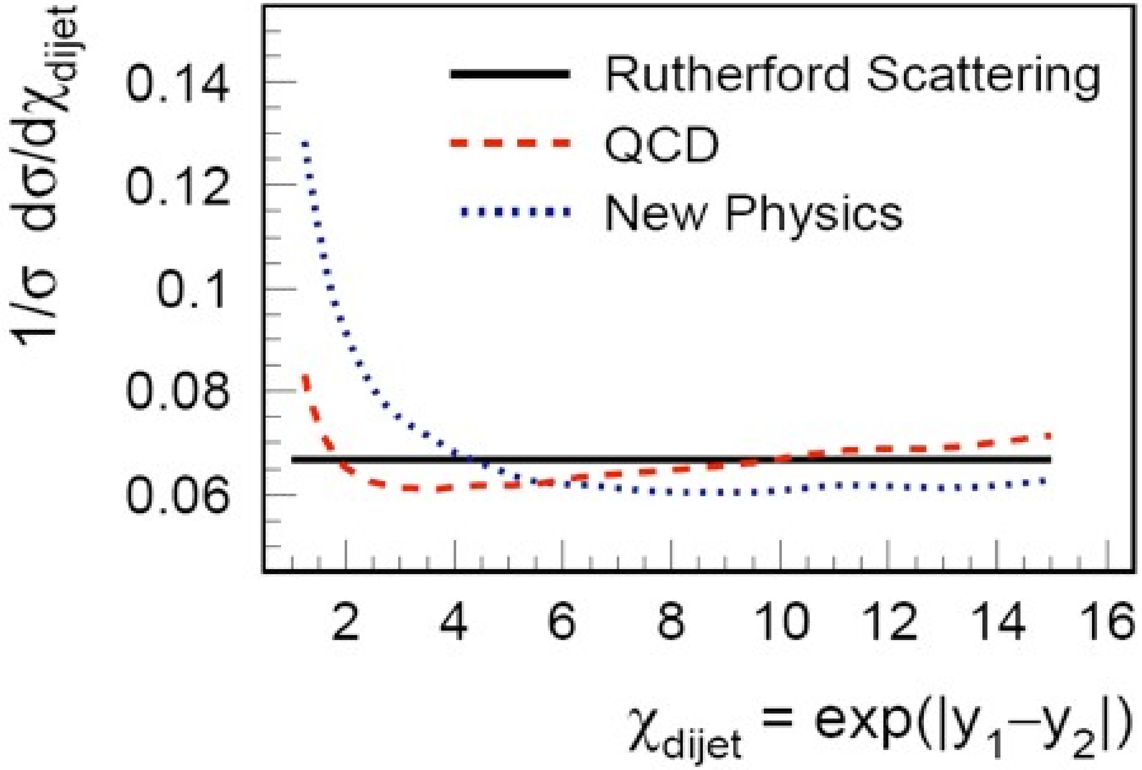
Approximation of low-energy effects as contact interaction:

How to find? →
Dijet angular distribution

QCD:
t-channel ~ Rutherford scattering
→ flat in X

$$\chi = \exp\left(|y_1 - y_2|\right) = \frac{1 + |\cos(\hat{\theta})|}{1 - |\cos(\hat{\theta})|}$$

New phenomena: More isotropic



New Limits from 13 TeV Data

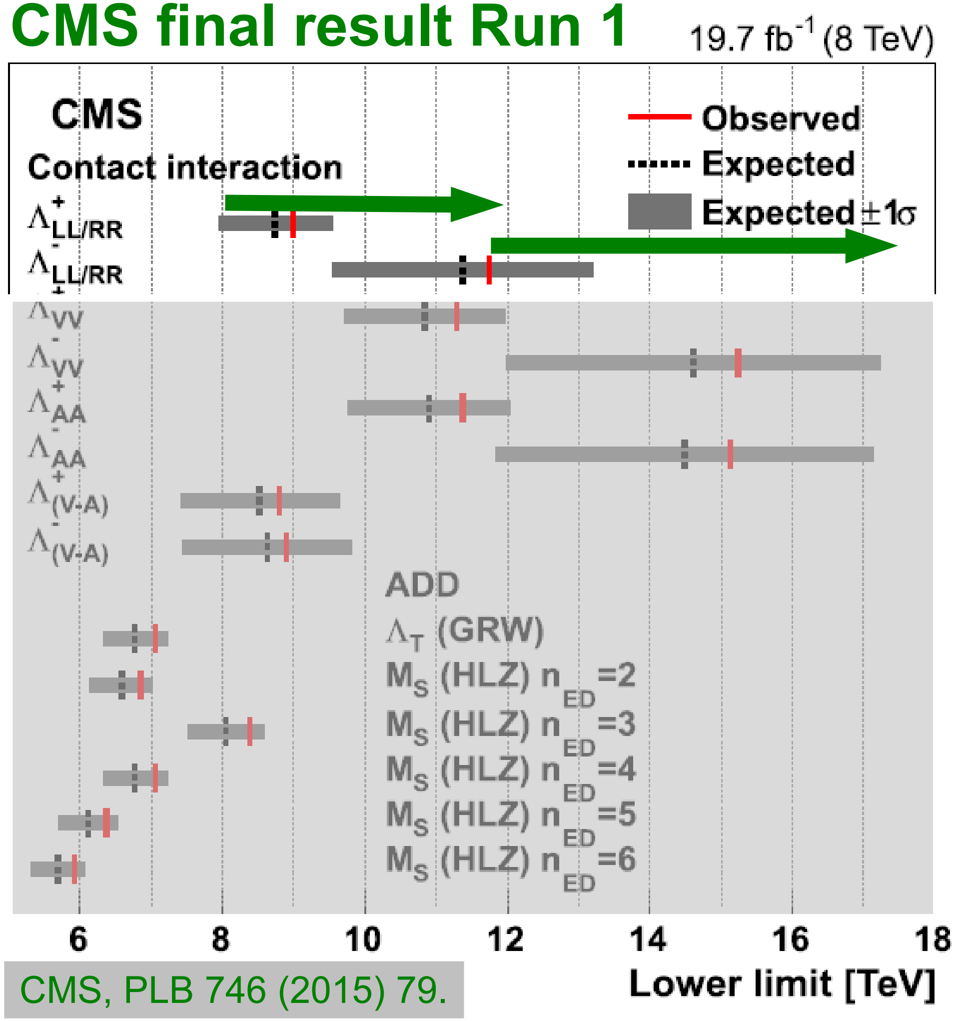
ATLAS 2015 data at 13 TeV:

Λ^{+}_{min} 8.1 → 12.0 TeV

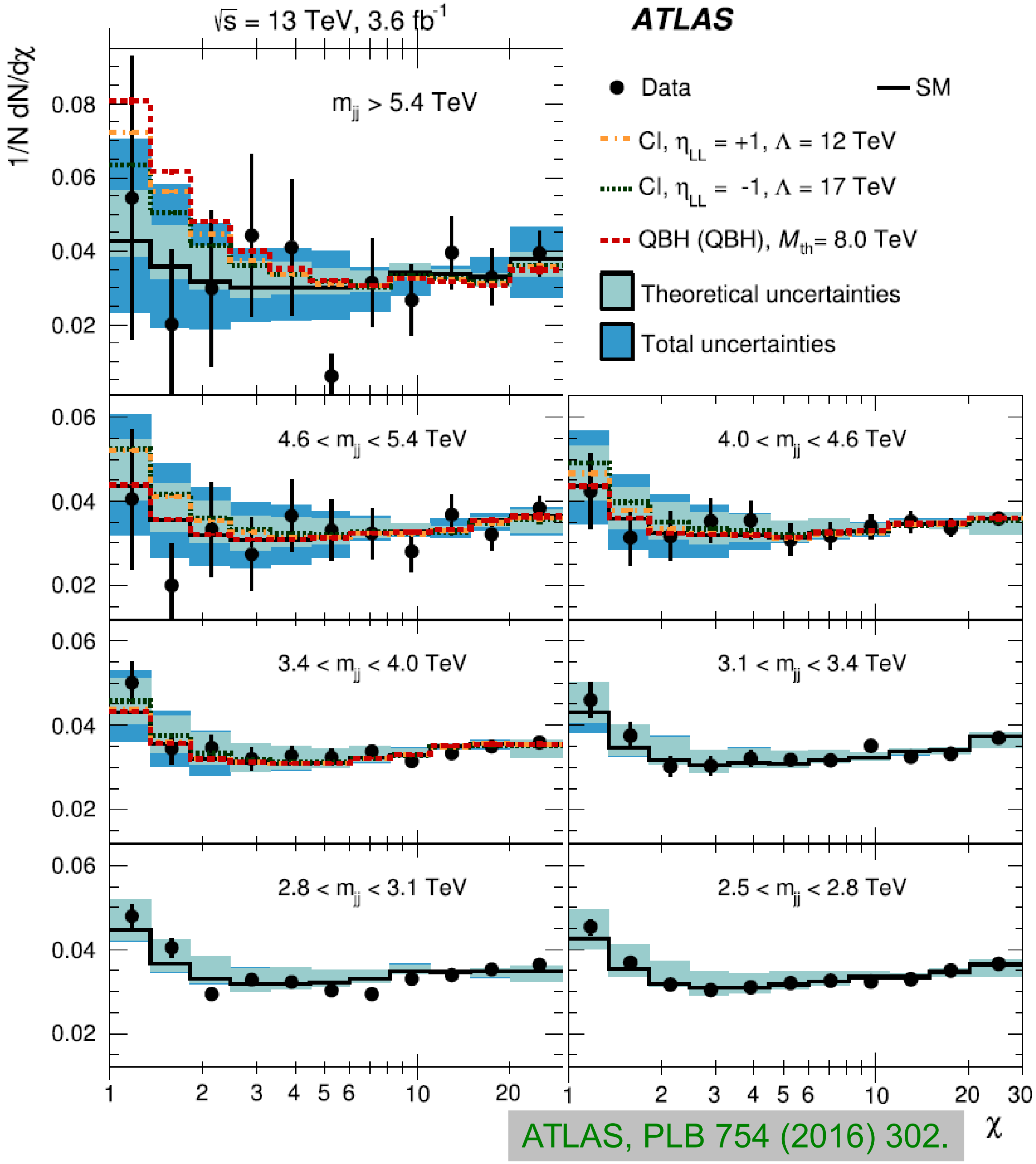
Λ^{-}_{min} 12.0 → 17.5 TeV

→ dramatic improvement!

CMS final result Run 1



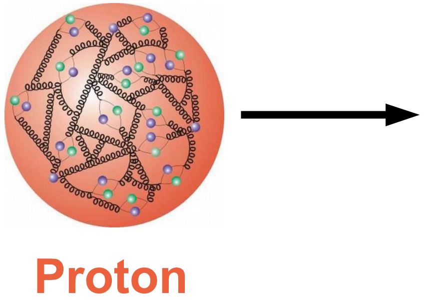
CMS, PLB 746 (2015) 79.

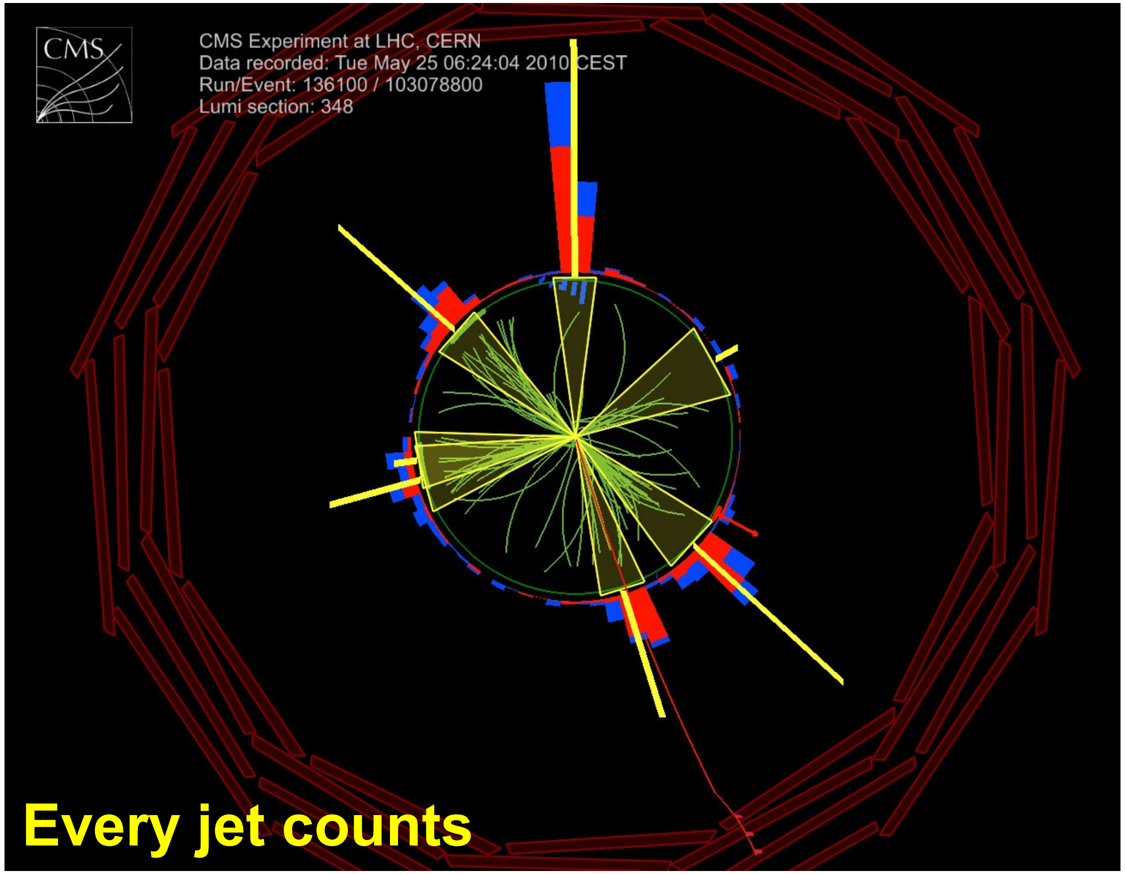


ATLAS, PLB 754 (2016) 302.

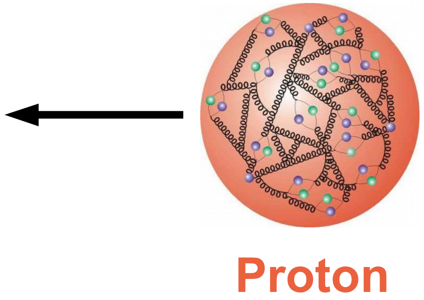
All Inclusive

High transverse Momenta


Proton


CMS Experiment at LHC, CERN
Data recorded: Tue May 25 06:24:04 2010 CEST
Run/Event: 136100 / 103078800
Lumi section: 348

Every jet counts

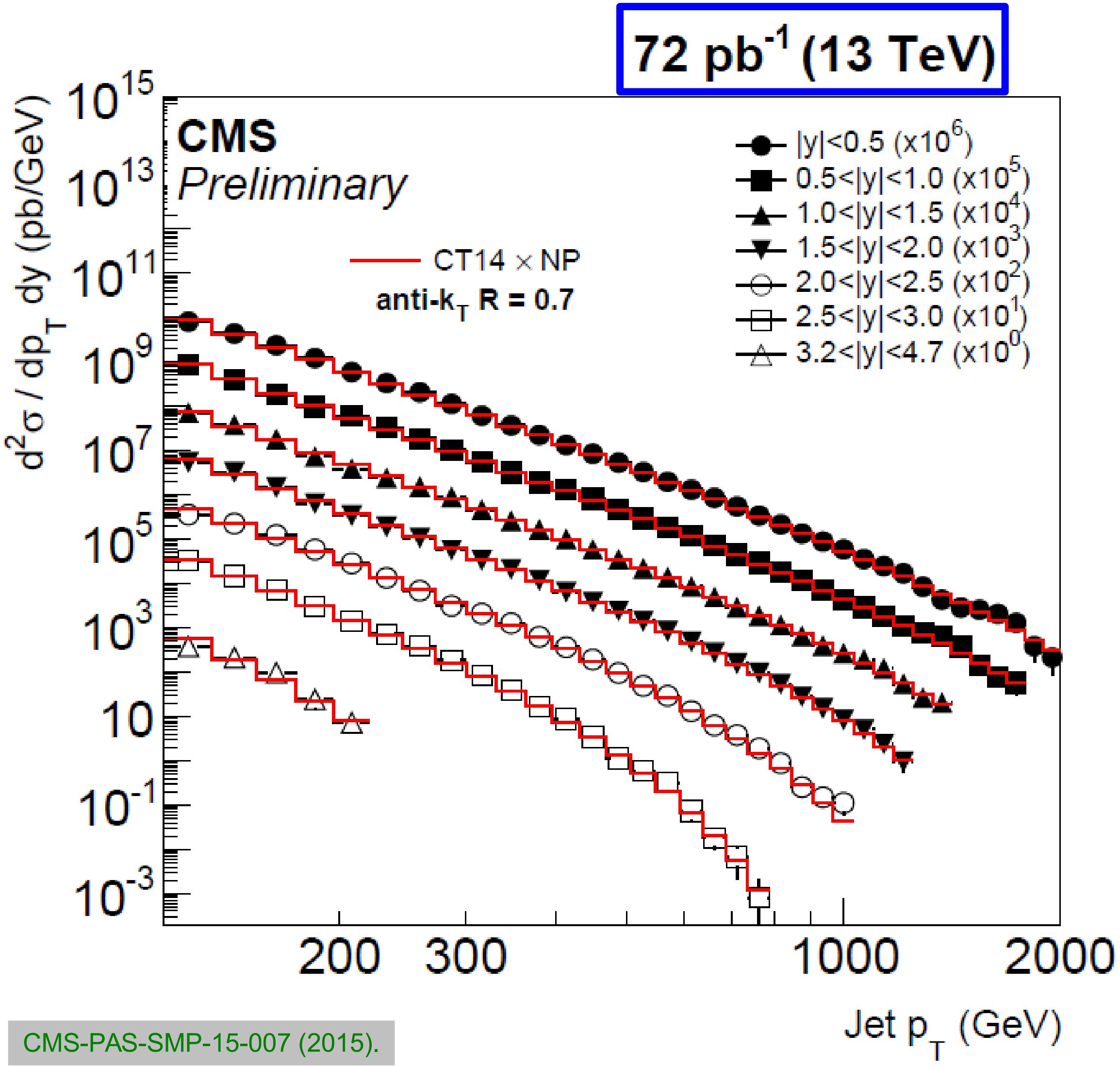

Proton

Inclusive Jets

Agreement with standard model predictions:

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

- over many orders of magnitude
- up to 2 TeV jet p_T
  (and beyond from 8 TeV data)
- up to rapidity |y| of ~ 4.7
  (1° from beam direction)
- Similar picture for ATLAS
- More luminosity at 13 TeV needed
  to pass beyond 2.2 TeV of jet p_T



CMS-PAS-SMP-15-007 (2015).

Proton Structure

- **Typical parameterization of the proton structure:**

$$xf(x) = Ax^{B}(1-x)^{C}(1+Dx+Ex^{2})$$

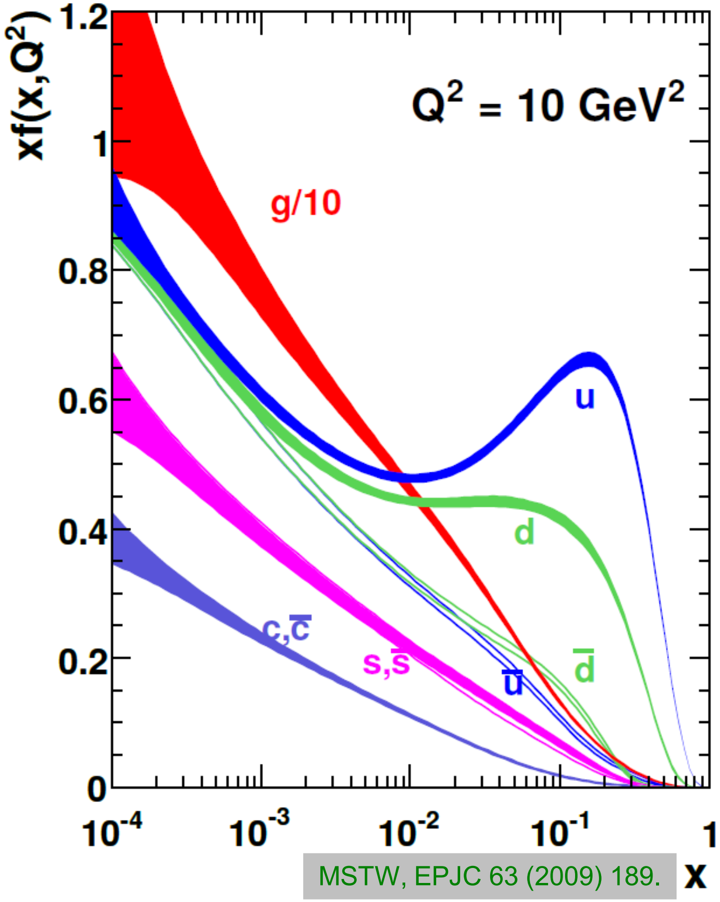
Normalization

Behaviour for $x \to 0$

Behaviour for $x \to 1$

Variability in the medium x range

- **and this for all flavours …**
  - **gluons**
  - **valence quarks**
  - **sea quarks**
- **Usually about 12 to 20 parameters to fit to data**



MSTW, EPJC 63 (2009) 189.

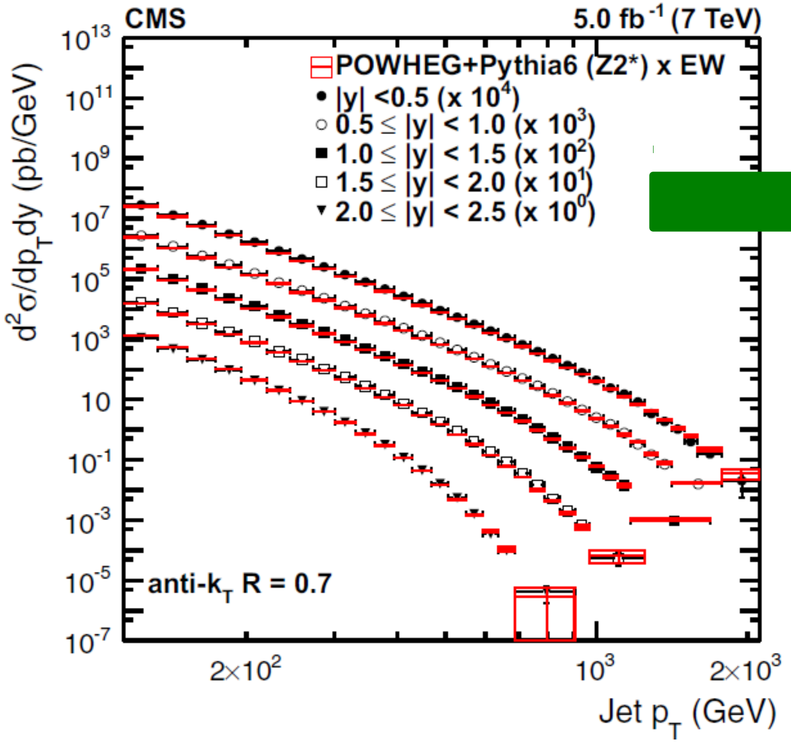
Inclusive Jets + α_s & PDFs

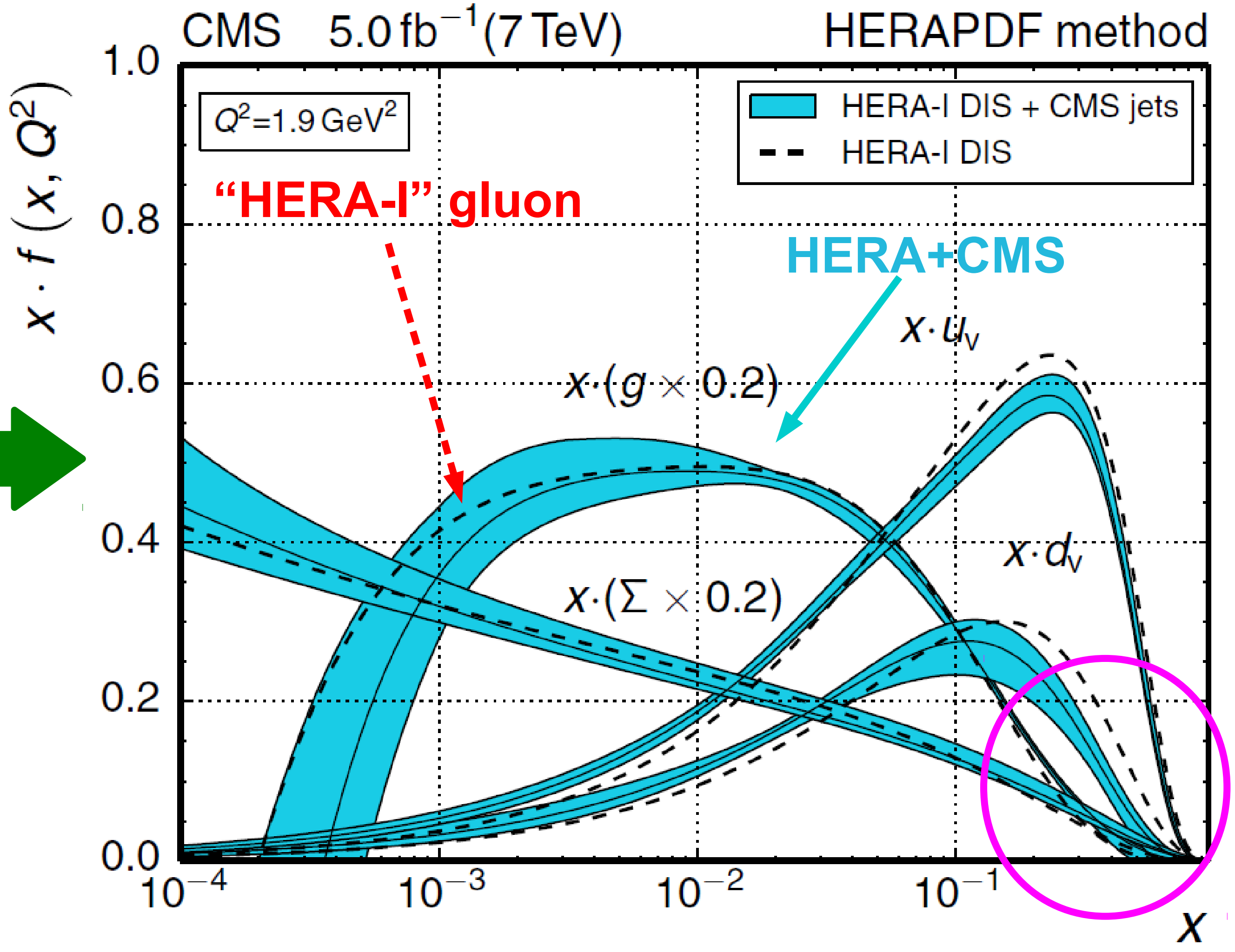
χ^2 fit using HERAFitter/xFitter and fastNLO → PDF parameters

Simultaneous fit of PDF and α_s possible

S. Alekhin, KR, et al., EPJC, 2015, 75, 304.

anti-kT, R=0.7, 7 TeV, 2011





"HERA-I" gluon

HERA+CMS

CMS, EPJC 75 (2015) 288,
JHEP 2011, 095 (2012).

"Harder" gluon at high x compared to DIS

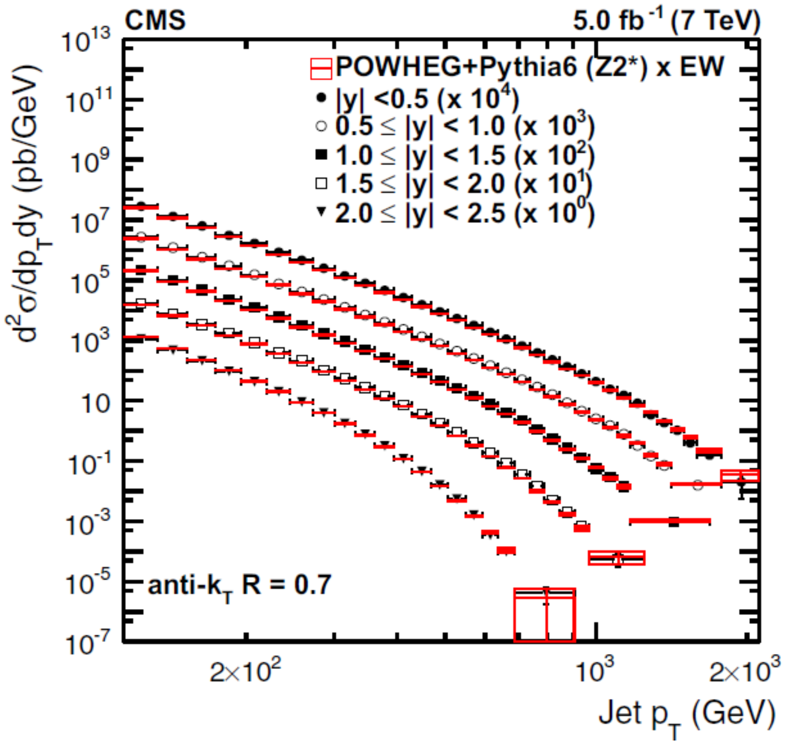
Inclusive Jets + α_s & PDFs

χ^2 fit using HERAFitter/xFitter and fastNLO → PDF parameters

Simultaneous fit of PDF and α_s possible

S. Alekhin, KR, et al., EPJC, 2015, 75, 304.

anti-kT, R=0.7, 7 TeV, 2011



CMS, EPJC 75 (2015) 288,
JHEP 2011, 095 (2012).

→ α_s

CT10-NLO: $\alpha_s(M_Z)$ = 0.1180

NLO

$$\alpha_s(M_Z) = 0.1185 \pm 0.0019\,(\mathrm{exp})$$

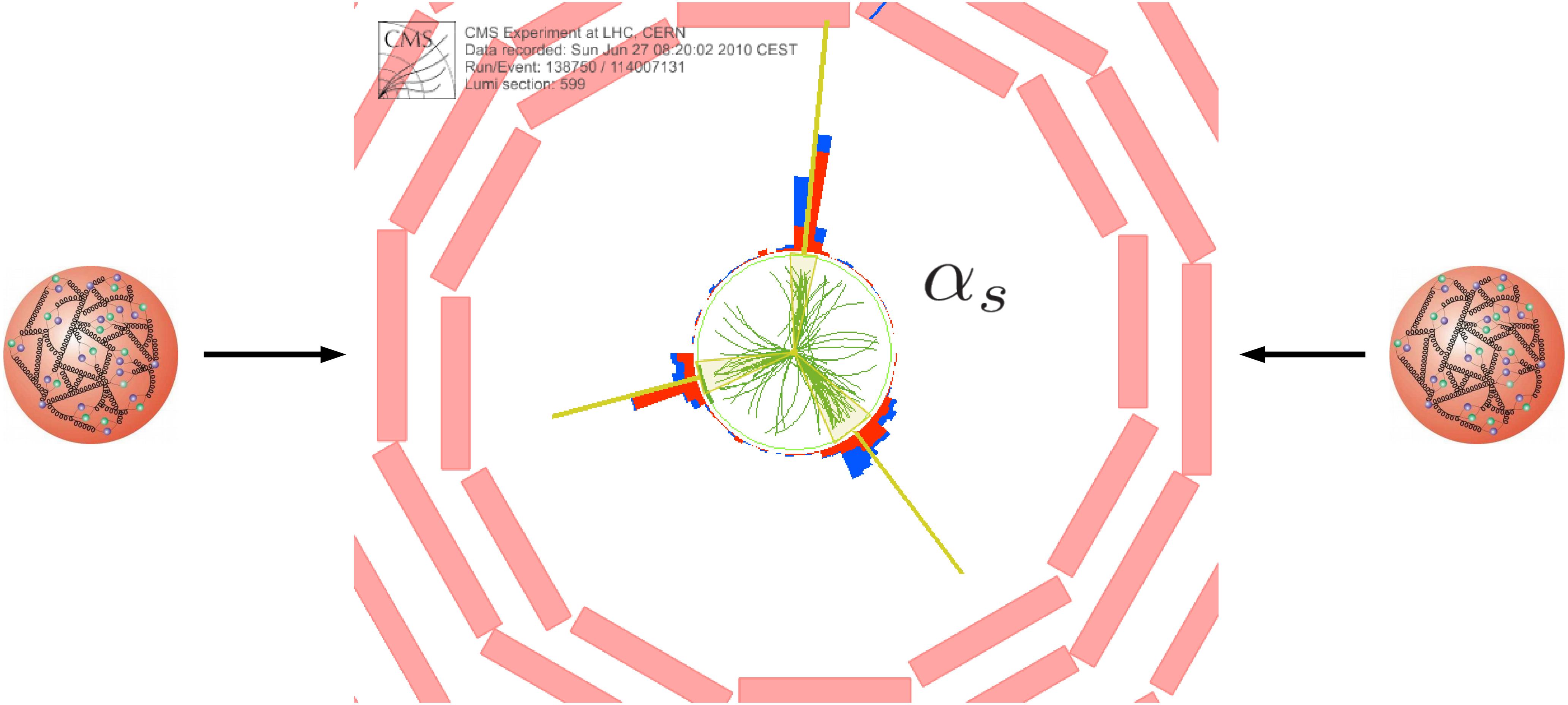
$$\pm 0.0028\,(\mathrm{PDF}) \pm 0.0004\,(\mathrm{NP}) \boxed{\pm^{0.0053}_{0.0024}}\,(\mathrm{scale})$$

$$= 0.1185 \pm 0.0035\,(\text{all w/o scale})$$

→ α_s & gluon (PDF)

$$\alpha_s(M_Z) = 0.1192^{+0.0023}_{-0.0019}\,(\text{all w/o scale})$$

Multi-Jets and α_s



3-Jet Mass

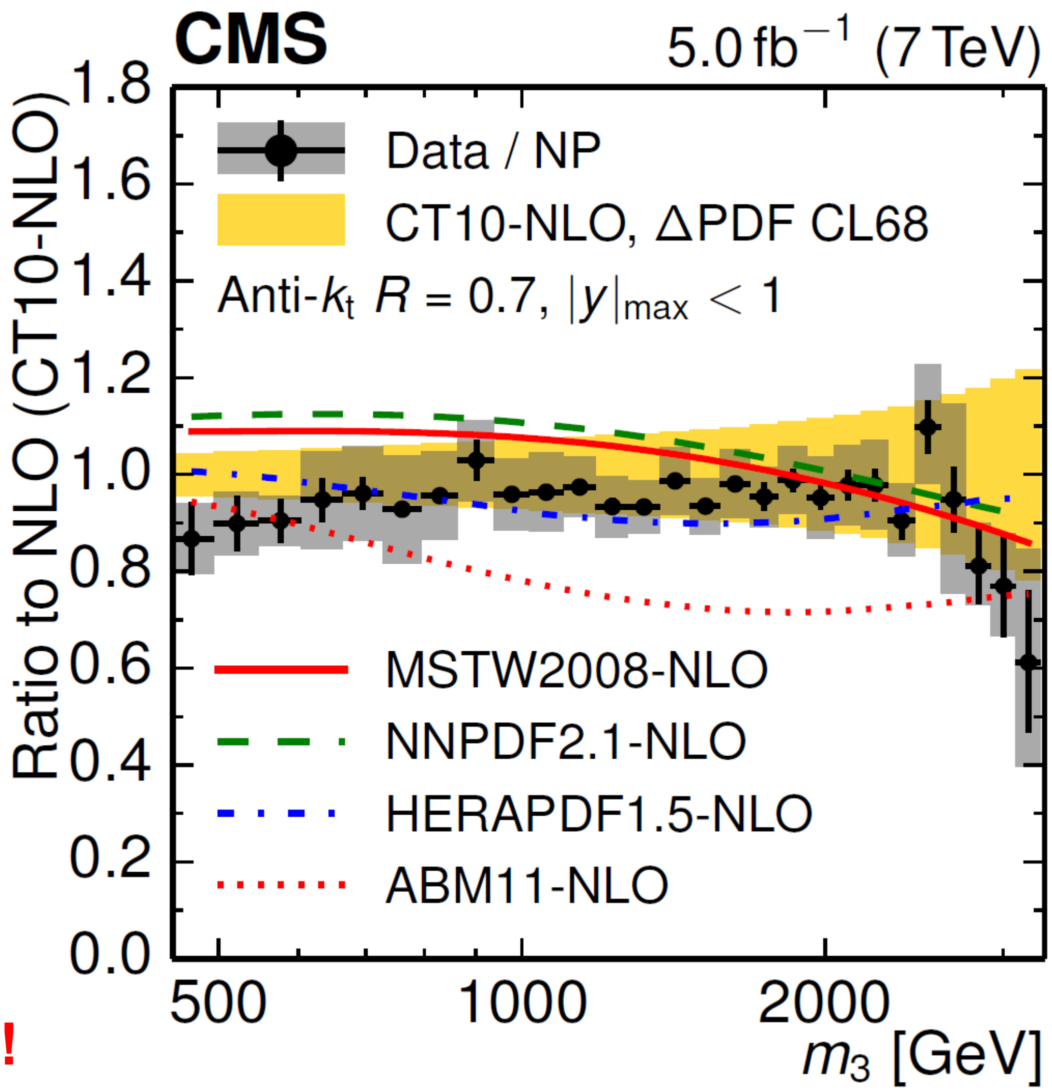
Sensitive to α_s beyond 2→2 process

$$\frac{d\sigma_{3jet}}{dm_{3jet}} \propto \alpha_s^3$$

Z. Nagy, PRL, 2002, 88, 122003;
PRD, 2003, 68, 094002.

NLO with 3-4 partons (NLOJet++)

Ratio of data over theory →



Most PDF sets compatible to data

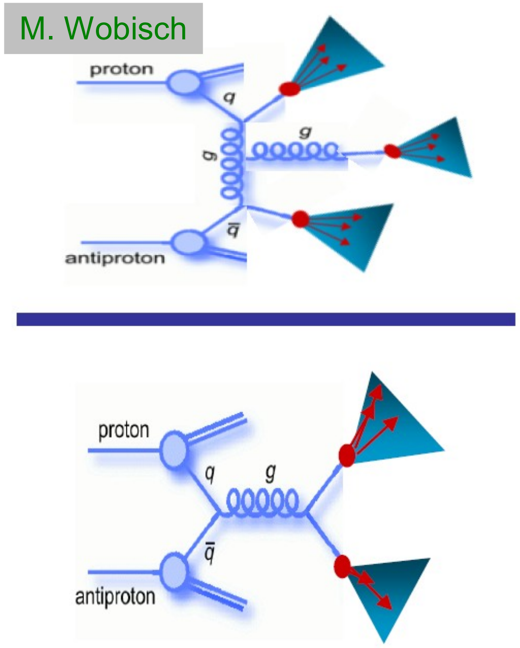
Extraction of $\alpha_s(M_Z)$:

Dominated by theory uncertainty (NLO)!

$$\alpha_S(M_Z) = 0.1171 \pm 0.0013(\mathrm{exp}) \pm 0.0024(\mathrm{PDF}) \pm 0.0008(\mathrm{NP}) \boxed{{}^{+0.0069}_{-0.0040}(\mathrm{scale})}$$

3- to 2-Jet Ratios

M. Wobisch

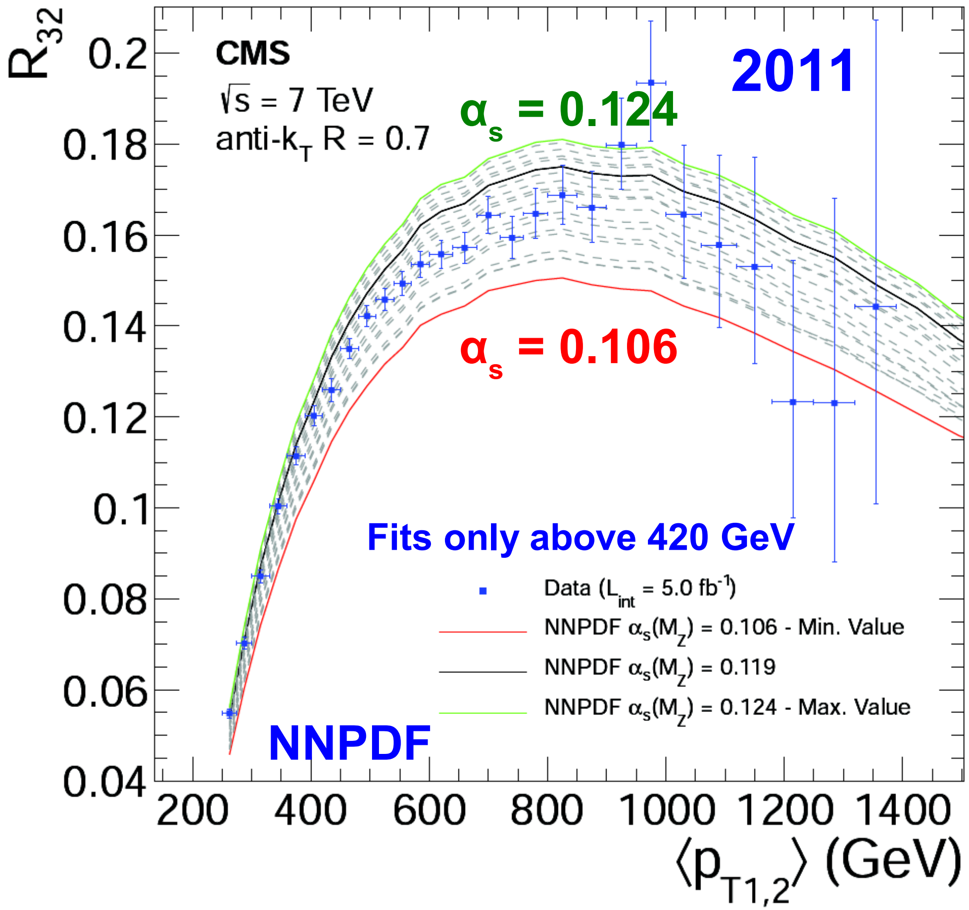


$R_{3/2}$

$\Leftrightarrow$ α_s

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

Sensitive to variation of $\alpha_s(M_Z)$



CMS: $R_{3/2}$

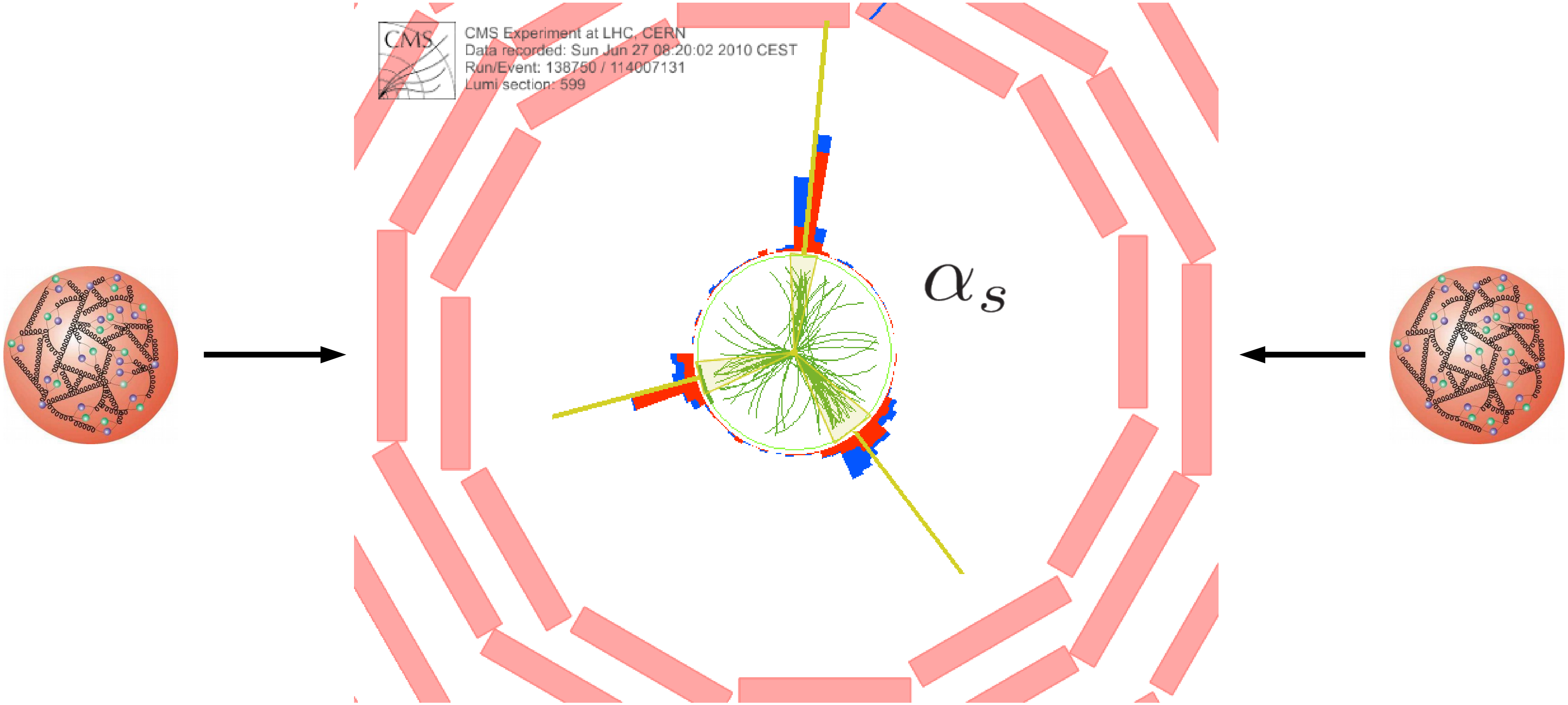
- Ratio of inclusive 3- to inclusive 2-jet events

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

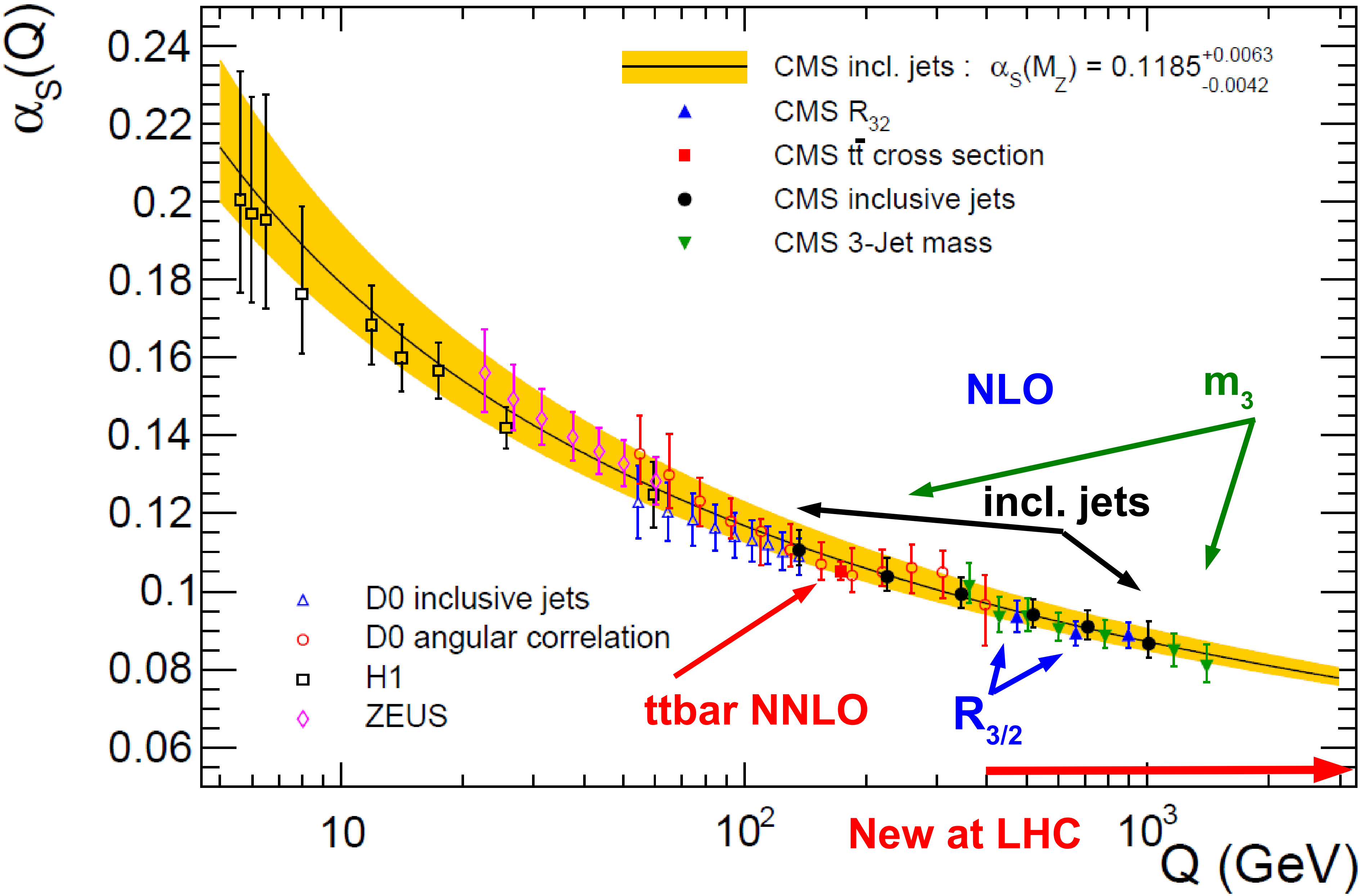
Dominated by NLO theory uncertainty!

CMS, EPJC 73 (2013) 2604.

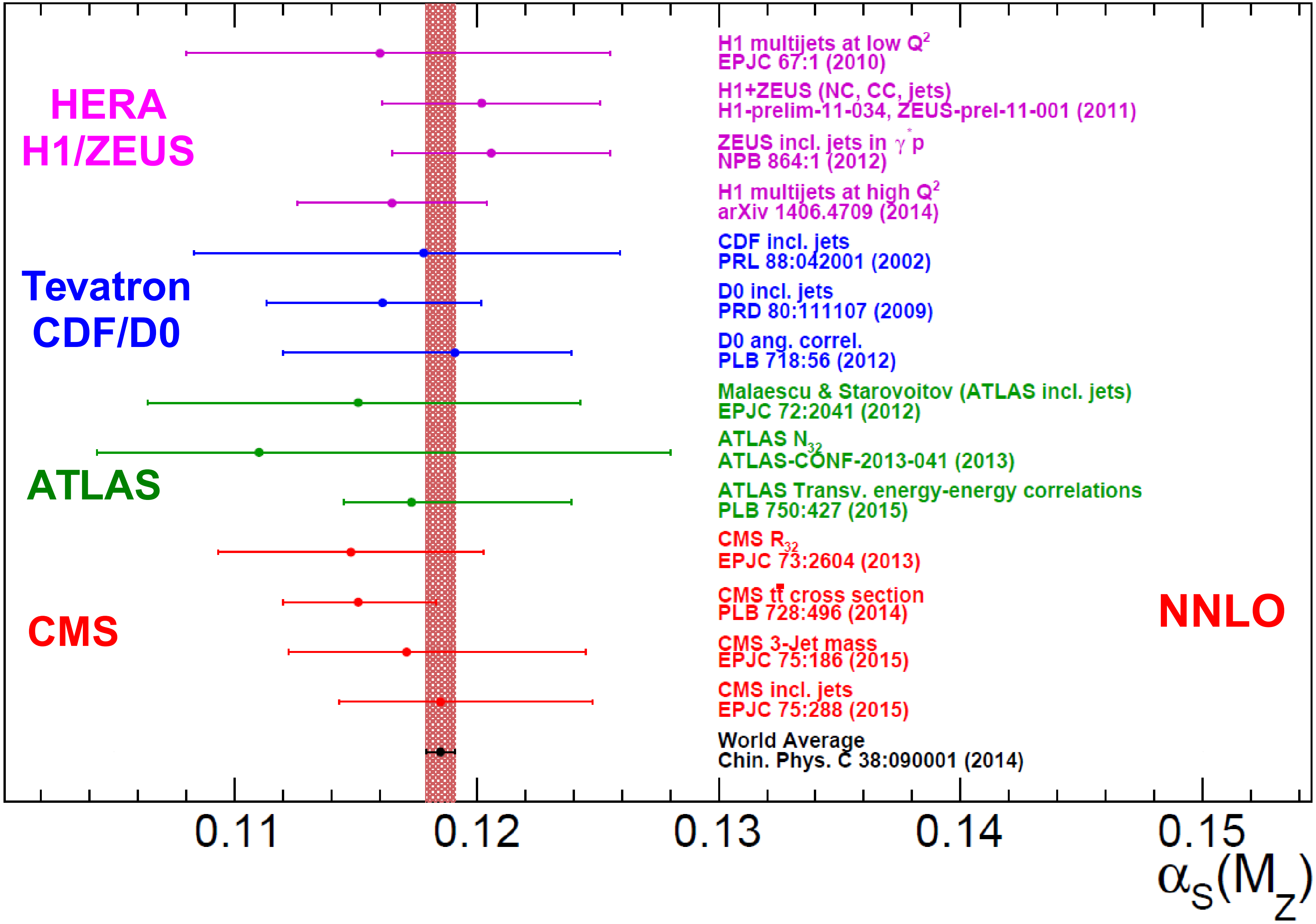
α_s (1 TeV) ?


CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Jun 27 08:20:02 2010 CEST
Run/Event: 138750 / 114007131
Lumi section: 599
α_s

CMS and α_s



α_s at Hadron Colliders



$\Delta\alpha_S / \alpha_S$ / %

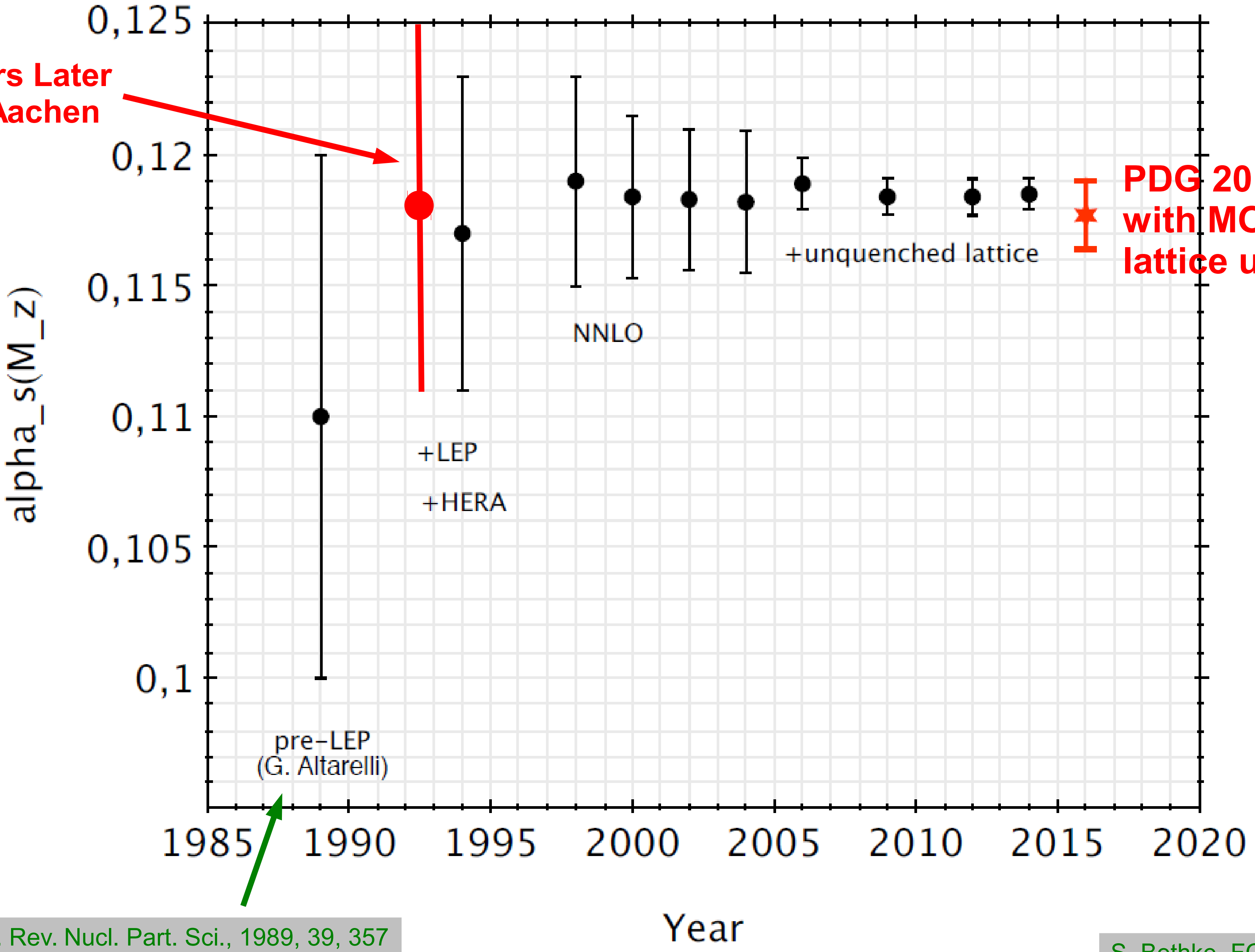
exp	PDF	scale
1.2	1.4	7.3
no final publ.		
1.9	1.9	2.5
0.7	0.8	3.1
7.5	5.0	5.0
2.9	1.0	2.3
0.7	1.2	4.7
4.1	1.8	2.4
no final publ.		
0.9	1.4	3.5
1.2	1.6	4.4
2.3	1.0	0.7
1.1	2.0	4.7
1.6	2.4	3.2

α_s Perspectives

- LHC at 7 TeV and 8 TeV enables measurements up to scales of 2 TeV
- 13 TeV data → 5 TeV?
- Theory at NNLO QCD + electroweak corrections are a must! In progress ...
- Typical uncertainties on $\alpha_s(M_Z)$:
  - Experimental: ~ 1 – 2 %
  - PDF: ~ 1 – 2 %
  - Scale: 3 – 5 %
  - Nonpert. Effects: ~ 1 %
- Beyond CMS:
  - Combined fits of ATLAS & CMS (LHC) measurements
  - Combined fits of HERA, Tevatron & LHC measurements

CHALLENGE: Determine α_s at percent level or better!

History of World Average of α_s



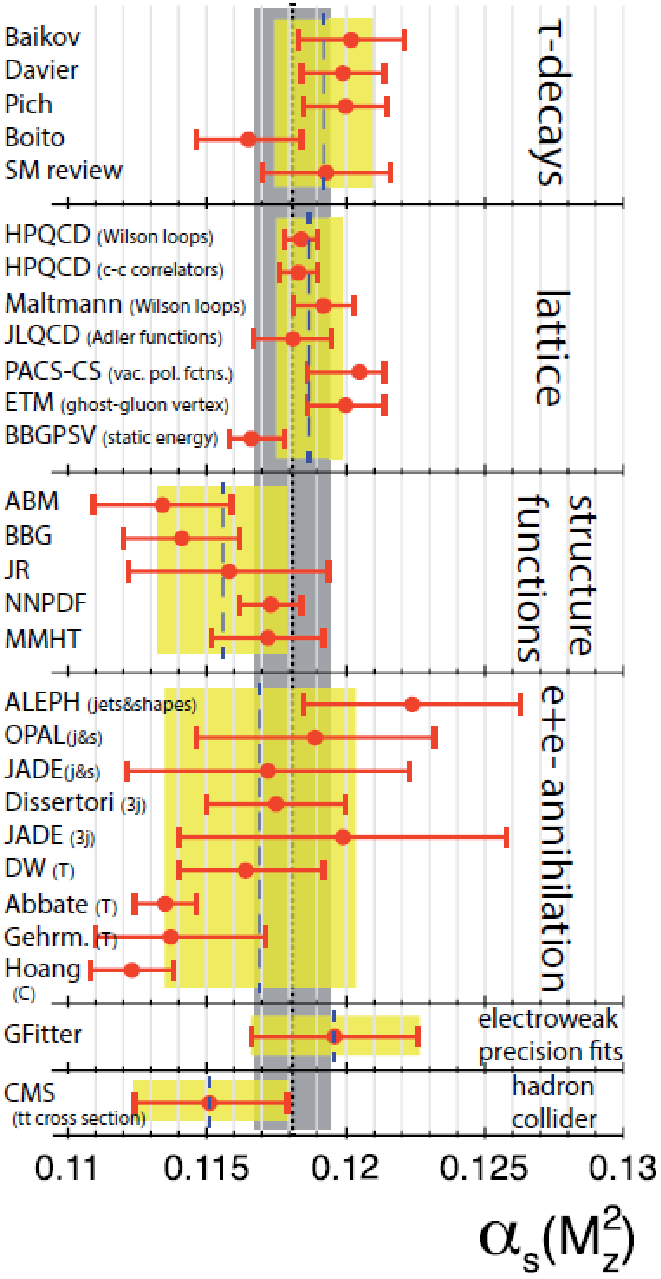
QCD – 20 Years Later at the RWTH Aachen

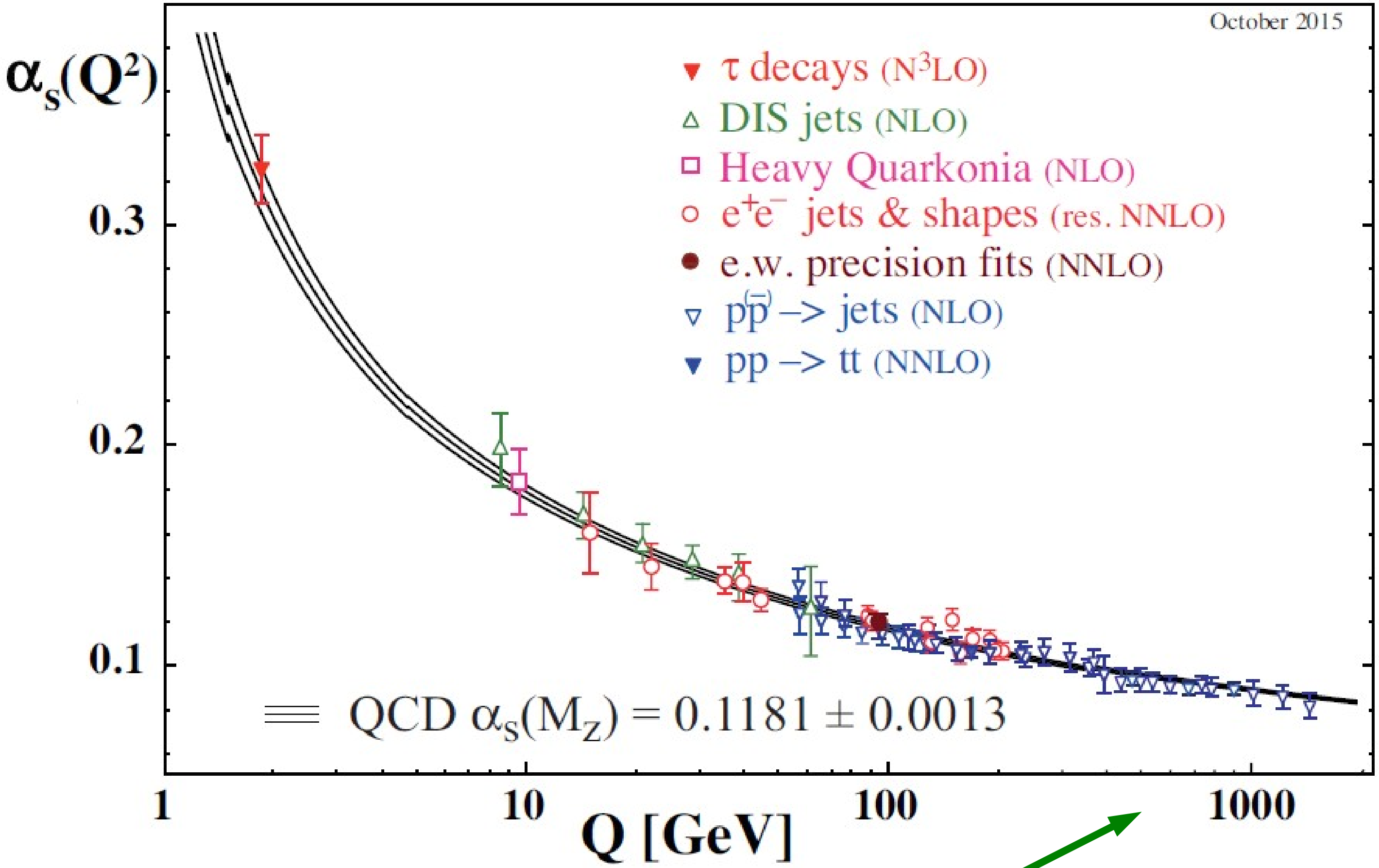
PDG 2015 update ... with MORE realistic lattice uncertainty!

G. Altarelli, Ann. Rev. Nucl. Part. Sci., 1989, 39, 357

S. Bethke, FCC-ee Workshop

PDG Update 2015





This is just the beginning

$$\alpha_s(M_Z) = 0.1181 \pm 0.0013$$

Particle Data Group
2015 Update, Feb. 2016.

Conclusions

I hope I could convince you that jets are powerful tools to

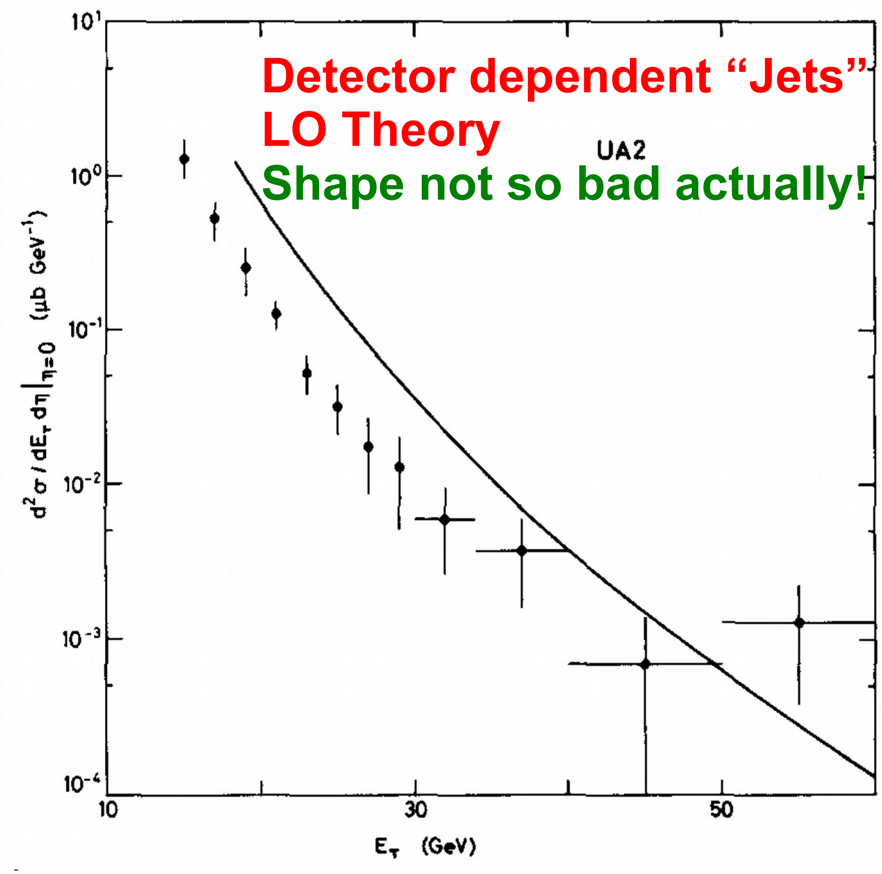
- perform precision tests of QCD and the standard model
- search for new phenomena
- improve our knowledge of the proton structure
- determine the strong coupling constant at unprecedented high scales and to good accuracy
- reduce the uncertainty on the gg → H channel :-)

Thank you for your attention!

Backup Slides

Achievements

30 years ago ...

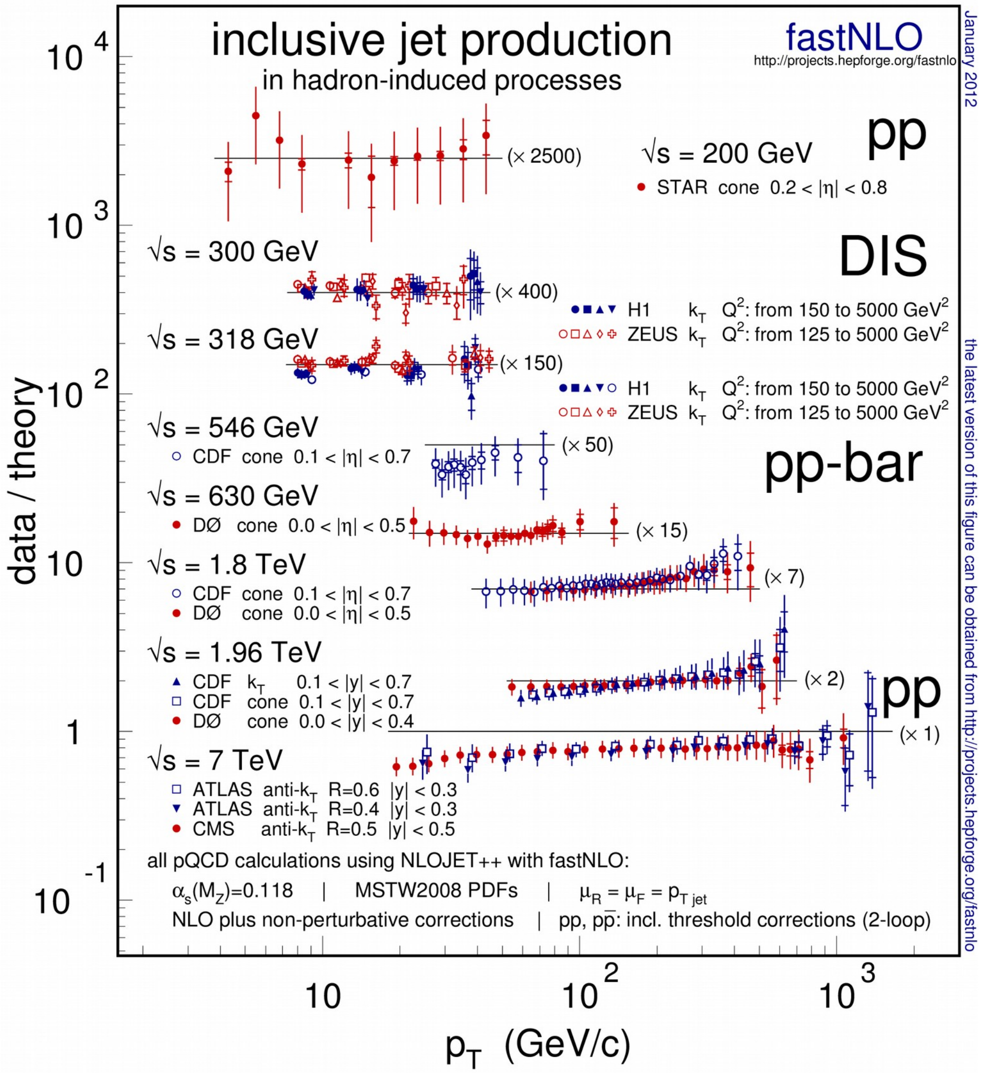


Detector dependent “Jets”
LO Theory
Shape not so bad actually!

Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

UA2, PLB 118 (1982).

… and nowadays!



fastNLO, arXiv:1109:1310v2, 2012

Hadron Collider Challenge

Triple Five:

- Within the next FIVE years
- Check running of $\alpha_s(Q)$ up to FIVE TeV and
- Determine $\alpha_s(M_Z)$ to FIVE permille accuracy

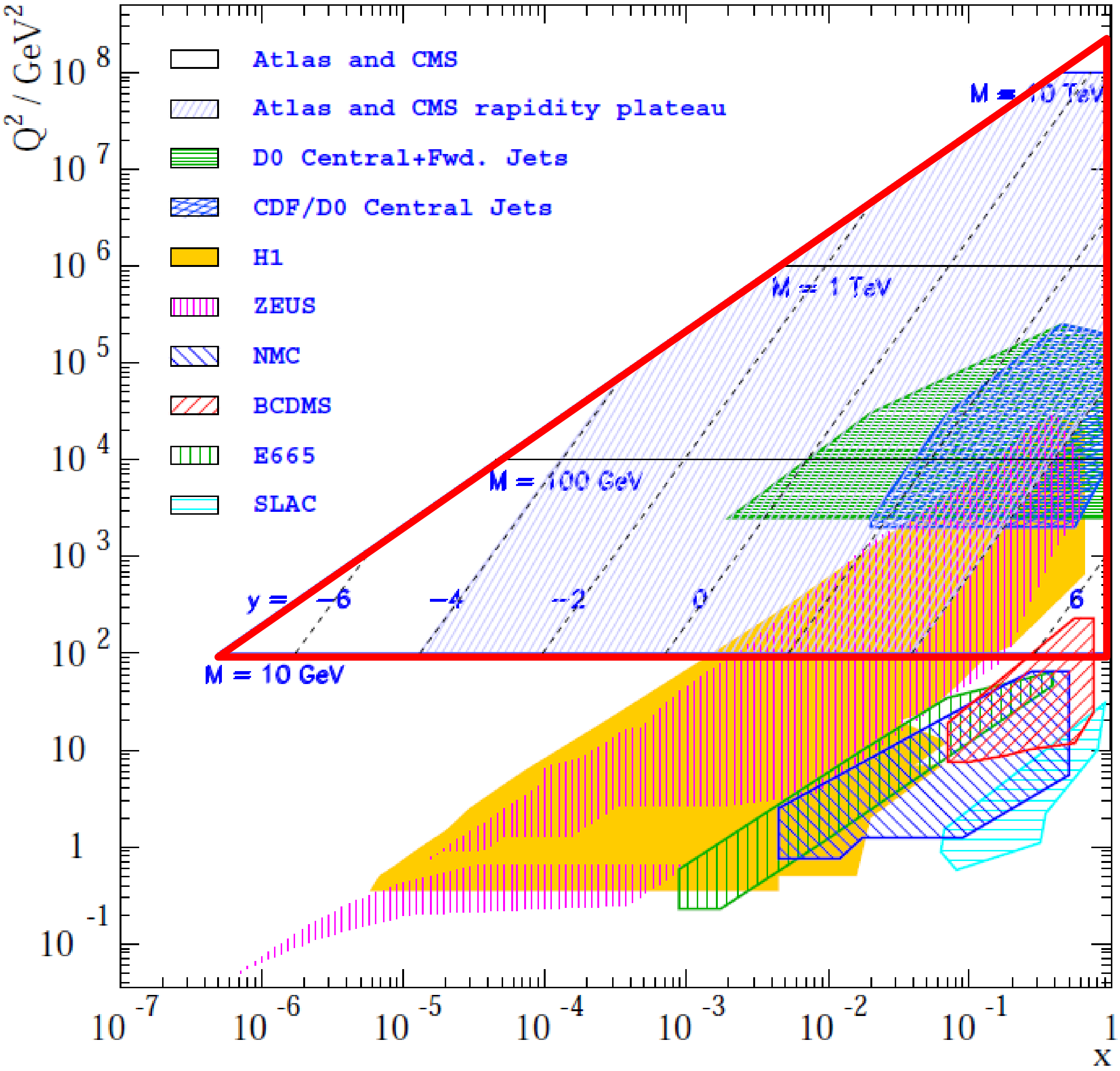
Perspectives & Educated Guesses

- **Experiment:**
  - Done: Observables $\sigma \sim \alpha_s^2, \alpha_s^3$; $R_{3/2} \sim \alpha_s$; 7 TeV; full phase space
  - 8 TeV data: Reduce experimental uncertainty by some permille?
  - Best JEC phase space: Another reduction by some permille?
  - Other observables: Ratios (n+m) / n jets (incl. γ, W, Z), $R_{\Delta\Phi}$, $R_{\Delta R}$ (→ D0)
    Normalized cross sections
- **Theory:**
  - Scales: NNLO → reduction by some percent!?
  - PDFs: Much improved after LHC I, also HERA 2 data available
    - Better known gluon (Attention circularity: jets → g(x) & jets → α_s)
    - Fits combining observables at various $\sqrt{s}$ to disentangle g(x), M_t, α_s
  - NNLO ratios?

Why QCD?

- **Fascinating –**
  comprises a huge variety of phenomena
- **Unavoidable –**
  hadrons are "made of QCD"
- **Indispensable –**
  linking piece between many processes
- **Demanding –**
  enormous background to searches for new physics
- **Uncharted –**
  dominating uncertainty for Higgs cross sections

Huge accessible phase space

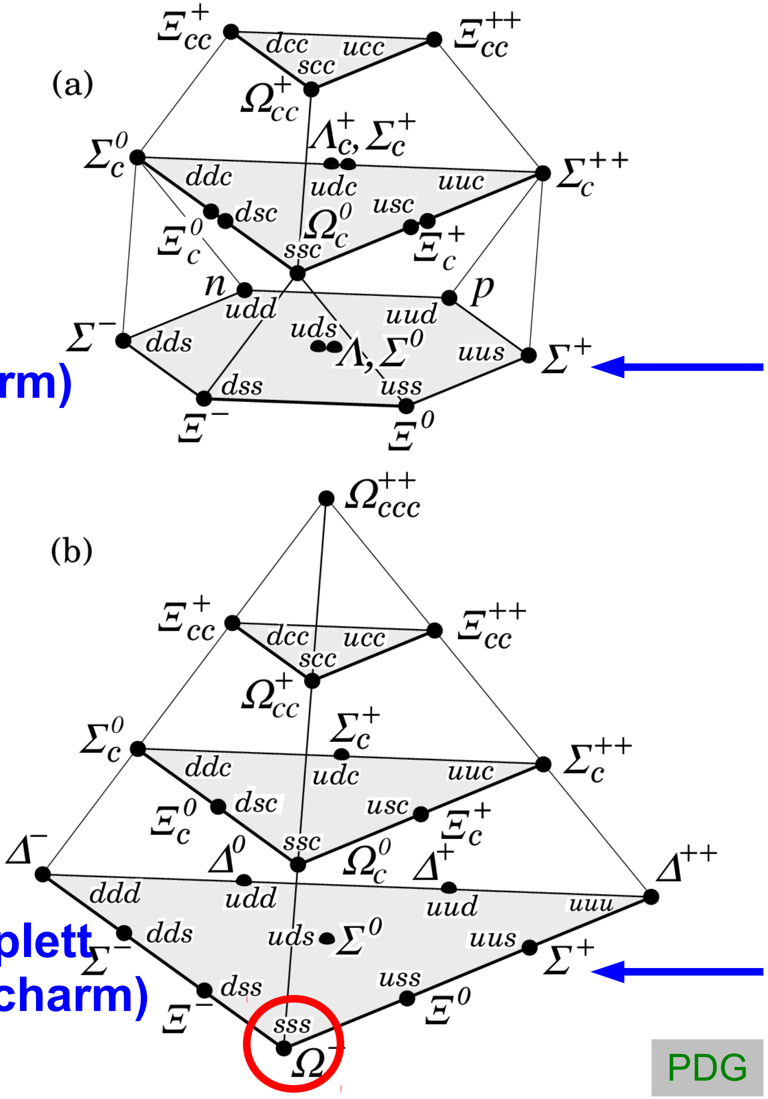


S. Glazov, Braz.J.Ph. 37 (2007) 793.

Mit Charme und Farbe

- Das J=3/2 Baryon-Dekuplett war zur Zeit Gell-Manns Idee noch nicht komplett bekannt (und charm sowieso nicht)
  - Vorhersage des Ω^- Baryons
- Aber: Wie auch beim Δ^{++} und Δ^-
  - Spin-Statistik-Problem!
- J=3/2 Fermionen mit symmetrischer Orts-, Spin- und Flavor-Wellenfunktion (Grundzustand, 3xSpin up, 3 identische Quarks) ist im Widerspruch zum Pauli-Prinzip!
  - Ein Ausweg:
    - O.W. Greenberg, 1964: Zusätzlicher Freiheitsgrad
    - M. Gell-Mann, 1972: Farbe = dreizählig, RGB

Mit strangeness und charm!



J = ½ Baryon-Oktett
mit C = 0 (d.h. ohne charm)

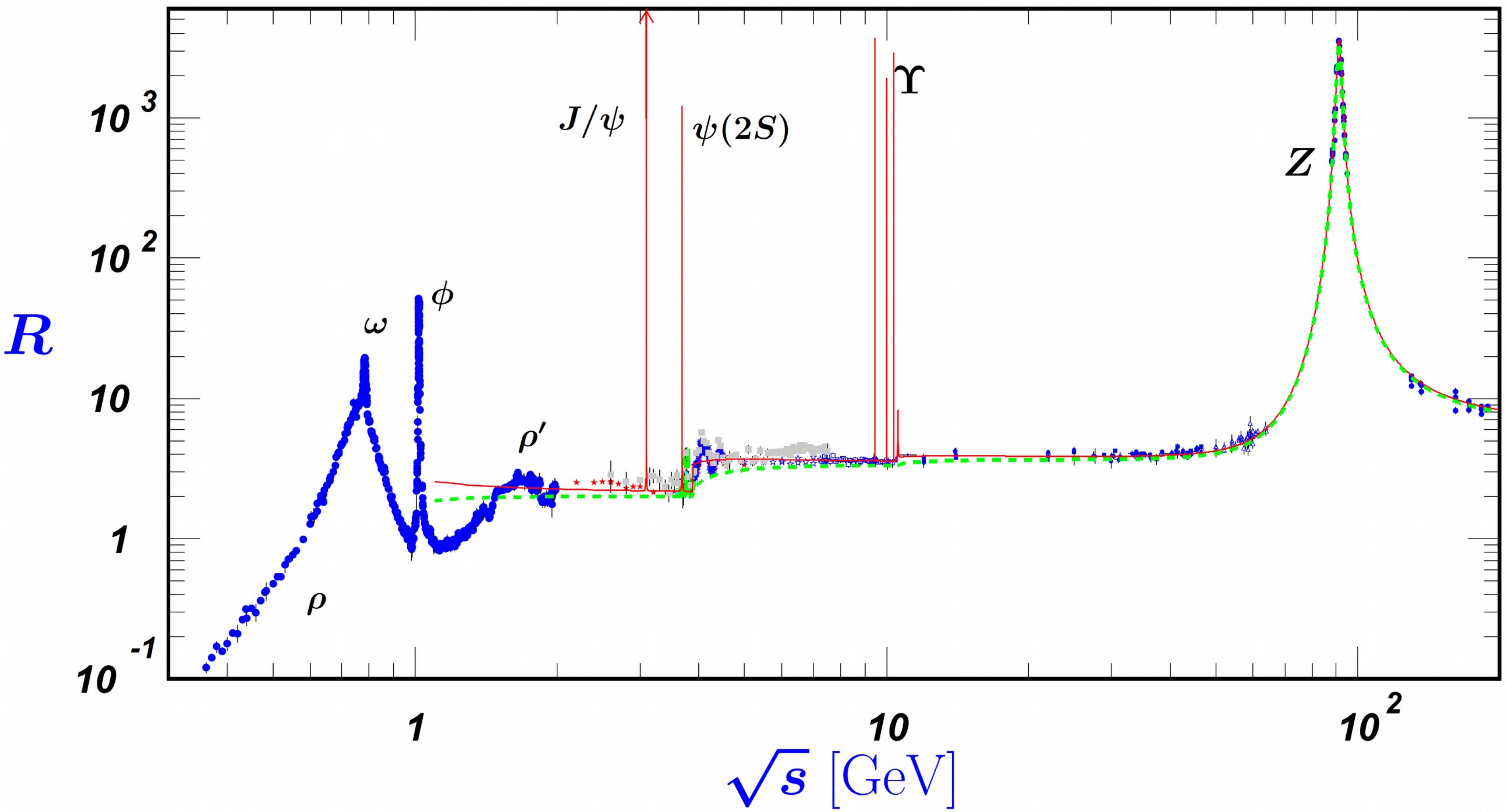
J = 3/2 Baryon-Dekuplett
mit C = 0 (d.h. ohne charm)

PDG

Weitere Evidenz für “Farbe”

Hadronisches Verzweigungsverhältnis in Elektron-Positron-Annihilation

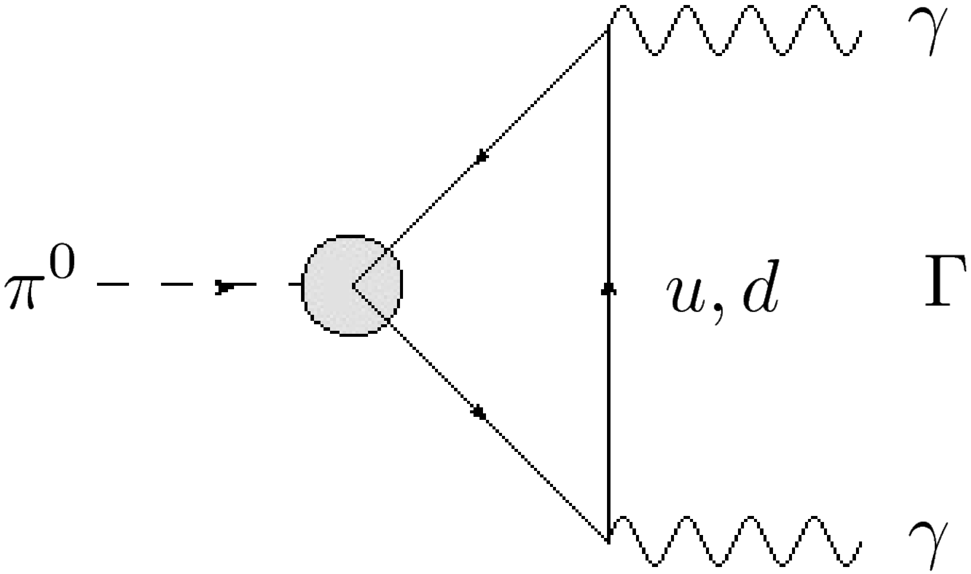
$$R(s) = \frac{\sigma(e^+e^- \to hadrons, s)}{\sigma(e^+e^- \to \mu^+\mu^-, s)}$$



PDG

Weitere Evidenz für “Farbe”

Pion-Zerfallsrate in zwei Photonen



LO Amplitude des Zerfalls

Masse

Farbfaktor

$$\Gamma(\pi^0 \to \gamma\gamma) = N_c^2 (e_u^2 - e_d^2)^2 \frac{\alpha^2 m_\pi^3}{64\pi^3 f_\pi^2}$$

Quarkladungen
(Achtung! Vorausgesetzt,
Aber nicht unabhängig von N_c ...)

Zerfallskonstante
(von gel. Pionen)

Einsetzen von unabhängigen Messungen andrer Grössen:

$$\Gamma(\pi^0 \to \gamma\gamma) = 7.33\,\mathrm{eV} \left(\frac{N_c}{3}\right)^2$$

Messwert:

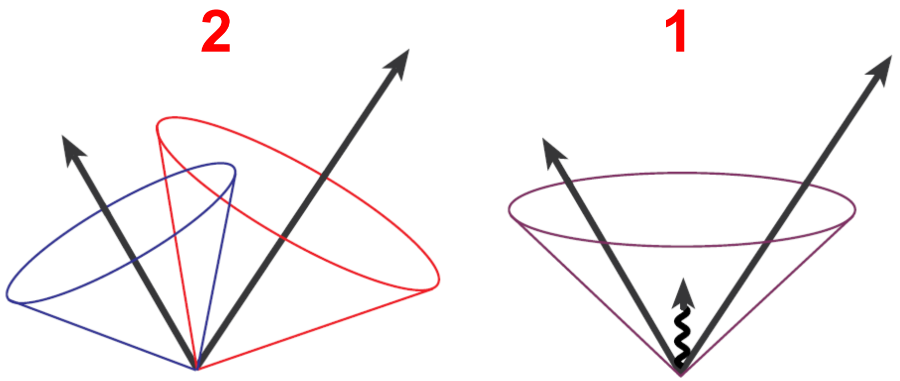
$$\Gamma(\pi^0 \to \gamma\gamma) = 7.84 \pm 0.56\,\mathrm{eV}$$

PDG

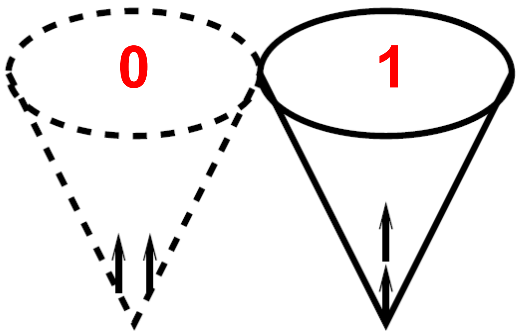
Jet Algorithms 2

- **Jet Algorithm Desiderata (Theory):**
  - **Infrared safety**
  - **Collinear safety**
  - **Longitudinal boost invariance**
    (recombination scheme!)
  - **Boundary stability**
    (→ 4-vector addition, rapidity y)
  - **Order independence**
    (parton, particle, detector)
  - **Ease of implementation**
    (standardized public code?)

See also:
“Snowmass Accord”, FNAL-C-90-249-E
Tevatron Run II Jet Physics, hep-ex/0005012
Les Houches 2007 Tools and Jets Summary , arXiv:0803.0678



IR unsafe: Sensitive to the addition of soft particles



Coll. unsafe: Sensitive to the splitting of a 4-vector (seeds!)

Jet Algorithms 3

Jet Algorithm Desiderata (Experiment):

- **Computational efficiency and predictability**
  (use in trigger?, reconstruction times?)
- **Maximal reconstruction efficiency**
- **Minimal resolution smearing and angular biasing**
- **Insensitivity to pile-up**
  (mult. collisions at high luminosity ...)
- **Ease of calibration**
- **Detector independence**
- **Fully specified**
  (details?, code?)
- **Ease of implementation**
  (standardized public code?)

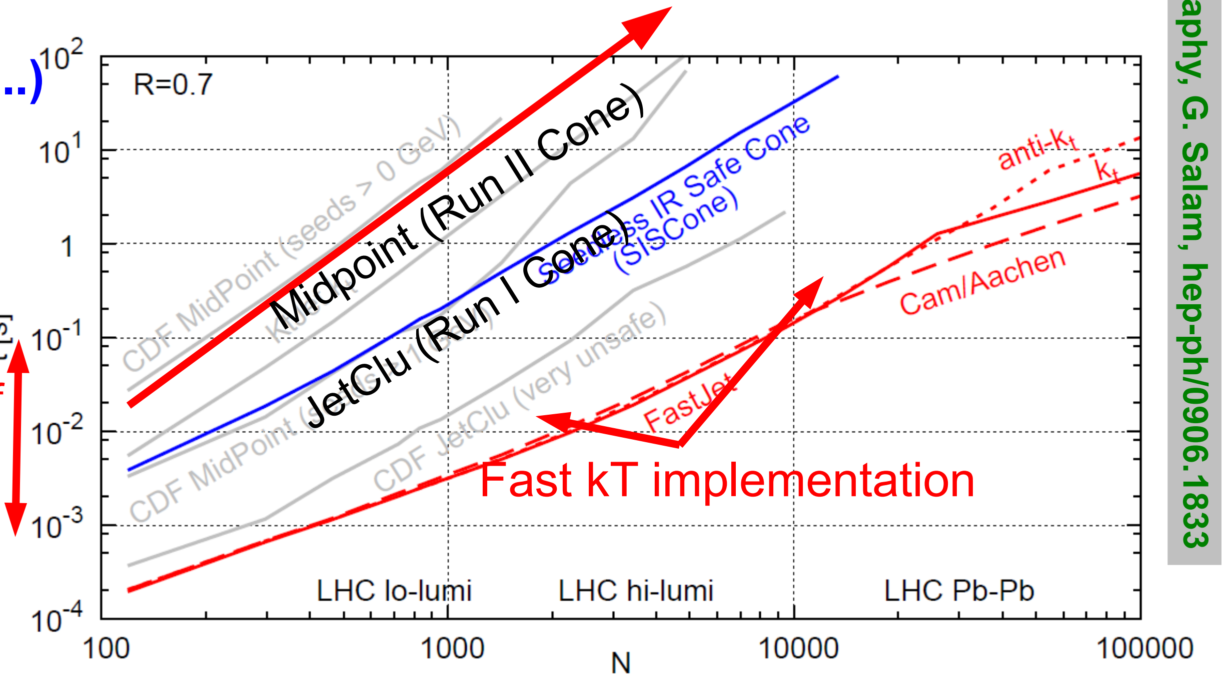
$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p} \,,$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

p = 1: kT
p = 0: Cambridge/Aachen
p = -1: anti-kT

Original kT implementation

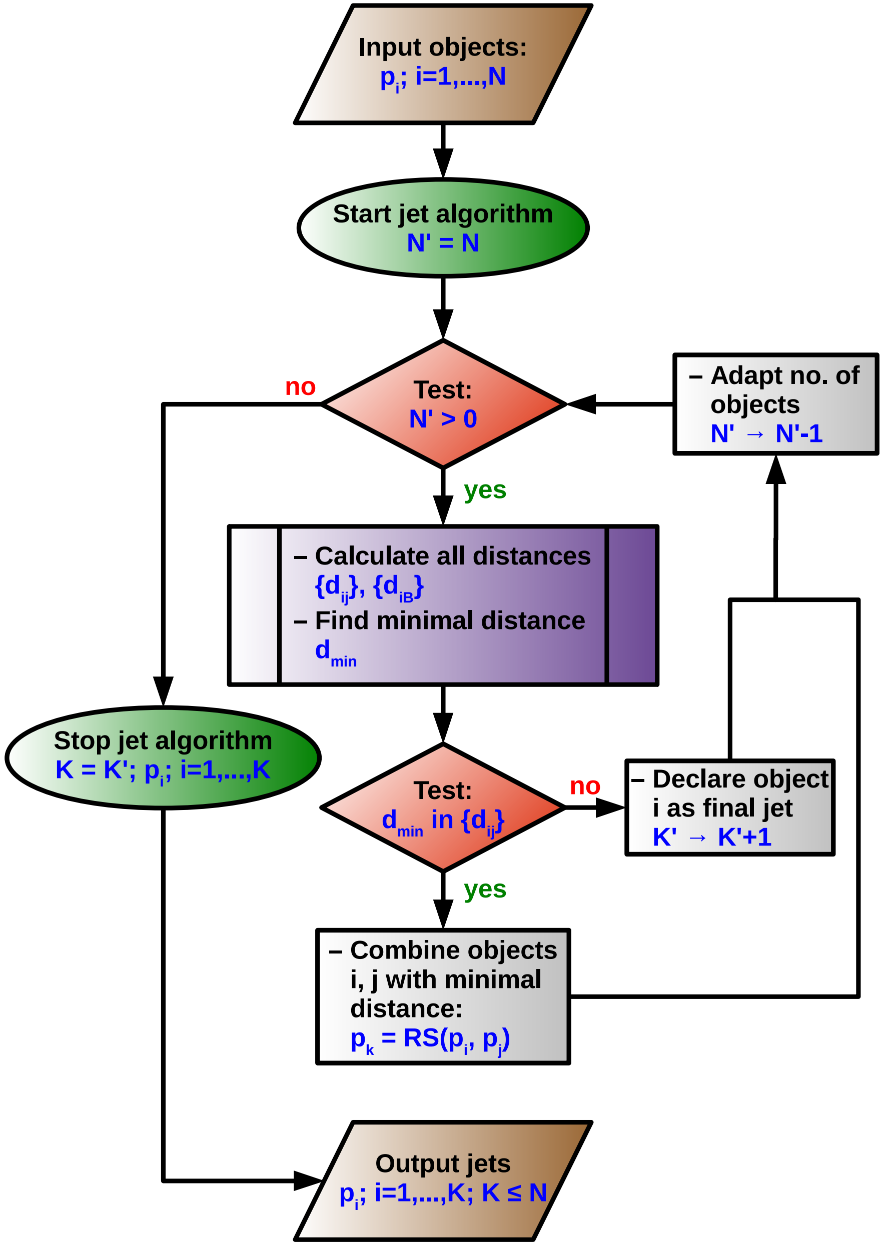


2-3 orders of magnitude

Fast kT implementation

Jetography, G. Salam, hep-ph/0906.1833

Sequential Recombination Algorithm



Input objects:
p_i; i=1,...,N

Start jet algorithm
N' = N

Test:
N' > 0

no

yes

- Calculate all distances $\{d_{ij}\}$, $\{d_{iB}\}$
- Find minimal distance d_{min}

Test:
d_{min} in $\{d_{ij}\}$

no

yes

- Declare object i as final jet
  K' → K'+1

- Combine objects i, j with minimal distance:
  $p_k = RS(p_i, p_j)$

- Adapt no. of objects
  N' → N'-1

Stop jet algorithm
K = K'; p_i; i=1,...,K

Output jets
p_i; i=1,...,K; K ≤ N

Jet Algo Desiderata --- Today

- **Theory:**
  - Infrared safety
  - Collinear safety
  - Longitudinal boost invariance
    (recombination scheme!)
  - Boundary stability
    (→ 4-vector addition, rapidity y)
  - Order independence
    (parton, particle, detector)
  - Ease of implementation
    (standardized public code: fastjet)

Many of these points were red, i.e. not fulfilled, in times just before the LHC!

- **Experiment:**
  - Ease of calibration
  - Insensitivity to pile-up
  - Minimal resolution smearing and angular biasing
  - Maximal reconstruction efficiency
  - Computational efficiency and predictability
    (use in reconstruction, trigger)
  - Detector independence
  - Fully specified
    (fastjet) Cacciari et al., EPJC72 (2012).
  - Ease of implementation
    (standardized public code: fastjet)

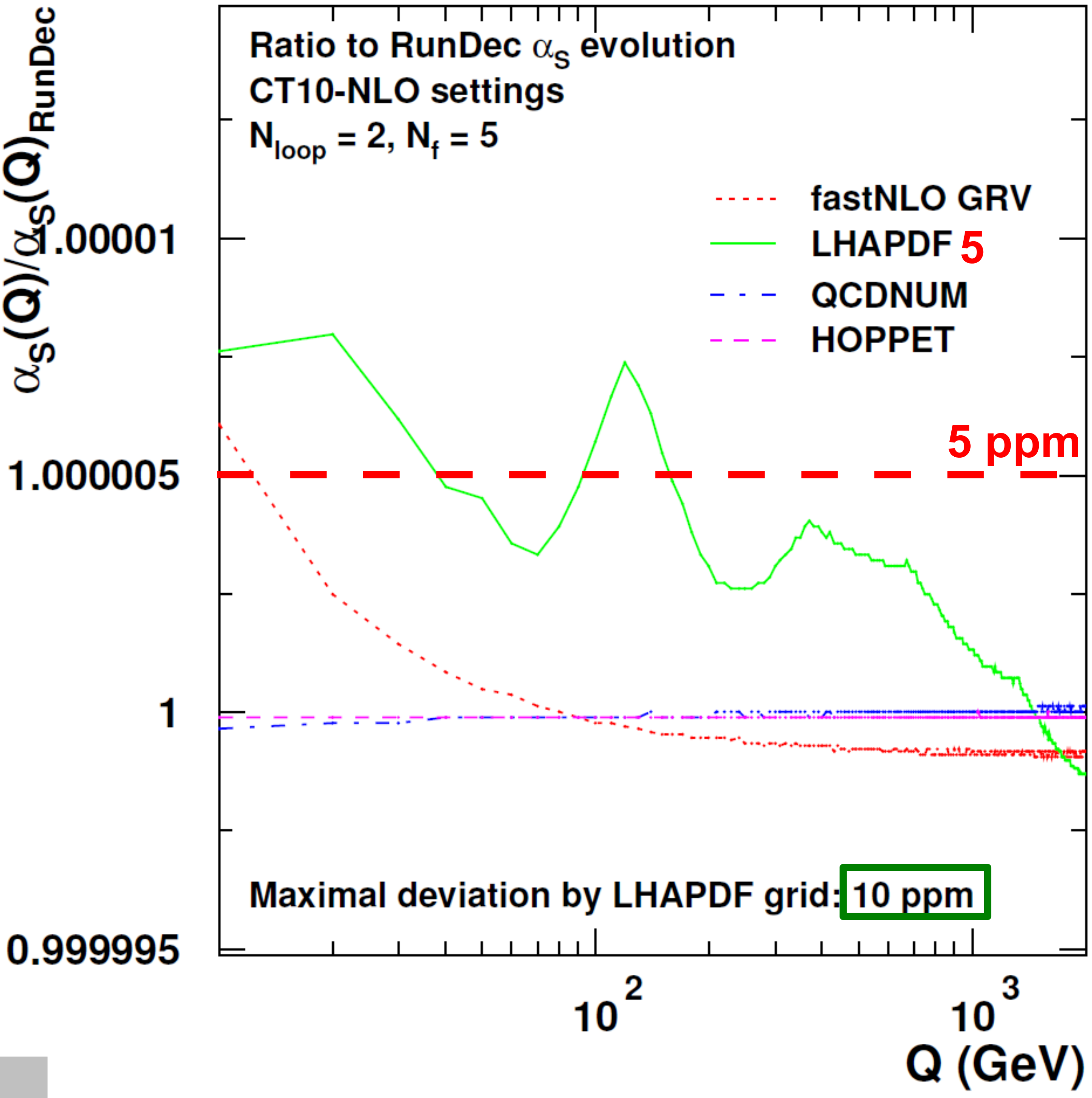
Jet Analysis Uncertainties

- Experimental Uncertainties (~ in order of importance):
  - Jet Energy Scale (JES)
    - Noise Treatment
    - Pile-Up Treatment
  - Luminosity (2 - 4%)
  - Jet Energy Resolution (JER)
  - Trigger Efficiencies
  - Resolution in Rapidity
  - Resolution in Azimuth
  - Non-Collision Background
  - • • •

- Theoretical Uncertainties:
  - pQCD (Scale) Dependence
  - PDF Uncertainty
  - Non-perturbative Corrections
  - PDF Parameterization
  - NLO-NLL matching schemes
  - Electroweak Corrections
  - Knowledge of $\alpha_s(M_Z)$
  - • • •

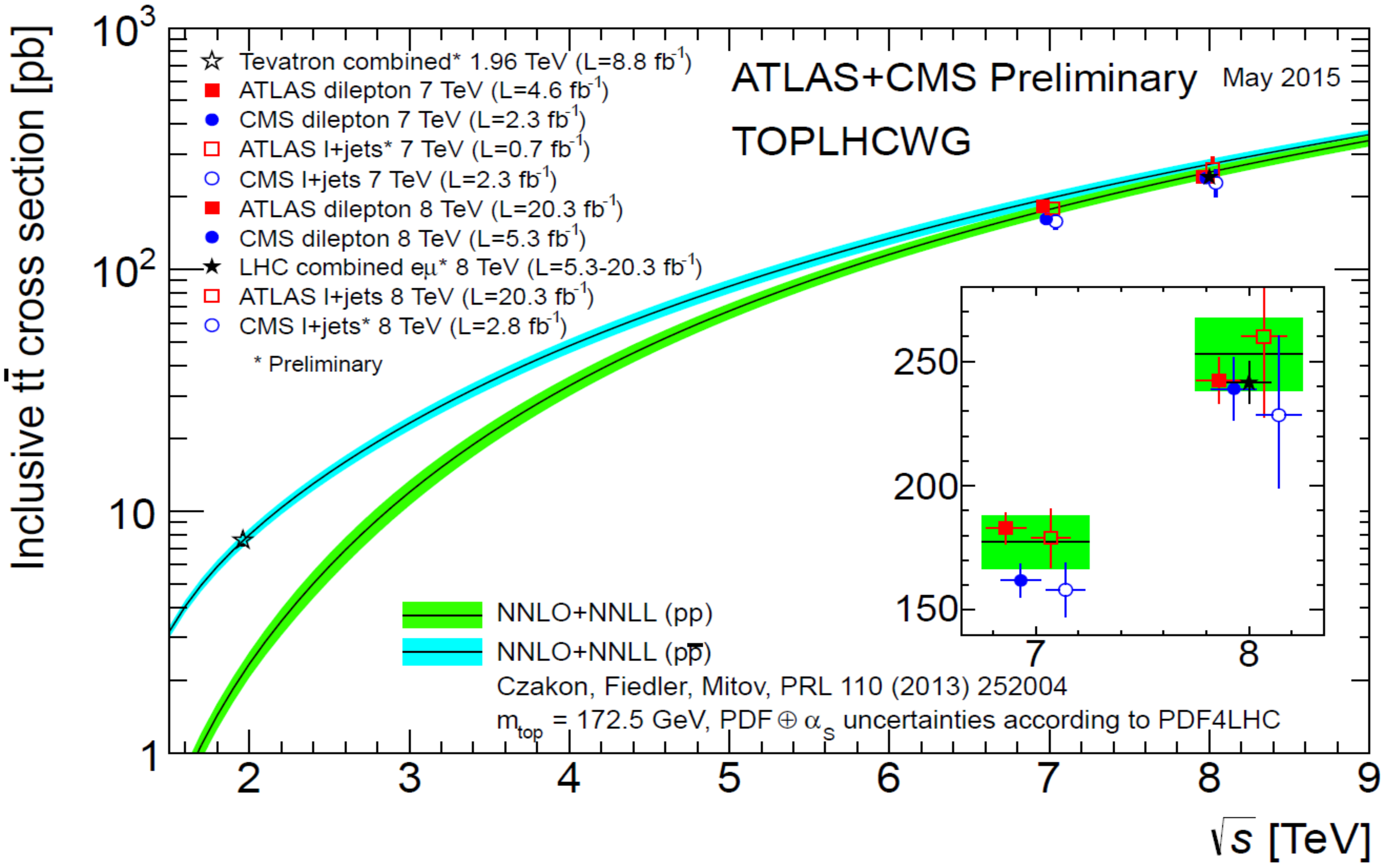
Use of alternative α_s evolutions

- **LHAPDF5/6**
- **CRunDec 08/2012**
  - included in fastNLO
- **QCDNUM v17-00-06**
  - … `[--with-qcdnum=/path/...]`
  - `Makefiles adapted, need -fPIC on x86_64 systems`
- **HOPPET v1.1.5**
  - … `[--with-hoppet=/path/...]`



RunDec, B. Schmidt, M. Steinhauser, CPC183, 2012;
K. Chetyrkin, J. Kühn, M. Steinhauser, CPC133, 2000.
QCDNUM, M. Botje, CPC182, 2011.
HOPPET, G. Salam, J. Rojo, CPC180, 2009.

ttbar Dilepton X Section in Comparison



New CMS prelim. results move up somewhat, but within uncertainty.

2 X (@ 7 TeV) and 4 X (@ 8 TeV) more data, improved reconstruction, plus further refinements.

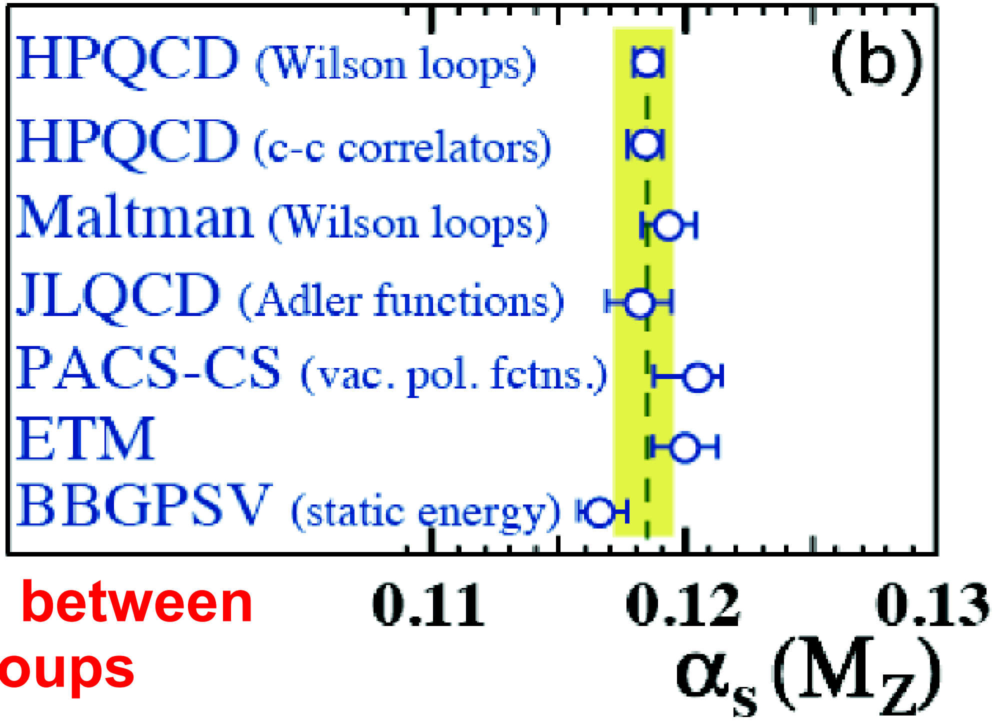
$$\sigma_{t\bar{t}} = 174.5 \pm 2.1(\text{stat}) \pm^{4.5}_{4.0} (\text{syst}) \pm 3.8(\text{lumi})\ \text{pb} \quad \text{at } \sqrt{s} = 7\ \text{TeV and}$$

$$\sigma_{t\bar{t}} = 245.6 \pm 1.3(\text{stat}) \pm^{6.6}_{5.5} (\text{syst}) \pm 6.5(\text{lumi})\ \text{pb} \quad \text{at } \sqrt{s} = 8\ \text{TeV},$$

CMS-TOP-13-004 (2012).

α_s from lattice QCD

our RPP summary 2015:



Result of collaboration between lattice gauge theory groups

shown: FLAG summary, $\alpha_s(M_Z) = 0.1184 \pm 0.0012$

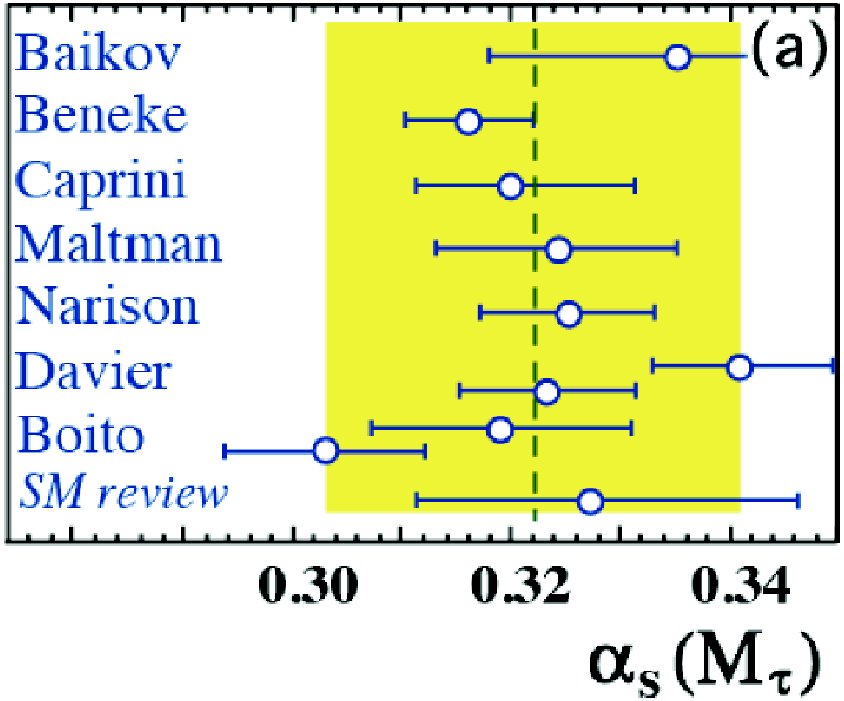
(if done as in previous RPP: $\alpha_s(M_Z) = 0.1185 \pm 0.0005$)

S. Bethke, FCC-ee Workshop

α_s from τ-decays

- complete N3LO prediction (Baikov, Chetyrkin, Kühn; arXiv:0801.1821)
- strong theor. activities, all based on ~same (ALEPH) datasets
- large dependence on details of perturbative expansion: FOPT vs. CIPT; some dependence on nonpert. corrections

Still unresolved differences in pert. theory treatment: fixed-order (FO) vs. contour-improved (CI) pert. theory



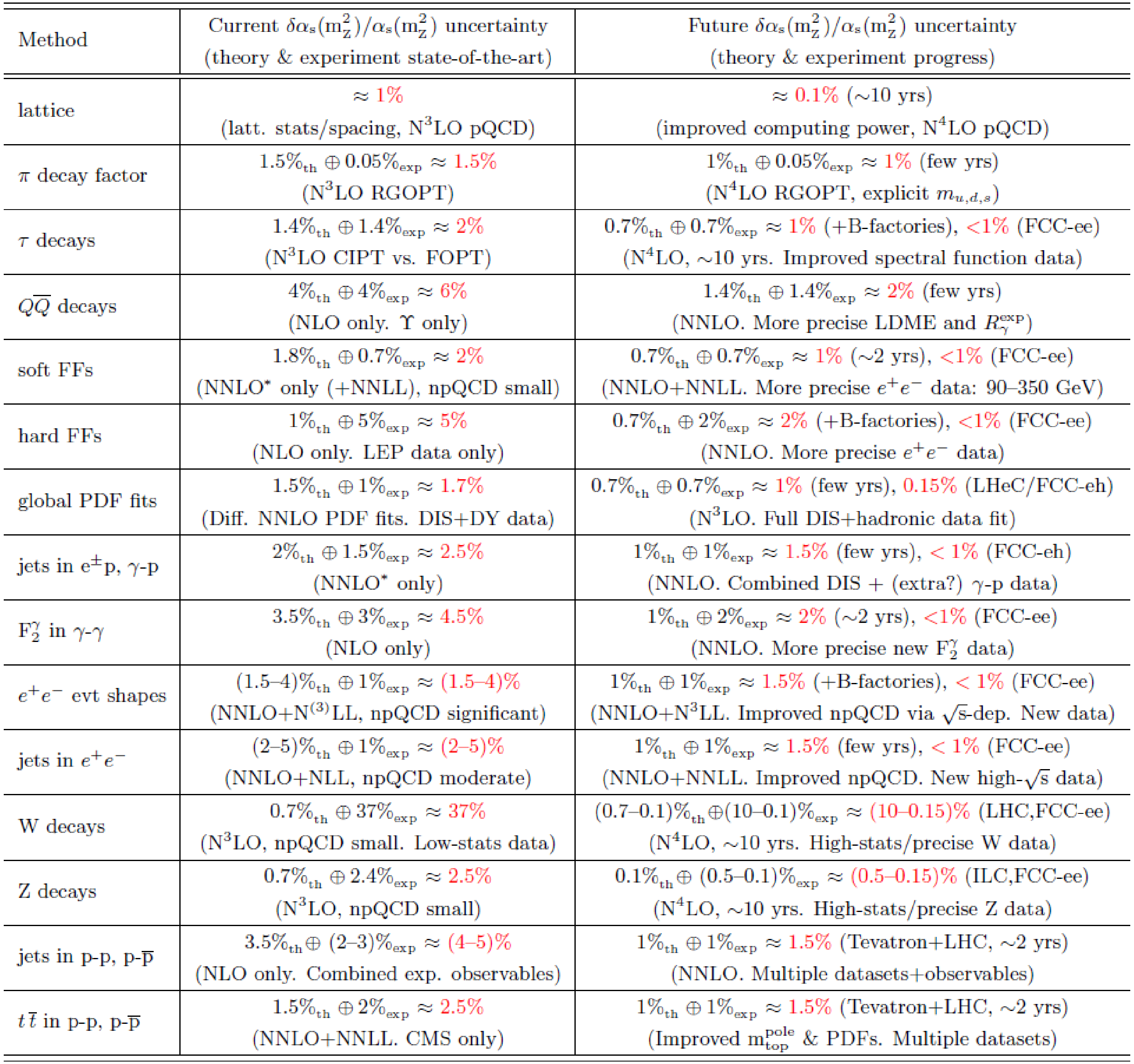
note: same new ALEPH data, large systematics between different authors!

- averaging and summarising: $\alpha_s(M_\tau) = 0.322 \pm 0.019$

–> $\alpha_s(M_Z) = 0.1187 \pm 0.0023$

S. Bethke, FCC-ee Workshop

Uncertainty Projections



Method	Current $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment state-of-the-art)	Future $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment progress)
lattice	$\approx 1\%$ (latt. stats/spacing, N^{3}LO pQCD)	$\approx 0.1\%$ ($\sim$10 yrs) (improved computing power, N^{4}LO pQCD)
π decay factor	$1.5\%_{\rm th} \oplus 0.05\%_{\rm exp} \approx 1.5\%$ (N^{3}LO RGOPT)	$1\%_{\rm th} \oplus 0.05\%_{\rm exp} \approx 1\%$ (few yrs) (N^{4}LO RGOPT, explicit $m_{u,d,s}$)
τ decays	$1.4\%_{\rm th} \oplus 1.4\%_{\rm exp} \approx 2\%$ (N^{3}LO CIPT vs. FOPT)	$0.7\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 1\%$ (+B-factories), $<1\%$ (FCC-ee) (N^{4}LO, $\sim$10 yrs. Improved spectral function data)
$Q\overline{Q}$ decays	$4\%_{\rm th} \oplus 4\%_{\rm exp} \approx 6\%$ (NLO only. Υ only)	$1.4\%_{\rm th} \oplus 1.4\%_{\rm exp} \approx 2\%$ (few yrs) (NNLO. More precise LDME and $R_\gamma^{\rm exp}$)
soft FFs	$1.8\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 2\%$ (NNLO* only (+NNLL), npQCD small)	$0.7\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 1\%$ ($\sim$2 yrs), $<1\%$ (FCC-ee) (NNLO+NNLL. More precise e^+e^- data: 90–350 GeV)
hard FFs	$1\%_{\rm th} \oplus 5\%_{\rm exp} \approx 5\%$ (NLO only. LEP data only)	$0.7\%_{\rm th} \oplus 2\%_{\rm exp} \approx 2\%$ (+B-factories), $<1\%$ (FCC-ee) (NNLO. More precise e^+e^- data)
global PDF fits	$1.5\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.7\%$ (Diff. NNLO PDF fits. DIS+DY data)	$0.7\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 1\%$ (few yrs), 0.15% (LHeC/FCC-eh) (N^{3}LO. Full DIS+hadronic data fit)
jets in e$^\pm$p, γ-p	$2\%_{\rm th} \oplus 1.5\%_{\rm exp} \approx 2.5\%$ (NNLO* only)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (few yrs), $<1\%$ (FCC-eh) (NNLO. Combined DIS + (extra?) γ-p data)
F$_2^\gamma$ in γ-γ	$3.5\%_{\rm th} \oplus 3\%_{\rm exp} \approx 4.5\%$ (NLO only)	$1\%_{\rm th} \oplus 2\%_{\rm exp} \approx 2\%$ ($\sim$2 yrs), $<1\%$ (FCC-ee) (NNLO. More precise new F$_2^\gamma$ data)
e^+e^- evt shapes	$(1.5–4)\%_{\rm th} \oplus 1\%_{\rm exp} \approx (1.5–4)\%$ (NNLO+N$^{(3)}$LL, npQCD significant)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (+B-factories), $<1\%$ (FCC-ee) (NNLO+N^{3}LL. Improved npQCD via $\sqrt{s}$-dep. New data)
jets in e^+e^-	$(2–5)\%_{\rm th} \oplus 1\%_{\rm exp} \approx (2–5)\%$ (NNLO+NLL, npQCD moderate)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (few yrs), $<1\%$ (FCC-ee) (NNLO+NNLL. Improved npQCD. New high-$\sqrt{s}$ data)
W decays	$0.7\%_{\rm th} \oplus 37\%_{\rm exp} \approx 37\%$ (N^{3}LO, npQCD small. Low-stats data)	$(0.7–0.1)\%_{\rm th} \oplus (10–0.1)\%_{\rm exp} \approx (10–0.15)\%$ (LHC,FCC-ee) (N^{4}LO, $\sim$10 yrs. High-stats/precise W data)
Z decays	$0.7\%_{\rm th} \oplus 2.4\%_{\rm exp} \approx 2.5\%$ (N^{3}LO, npQCD small)	$0.1\%_{\rm th} \oplus (0.5–0.1)\%_{\rm exp} \approx (0.5–0.15)\%$ (ILC,FCC-ee) (N^{4}LO, $\sim$10 yrs. High-stats/precise Z data)
jets in p-p, p-$\overline{\rm p}$	$3.5\%_{\rm th} \oplus (2–3)\%_{\rm exp} \approx (4–5)\%$ (NLO only. Combined exp. observables)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (Tevatron+LHC, $\sim$2 yrs) (NNLO. Multiple datasets+observables)
$t\bar{t}$ in p-p, p-$\overline{\rm p}$	$1.5\%_{\rm th} \oplus 2\%_{\rm exp} \approx 2.5\%$ (NNLO+NNLL. CMS only)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (Tevatron+LHC, $\sim$2 yrs) (Improved m$_{\rm top}^{\rm pole}$ & PDFs. Multiple datasets)

Workshop Proceeedings:
arXiv: 1512.05194

α_s Projections

Still at LHC:

Only jets probe running α_s at highest scales

< 1% uncertainty at M_Z challenging, but not impossible

Need NNLO and improved PDFs (gluon) plus some experimental optimization

Method	Current relative precision	Future relative precision
e^+e^- evt shapes	expt $\sim 1\%$ (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	$< 1\%$ possible (ILC/TLEP) $\sim 1\%$ (control n.p. via Q^2-dep.)
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9, 29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, $\sim$ 10 yrs)
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, $\sim$ 10 yrs)
ep colliders	~ 1–2% (pdf fit dependent) [30, 31], (mostly theory, NNLO) [32, 33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17, 21, 34]	$< 1\%$ challenging (NNLO jets imminent [22])
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ ($\sim$ 5 yrs [38])

~1%

<1%

<1%

~1%

<0.5%

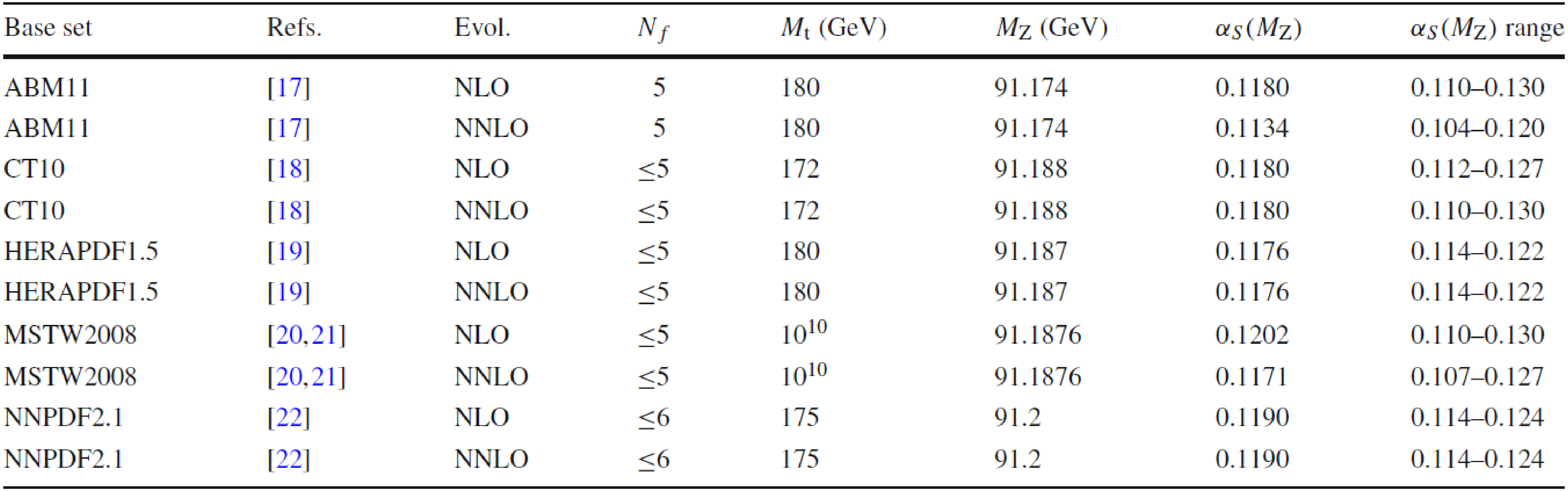
Snowmass QCD Report, arXiv:1310.5189.

Uncertainties at Hadron Colliders

Process	LO	$\sqrt{s}$	Q	N_p	$\alpha_s(m_Z)$	$\Delta\alpha_s(m_Z)/\alpha_s(m_Z)$ [%]				
ep, $p\bar{p}$, pp	α_s^n	[TeV]	[GeV]			exp	PDF	scale	NP	other
H1 jets low Q^2	1	0.32	5–57	62	0.1160	1.2	1.4	8.0	scl	–
ZEUS γp jets	1	0.32	21–71	18	0.1206	1.9	1.9	2.5	0.4	–
H1 jets high Q^2	1	0.32	10–94	64	0.1165	0.7	0.8	3.1	0.7	–
CDF incl. jets	2	1.8	40–250	27	0.1178	7.5	5.0	5.0	–	2.5
D0 incl. jets	2	1.96	50–145	22	0.1161	2.9	1.0	2.5	1.1	–
D0 ang. corr.	1	1.96	50–450	102	0.1191	0.7	1.2	5.5	0.1	–
ATLAS incl. jets	2	7	45–600	42	0.1151	4.3	1.8	3.8	1.9	5.2
ATLAS EEC	1	7	250–1300	22	0.1173	0.9	1.4	5.4	0.2	–
CMS $R_{3/2}$	1	7	420–1390	21	0.1148	1.2	1.6	4.4	scl	–
CMS $\sigma(t\bar{t})$	2	7	M_t^{pole}	1	0.1151	2.2	1.5	0.7	–	1.1
CMS 3-jet mass	3	7	332–1635	46	0.1171	1.1	2.0	5.9	0.7	–
CMS incl. jets	2	7	114–2116	133	0.1185	1.6	2.4	4.5	0.3	–

Workshop Proceeedings:
arXiv: 1512.05194

PDF Sets



Base set	Refs.	Evol.	N_f	M_t (GeV)	M_Z (GeV)	$\alpha_S(M_Z)$	$\alpha_S(M_Z)$ range
ABM11	[17]	NLO	5	180	91.174	0.1180	0.110–0.130
ABM11	[17]	NNLO	5	180	91.174	0.1134	0.104–0.120
CT10	[18]	NLO	≤ 5	172	91.188	0.1180	0.112–0.127
CT10	[18]	NNLO	≤ 5	172	91.188	0.1180	0.110–0.130
HERAPDF1.5	[19]	NLO	≤ 5	180	91.187	0.1176	0.114–0.122
HERAPDF1.5	[19]	NNLO	≤ 5	180	91.187	0.1176	0.114–0.122
MSTW2008	[20,21]	NLO	≤ 5	10^{10}	91.1876	0.1202	0.110–0.130
MSTW2008	[20,21]	NNLO	≤ 5	10^{10}	91.1876	0.1171	0.107–0.127
NNPDF2.1	[22]	NLO	≤ 6	175	91.2	0.1190	0.114–0.124
NNPDF2.1	[22]	NNLO	≤ 6	175	91.2	0.1190	0.114–0.124

CMS, EPJC 75 (2015) 288.

Details: α_s from inclusive Jets

$\lvert y \rvert$ range	No. of data points	$\alpha_S(M_Z)$	χ^2/n_{dof}
$\lvert y \rvert < 0.5$	33	$0.1189 \pm 0.0024\,(\text{exp}) \pm 0.0030\,(\text{PDF})$ $\pm 0.0008\,(\text{NP})^{+0.0045}_{-0.0027}\,(\text{scale})$	16.2/32
$0.5 \leq \lvert y \rvert < 1.0$	30	$0.1182 \pm 0.0024\,(\text{exp}) \pm 0.0029\,(\text{PDF})$ $\pm 0.0008\,(\text{NP})^{+0.0050}_{-0.0025}\,(\text{scale})$	25.4/29
$1.0 \leq \lvert y \rvert < 1.5$	27	$0.1165 \pm 0.0027\,(\text{exp}) \pm 0.0024\,(\text{PDF})$ $\pm 0.0008\,(\text{NP})^{+0.0043}_{-0.0020}\,(\text{scale})$	9.5/26
$1.5 \leq \lvert y \rvert < 2.0$	24	$0.1146 \pm 0.0035\,(\text{exp}) \pm 0.0031\,(\text{PDF})$ $\pm 0.0013\,(\text{NP})^{+0.0037}_{-0.0020}\,(\text{scale})$	20.2/23
$2.0 \leq \lvert y \rvert < 2.5$	19	$0.1161 \pm 0.0045\,(\text{exp}) \pm 0.0054\,(\text{PDF})$ $\pm 0.0015\,(\text{NP})^{+0.0034}_{-0.0032}\,(\text{scale})$	12.6/18
$\lvert y \rvert < 2.5$	133	$0.1185 \pm 0.0019\,(\text{exp}) \pm 0.0028\,(\text{PDF})$ $\pm 0.0004\,(\text{NP})^{+0.0053}_{-0.0024}\,(\text{scale})$	104.1/132

Fit results in separate |y| bins
PDF: CT10-NLO
(best consistency between fit and PDF preferred $\alpha_s(M_Z)$)

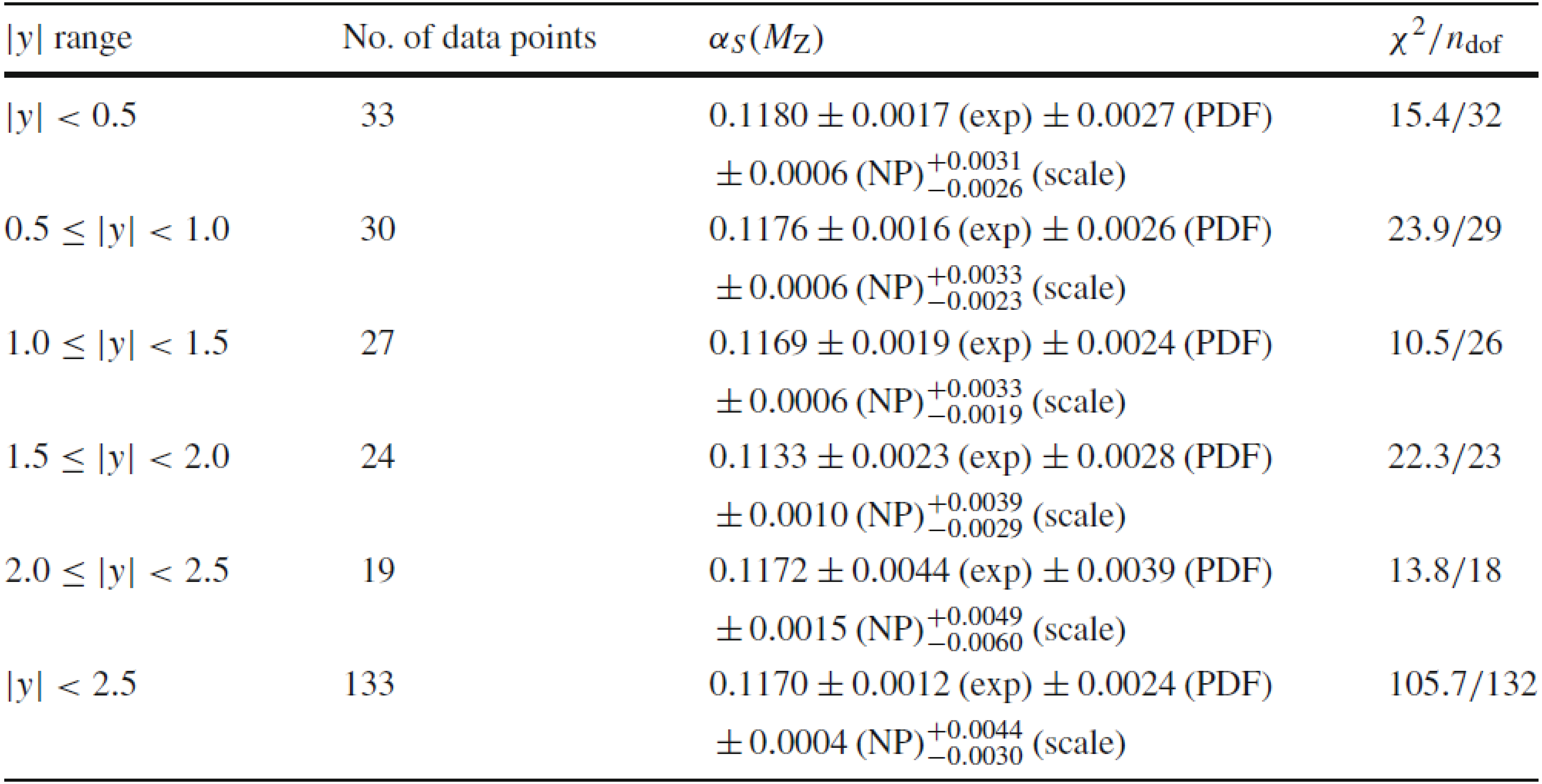
Fit results for all |y| bins with other PDFs

	$\alpha_S(M_Z)$	χ^2/n_{dof}
CT10-NLO	$0.1185 \pm 0.0019\,(\text{exp}) \pm 0.0028\,(\text{PDF})$ $\pm 0.0004\,(\text{NP})^{+0.0053}_{-0.0024}\,(\text{scale})$	104.1/132
NNPDF2.1-NLO	$0.1150 \pm 0.0015\,(\text{exp}) \pm 0.0024\,(\text{PDF})$ $\pm 0.0003\,(\text{NP})^{+0.0025}_{-0.0025}\,(\text{scale})$	103.5/132
MSTW2008-NLO	$0.1159 \pm 0.0012\,(\text{exp}) \pm 0.0014\,(\text{PDF})$ $\pm 0.0001\,(\text{NP})^{+0.0024}_{-0.0030}\,(\text{scale})$	107.9/132
CT10-NNLO	$0.1170 \pm 0.0012\,(\text{exp}) \pm 0.0024\,(\text{PDF})$ $\pm 0.0004\,(\text{NP})^{+0.0044}_{-0.0030}\,(\text{scale})$	105.7/132
NNPDF2.1-NNLO	$0.1175 \pm 0.0012\,(\text{exp}) \pm 0.0019\,(\text{PDF})$ $\pm 0.0001\,(\text{NP})^{+0.0018}_{-0.0020}\,(\text{scale})$	103.0/132
MSTW2008-NNLO	$0.1136 \pm 0.0010\,(\text{exp}) \pm 0.0011\,(\text{PDF})$ $\pm 0.0001\,(\text{NP})^{+0.0019}_{-0.0024}\,(\text{scale})$	108.8/132

CMS, EPJC 75 (2015) 288.

Details: α_s from inclusive Jets

Fit results in separate |y| bins
PDF: CT10-NNLO



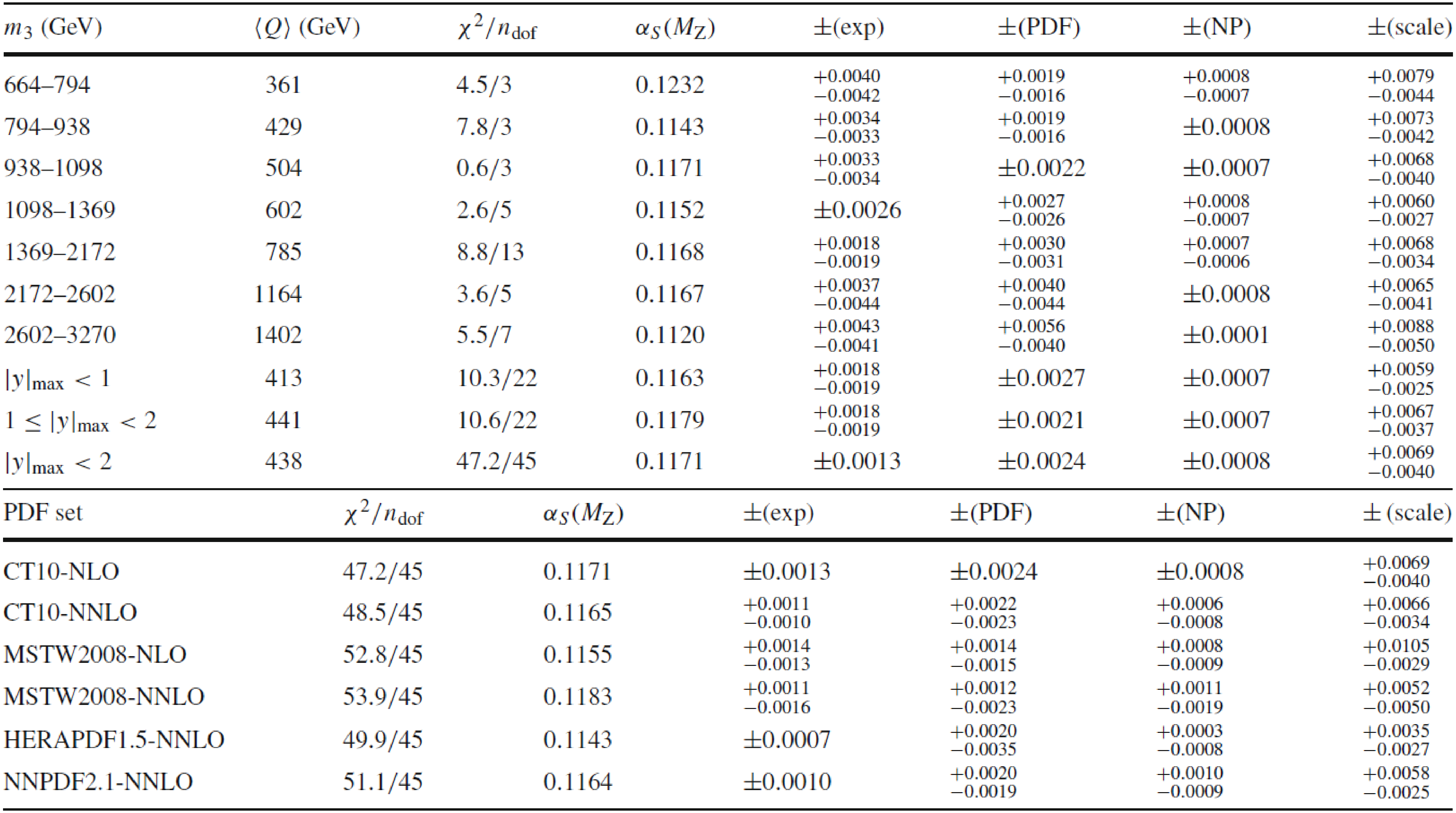
$\lvert y\rvert$ range	No. of data points	$\alpha_S(M_Z)$	χ^2/n_{dof}
$\lvert y\rvert < 0.5$	33	$0.1180 \pm 0.0017\,(\mathrm{exp}) \pm 0.0027\,(\mathrm{PDF}) \pm 0.0006\,(\mathrm{NP})^{+0.0031}_{-0.0026}\,(\mathrm{scale})$	15.4/32
$0.5 \leq \lvert y\rvert < 1.0$	30	$0.1176 \pm 0.0016\,(\mathrm{exp}) \pm 0.0026\,(\mathrm{PDF}) \pm 0.0006\,(\mathrm{NP})^{+0.0033}_{-0.0023}\,(\mathrm{scale})$	23.9/29
$1.0 \leq \lvert y\rvert < 1.5$	27	$0.1169 \pm 0.0019\,(\mathrm{exp}) \pm 0.0024\,(\mathrm{PDF}) \pm 0.0006\,(\mathrm{NP})^{+0.0033}_{-0.0019}\,(\mathrm{scale})$	10.5/26
$1.5 \leq \lvert y\rvert < 2.0$	24	$0.1133 \pm 0.0023\,(\mathrm{exp}) \pm 0.0028\,(\mathrm{PDF}) \pm 0.0010\,(\mathrm{NP})^{+0.0039}_{-0.0029}\,(\mathrm{scale})$	22.3/23
$2.0 \leq \lvert y\rvert < 2.5$	19	$0.1172 \pm 0.0044\,(\mathrm{exp}) \pm 0.0039\,(\mathrm{PDF}) \pm 0.0015\,(\mathrm{NP})^{+0.0049}_{-0.0060}\,(\mathrm{scale})$	13.8/18
$\lvert y\rvert < 2.5$	133	$0.1170 \pm 0.0012\,(\mathrm{exp}) \pm 0.0024\,(\mathrm{PDF}) \pm 0.0004\,(\mathrm{NP})^{+0.0044}_{-0.0030}\,(\mathrm{scale})$	105.7/132

CMS, EPJC 75 (2015) 288.

Details: 3-Jet Mass

Fit results in separate |y| bins (CT10-NLO) and with other PDFs

CMS, EPJC 75 (2015) 186.



m_3 (GeV)	$\langle Q \rangle$ (GeV)	χ^2/n_{dof}	$\alpha_S(M_Z)$	±(exp)	±(PDF)	±(NP)	±(scale)
664–794	361	4.5/3	0.1232	$^{+0.0040}_{-0.0042}$	$^{+0.0019}_{-0.0016}$	$^{+0.0008}_{-0.0007}$	$^{+0.0079}_{-0.0044}$
794–938	429	7.8/3	0.1143	$^{+0.0034}_{-0.0033}$	$^{+0.0019}_{-0.0016}$	±0.0008	$^{+0.0073}_{-0.0042}$
938–1098	504	0.6/3	0.1171	$^{+0.0033}_{-0.0034}$	±0.0022	±0.0007	$^{+0.0068}_{-0.0040}$
1098–1369	602	2.6/5	0.1152	±0.0026	$^{+0.0027}_{-0.0026}$	$^{+0.0008}_{-0.0007}$	$^{+0.0060}_{-0.0027}$
1369–2172	785	8.8/13	0.1168	$^{+0.0018}_{-0.0019}$	$^{+0.0030}_{-0.0031}$	$^{+0.0007}_{-0.0006}$	$^{+0.0068}_{-0.0034}$
2172–2602	1164	3.6/5	0.1167	$^{+0.0037}_{-0.0044}$	$^{+0.0040}_{-0.0044}$	±0.0008	$^{+0.0065}_{-0.0041}$
2602–3270	1402	5.5/7	0.1120	$^{+0.0043}_{-0.0041}$	$^{+0.0056}_{-0.0040}$	±0.0001	$^{+0.0088}_{-0.0050}$
$\lvert y\rvert_{\mathrm{max}} < 1$	413	10.3/22	0.1163	$^{+0.0018}_{-0.0019}$	±0.0027	±0.0007	$^{+0.0059}_{-0.0025}$
$1 \leq \lvert y\rvert_{\mathrm{max}} < 2$	441	10.6/22	0.1179	$^{+0.0018}_{-0.0019}$	±0.0021	±0.0007	$^{+0.0067}_{-0.0037}$
$\lvert y\rvert_{\mathrm{max}} < 2$	438	47.2/45	0.1171	±0.0013	±0.0024	±0.0008	$^{+0.0069}_{-0.0040}$

PDF set	χ^2/n_{dof}	$\alpha_S(M_Z)$	±(exp)	±(PDF)	±(NP)	± (scale)
CT10-NLO	47.2/45	0.1171	±0.0013	±0.0024	±0.0008	$^{+0.0069}_{-0.0040}$
CT10-NNLO	48.5/45	0.1165	$^{+0.0011}_{-0.0010}$	$^{+0.0022}_{-0.0023}$	$^{+0.0006}_{-0.0008}$	$^{+0.0066}_{-0.0034}$
MSTW2008-NLO	52.8/45	0.1155	$^{+0.0014}_{-0.0013}$	$^{+0.0014}_{-0.0015}$	$^{+0.0008}_{-0.0009}$	$^{+0.0105}_{-0.0029}$
MSTW2008-NNLO	53.9/45	0.1183	$^{+0.0011}_{-0.0016}$	$^{+0.0012}_{-0.0023}$	$^{+0.0011}_{-0.0019}$	$^{+0.0052}_{-0.0050}$
HERAPDF1.5-NNLO	49.9/45	0.1143	±0.0007	$^{+0.0020}_{-0.0035}$	$^{+0.0003}_{-0.0008}$	$^{+0.0035}_{-0.0027}$
NNPDF2.1-NNLO	51.1/45	0.1164	±0.0010	$^{+0.0020}_{-0.0019}$	$^{+0.0010}_{-0.0009}$	$^{+0.0058}_{-0.0025}$

$R_{3/2}$ Details

Fit results in separate Q ranges (NNPDF21-NNLO) and with other PDFs

$\langle p_{T1,2}\rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$	No. of data points	χ^2/N_{dof}
420–600	474	0.1147 ± 0.0061	0.0936 ± 0.0041	6	4.4/5
600–800	664	0.1132 ± 0.0050	0.0894 ± 0.0031	5	5.9/4
800–1390	896	0.1170 ± 0.0058	0.0889 ± 0.0034	10	5.7/9

$\langle p_{T1,2}\rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	exp.	PDF	theory
420–600	474	0.1147	±0.0015	±0.0015	±0.0057
600–800	664	0.1132	±0.0018	±0.0025	±0.0039
800–1390	896	0.1170	±0.0024	±0.0021	±0.0048

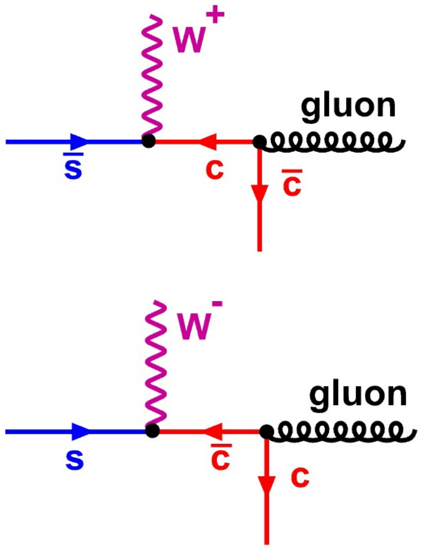
$$\text{MSTW2008:} \quad \alpha_S(M_Z) = 0.1141 \pm 0.0022\ (\text{exp.}),$$

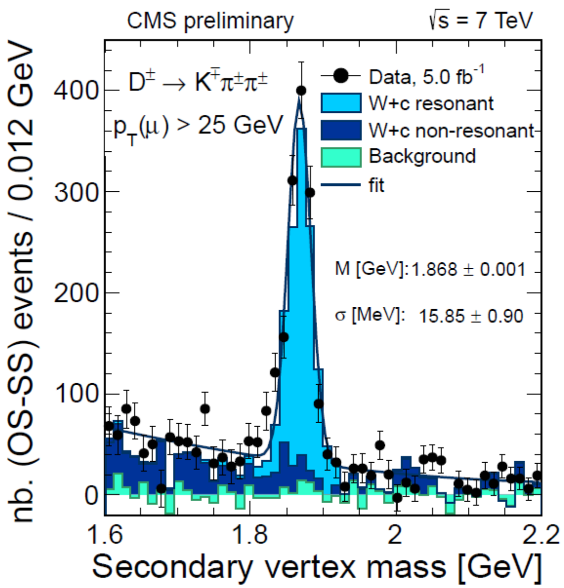
$$\text{CT10:} \quad \alpha_S(M_Z) = 0.1135 \pm 0.0019\ (\text{exp.}),$$

$\mu_r/\langle p_{T1,2}\rangle$	$\mu_f/\langle p_{T1,2}\rangle$	$\alpha_S(M_Z) \pm$ (exp.)	χ^2/N_{dof}
1	1	0.1148 ± 0.0014	22.0/20
1/2	1/2	0.1198 ± 0.0021	30.6/20
1/2	1	0.1149 ± 0.0014	22.2/20
1	1/2	0.1149 ± 0.0014	22.2/20
1	2	0.1150 ± 0.0015	21.9/20
2	1	0.1159 ± 0.0014	20.7/20
2	2	0.1172 ± 0.0018	21.3/20

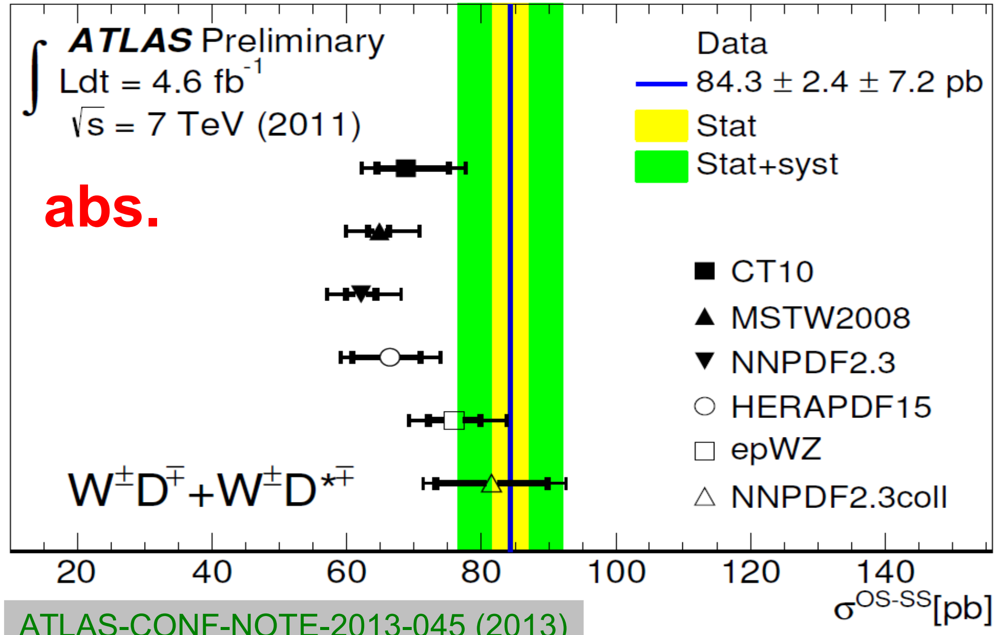
CMS, EPJC 73 (2013) 2604.

W + c

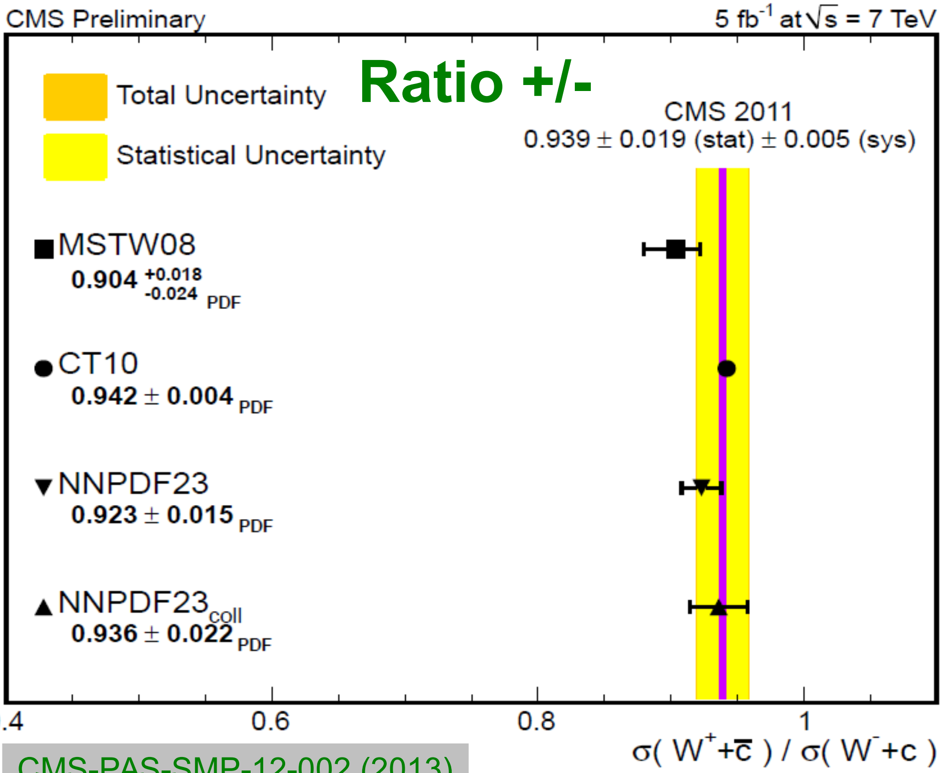




- New measurements from ATLAS & CMS
- Explicit reconstruction of charmed meson decays ($D^\pm$, $D^{\pm *}$) or incl. semileptonic (CMS)
- Different phase space ATLAS vs. CMS
- ATLAS finds smaller abs. cross sections ratio W+/W- ok
- CMS finds agreement within uncertainties for both

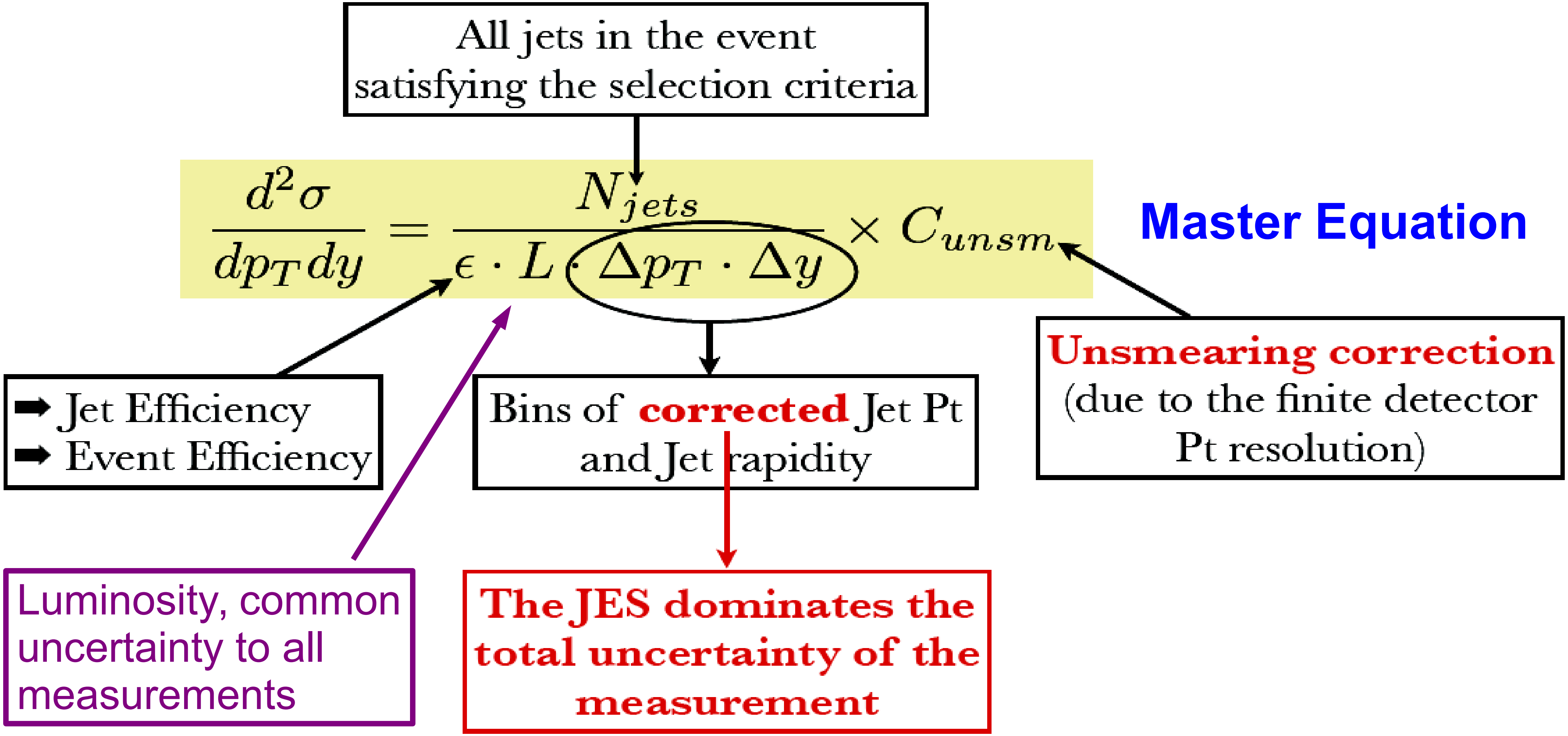


ATLAS-CONF-NOTE-2013-045 (2013)



CMS-PAS-SMP-12-002 (2013)

Inclusive Jet Measurements



All jets in the event satisfying the selection criteria

$$\frac{d^2\sigma}{dp_T\,dy} = \frac{N_{jets}}{\epsilon \cdot L \cdot \Delta p_T \cdot \Delta y} \times C_{unsm}$$

Master Equation

- ➡ Jet Efficiency
- ➡ Event Efficiency

Bins of **corrected** Jet Pt and Jet rapidity

Unsmearing correction (due to the finite detector Pt resolution)

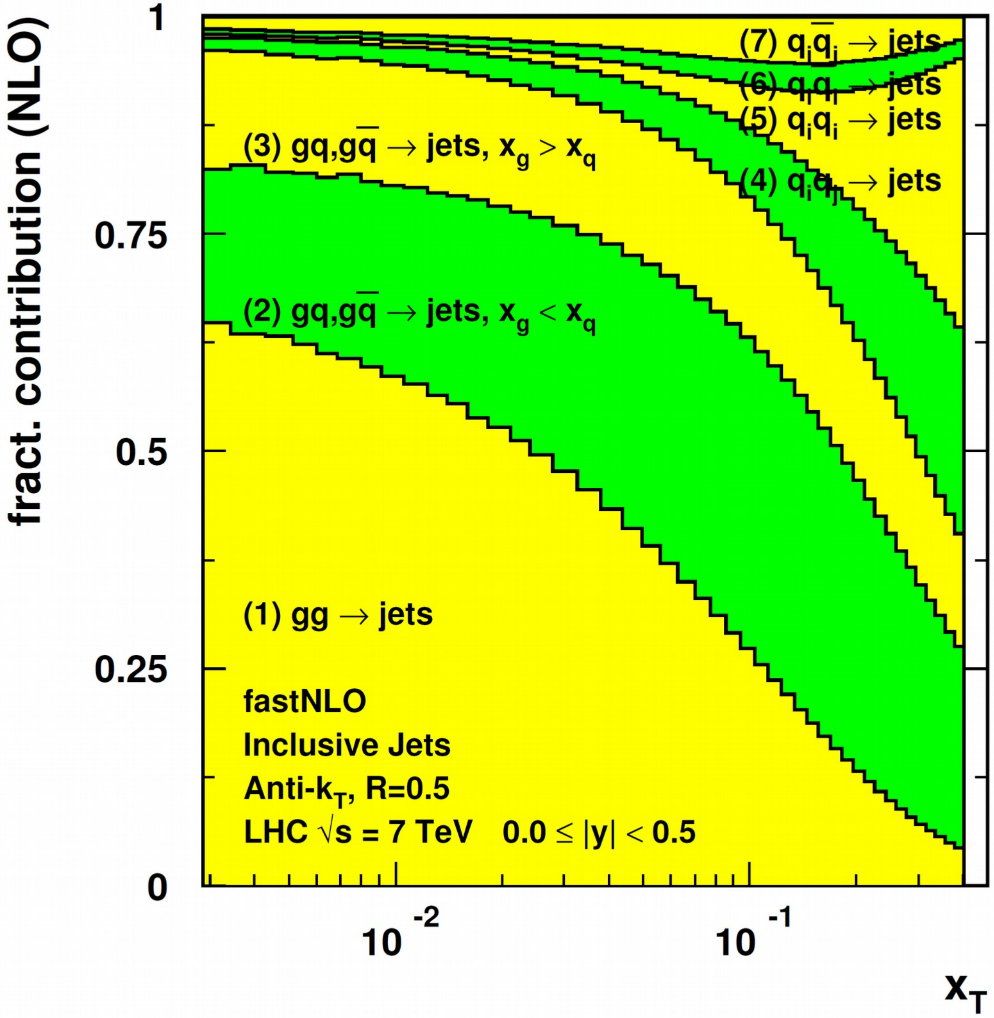
Luminosity, common uncertainty to all measurements

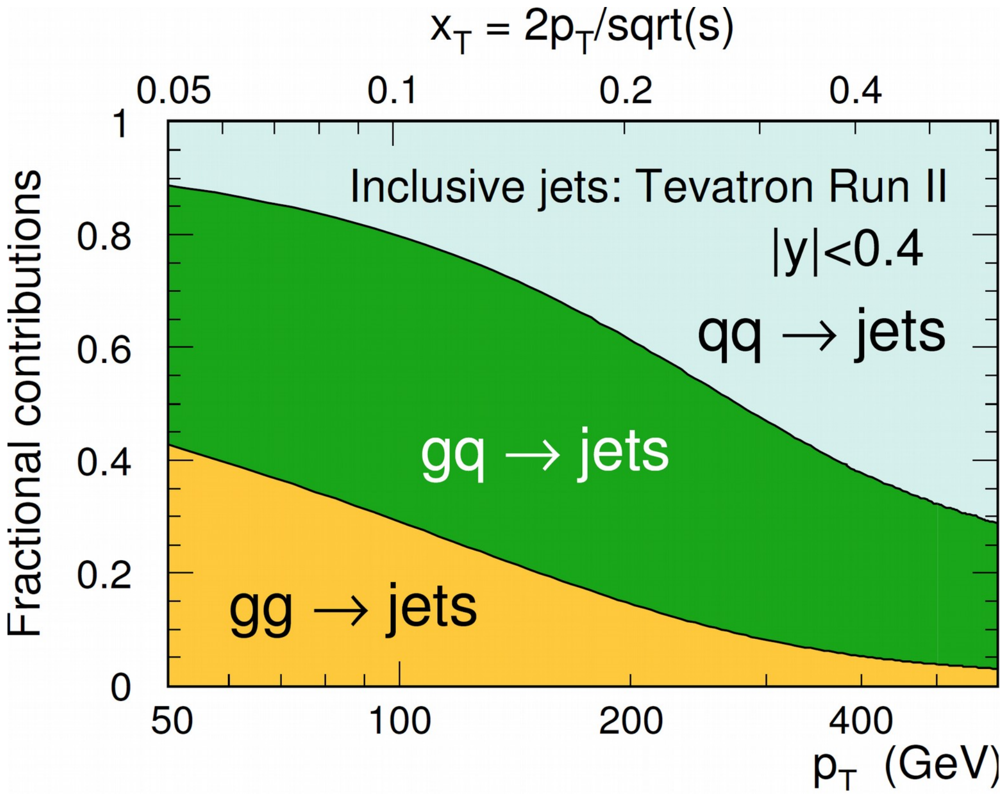
The JES dominates the total uncertainty of the measurement

K. Kousouris

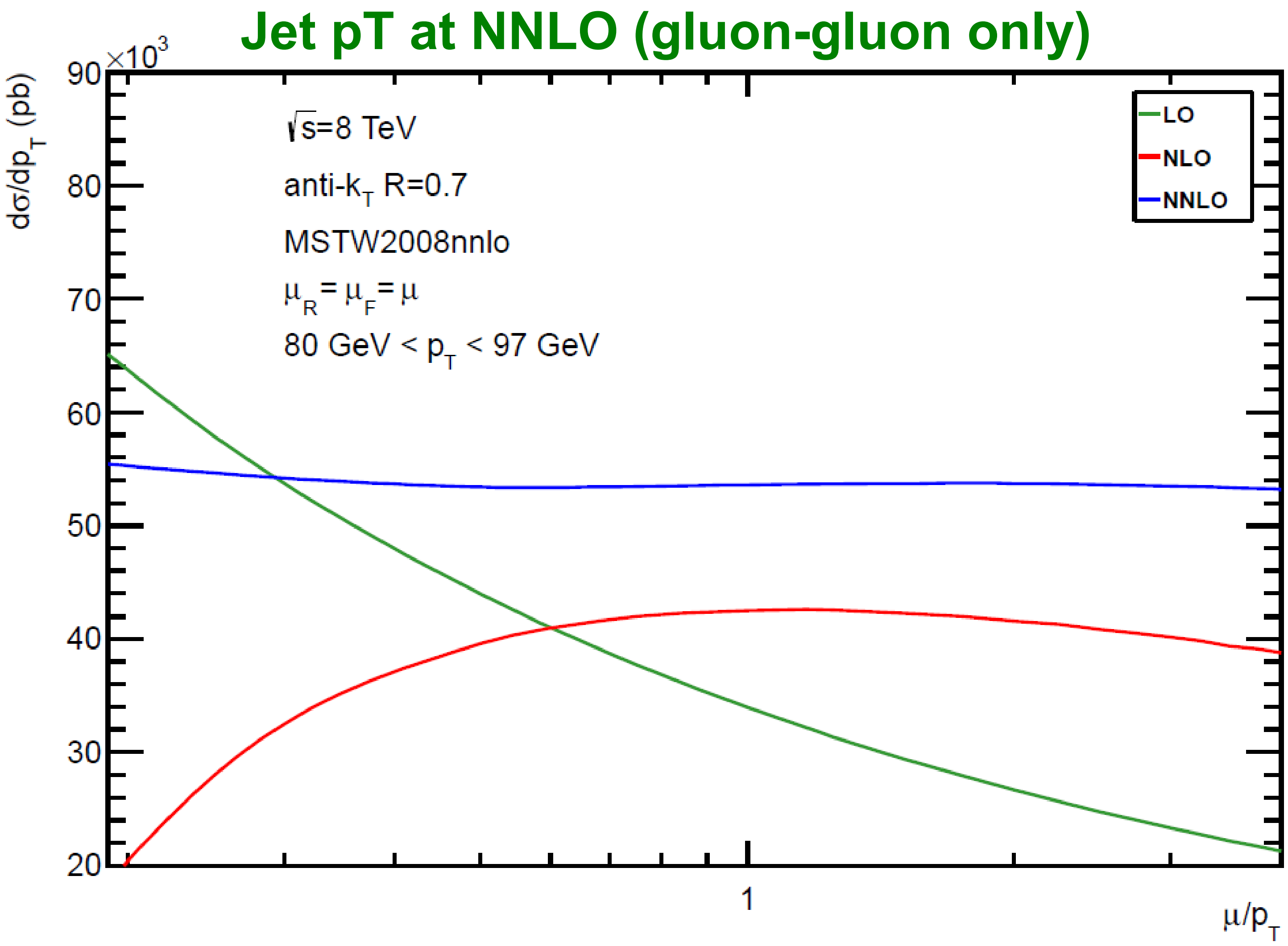
Inclusive Jets

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





NNLO Scale Dependence



New

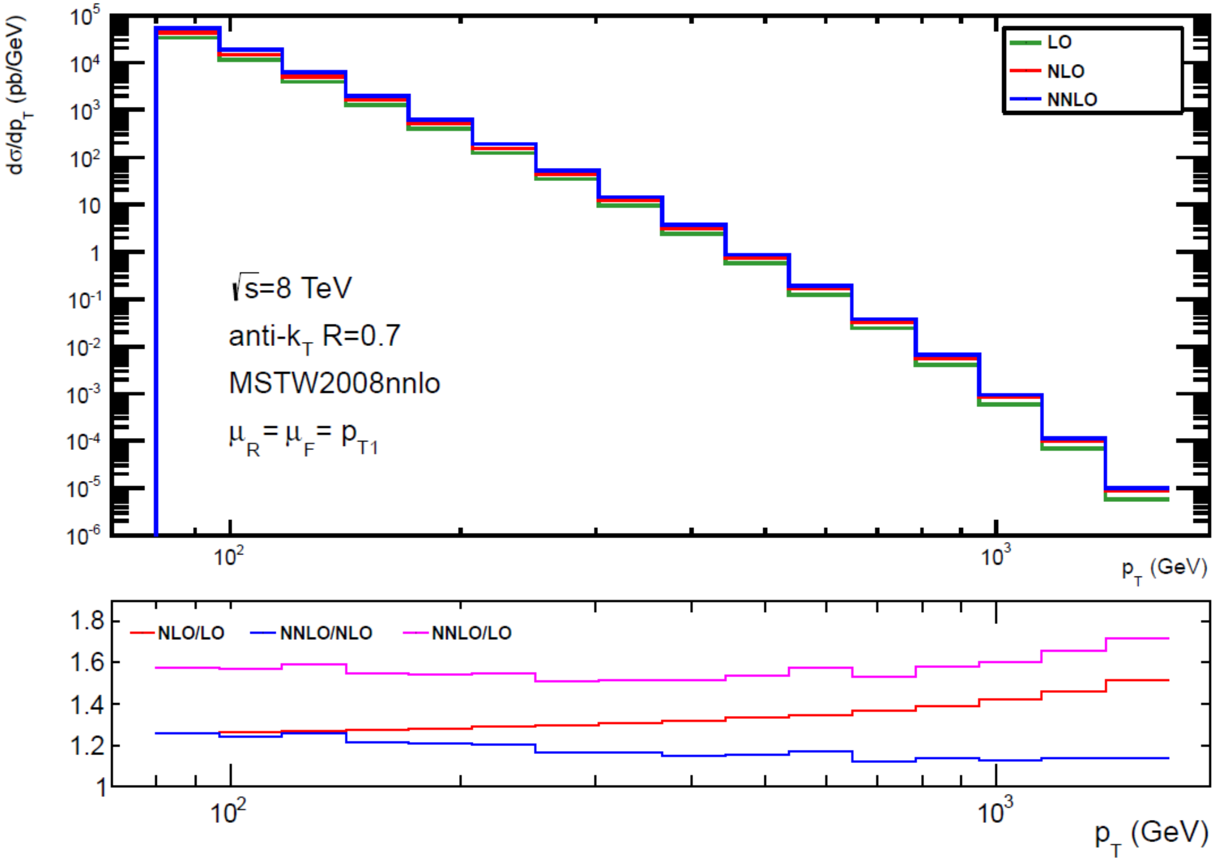
Drastically reduced scale dependence!

$$|y| < 4.4,\ 80\ \text{GeV} < p_T < 97\ \text{GeV}$$

From talk by N. Glover, see also:
Gehrmann- de Ridder et al.,
PRL110 (2013), JHEP1302 (2013).

Fortschritte in der Theorie

Jet pT zu NNLO (nur gluon-gluon)

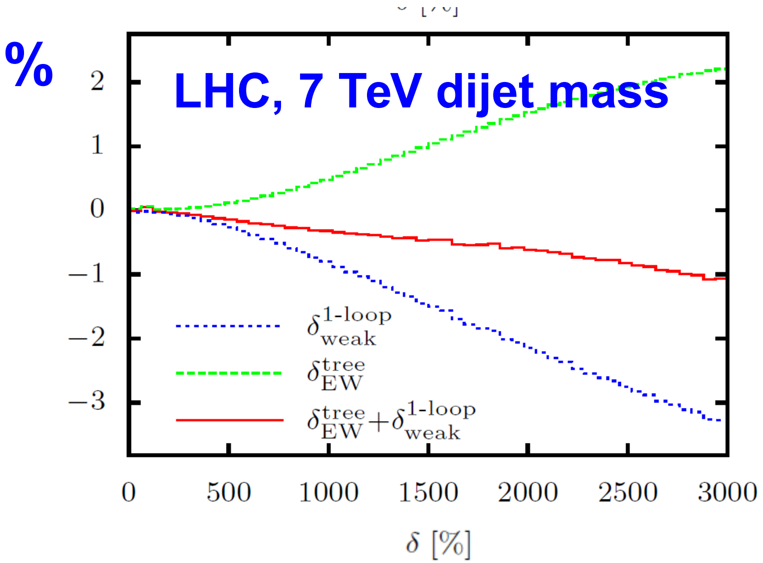


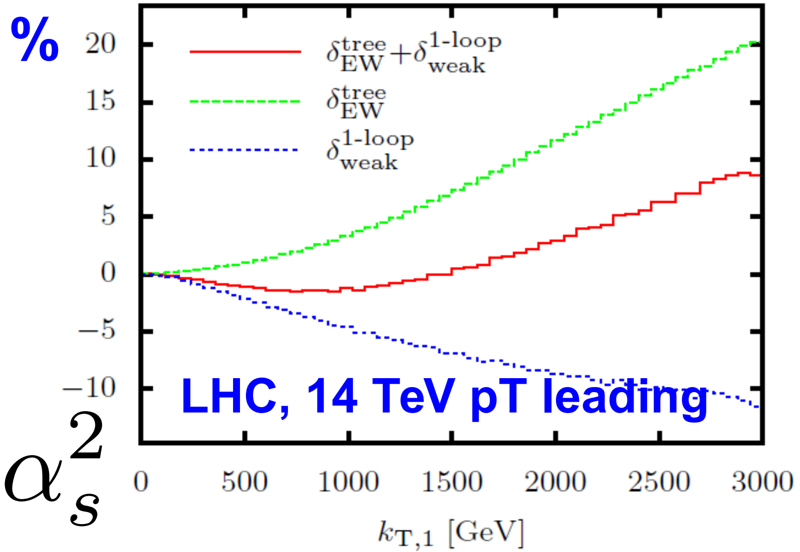
K Faktoren = NLO/LO

From talk by N. Glover:
Gehrmann- de Ridder, Gehrmann, Glover, Pires

$$\propto \alpha_S^4$$

Electroschwache Korrekturen





$$\propto \alpha\alpha_s^2$$

S. Dittmaier, A. Huss, C. Speckner, JHEP11 (2012).

Fits with top-pair Production

Top-pair production is especially sensitive to:

m_t^{pole} and α_s and $g(x,\mu_f^2)$ as the main production process at LHC is from gg

Using only the ttbar cross section measurement (dilepton channel) combined fits are not possible. Fixing the gluon to one of 5 PDF sets, however, it is possible to extract m_t^{pole} while fixing α_s or vice versa.

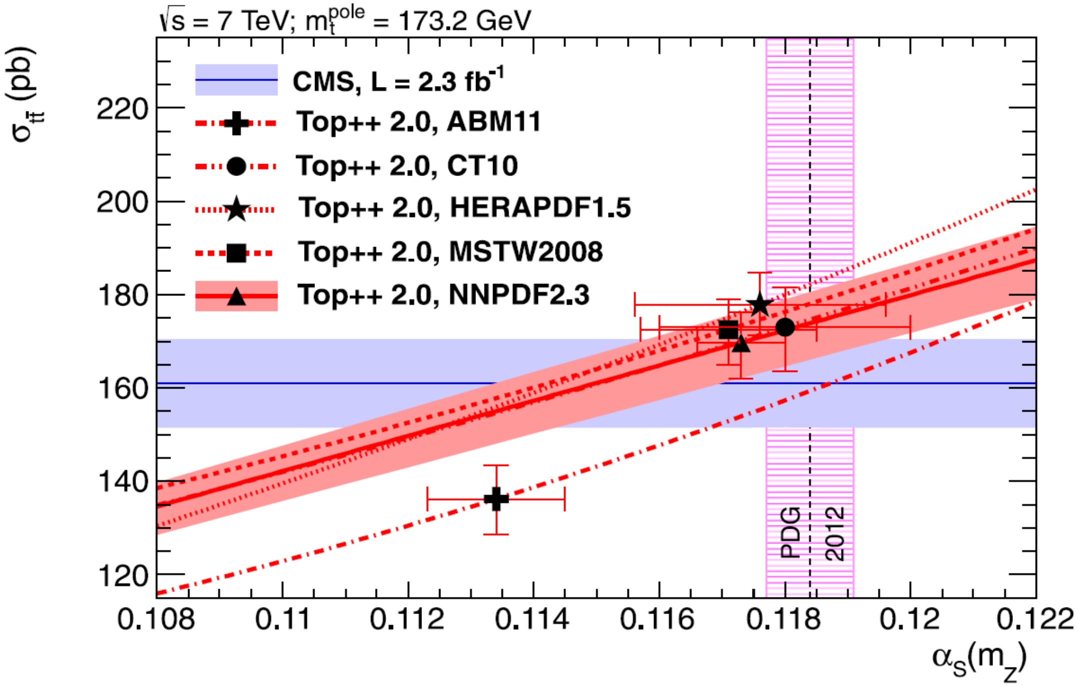
$$\alpha_s(M_Z) = 0.1151 \pm 0.0025(\mathrm{exp})^{+0.0013}_{-0.0011}(\mathrm{PDF})$$

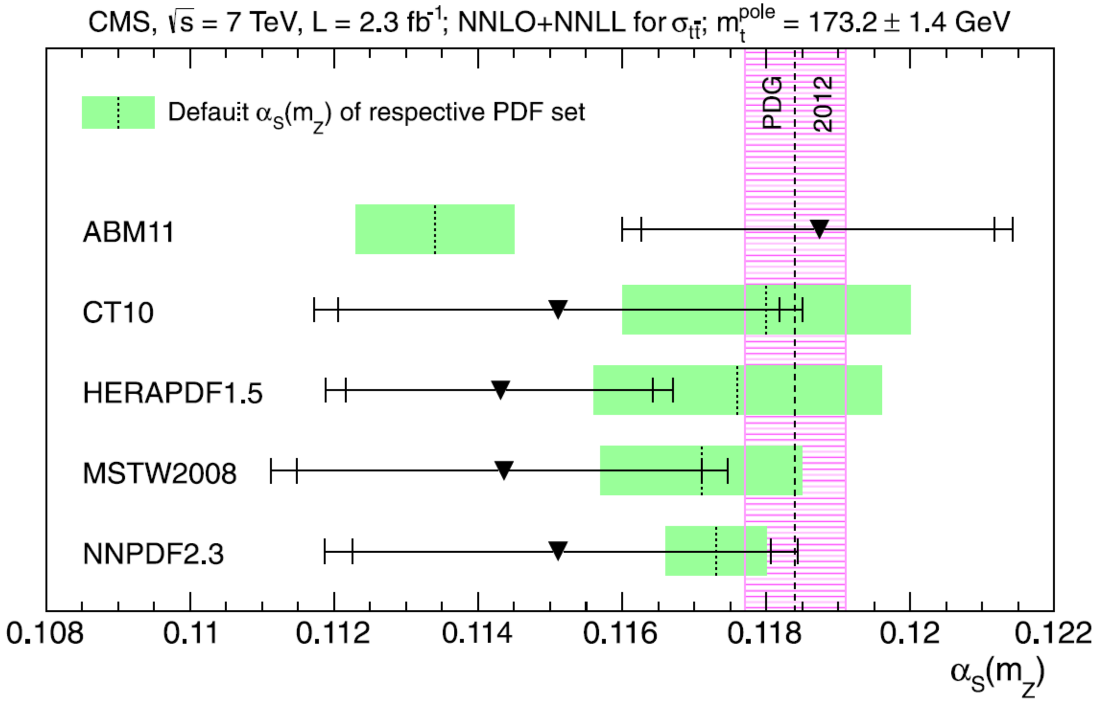
NNLO + NNLL

$$\boxed{^{+0.0009}_{-0.0008}(\mathrm{scale})} \pm \boxed{0.0013(\mathrm{m_t^{pole}}) \pm 0.0008(\mathrm{E_{LHC}})}$$

new top related

Fix m_t^{pole} → constrain α_s





CMS, PLB 728, 496 (2013), JHEP 11, 067 (2012).

Inclusive Jet Ratios: “2.76 / 8.0”

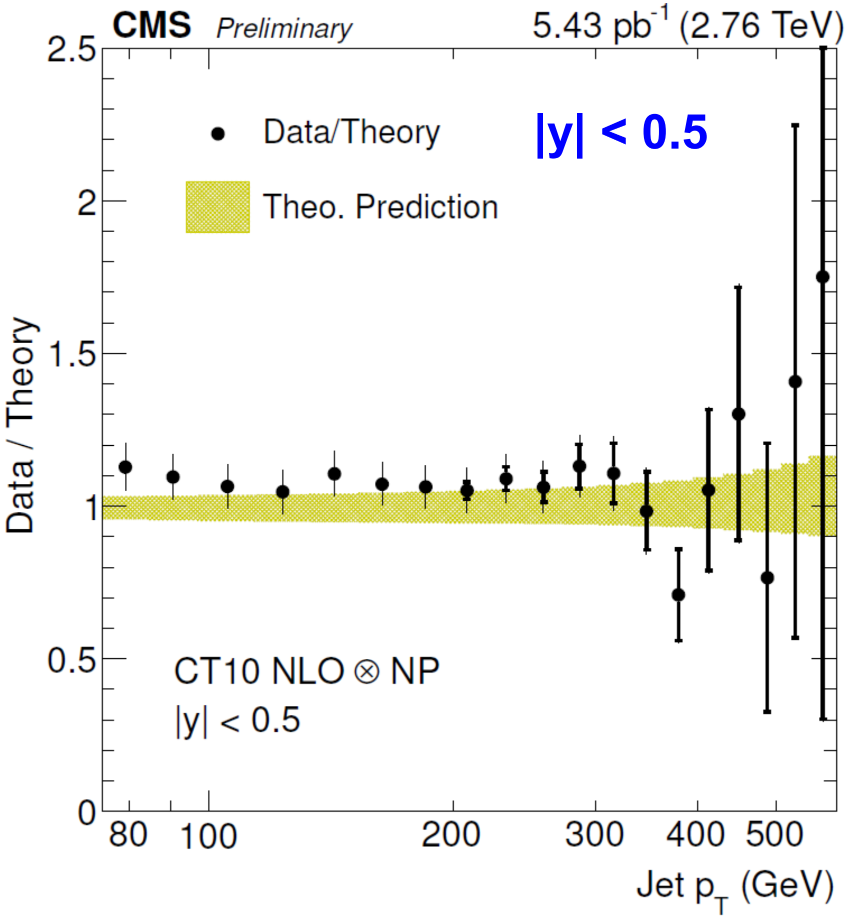
New from CMS:
- cross sections at 2.76 TeV
- ratios to 8 TeV

Shown
- double ratio to theory

Ratio at E_{cms} = 2.76 and 8.0 TeV

→ at least partial cancellation of uncertainties

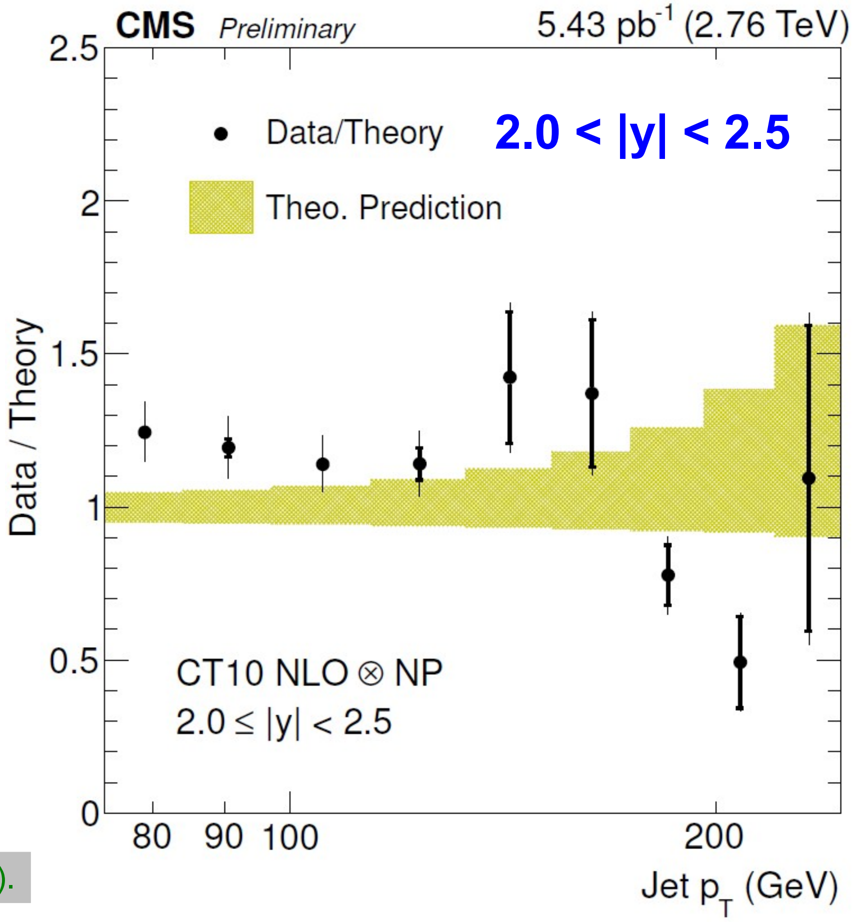
→ more precise comparisons



Disentangle α_s & g(x) by fitting in wide phase space of pT, y, and √s ?

→ gluon (PDF)

CMS-PAS-SMP-14-017 (2015).

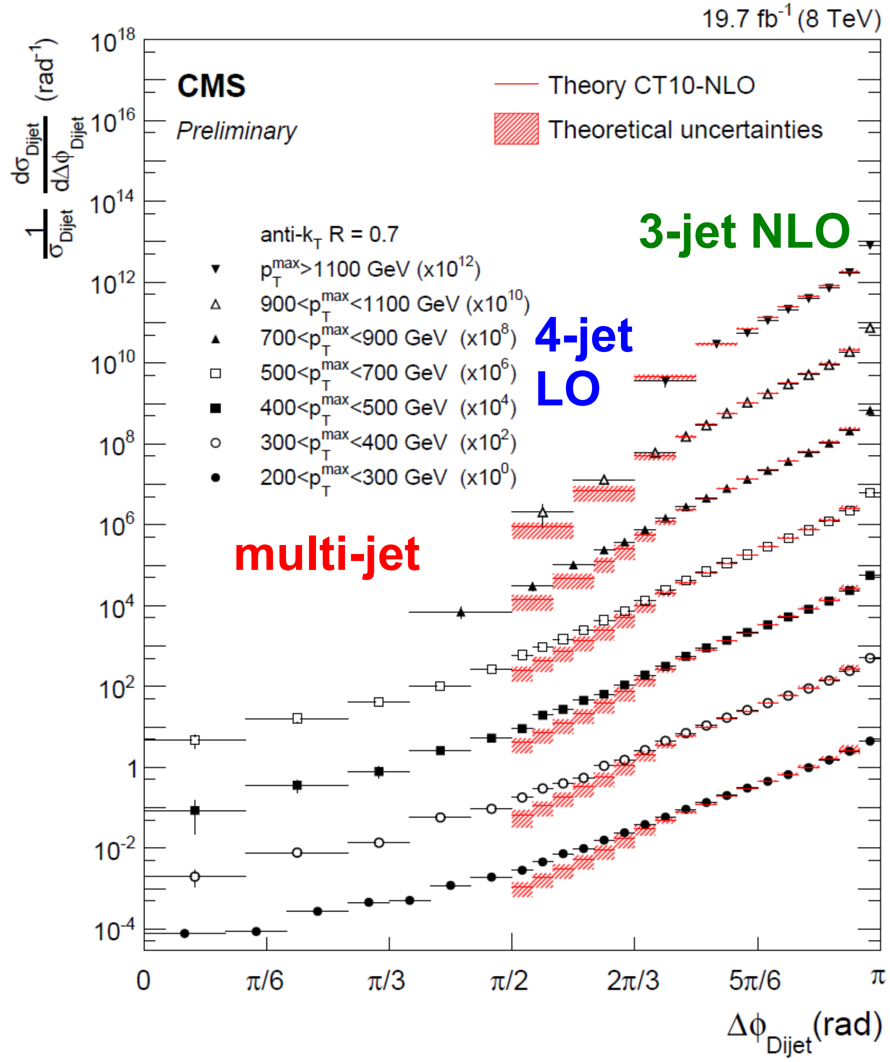


Azimuthal Decorrelations at 8 TeV

$\Delta\varphi_{jj}$ in bins of p_{T1}
- dijet LO has always $\Delta\varphi_{jj} = \pi$
- deviations through multi-jets

Related ratio observable $R_{\Delta\varphi}$ proposed for α_s det.

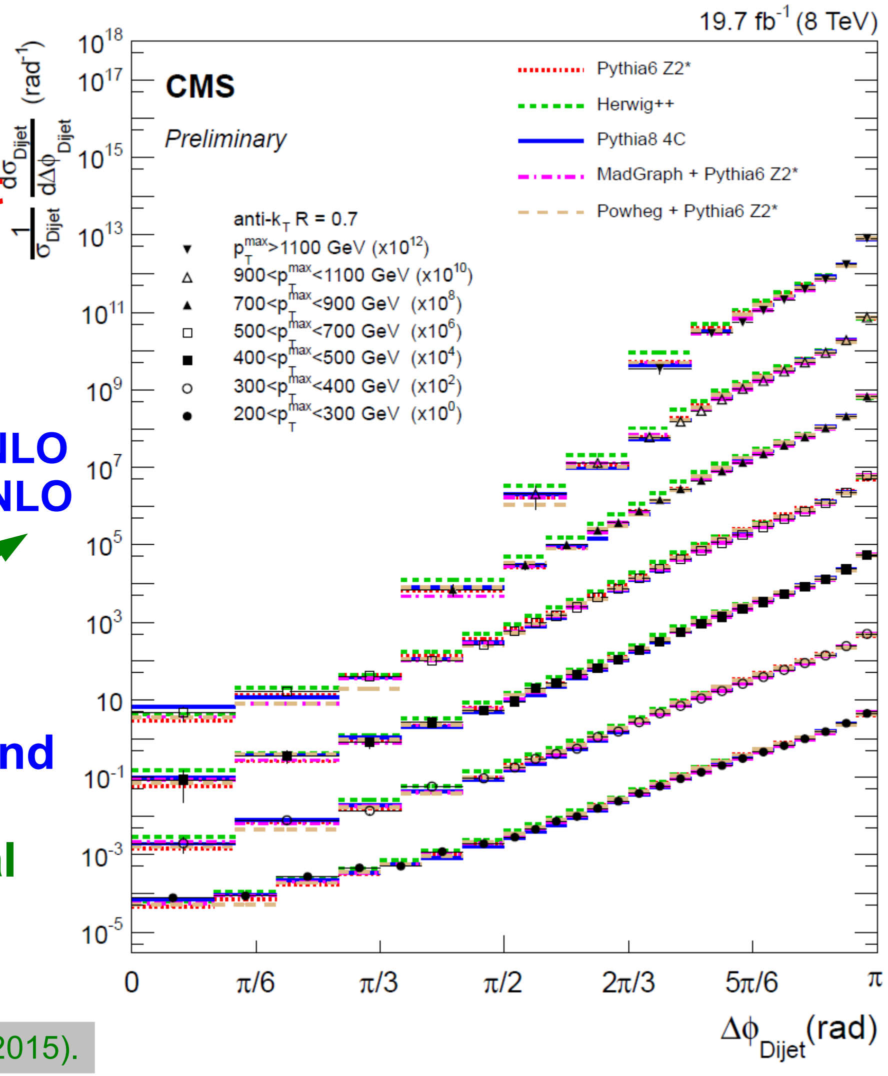
Wobisch et al., JHEP01 (2013) 172,
D0, PLB 721 (2013) 212.



Comparison to fixed-order PQCD
→ need multijet NLO

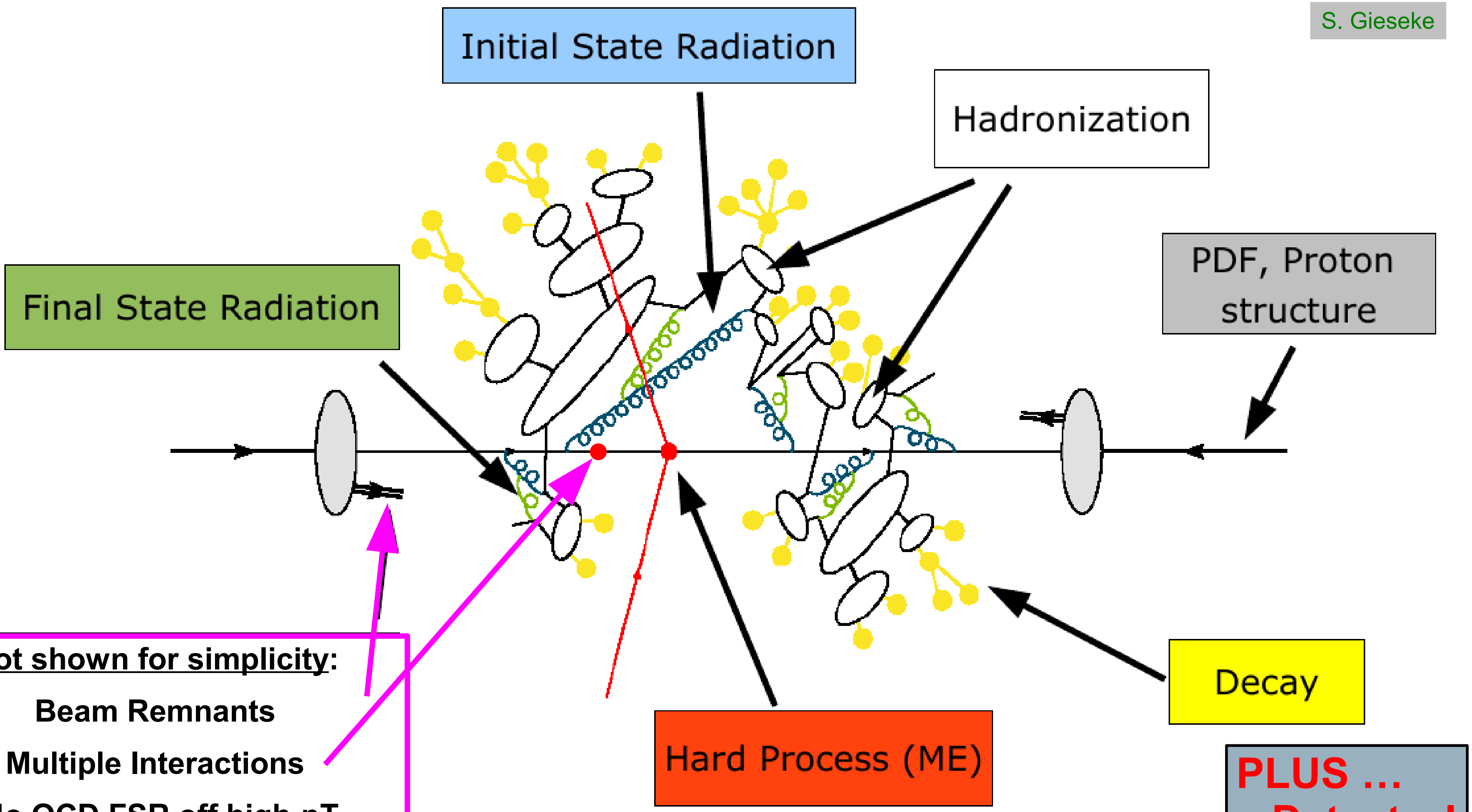
Sherpa + BlackHat → 4-jet NLO
Njet → 5-jet NLO
to be checked

Comparison to LO ME+PS and multijet ME+PS
→ good general description



CMS-PAS-SMP-14-015 (2015).

Event Display from Theory



S. Gieseke

Initial State Radiation

Hadronization

PDF, Proton structure

Final State Radiation

Hard Process (ME)

Decay

Not shown for simplicity:

Beam Remnants

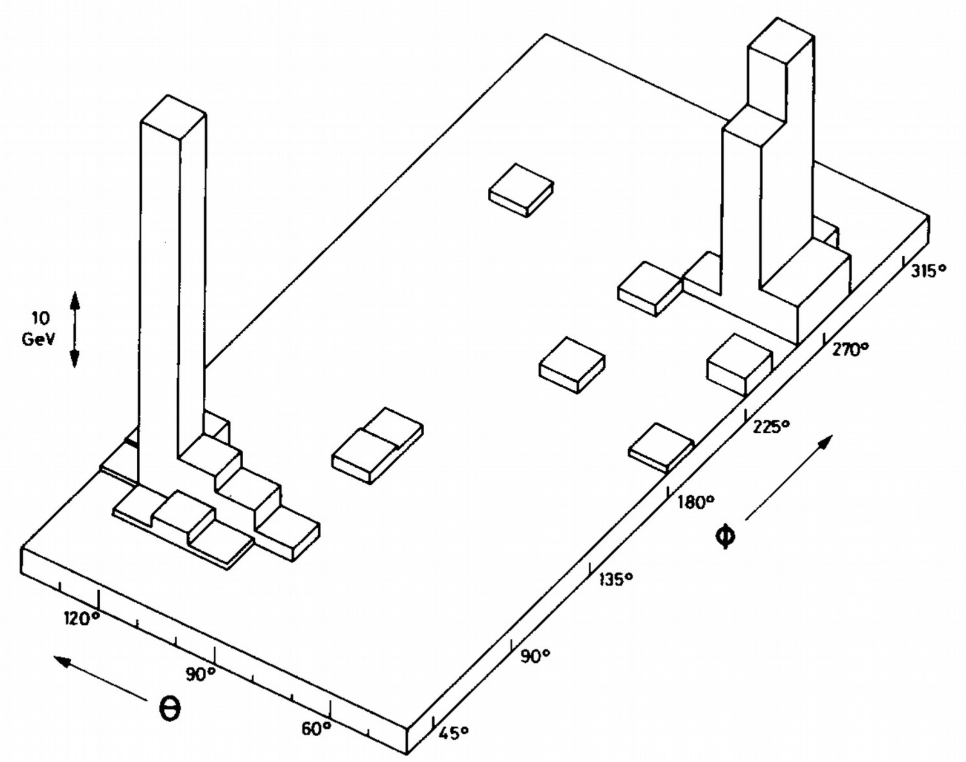
Multiple Interactions

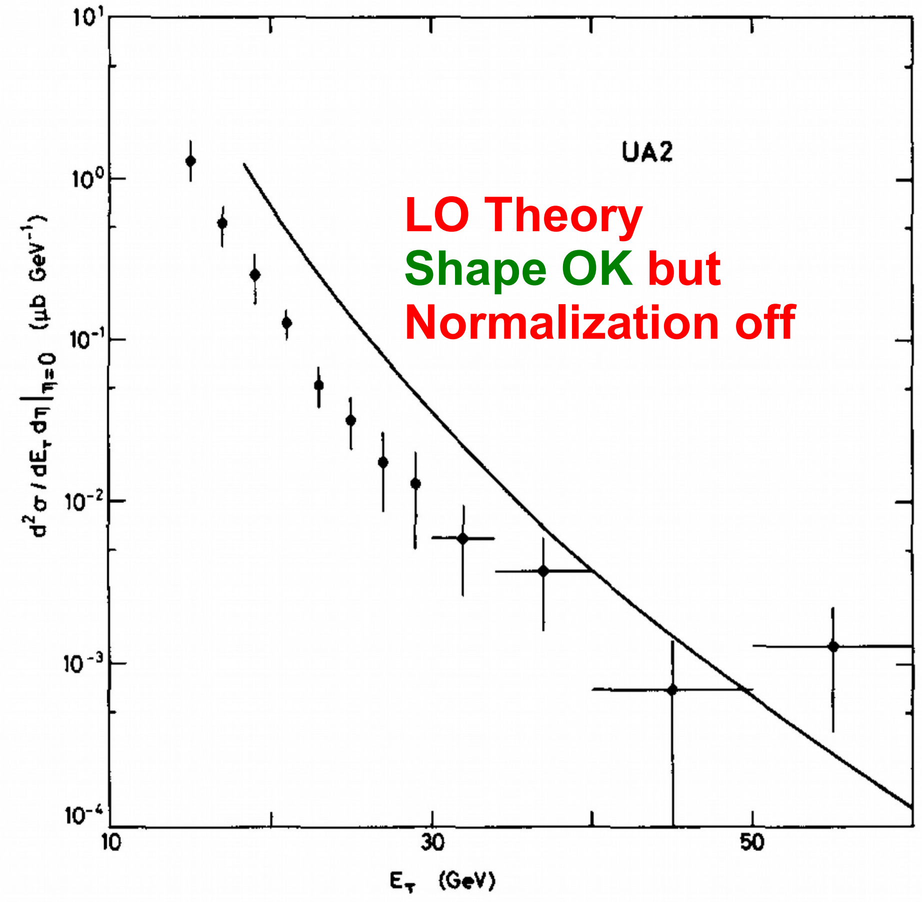
(No QCD FSR off high-pT lepton pair.)

PLUS … a Detector!

First Jets in hadronic Collisions

Dijet event energy depositions in azimuth Φ and polar angle θ





LO Theory
Shape OK but
Normalization off

Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses $\Lambda = 0.5$ GeV while $\Lambda = 0.15$ GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

UA2, PLB 118 (1982).

'Jet-Algorithm' based on calorimeter cells (UA1 & UA2)

UA1 later used cone-type jet algorithm!

Jet Algorithms at LHC

Primary algorithm at LHC:

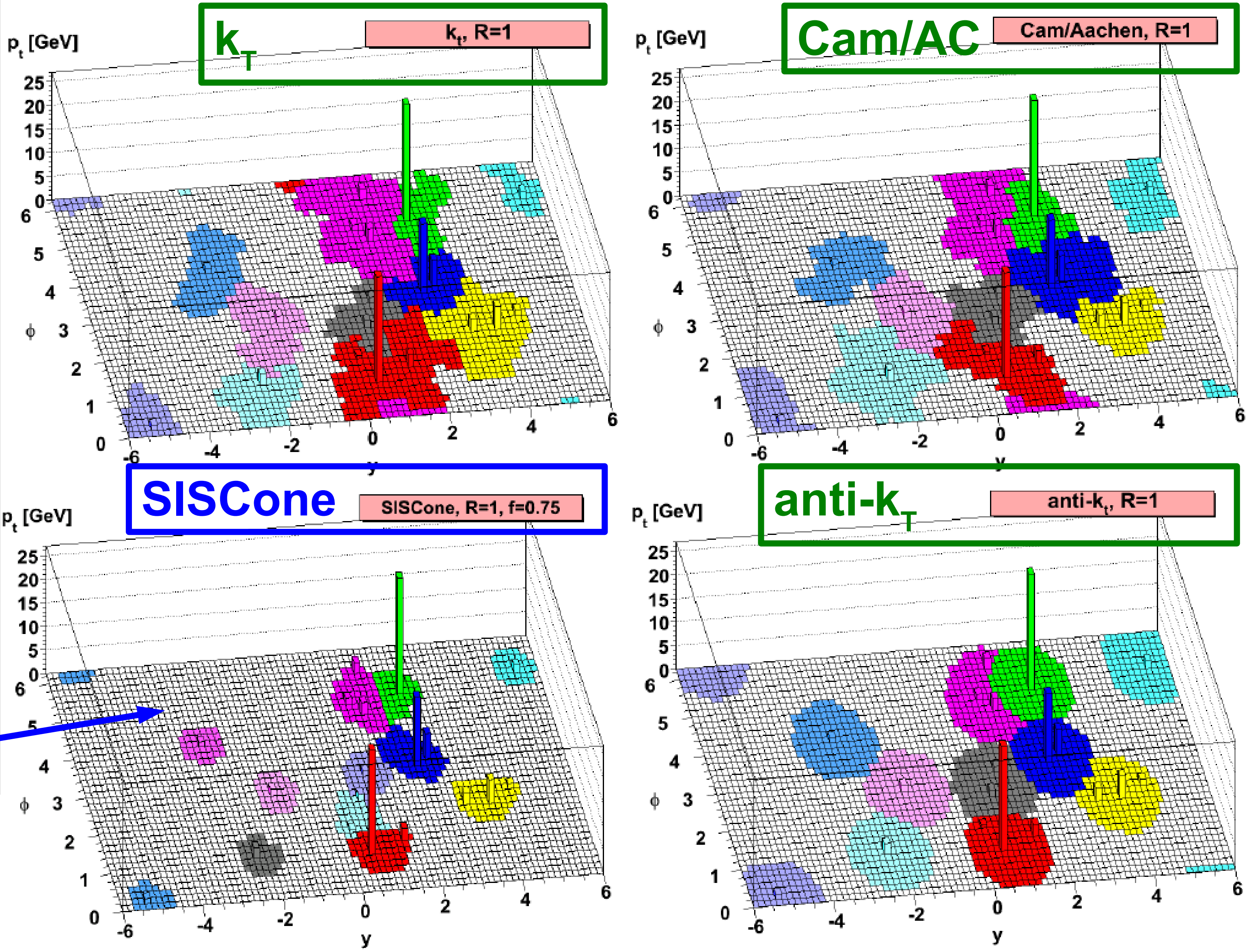
- **Anti-k_T:**

  ATLAS R = 0.4, 0.6
  CMS R = 0.5, 0.7
- k_T **0.4, 0.8 Run 2**

- SISCone ("real" cone algo)
- Cambridge/Aachen
  used in jet substructure, for example in boosted top

General interest to work with all four!

Only "real" cone Algorithm left!



kT hh, Ellis, Soper, PRD48 (1993),
Cam/AC, Dokshitzer et al., JHEP08 (1997),
Wobisch, Wengler, arXiv:hep-ph/9907280,
Fast kT, Cacciari/Salam, PLB641, 2006
SISCone, Salam/Soyez, JHEP05, 2007
anti-kT, Cacciari et al., JHEP04, 2008

Kontaktwechselwirkung (CI)

Viele Modelle versuchen heutige "Elementar-Teilchen" wieder als zusammengesetzt zu beschreiben: "Compositeness", Preonen, ...

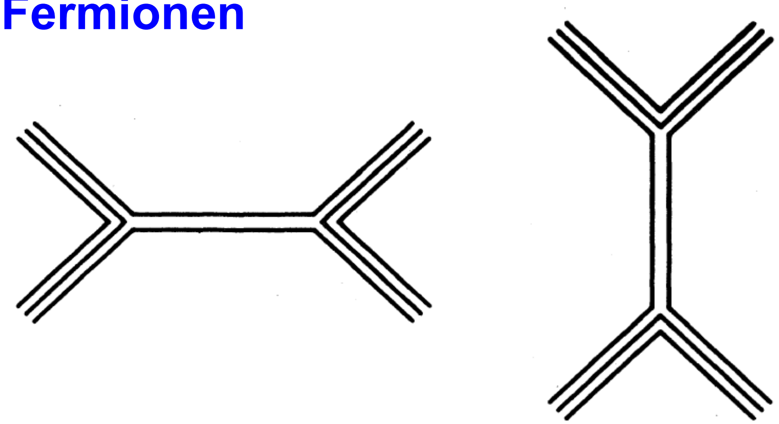
Terazawa, Phys. Rev. D, 1980, 22, 184.
Eichten, Lane, Peskin, Phys. Rev. Lett., 1983, 50, 811,
Baur, Hinchcliffe, Zeppenfeld, Int. J. Mod. Phys. A, 1987, 2, 1285.
Hewett, Rizzo, Phys. Rept., 1989, 183, 193.
Frampton, Glashow, Phys. Lett. B, 1987, 190, 157.
Simmons, Phys. Rev. D, 1997, 55, 1678.
Randall, Sundrum, Phys. Rev. Lett., 1999, 83, 3370.

"Nieder"-Energiephänomene im Vergleich zur Compositeness Scale Λ lassen sich dann wieder als Kontaktwechselwirkung approximieren:

CI-Zusatz zum SM Langrangian

(flavour-diagonal, vermeide FCNC)

Elastische Preon-WW zwischen Komposit-Fermionen



$$\mathcal{L}_{qq} = \frac{g^2}{2\Lambda^2}\Big\{\eta_{LL}\left(\bar{q}_L\gamma^\mu q_L\right)\left(\bar{q}_L\gamma_\mu q_L\right) + 2\eta_{LR}\left(\bar{q}_L\gamma^\mu q_L\right)\left(\bar{q}_R\gamma_\mu q_R\right) + \eta_{RR}\left(\bar{q}_R\gamma^\mu q_R\right)\left(\bar{q}_R\gamma_\mu q_R\right)\Big\}$$

Eichten, Hinchcliffe, Lane, Quigg, Rev. Mod. Phys., 1984, 56, 579.

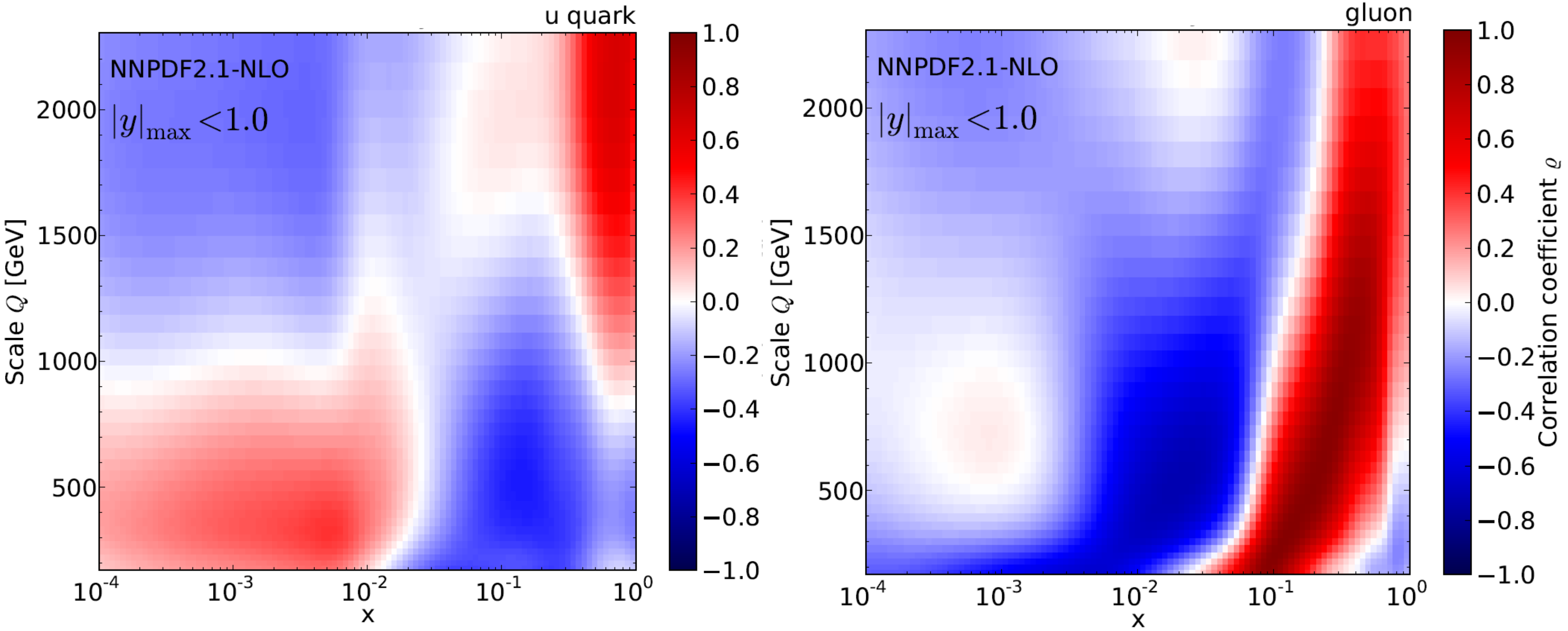
Korrelation σ Messung - PDF

Messung inklusiver Jets bei hohem pT beeinflusst:

- **Gluondichte bei hohem x (> 0.1)**
- **Quarkdichten bei hohem x (> 0.3)**

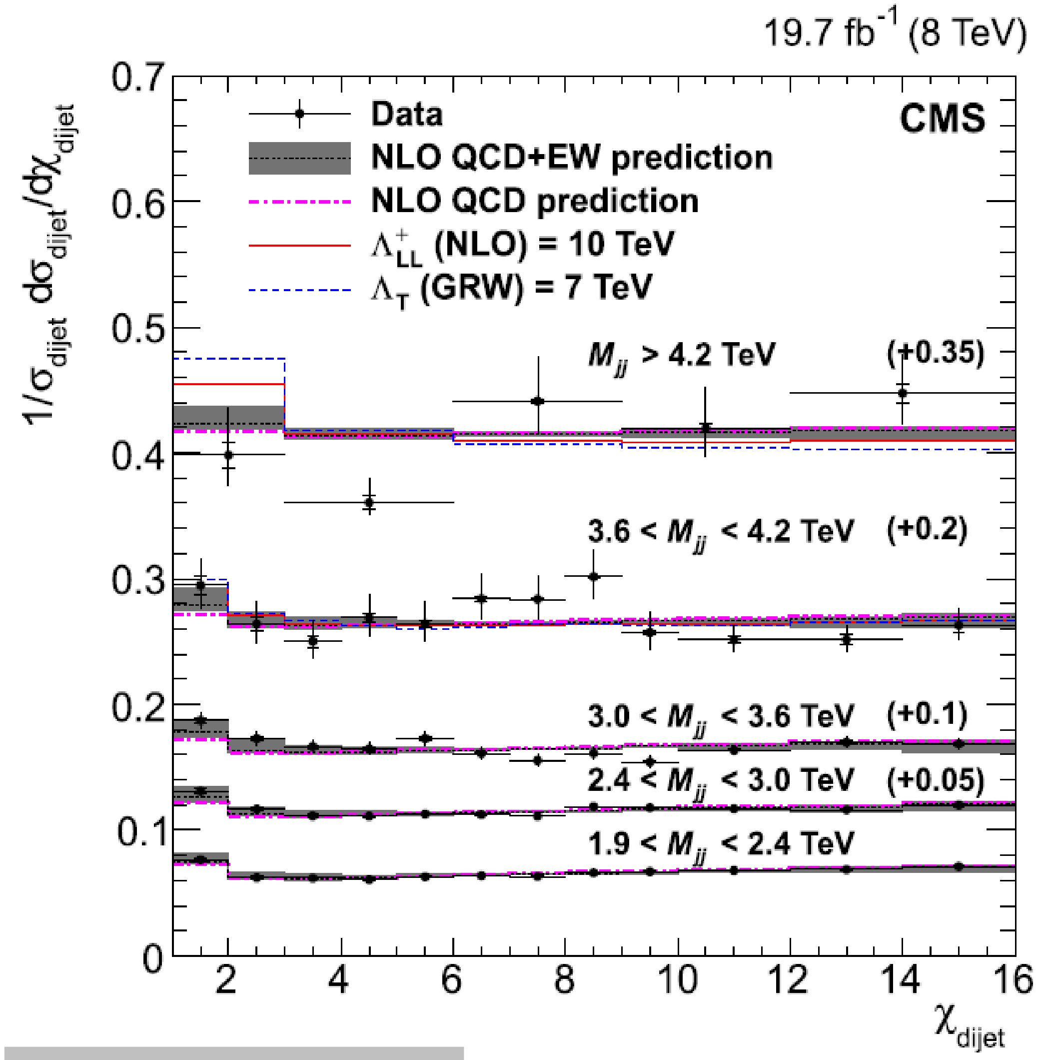
Geht so nur mit statistischem Unsicherheitsensemble von NNPDF!

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

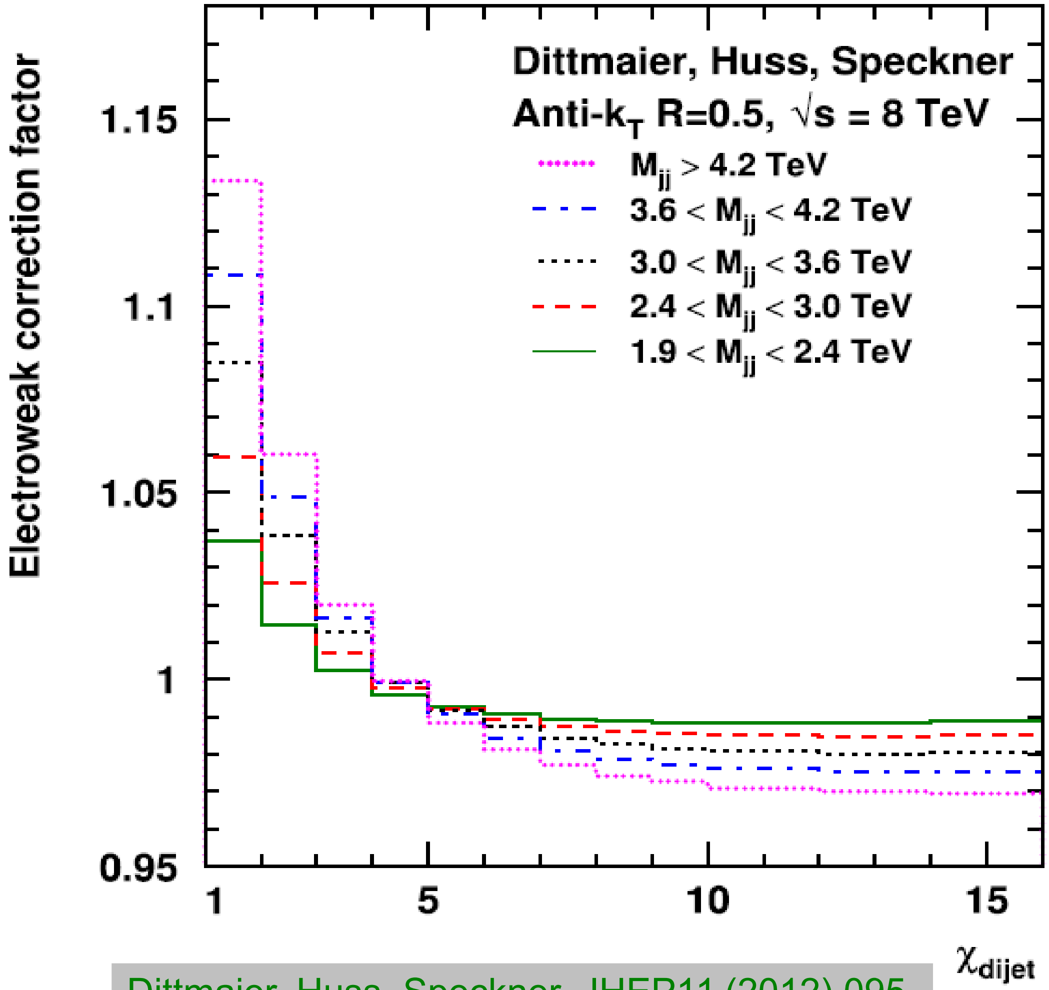


Dijet Angular & EW Corrections

Better agreement theory vs. data WITH ew corrections
→ ~ 5% higher exclusion limits for searches



CMS, PLB 746 (2015) 79.



Dittmaier, Huss, Speckner, JHEP11 (2012) 095.

Jet Energy Scale and α_s

Two goals for α_s:

1. **Measure the running of $\alpha_s(Q)$ up to the highest scales possible**

→ In CMS mostly looked into $\alpha_s(Q)$!

2. **Measure $\alpha_s(M_Z)$ as precisely as possible**

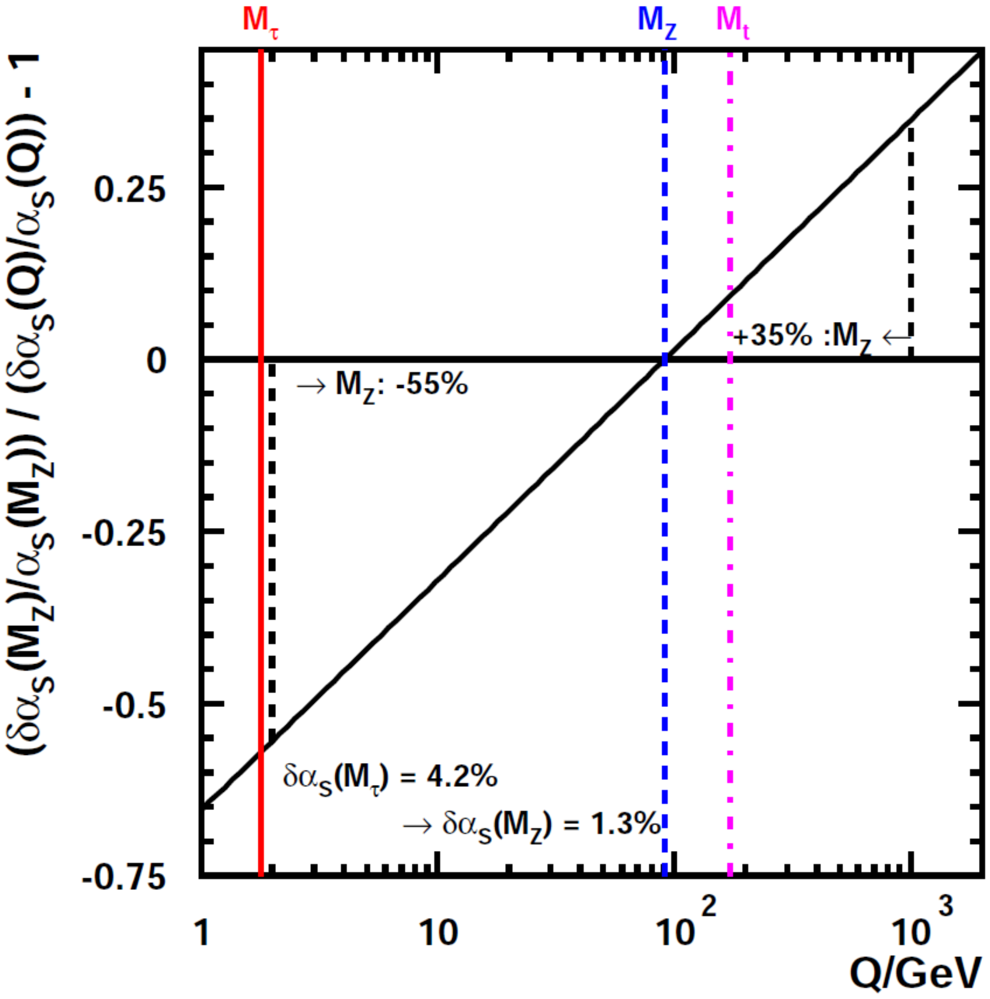
→ For $\alpha_s(M_Z)$ might want to stay at minimal JEC uncertainty: **200 – 800 GeV, central rapidity**

Better in:
- ➔ JEC uncertainty
- ➔ PDF uncertainty
- ➔ Evolution to M_Z

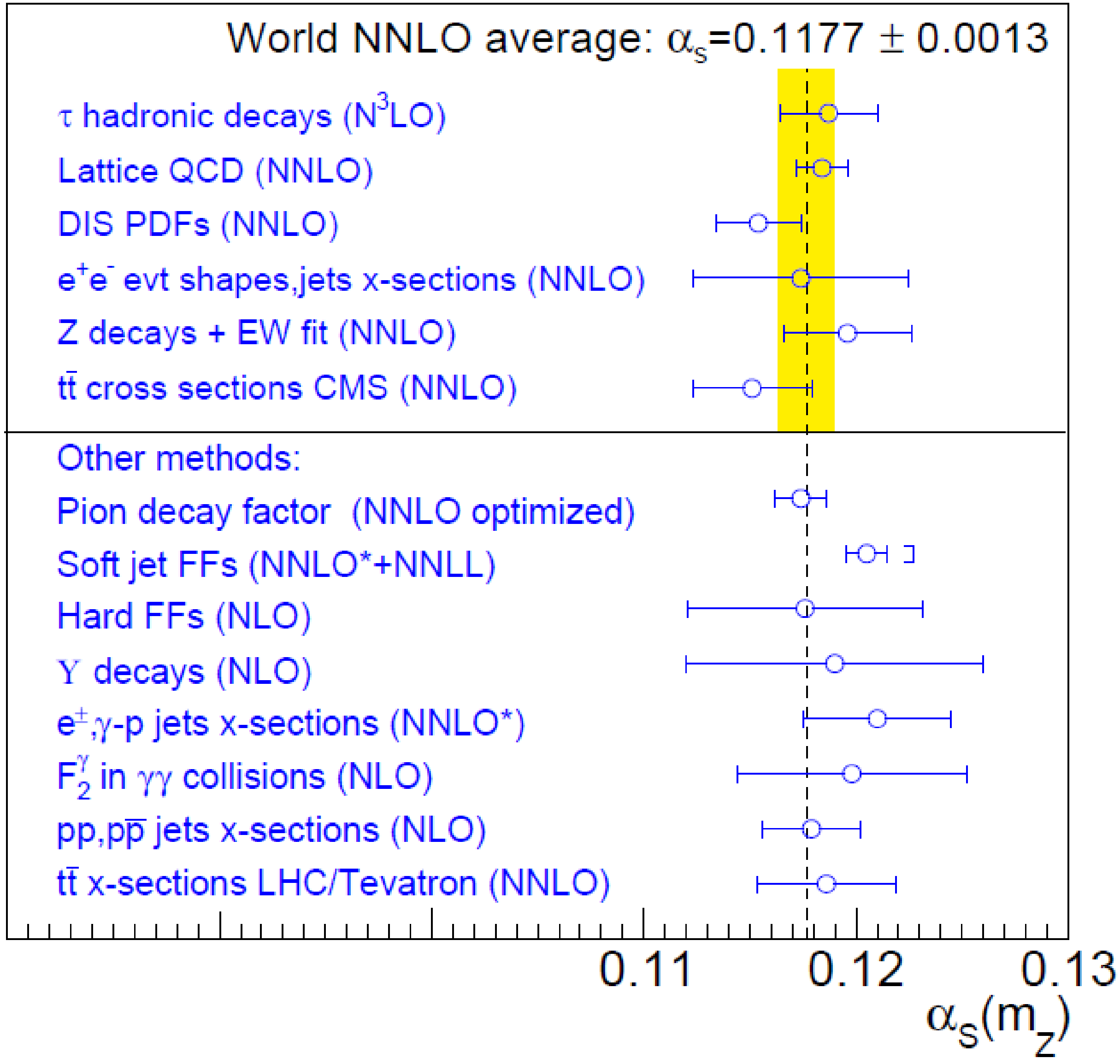
Worse in: NP effects

Incredibly shrinking error →

← Uncomfortably growing error



Preliminary Average 2015



Workshop Proceeedings:
arXiv: 1512.05194