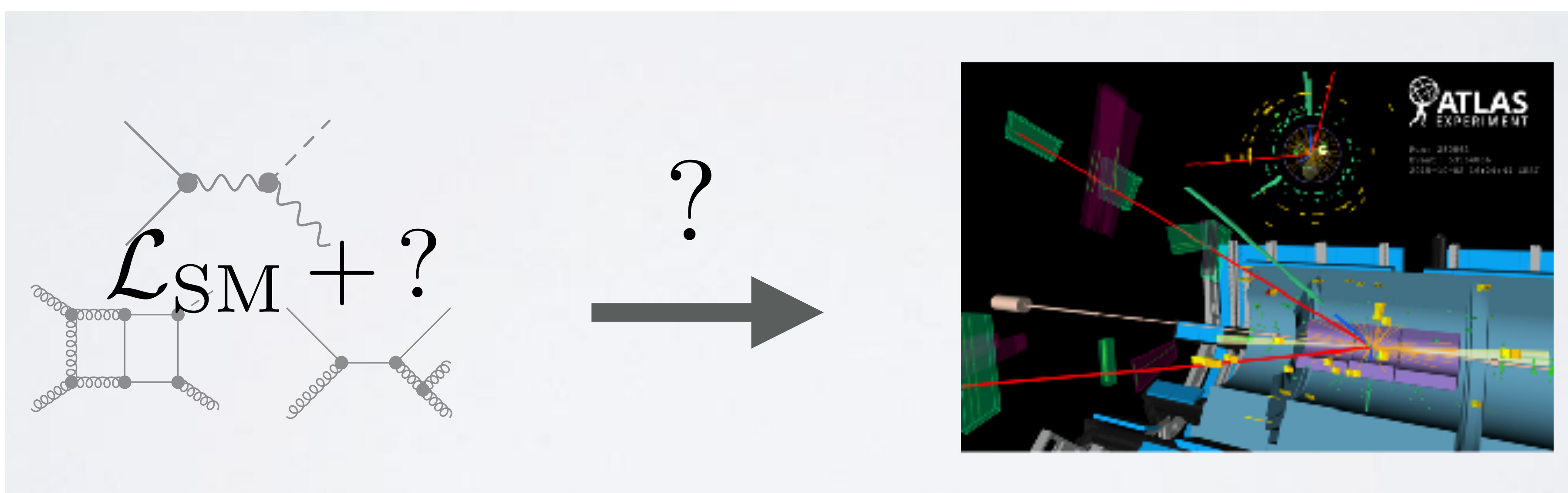
Collider Phenomenology

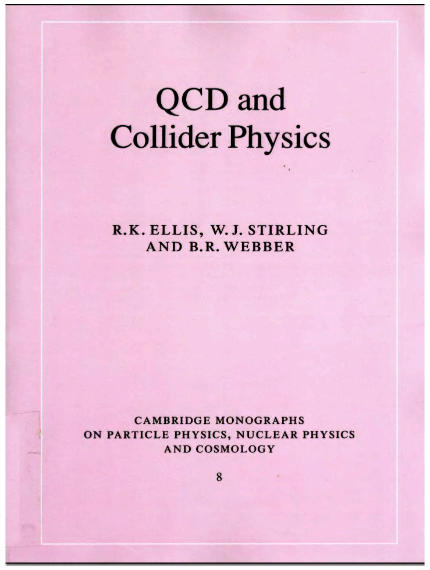
Lucian Harland-Lang, University of Oxford



UNIVERSITY OF
OXFORD

Background Reading

- Ellis, Stirling, Webber, “QCD and Collider Physics”, aka “The Pink Book”.

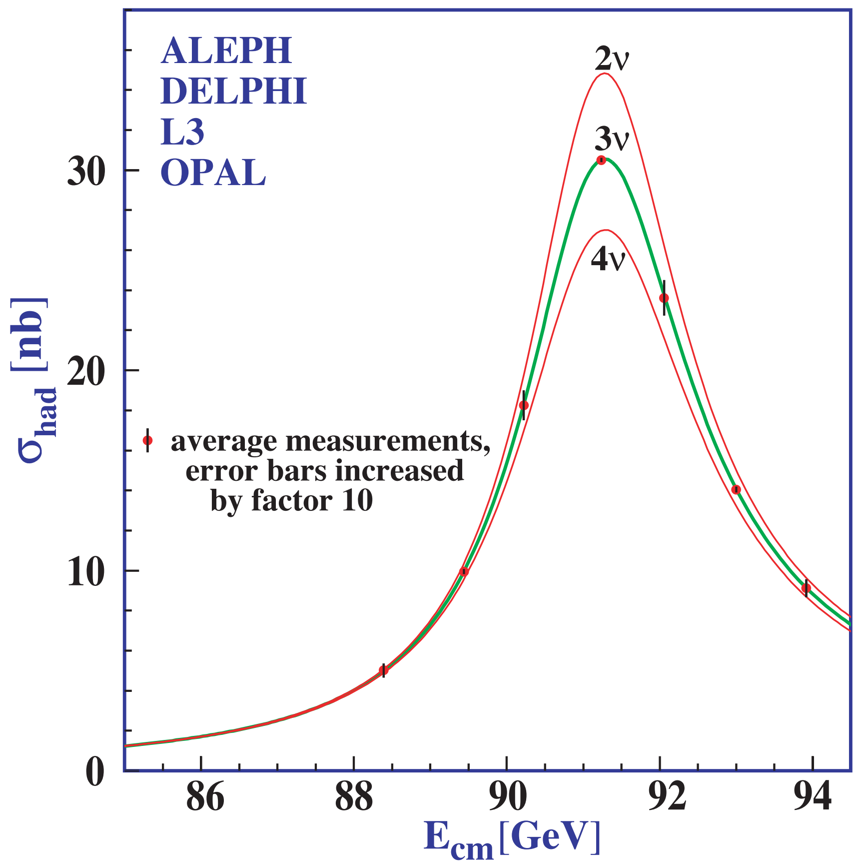


- Gunion, Kaber, Kane, Dawson, “Higgs Hunter’s Guide”

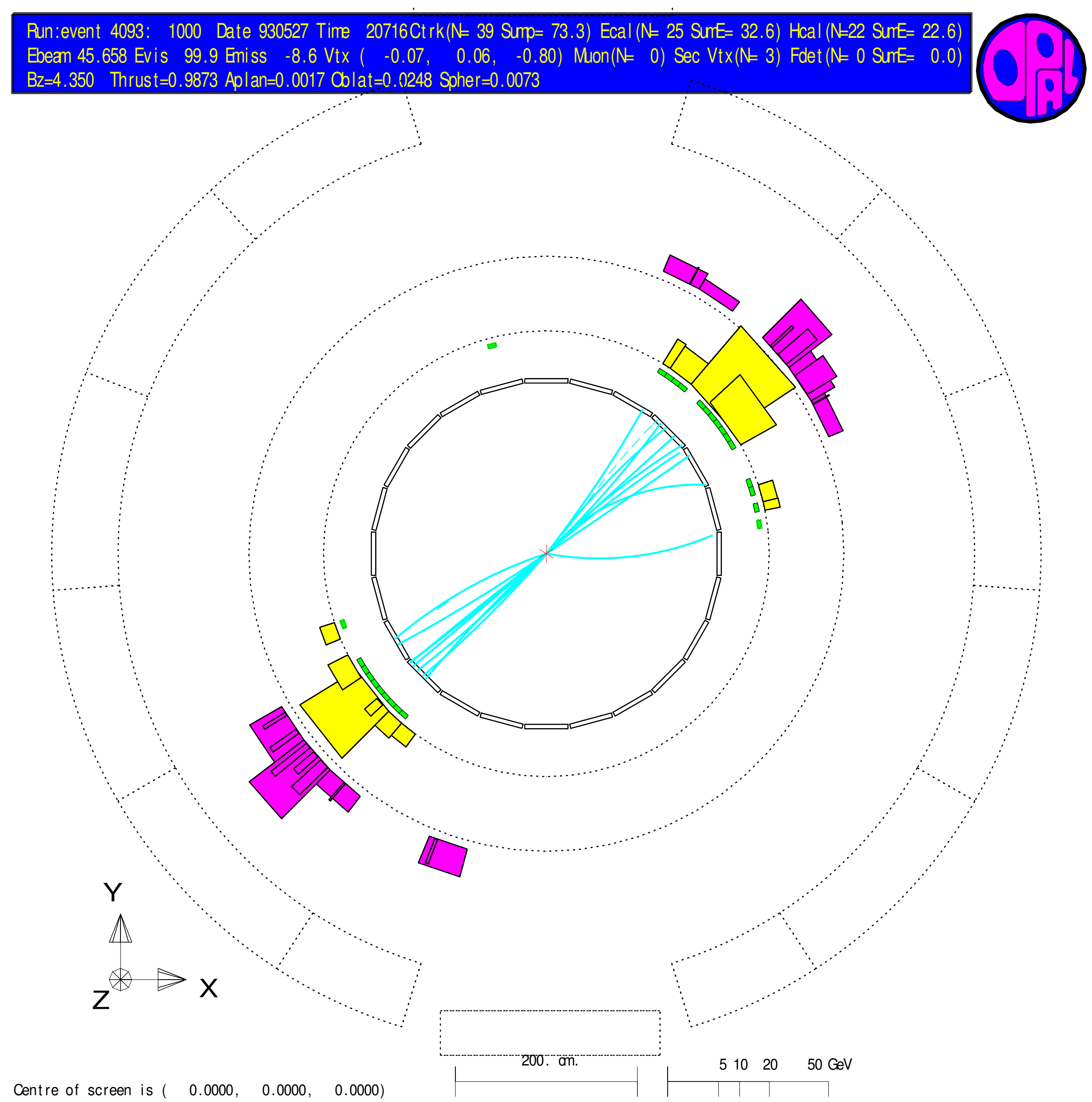
- Many nice review/lecture notes online: hep-ph/0011256, http://cds.cern.ch/record/454171, arXiv:1011.5131, arXiv:0906.1833, hep-ph/0505192, arXiv:1709.04533, arXiv:1312.5672…

Purpose of Slides

- Lecture notes will be given on board, but see online notes for more detail (will not cover everything there).
- These slides: plots that I cannot draw easily!



(2-jet) Event Display

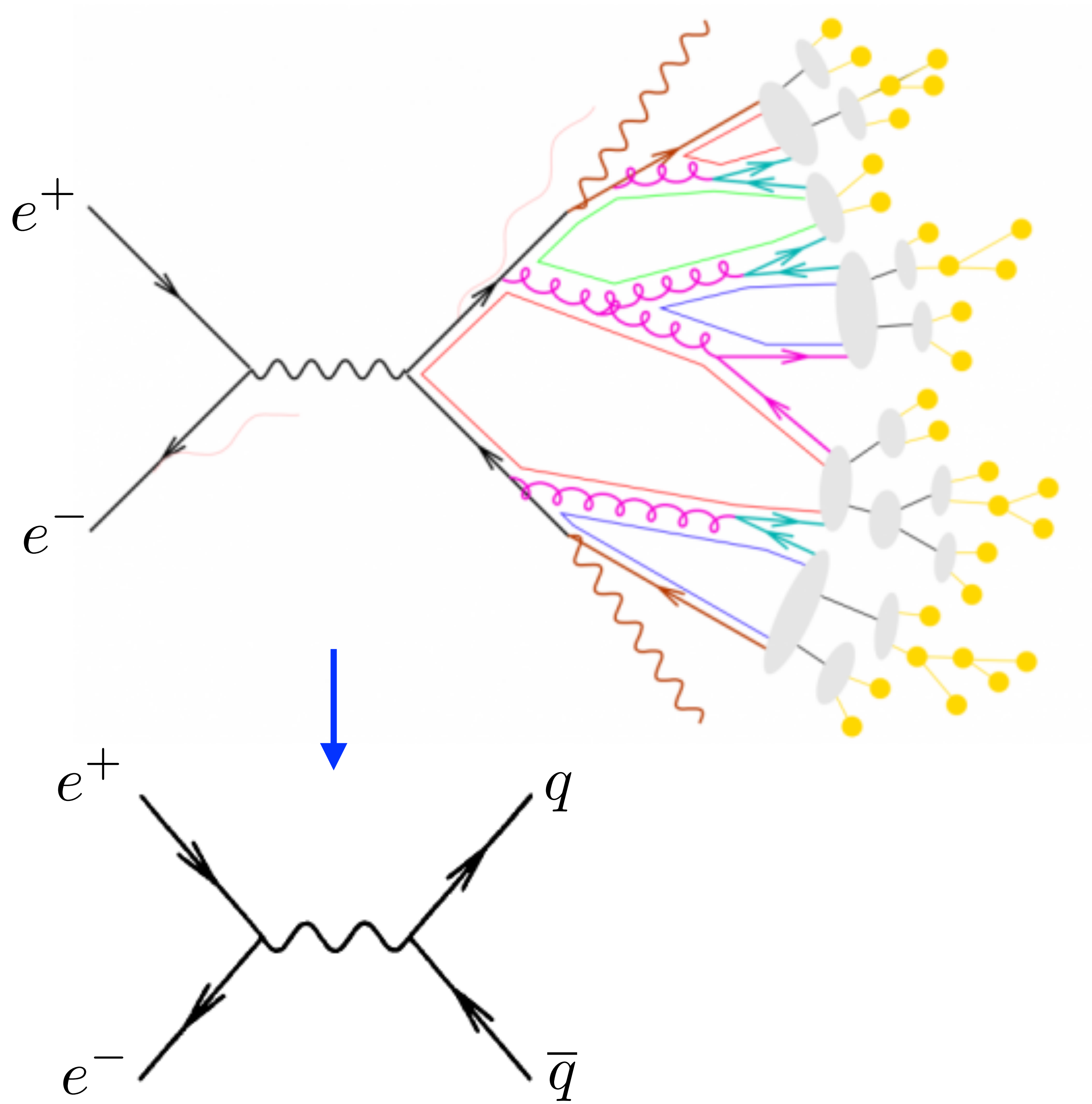


- Example event display from e^+e^- collisions.

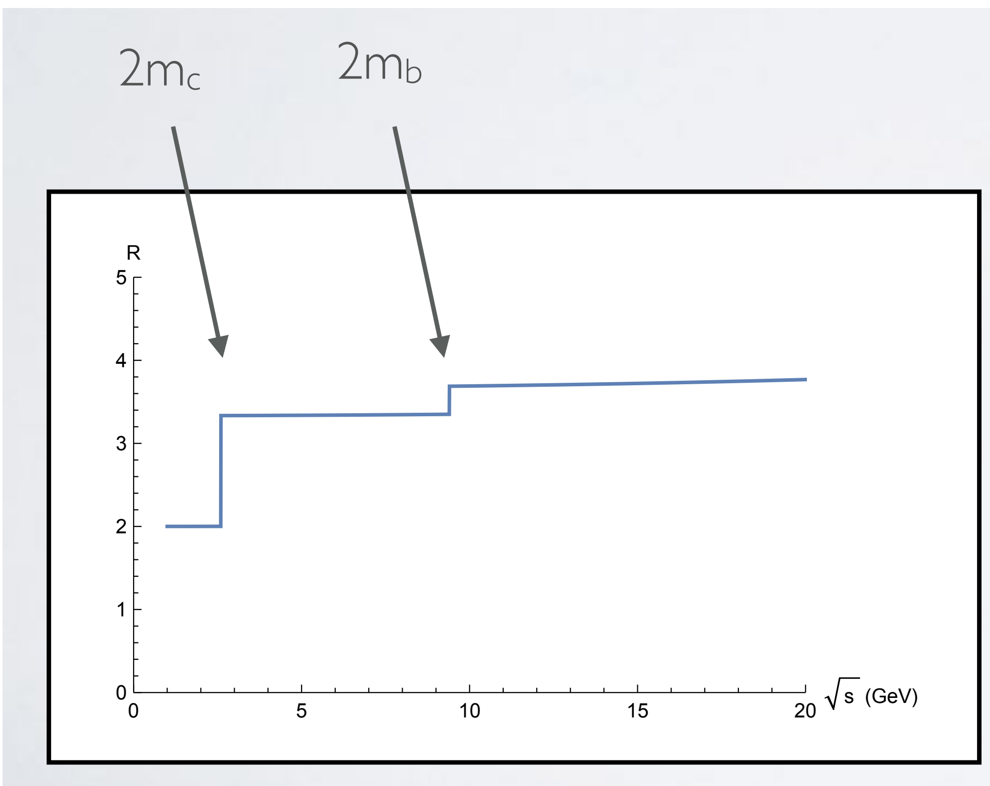
R(hadrons/muons)

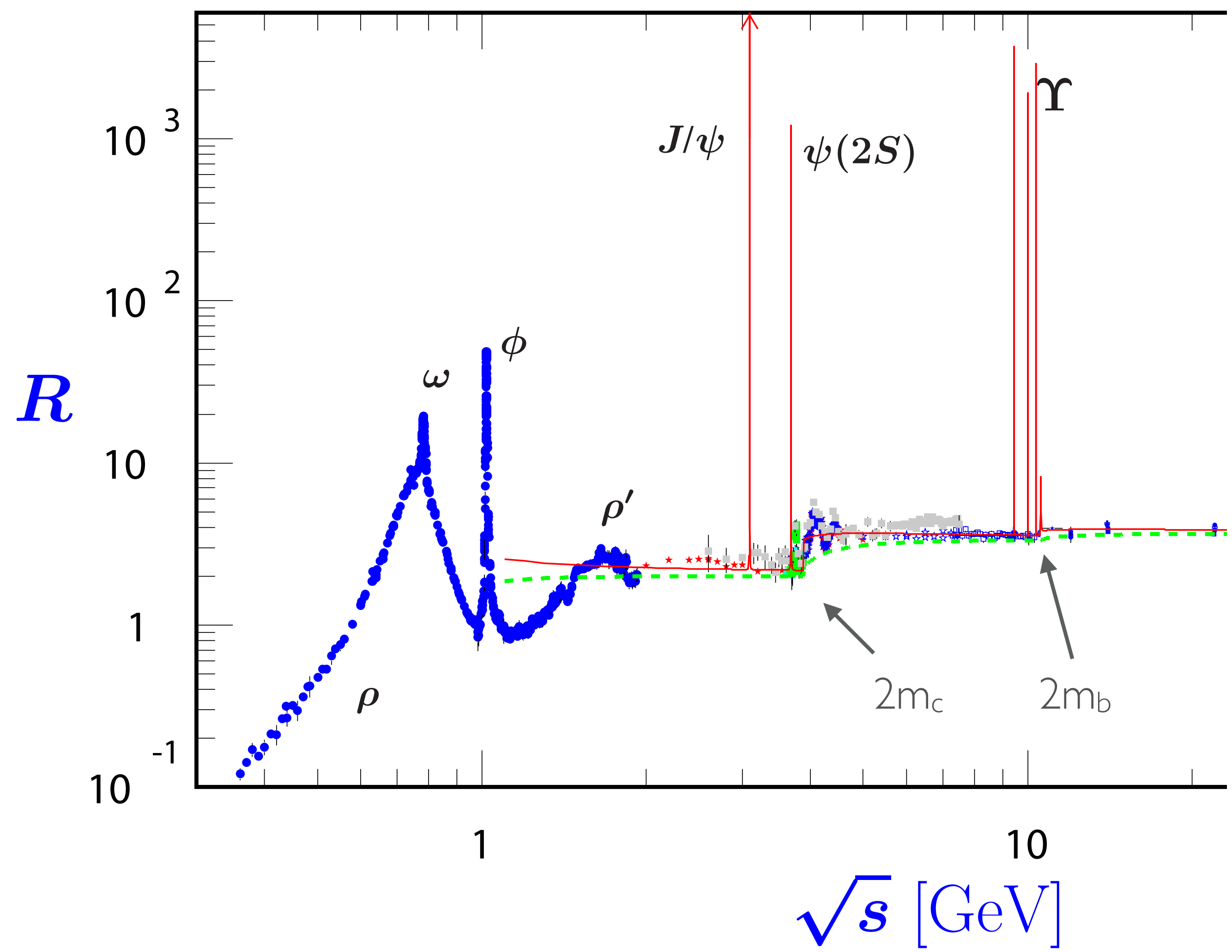
Full Event

LO parton-level cross section



R(hadrons/muons)

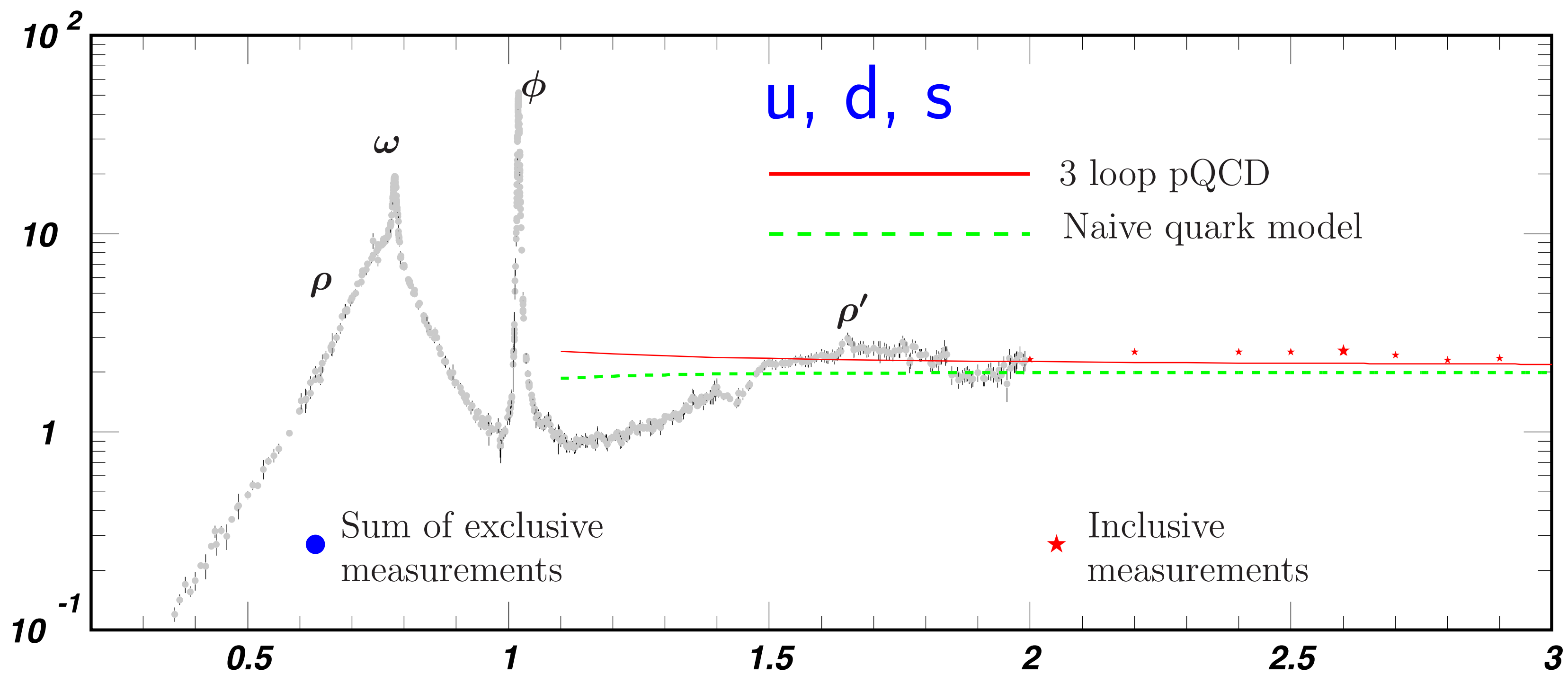




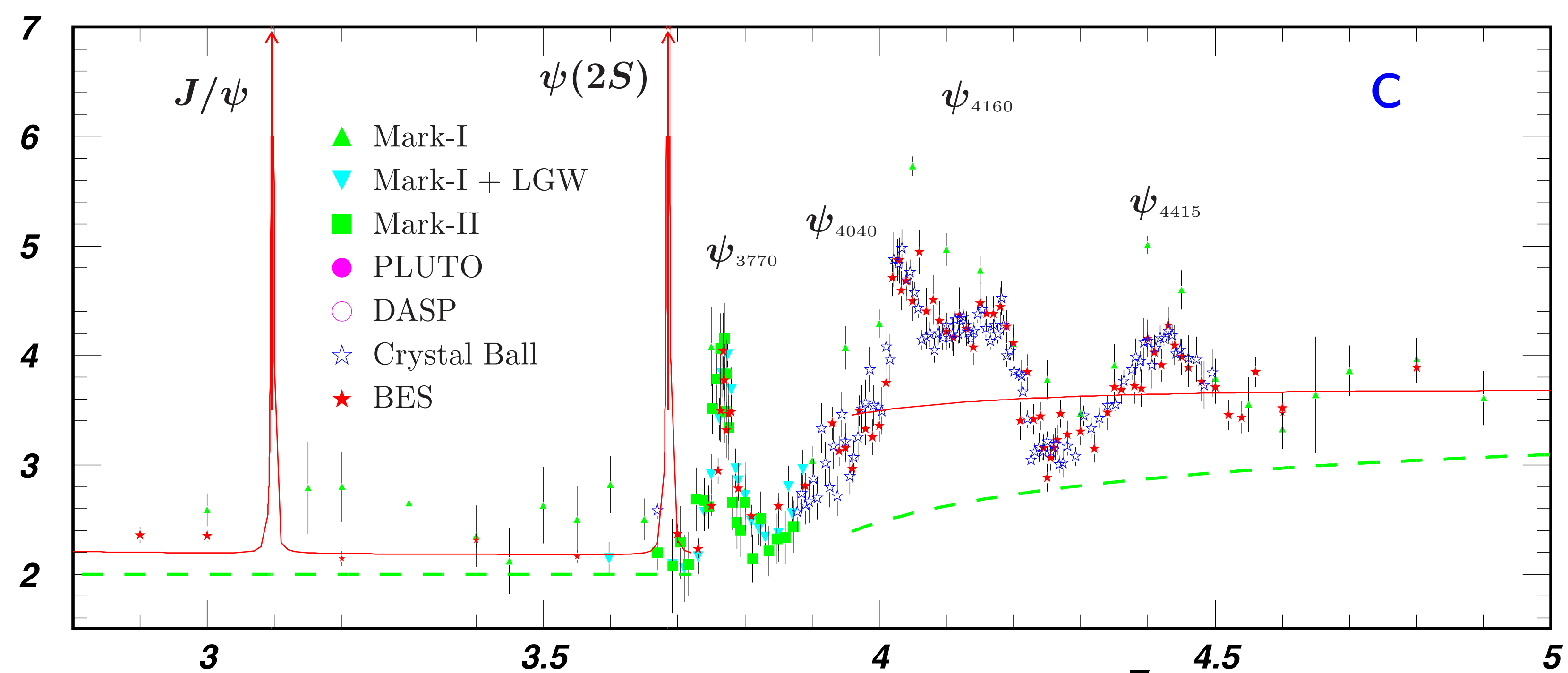
(Approx.!)
Theory

Data

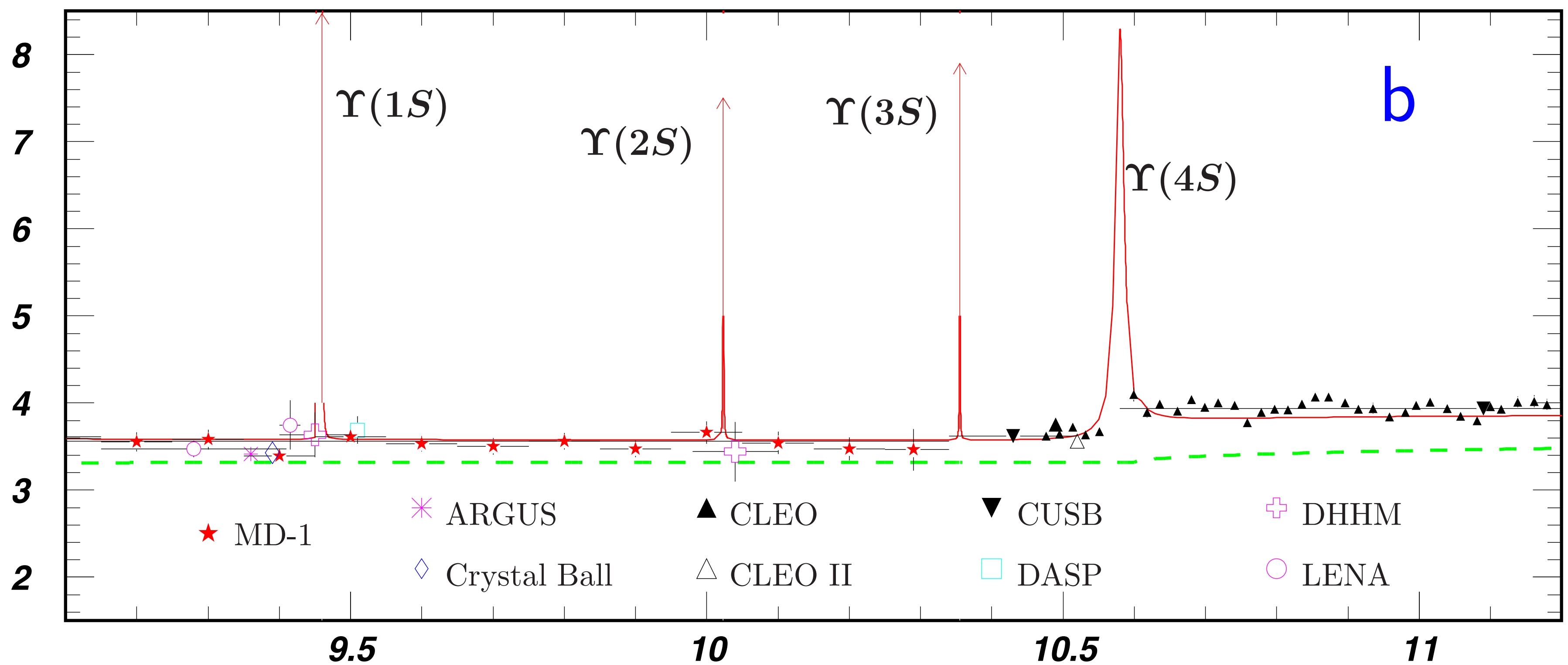
R(hadrons/muons) - Closer Look



$$R = \sum_q e_q^2 N_c = N_c \Big(\underbrace{\underbrace{\underbrace{\frac{4}{9} + \frac{1}{9} + \frac{1}{9}}_{u,d,s} + \frac{4}{9}}_{u,d,s,c} + \frac{1}{9}}_{u,d,s,c,b} \Big) \ .$$



R(hadrons/muons) - Closer Look



$$R = \sum_q e_q^2 N_c = N_c \left(\underbrace{\overbrace{\overbrace{\frac{4}{9} + \frac{1}{9} + \frac{1}{9}}^{}}^{} + \frac{4}{9}}_{} + \frac{1}{9} \right) \ .$$

$$\underbrace{\frac{4}{9} + \frac{1}{9} + \frac{1}{9}}_{u,d,s}, \quad \underbrace{\frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{4}{9}}_{u,d,s,c}, \quad \underbrace{\frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{4}{9} + \frac{1}{9}}_{u,d,s,c,b}$$

- Data from last three slides:

Mark I/II @ SLAC (1974-1975)

PLUTO @ DESY (1974-1982)

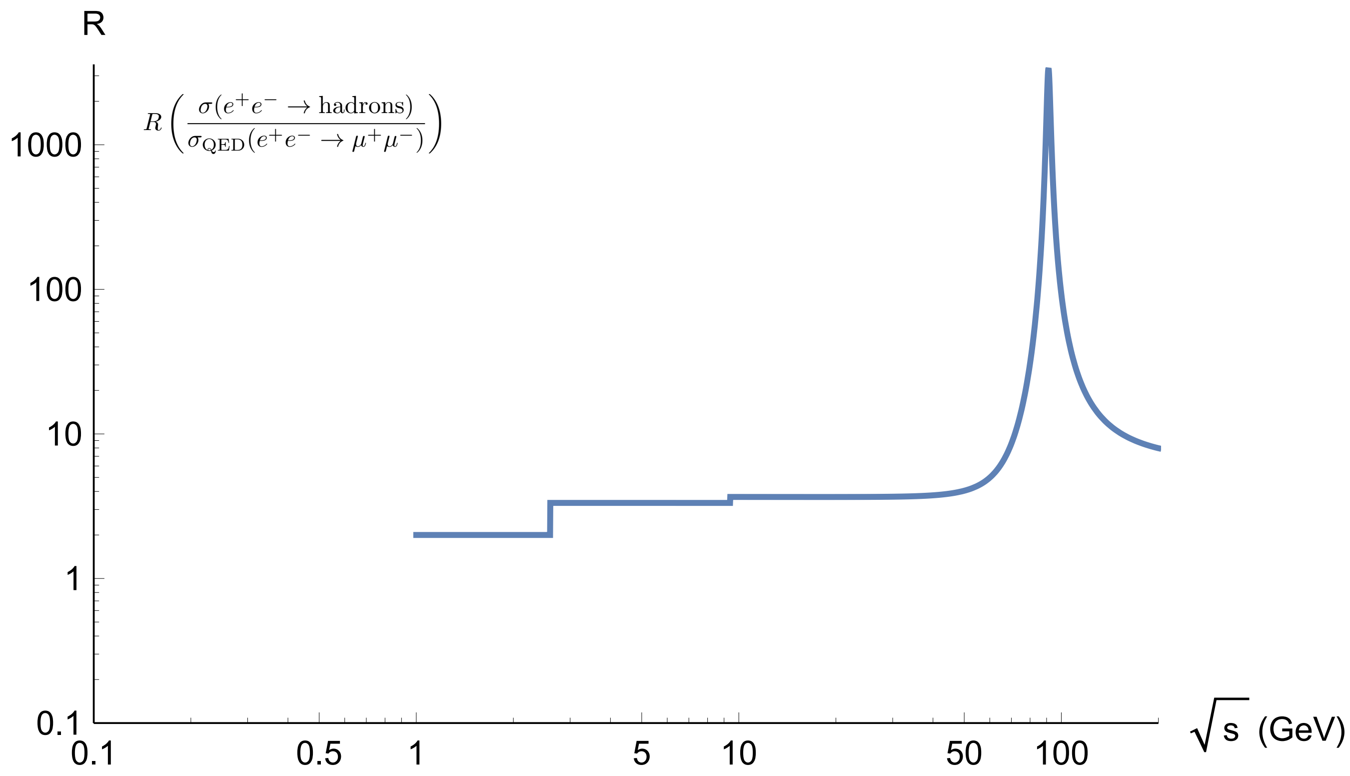
w/ DORIS I/II and PETRA

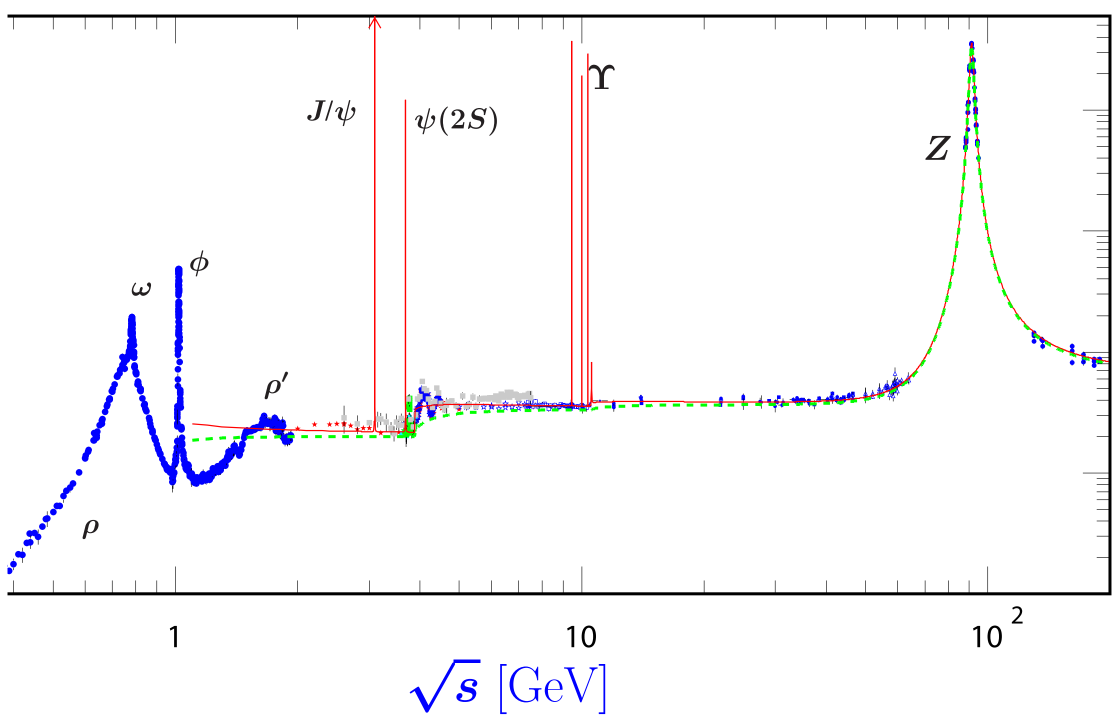
DASP @ DESY (1974-1982)

w/ DORIS I

BES @ BEPC (1995-)

R(hadrons/muons) - up to Z peak

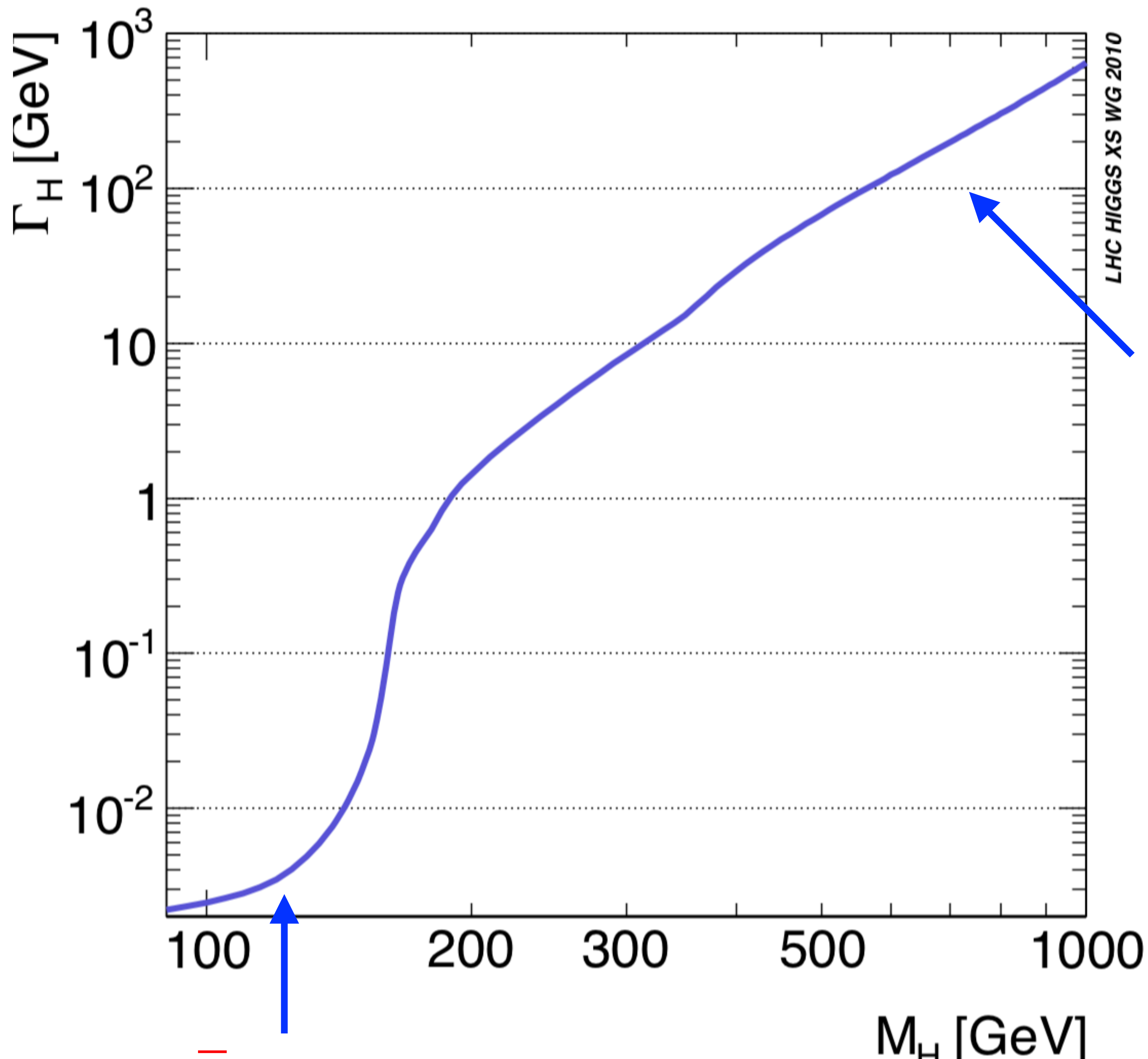




(Approx.!)
Theory

Data

Higgs Width



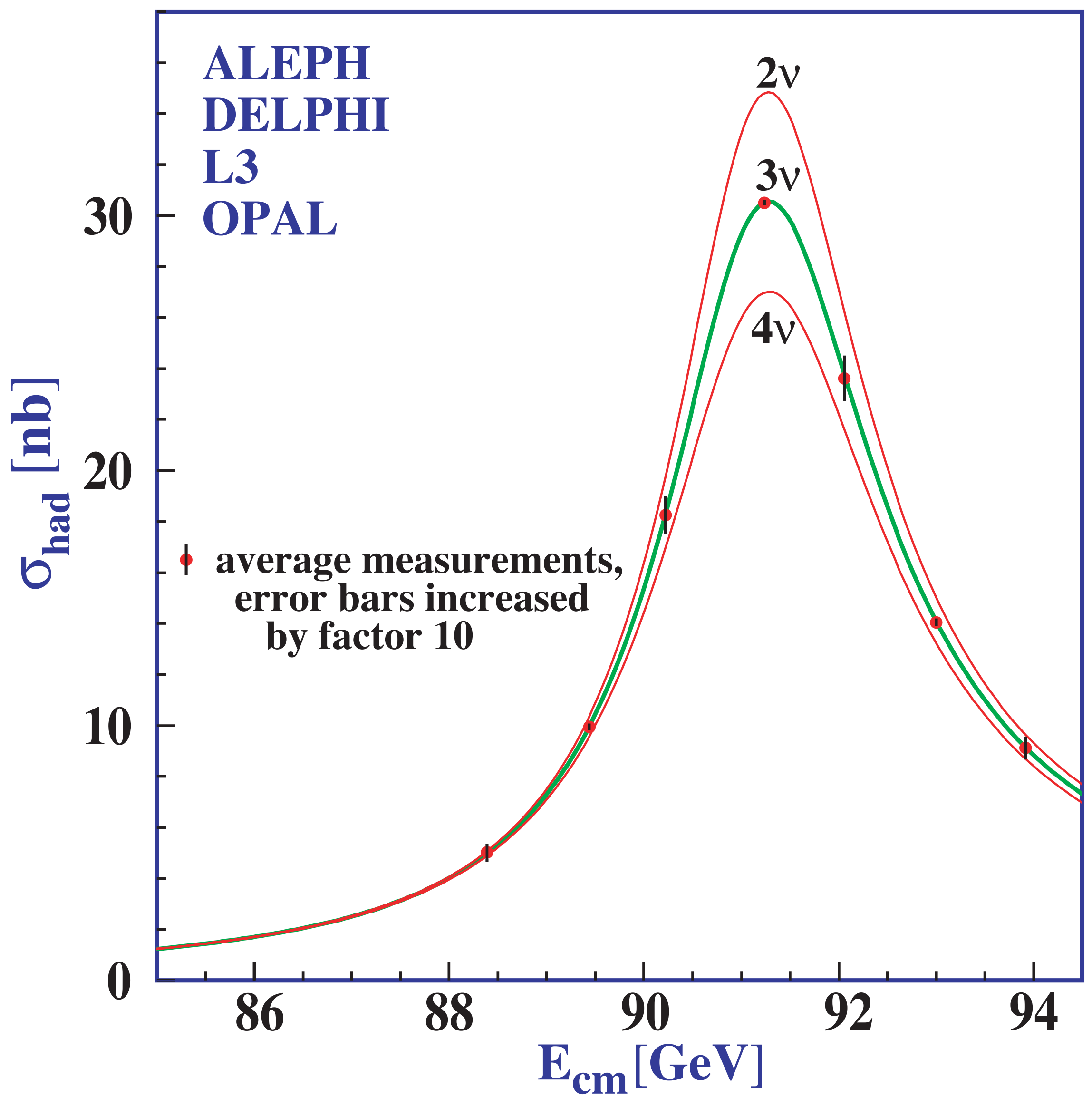
$h \to WW(ZZ)$: broad peak

$h \to b\bar{b}$: narrow peak

Sigma(hadronic) - Z peak

$$\sigma_Z \sim \frac{s^2}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2}$$

$$Z \to \nu\bar{\nu} + \cdots$$



- Clear evidence for 3 light neutrino families ($2m_\nu < M_Z$).

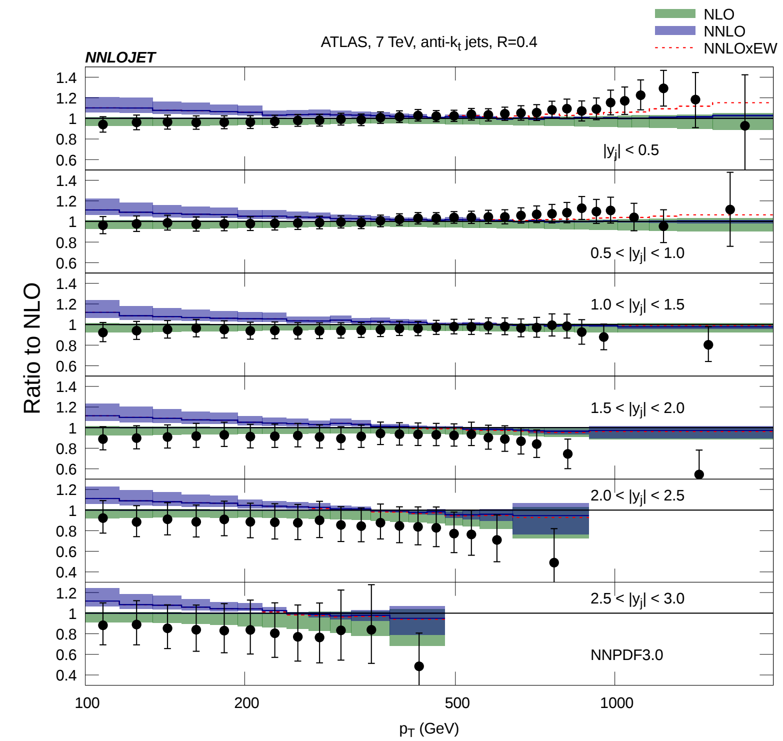
LHC jets @NNLO

Phys.Rev.Lett. 118 (2017) 7, 072002

NNLO QCD predictions for single jet inclusive production at the LHC

J. Currie[a], E.W.N. Glover[a], J. Pires[b]
[a] *Institute for Particle Physics Phenomenology, University of Durham, Durham DH1 3LE, England*
[b] *Max-Planck-Institut für Physik, Föhringer Ring 6 D-80805 Munich, Germany*

We report the first calculation of fully differential jet production at leading colour in all partonic channels at next-to-next-to leading order (NNLO) in perturbative QCD and compare to the available ATLAS 7 TeV data. We discuss the size and shape of the perturbative corrections along with their



J. Currie et al., *JHEP* 01 (2014) 110

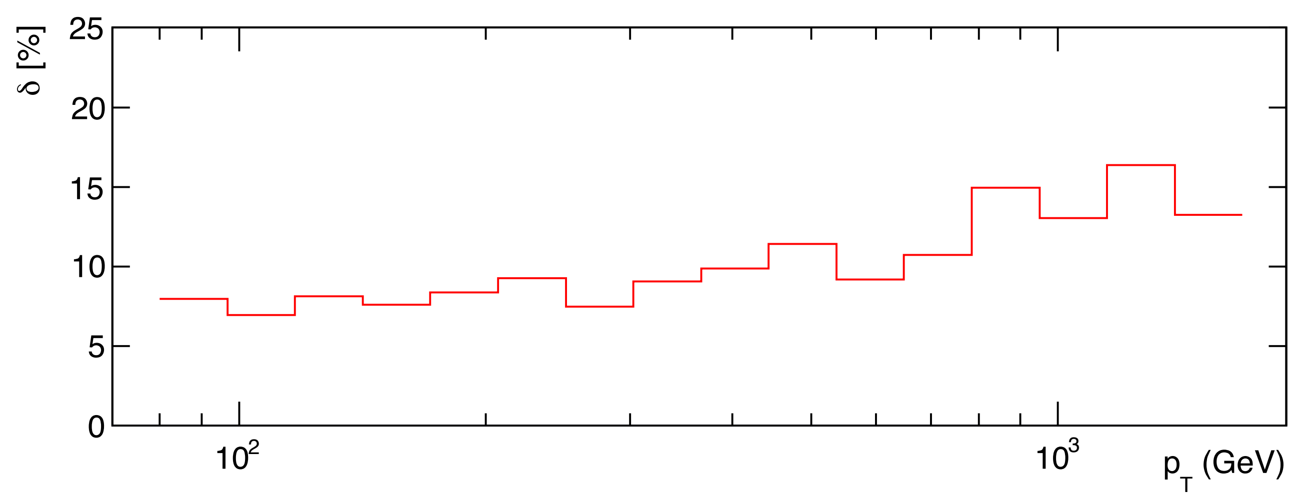
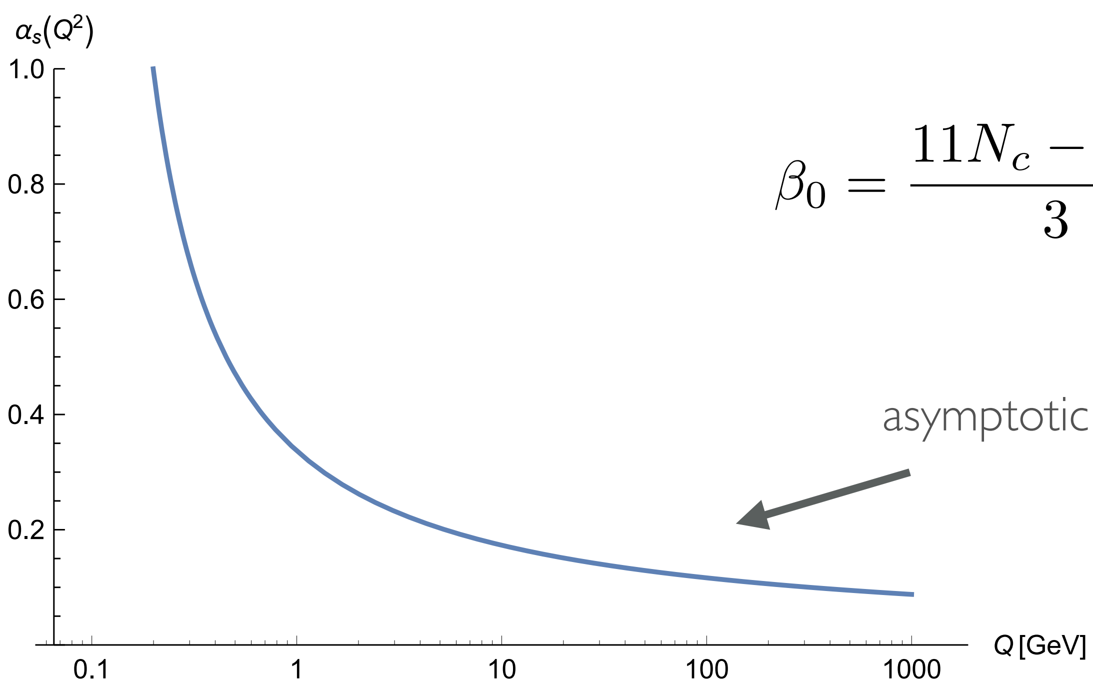


Figure 1: The percentage contribution of the sub-leading colour to full colour NNLO correction, δ, for the single jet inclusive transverse energy distribution as a function of p_T.

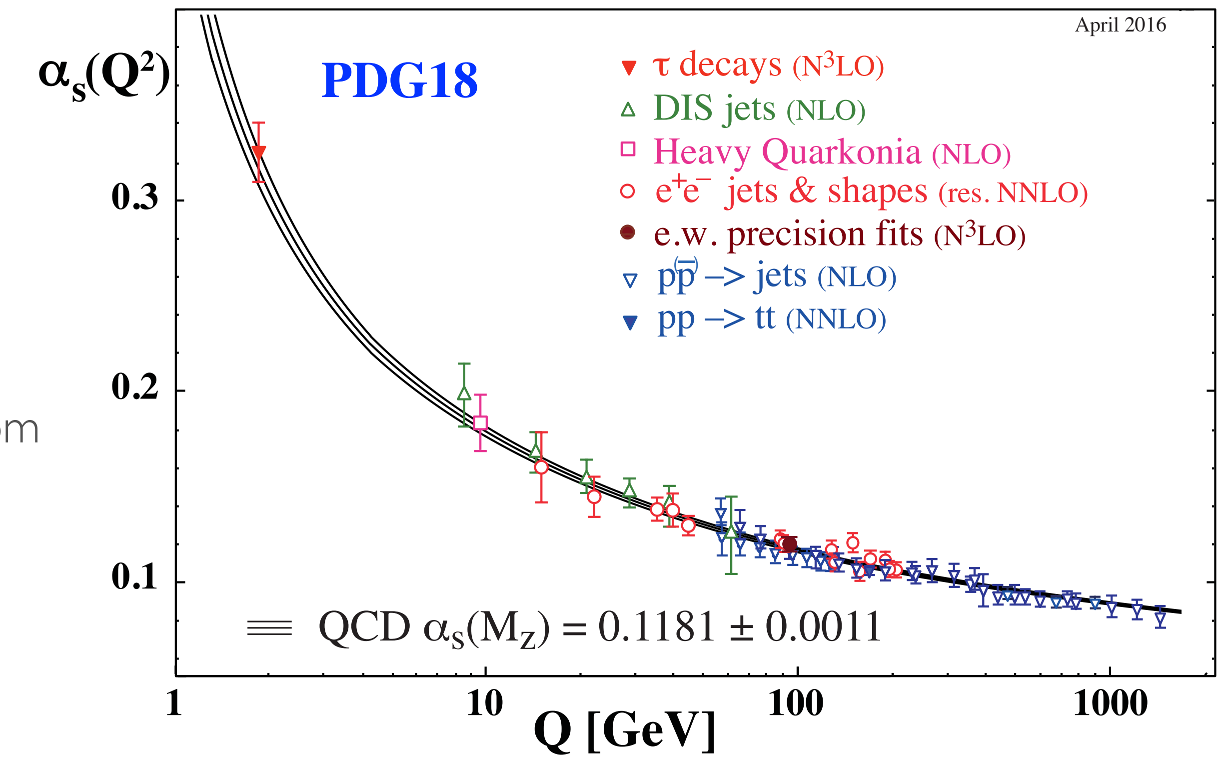
Running (Strong) Coupling



$$\beta_0 = \frac{11N_c - 2N_f}{3}$$

asymptotic freedom

$\alpha_s(\Lambda_{QCD}) = 1 \quad \Lambda_{QCD} \approx 200$ MeV

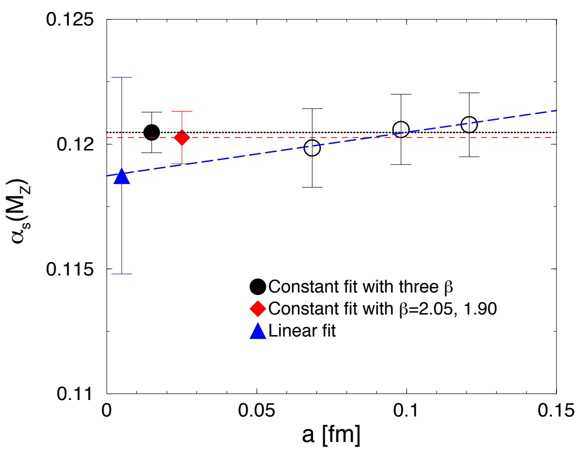


(Approx.!) Theory

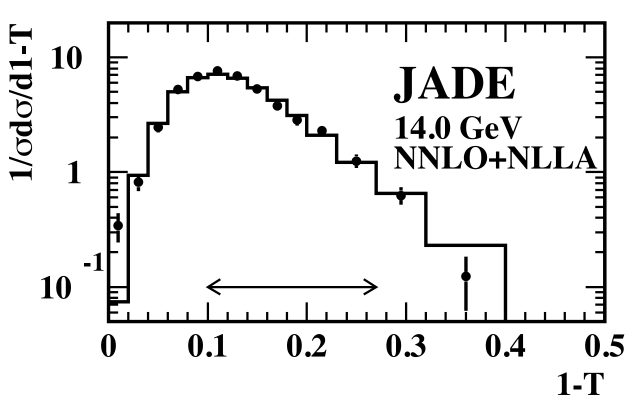
Data + Theory

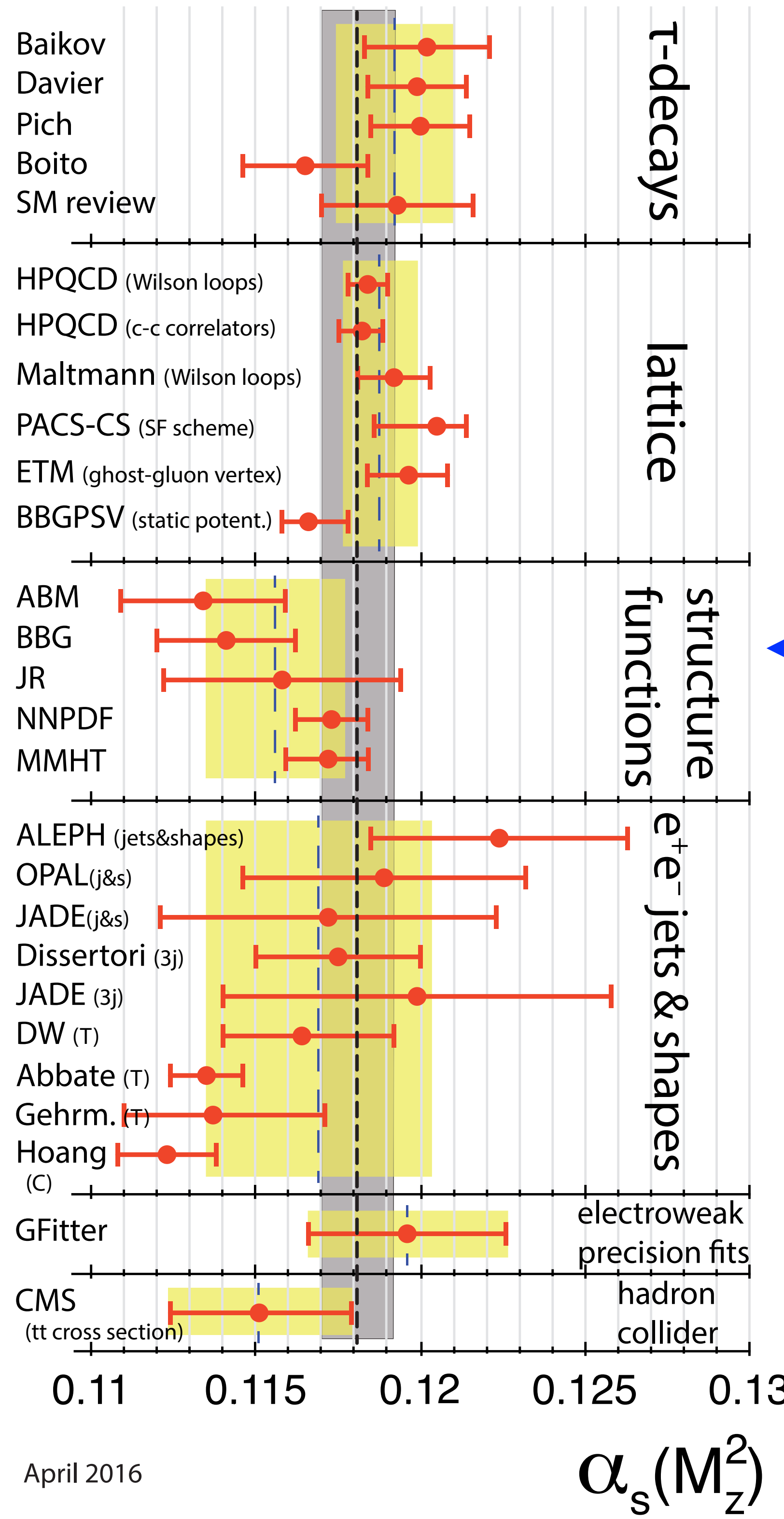
Strong Coupling Determination

arXiv:0906.3906

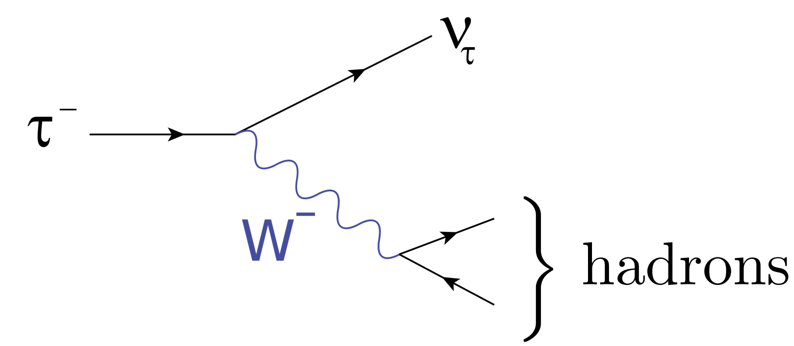


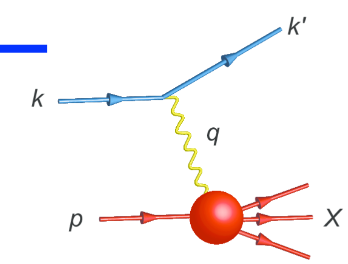
arXiv:0810.1389

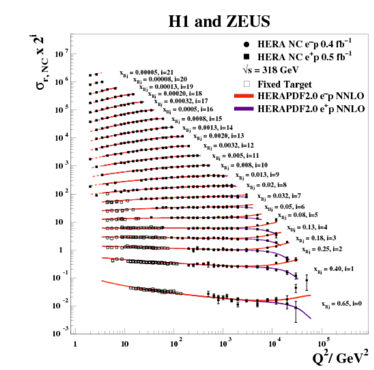




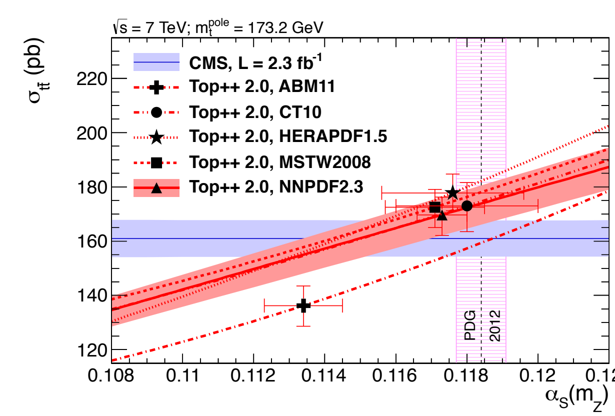
$$R_\tau \equiv \frac{\Gamma[\tau^- \to \text{hadrons}\, \nu_\tau(\gamma)]}{\Gamma[\tau^- \to e^- \overline{\nu}_e \nu_\tau(\gamma)]}$$







arXiv:1307.1907

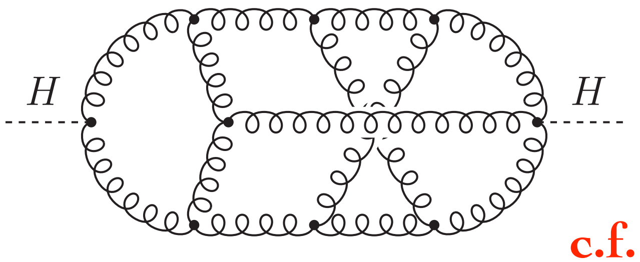


$$\alpha_s(M_Z^2) = 0.1181 \pm 0.0011$$

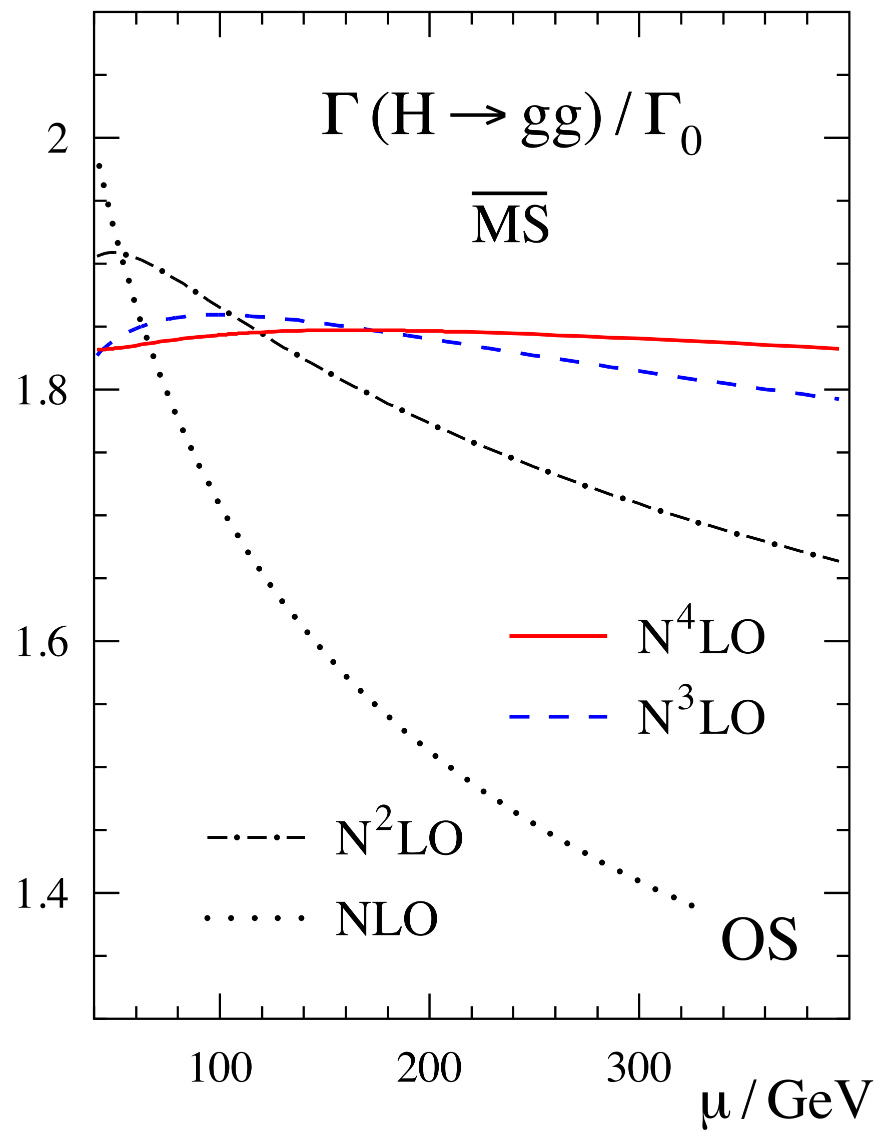
Renormalization Scale Dependence

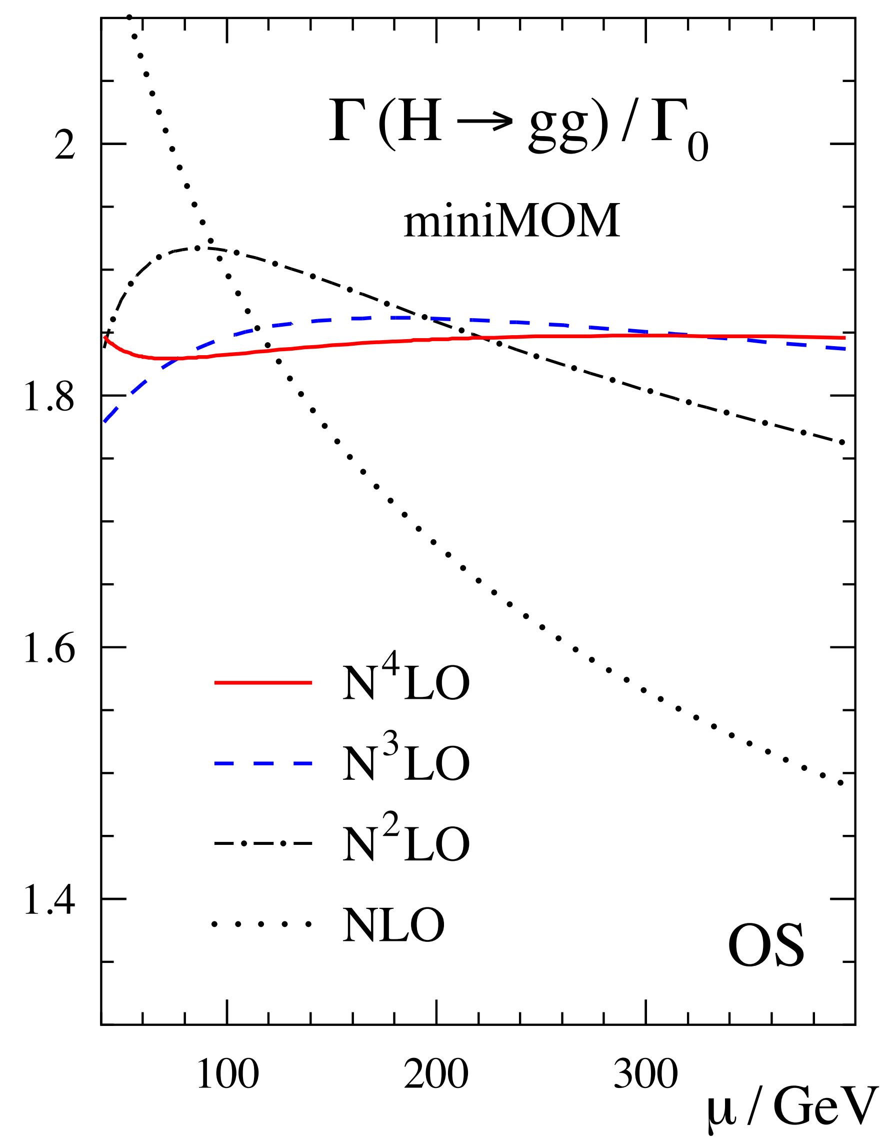
- Two nice recent examples from **arXiv:1707.01044**:

Up to $O(\alpha_S^4)$ corrections to $H \to gg$:



c.f. optical theorem





- Decreasing dependence on μ_R and scheme with increasing order.

Renormalization Scale Dependence

- Two nice recent examples from **arXiv:1707.01044**:

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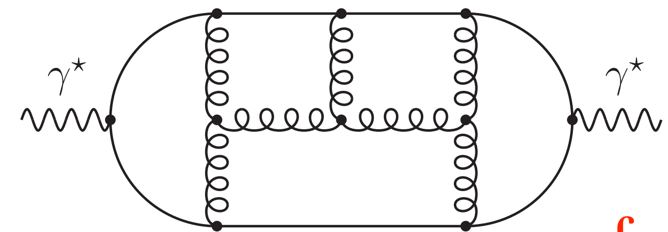

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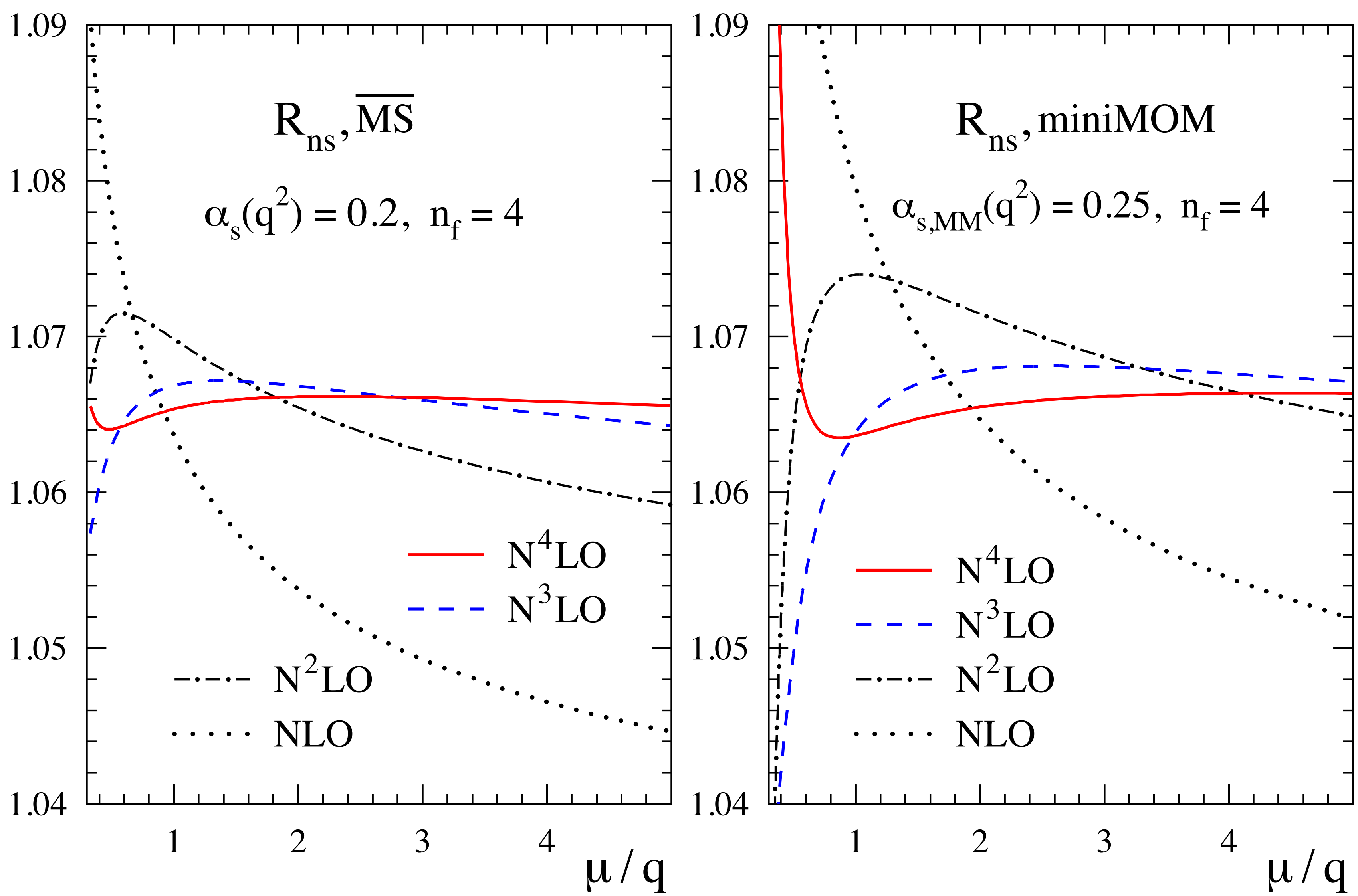
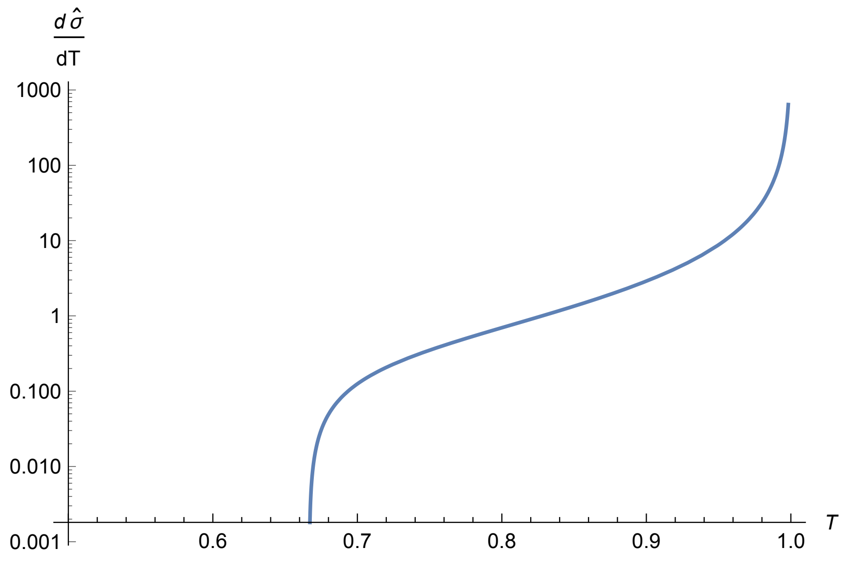


- Decreasing dependence on μ_R and scheme with increasing order.

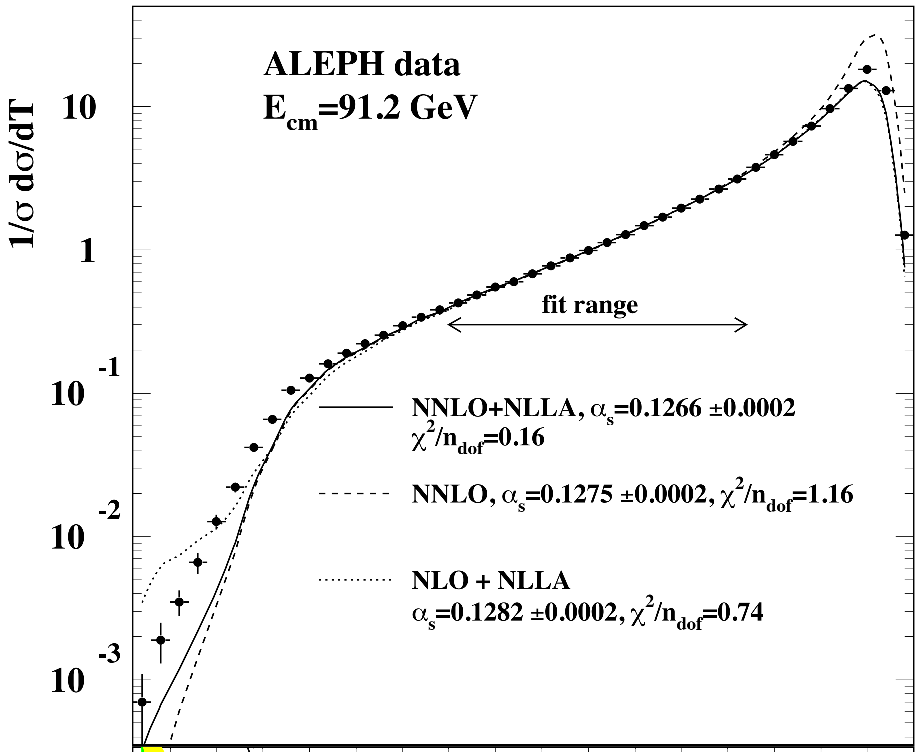
Thrust

- Basic (LO in QCD) expectation:



arXiv:0906.3436

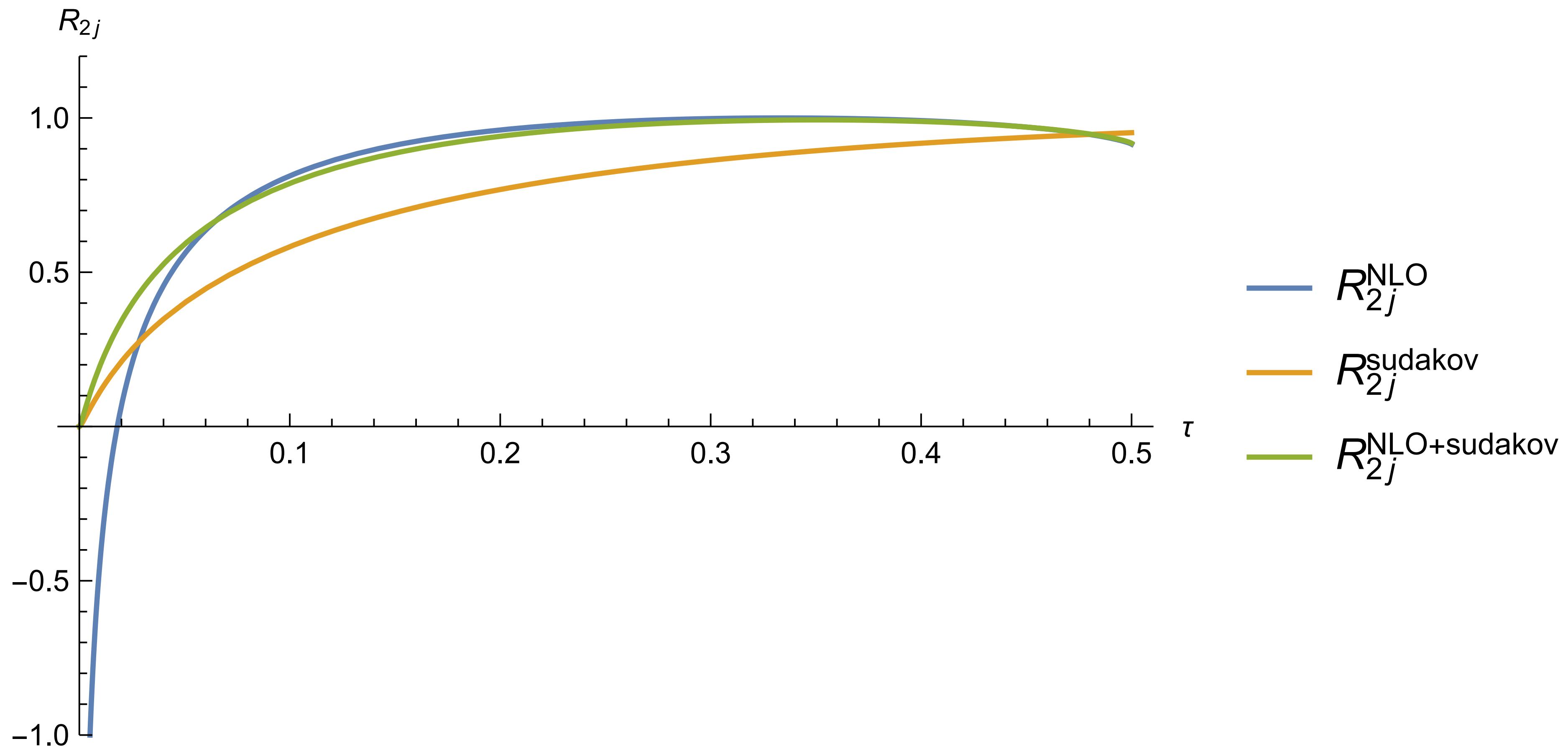
- Modern (NNLO in QCD + NLL resummation) result vs. data.



- Nice description. Sensitive to (colour/spin) nature of gluons.

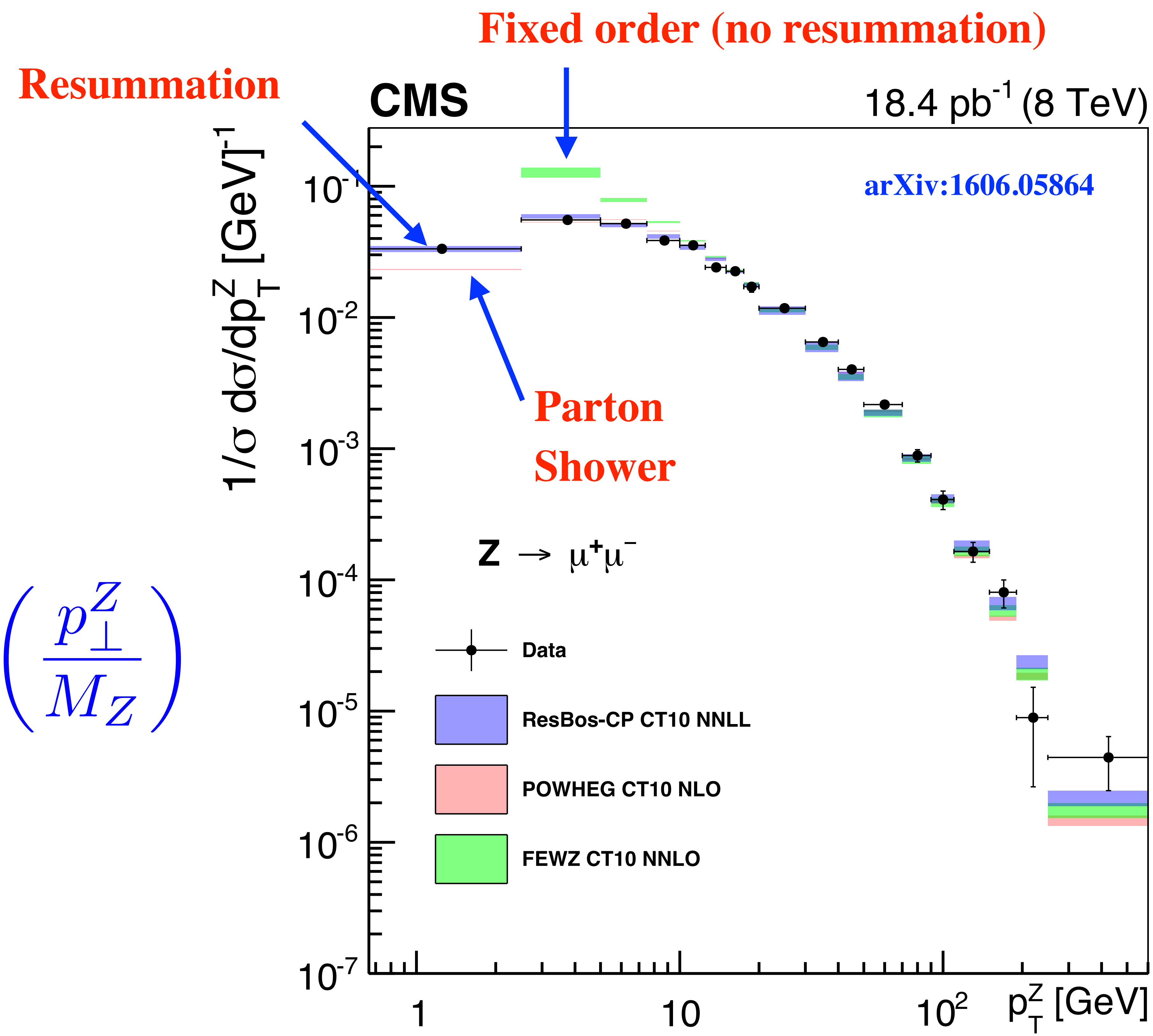
Thrust - Resummed Prediction

- Impact of resummation: including Sudakov form factor.

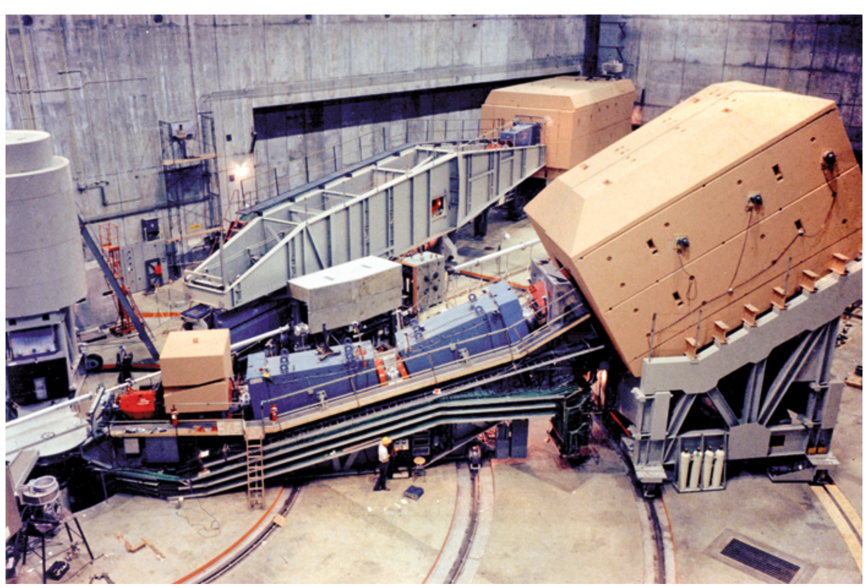


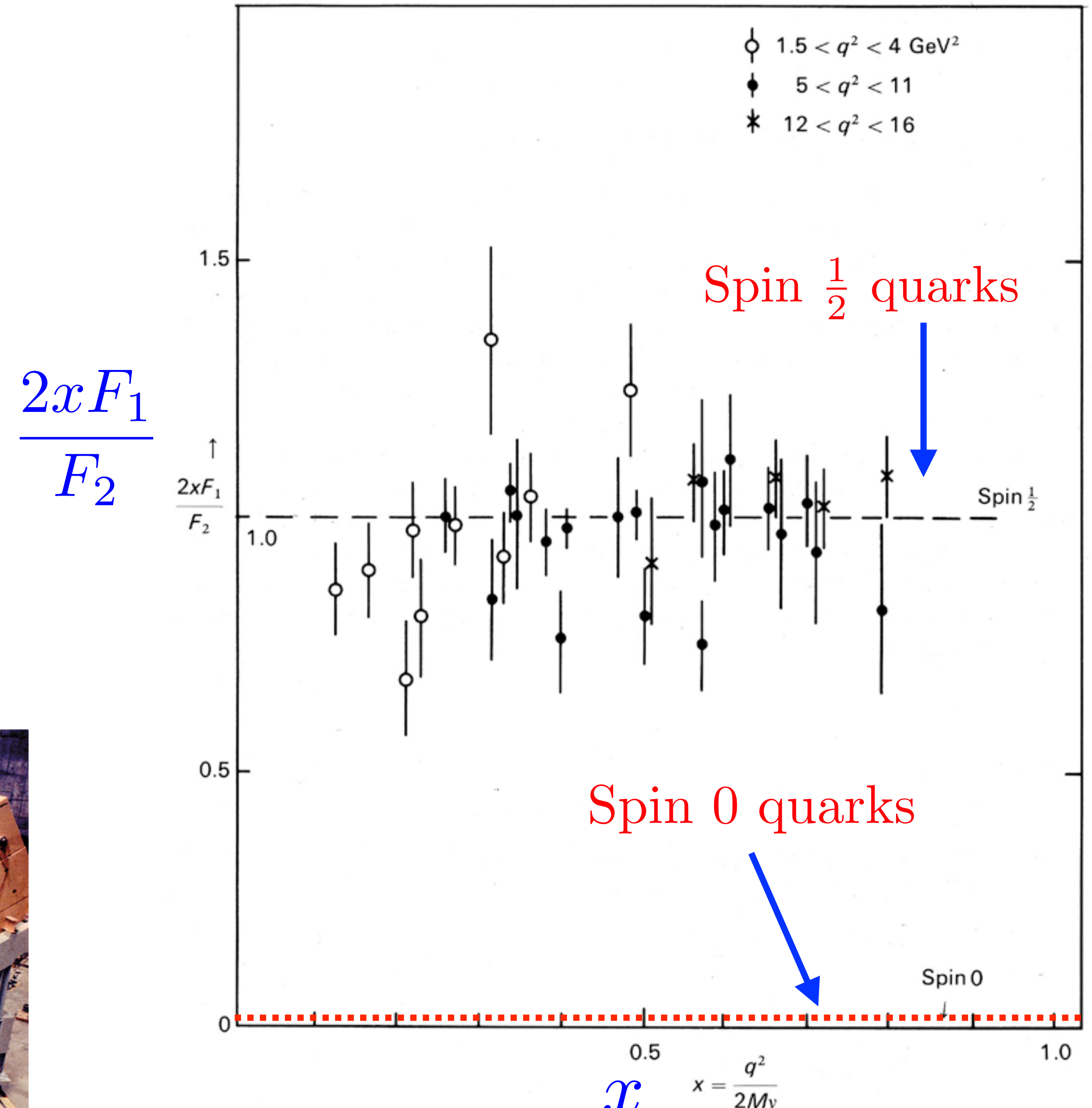
Resummation - Z transverse momentum

$$\sigma \sim \ln\left(\frac{p_\perp^Z}{M_Z}\right)$$



Callan-Gross Relation



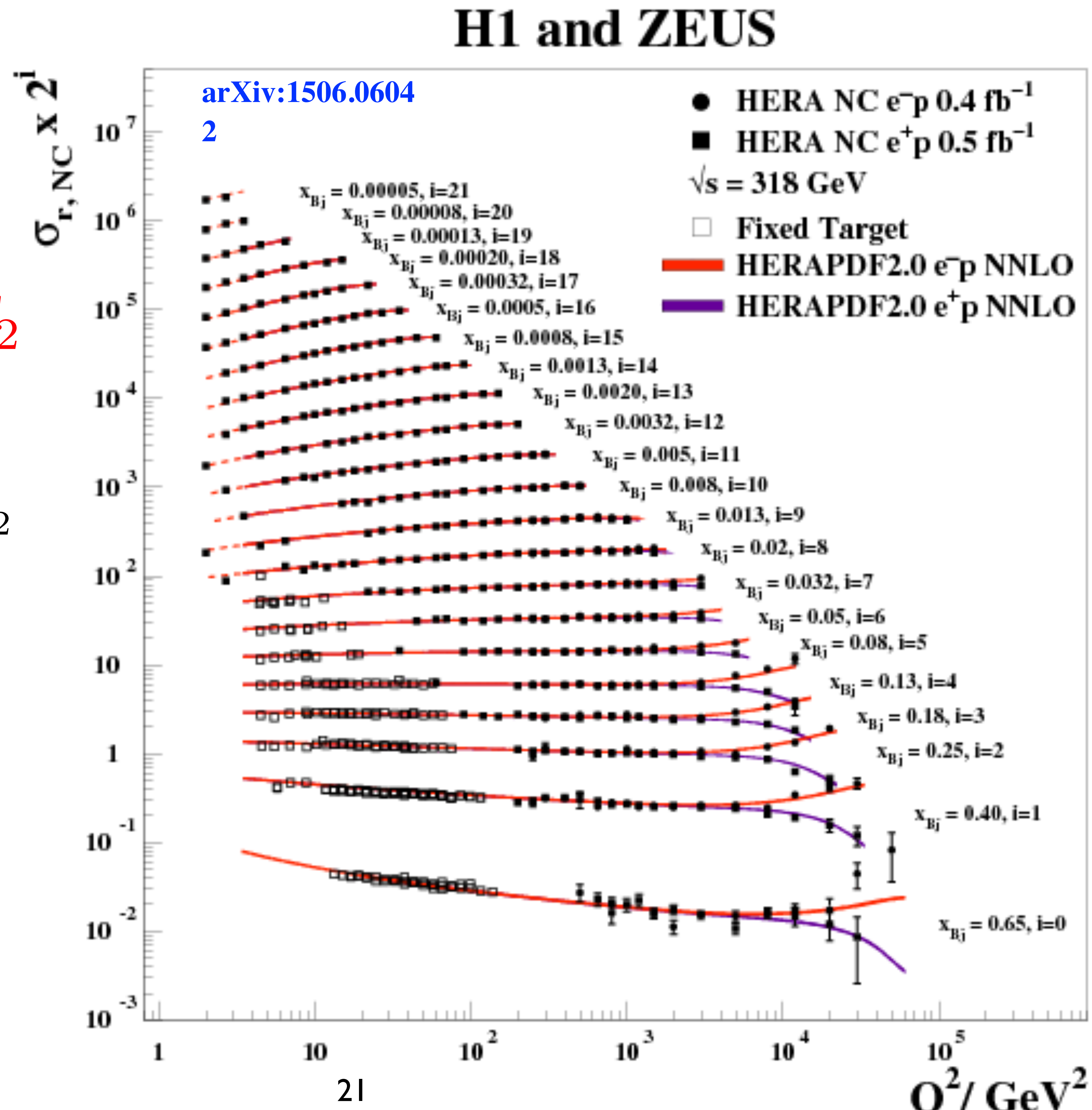


Data from SLAC

Bjorken Scaling

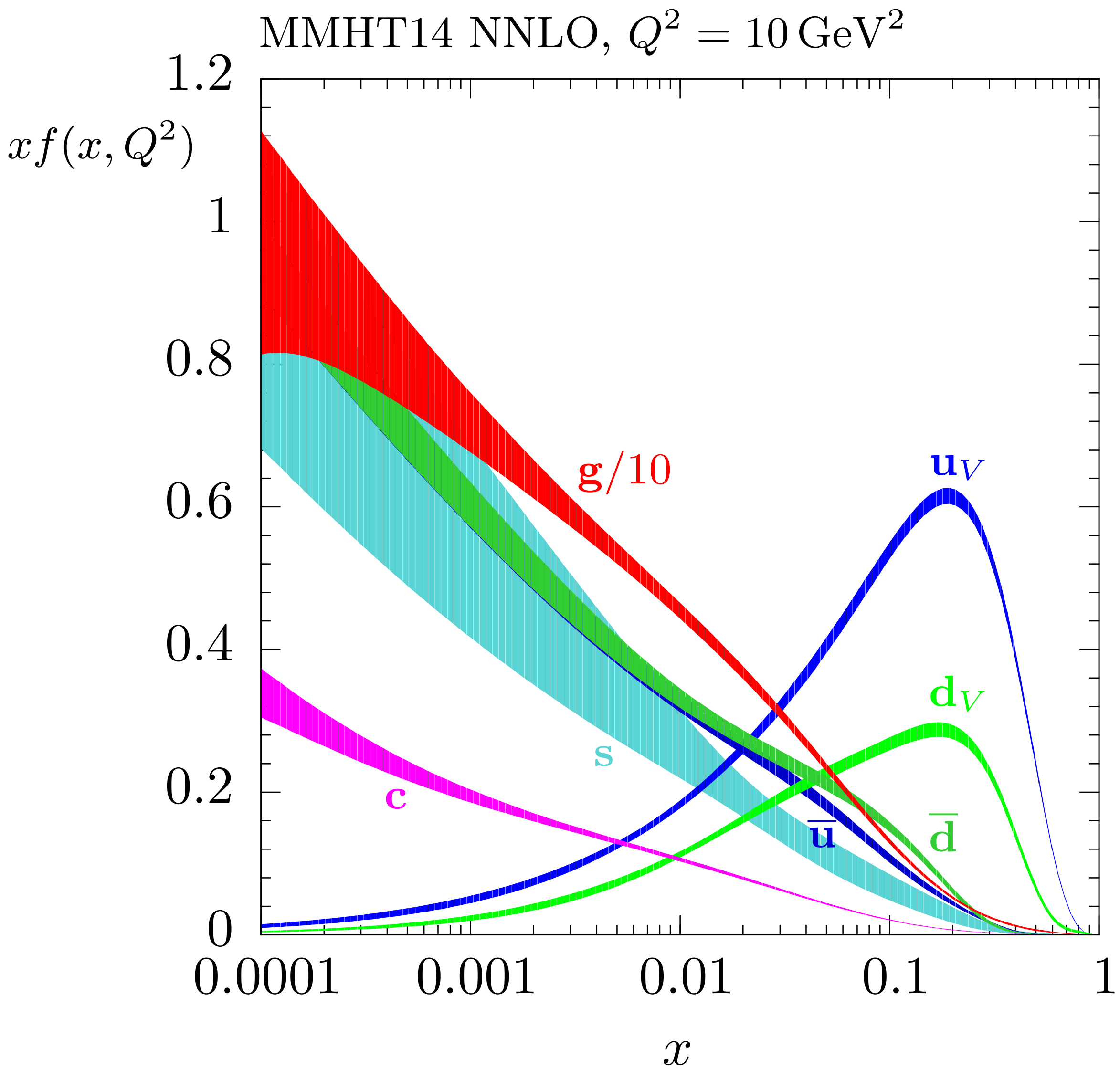
$\propto F_2$

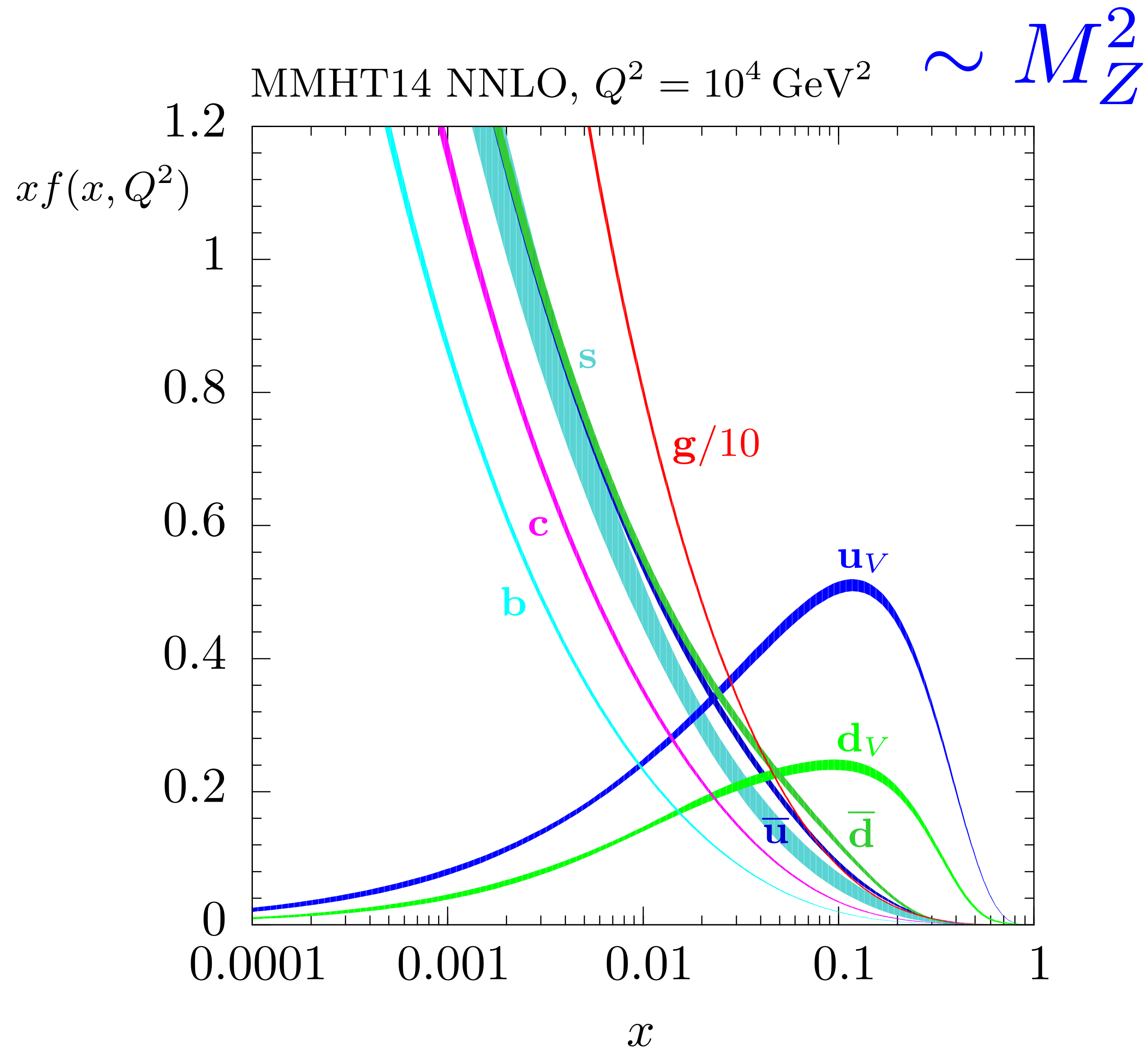
- Roughly flat with Q^2 but not exactly!

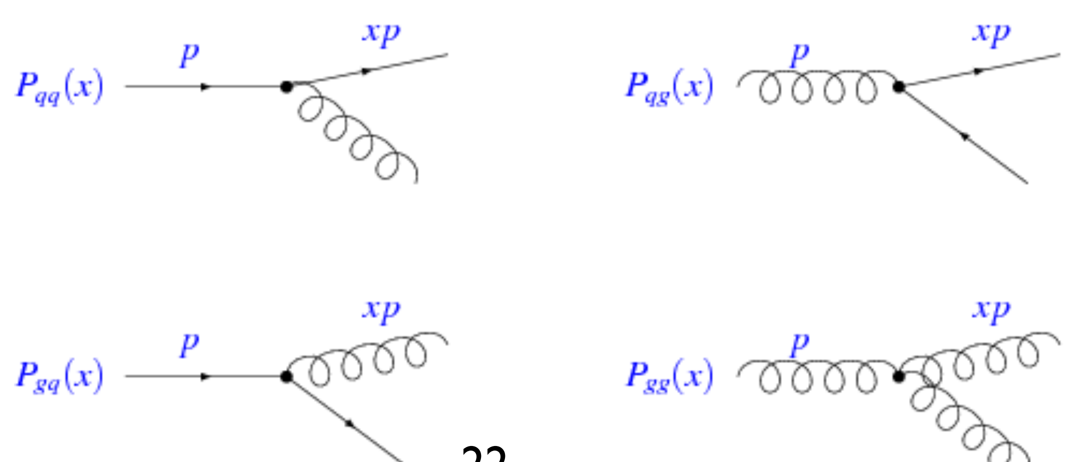


PDFs & DGLAP

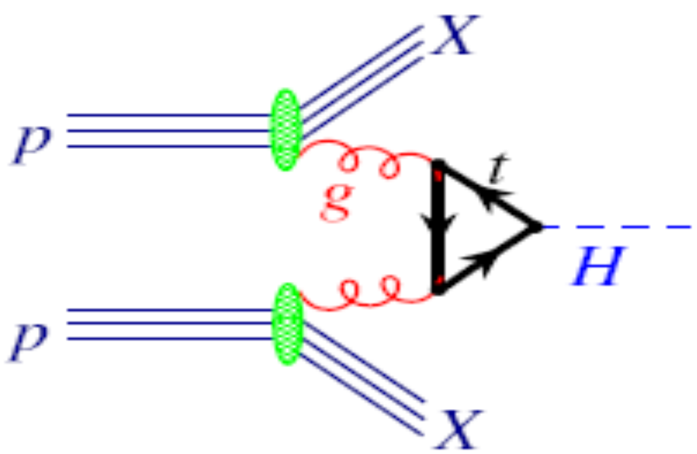
Increase Scale (DGLAP) →





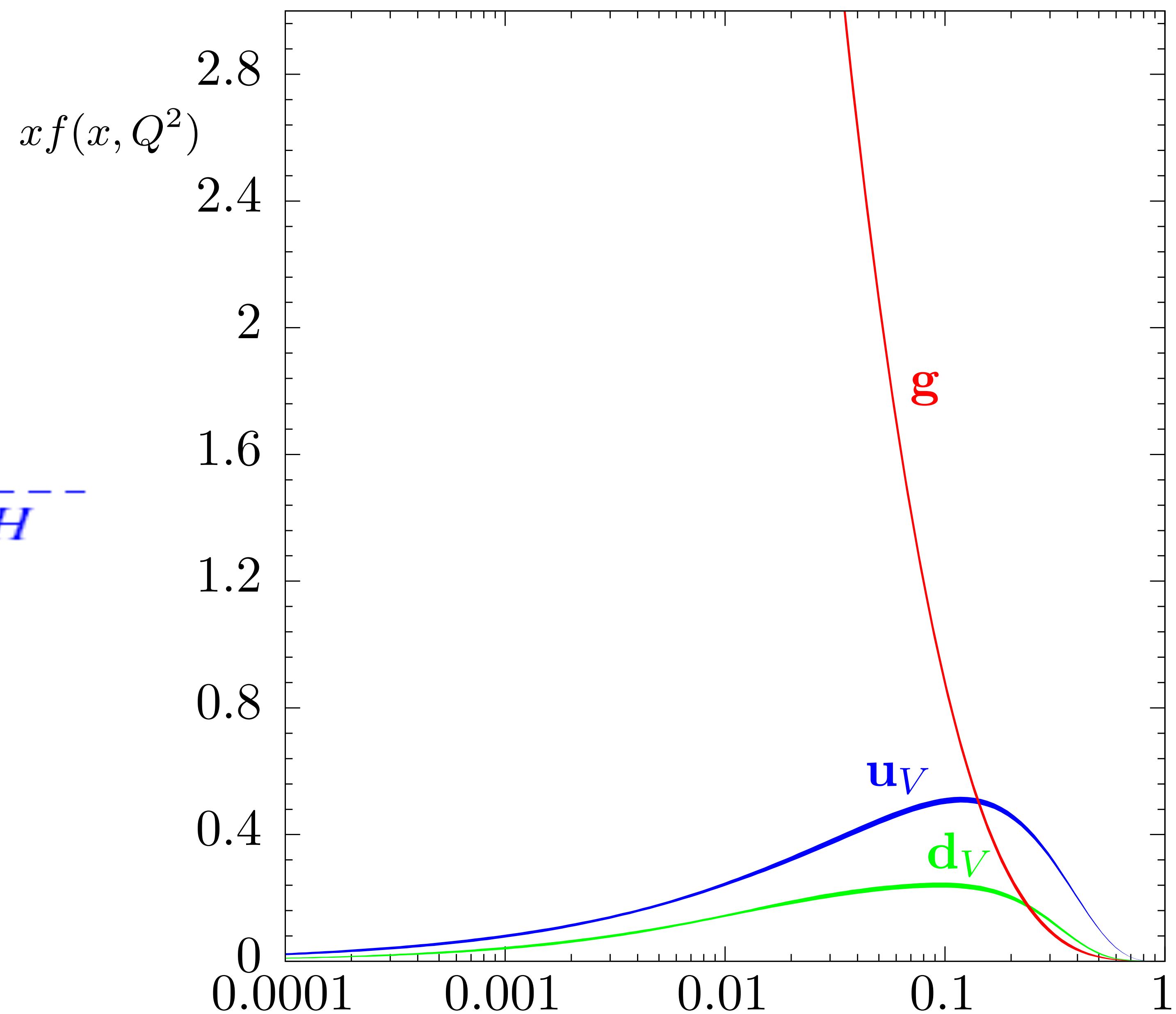


The Proton @ LHC: Mostly Gluons



Gluon Fusion

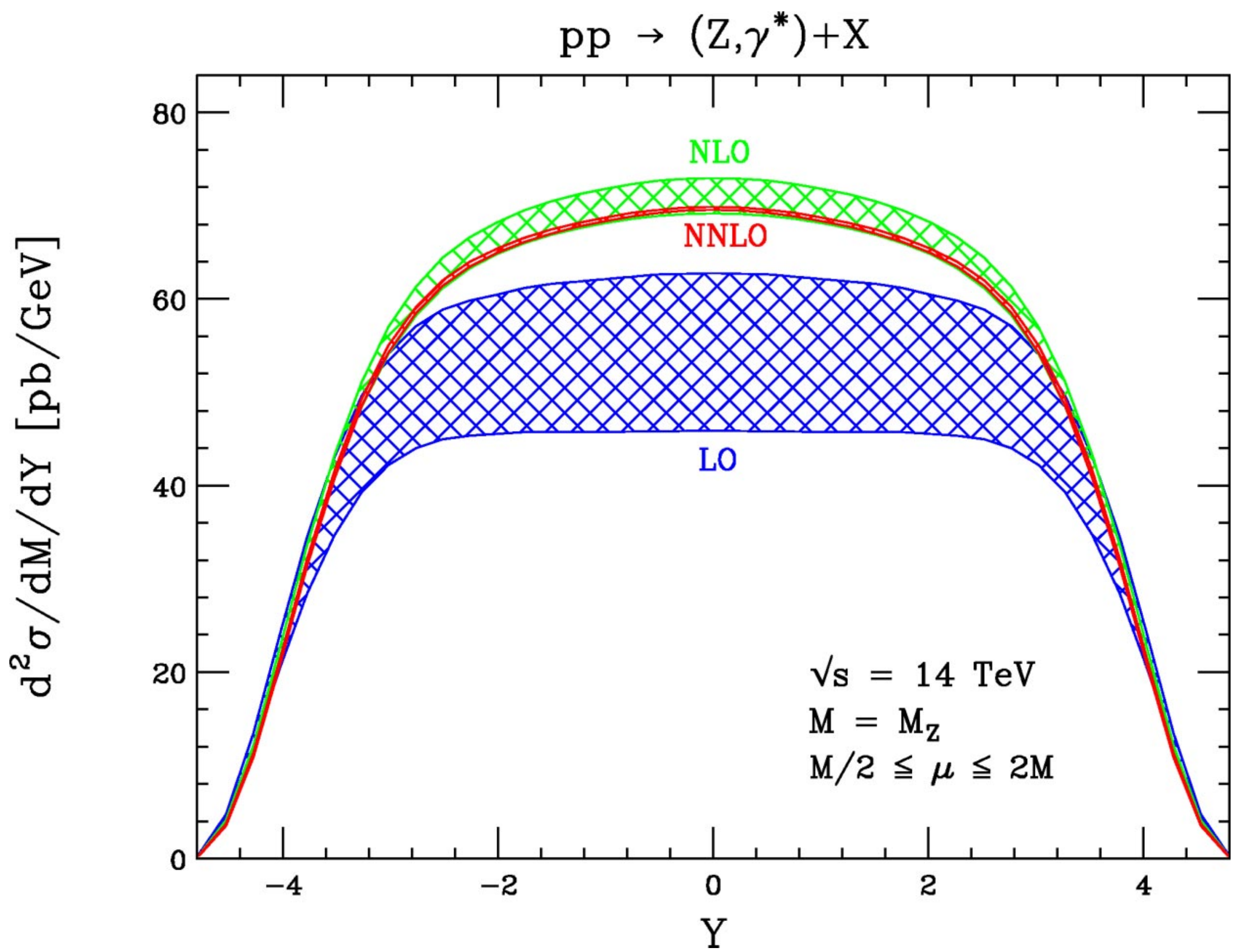
MMHT14 NNLO, $Q^2 = 10^4\,\mathrm{GeV}^2$ $\sim M_Z^2$



(Keeping just valence quarks + gluon for clarity)

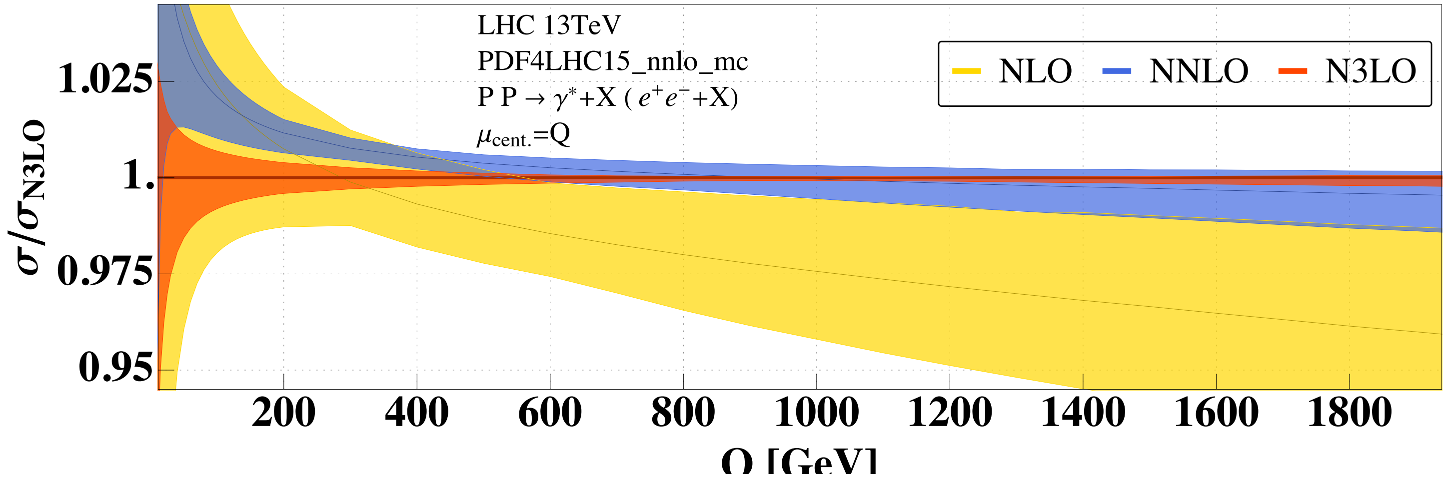
Drell-Yan

NNLO:



C. Anastasiou et al., Phys. Rev. D69 (2004) 094008

N3LO:



C. Duhr, F. Dulat, B. Mistlberger, *Phys.Rev.Lett*. 125 (2020) 17, 172001

PDF Fits

- Wide range of data/ experiments in modern 'global' PDF fits.

$\Rightarrow$ **Highly Non-trivial check of QCD.**

S. Bailey et al., arXiv:2012.04684

MSHT20

Data set	NLO	NNLO
BCDMS μp F_2 [49]	169.4/163	180.2/163
BCDMS μd F_2 [49]	135.0/151	146.0/151
NMC μp F_2 [50]	142.9/123	124.1/123
NMC μd F_2 [50]	128.2/123	112.4/123
NMC $\mu n/\mu p$ [51]	127.8/148	130.8/148
E665 μp F_2 [52]	59.5/53	64.7/53
E665 μd F_2 [52]	50.3/53	59.7/53
SLAC ep F_2 [53, 54]	29.4/37	32.0/37
SLAC ed F_2 [53, 54]	37.4/38	23.0/38
NMC/BCDMS/SLAC/HERA F_L [49, 50, 54, 146–148]	79.4/57	68.4/57
E866/NuSea pp DY [149]	216.2/184	225.1/184
E866/NuSea pd/pp DY [150]	10.6/15	10.4/15
NuTeV νN F_2 [55]	43.7/53	38.3/53
CHORUS νN F_2 [56]	27.8/42	30.2/42
NuTeV νN xF_3 [55]	37.8/42	30.7/42
CHORUS νN xF_3 [56]	22.0/28	18.4/28
CCFR $\nu N \to \mu\mu X$ [57]	73.2/86	67.7/86
NuTeV $\nu N \to \mu\mu X$ [57]	41.0/84	58.4/84
HERA e^+p CC [84]	54.3/39	52.0/39
HERA e^-p CC [84]	80.4/42	70.2/42
HERA e^+p NC 820 GeV [84]	91.6/75	89.8/75
HERA e^+p NC 920 GeV [84]	553.9/402	512.7/402
HERA e^-p NC 460 GeV [84]	253.3/209	248.3/209
HERA e^-p NC 575 GeV [84]	268.1/259	263.0/259
HERA e^-p NC 920 GeV [84]	252.3/159	244.4/159
HERA ep F_2^{charm} [26]	125.6/79	132.3/79
DØ II $p\bar{p}$ incl. jets [125]	117.2/110	120.2/110
CDF II $p\bar{p}$ incl. jets [124]	70.4/76	60.4/76
CDF II W asym. [90]	19.1/13	19.0/13
DØ II $W \to \nu e$ asym. [151]	44.4/12	33.9/12
DØ II $W \to \nu\mu$ asym. [152]	13.9/10	17.3/10
DØ II Z rap. [153]	15.9/28	16.4/28
CDF II Z rap. [154]	36.9/28	37.1/28
DØ W asym. [21]	13.1/14	12.0/14

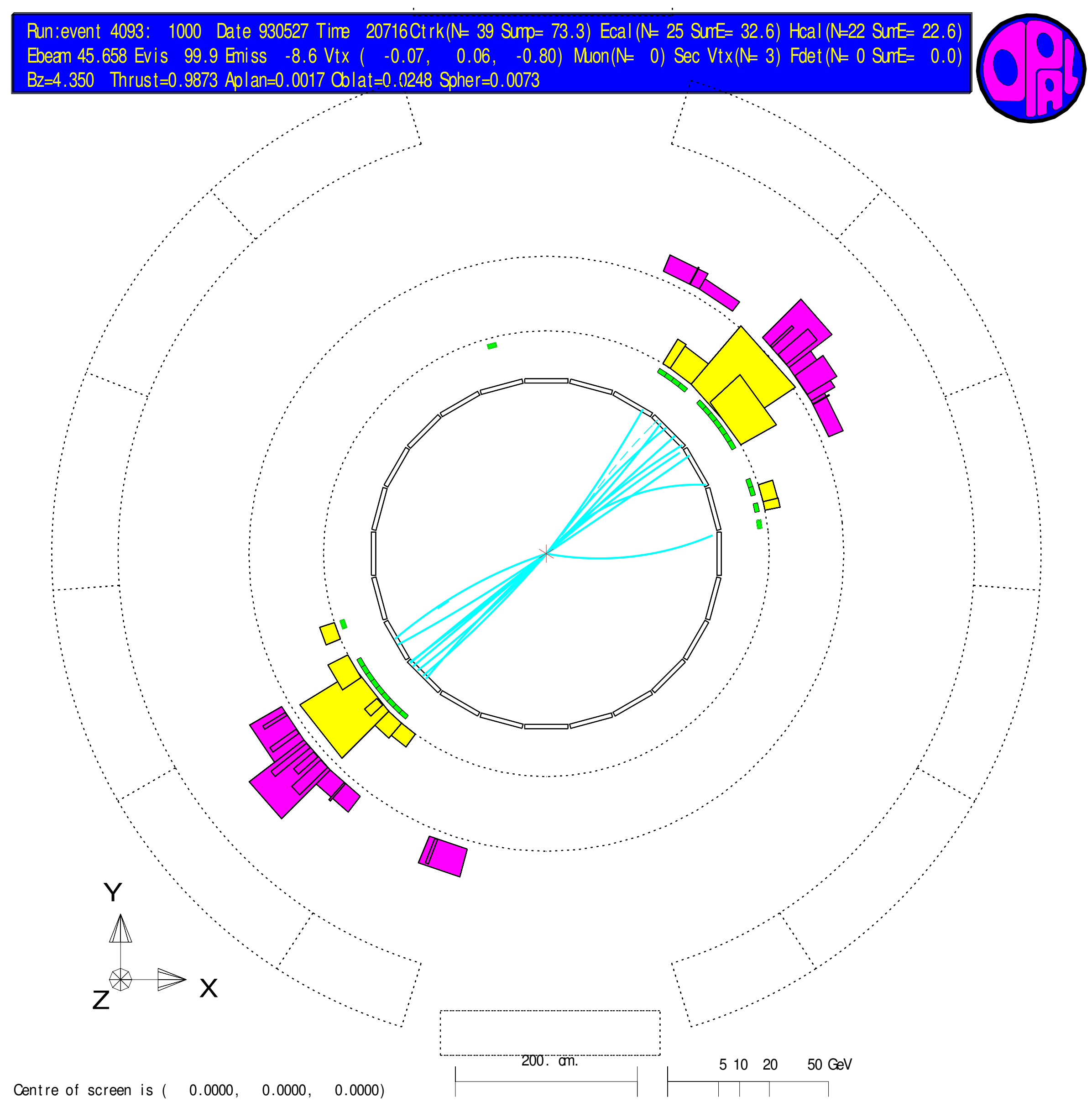
LHC

Data set	NLO	NNLO
ATLAS W^+, W^-, Z [119]	34.7/30	29.9/30
CMS W asym. $p_T > 35$ GeV [155]	11.8/11	7.8/11
CMS asym. $p_T > 25, 30$ GeV [156]	11.8/24	7.4/24
LHCb $Z \to e^+e^-$ [157]	14.1/9	22.7/9
LHCb W asym. $p_T > 20$ GeV [158]	10.5/10	12.5/10
CMS $Z \to e^+e^-$ [159]	18.9/35	17.9/35
ATLAS High-mass Drell-Yan [160]	20.7/13	18.9/13
CMS double diff. Drell-Yan [72]	222.2/132	144.5/132
Tevatron, ATLAS, CMS $\sigma_{t\bar{t}}$ [93]- [94]	22.8/17	14.5/17
LHCb 2015 W, Z [95, 96]	114.4/67	99.4/67
LHCb 8 TeV $Z \to ee$ [97]	39.0/17	26.2/17
CMS 8 TeV W [98]	23.2/22	12.7/22
ATLAS 7 TeV jets [18]	226.2/140	221.6/140
CMS 7 TeV $W + c$ [99]	8.2/10	8.6/10
ATLAS 7 TeV high precision W, Z [20]	304.7/61	116.6/61
CMS 7 TeV jets [100]	200.6/158	175.8/158
CMS 8 TeV jets [101]	285.7/174	261.3/174
CMS 2.76 TeV jet [107]	124.2/81	102.9/81
ATLAS 8 TeV Z p_T [75]	235.0/104	188.5/104
ATLAS 8 TeV single diff $t\bar{t}$ [102]	39.1/25	25.6/25
ATLAS 8 TeV single diff $t\bar{t}$ dilepton [103]	4.7/5	3.4/5
CMS 8 TeV double differential $t\bar{t}$ [105]	32.8/15	22.5/15
CMS 8 TeV single differential $t\bar{t}$ [108]	12.9/9	13.2/9
ATLAS 8 TeV High-mass Drell-Yan [73]	85.8/48	56.7/48
ATLAS 8 TeV W [106]	84.6/22	57.4/22
ATLAS 8 TeV W + jets [104]	33.9/30	18.1/30
ATLAS 8 TeV double differential Z [74]	157.4/59	85.6/59
Total	5822.0/4363	5121.9/4363

$\chi^2/\text{N}_{\text{pts}} \sim 1!$

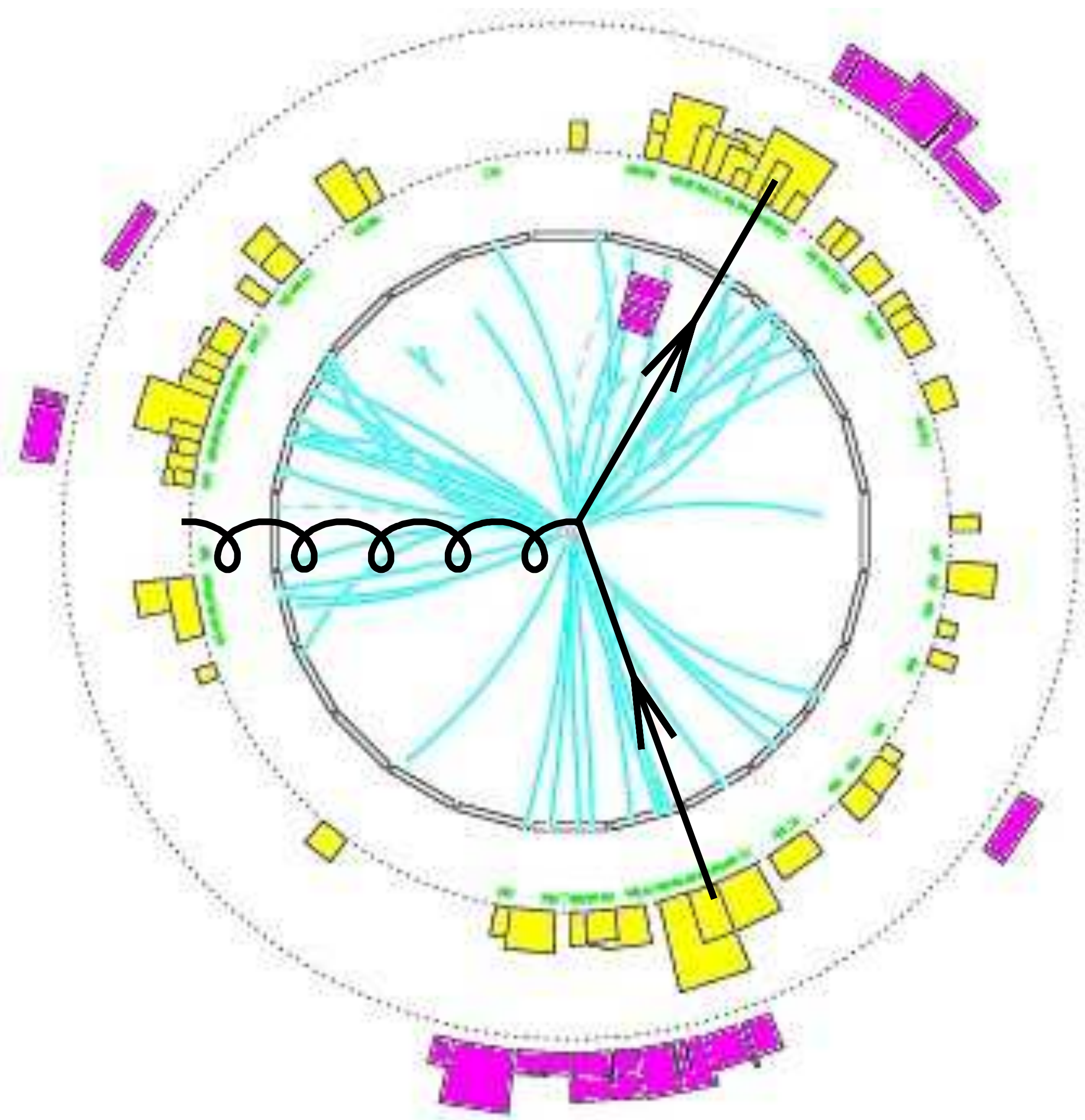
	NLO	NNLO
	1.33	1.17

(2-jet) Event Display



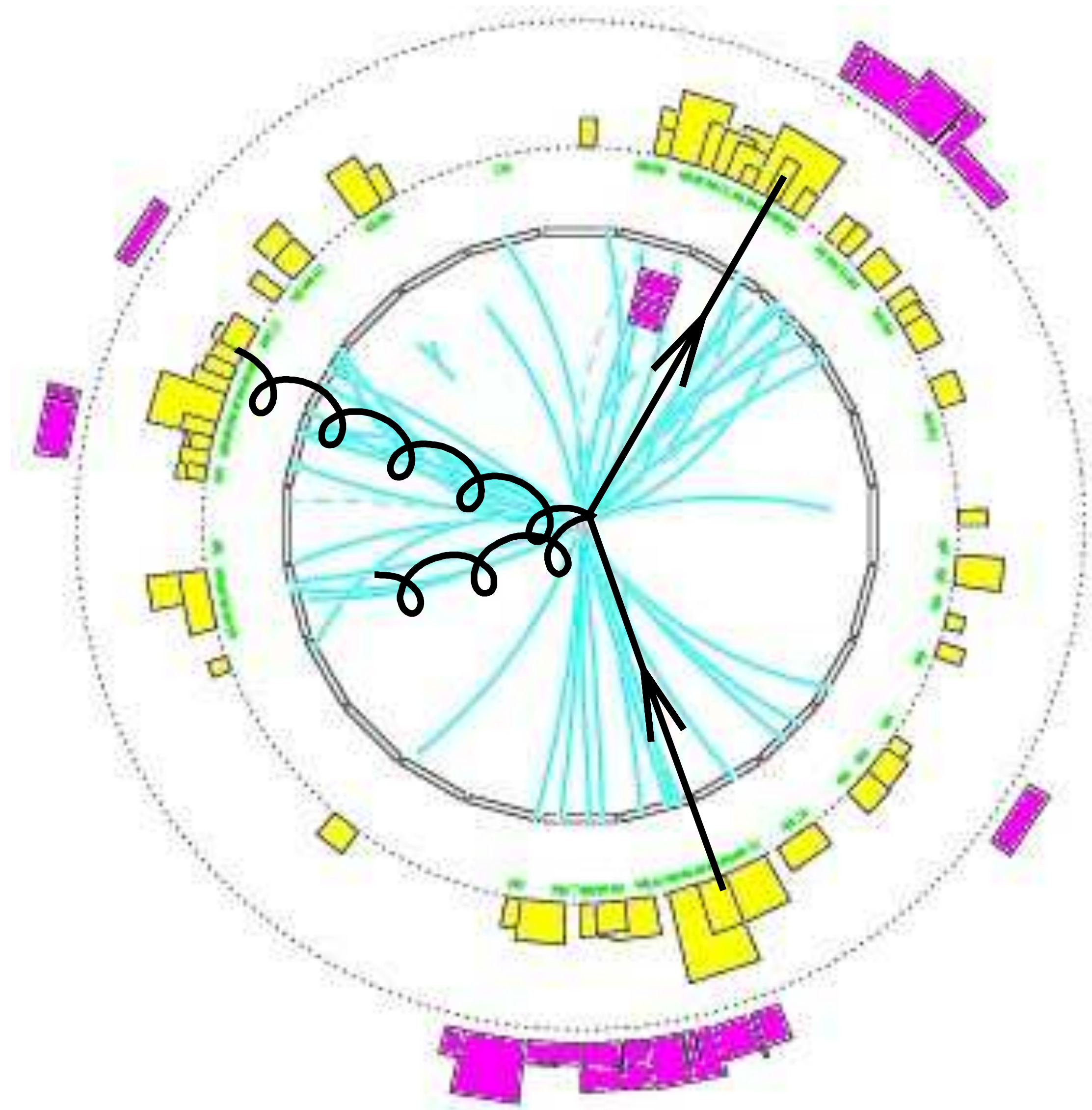
- Example event display from e^+e^- collisions.

How Many Jets?



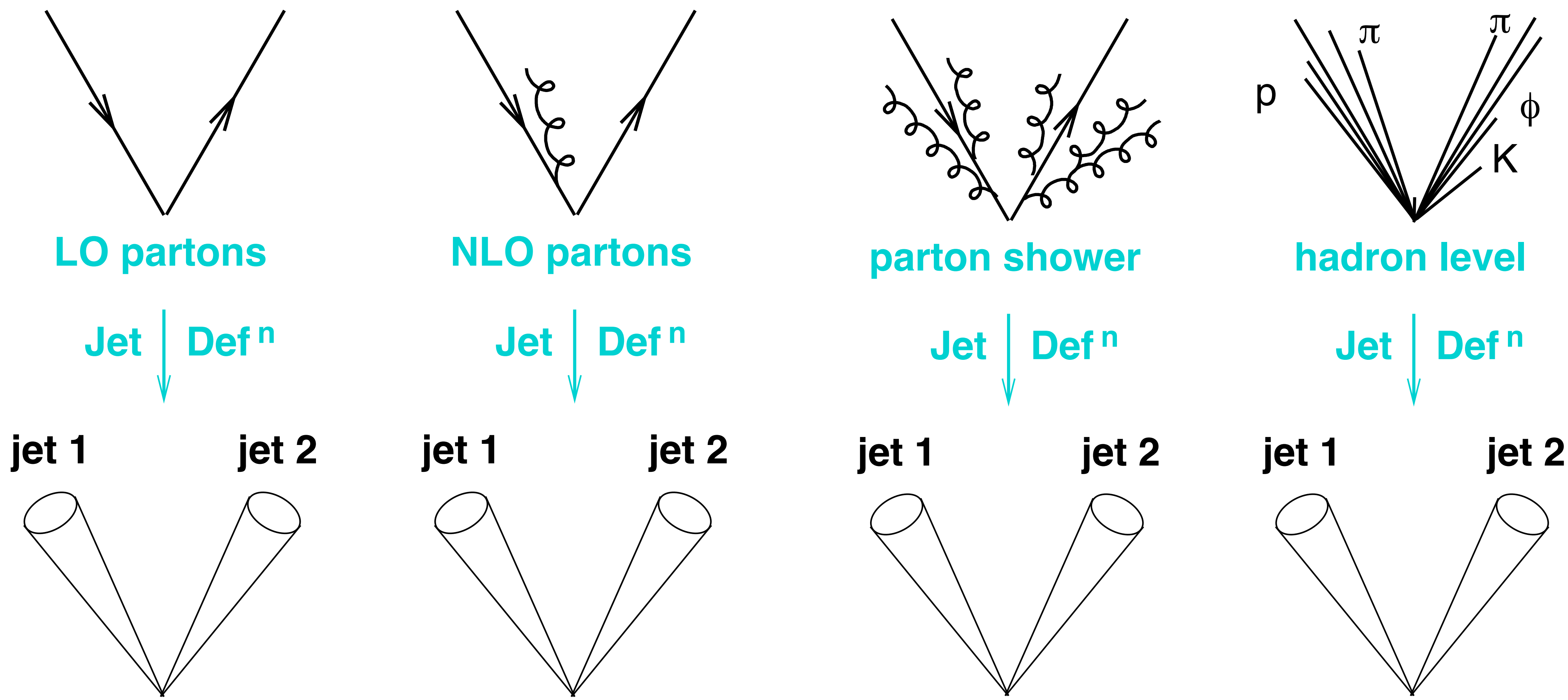
vs.

?



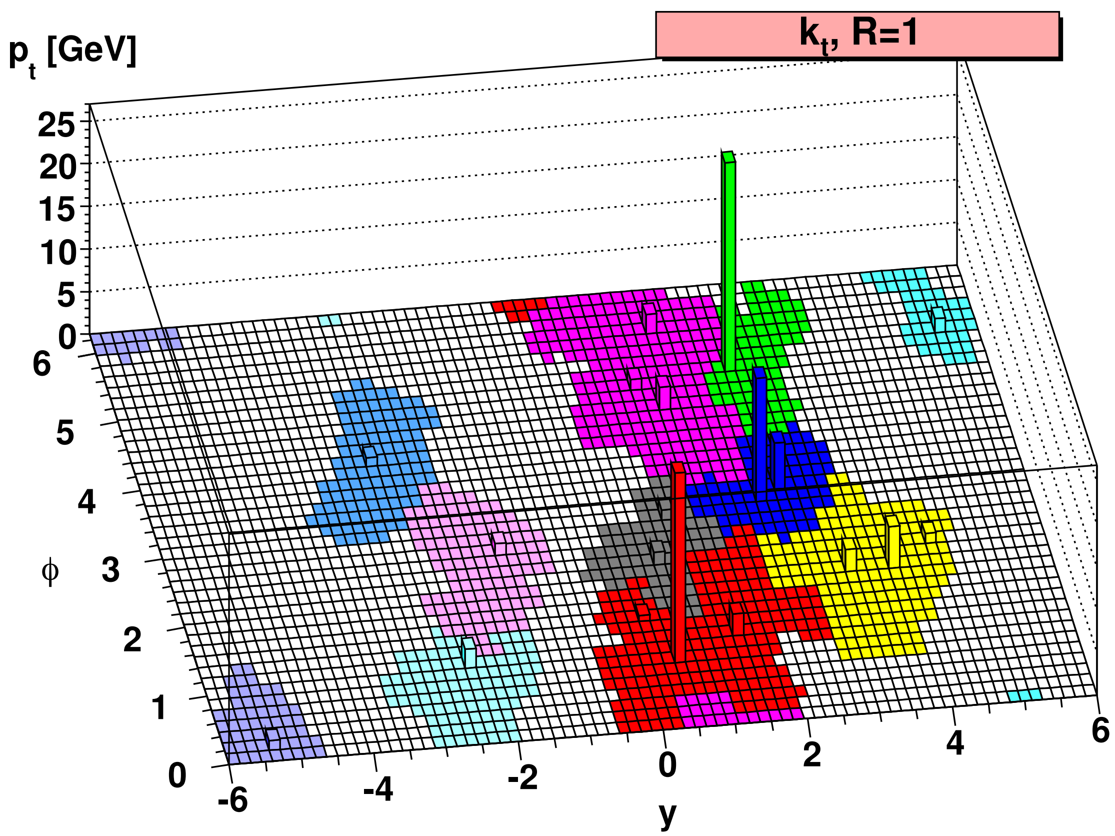
arXiv:1011.5131

Jet Algorithm: Basic Idea

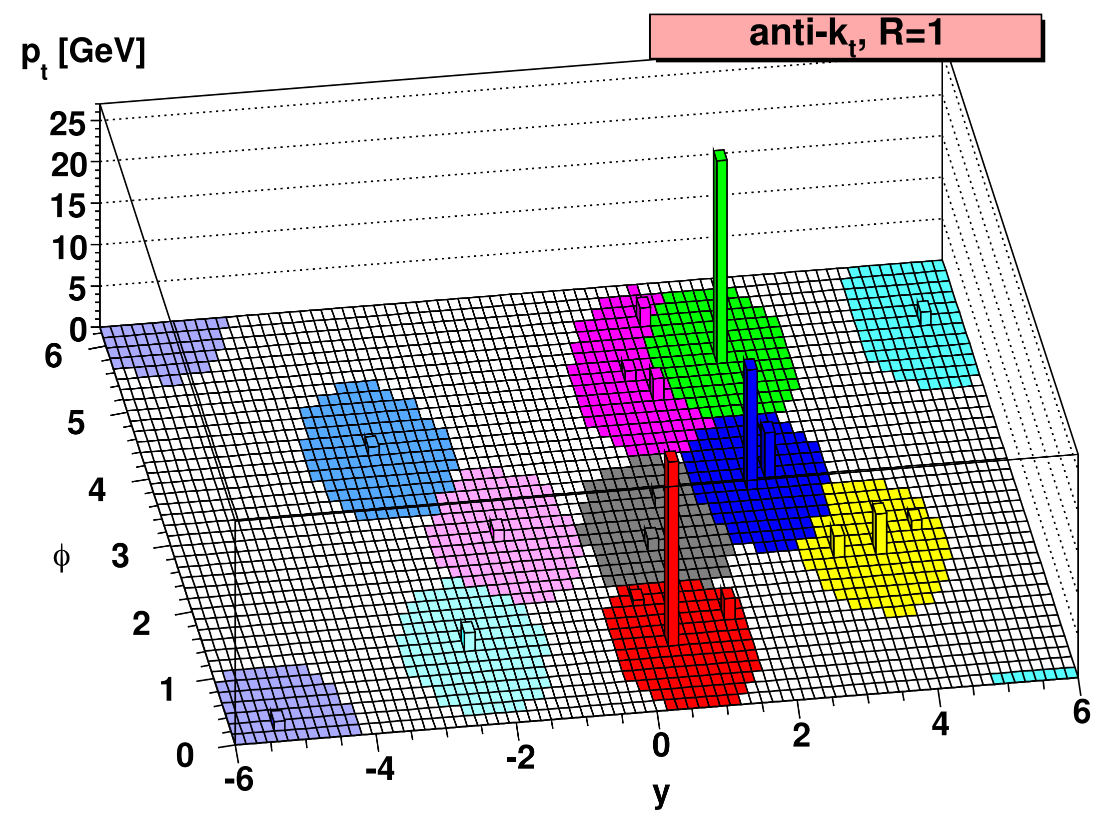


arXiv:1011.5131

Jet Algorithms

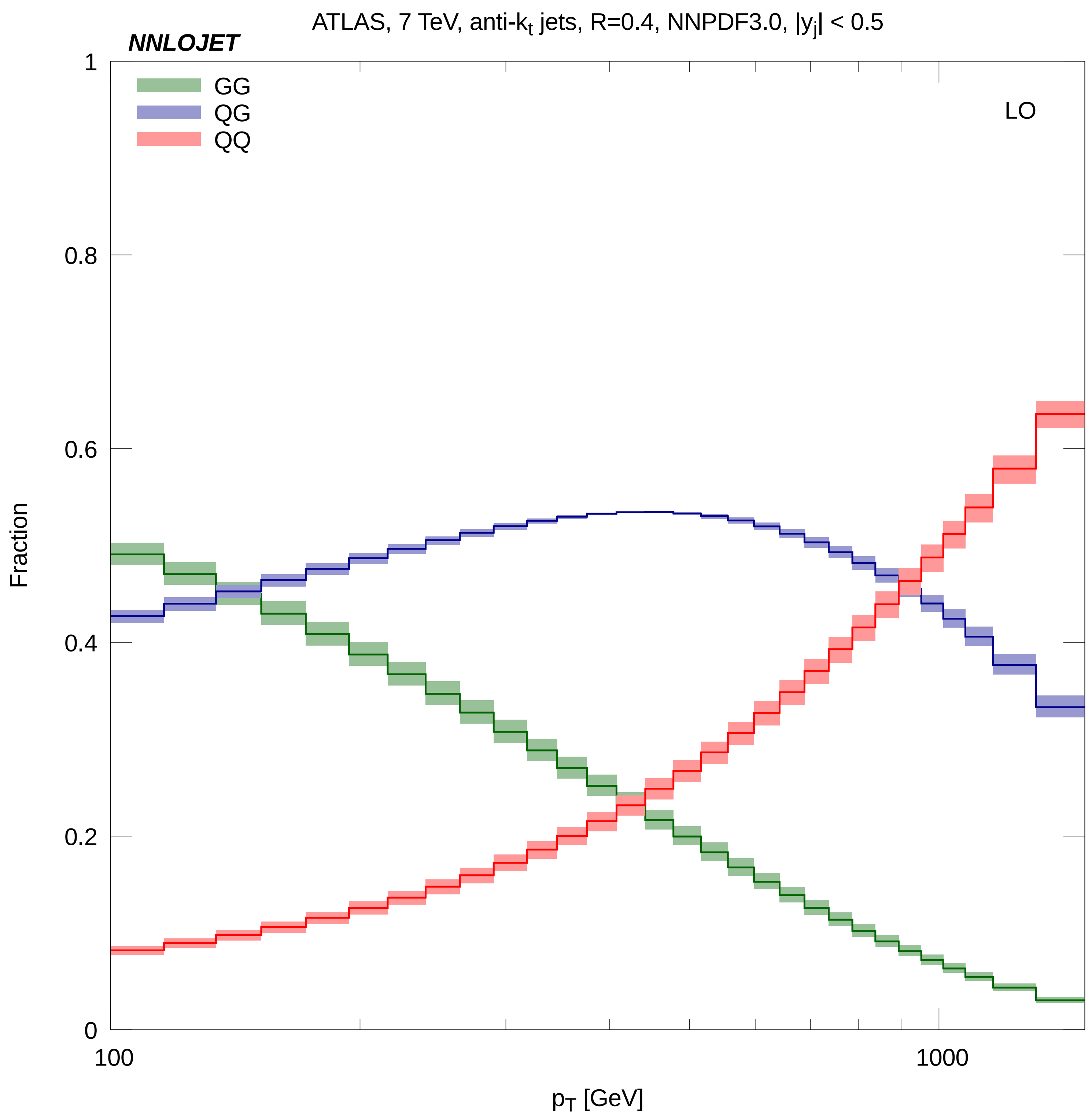


k_T

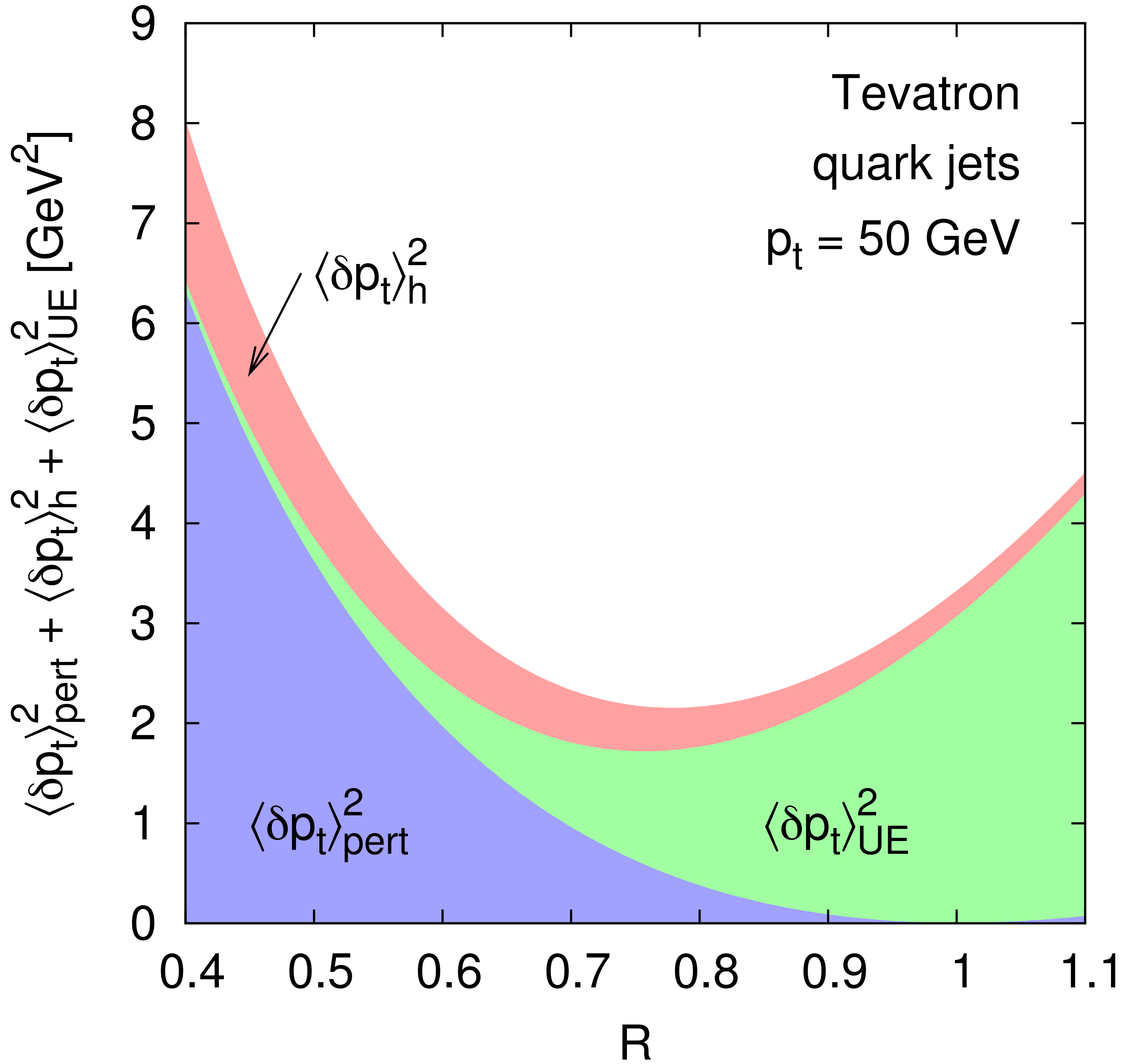


anti-k_T

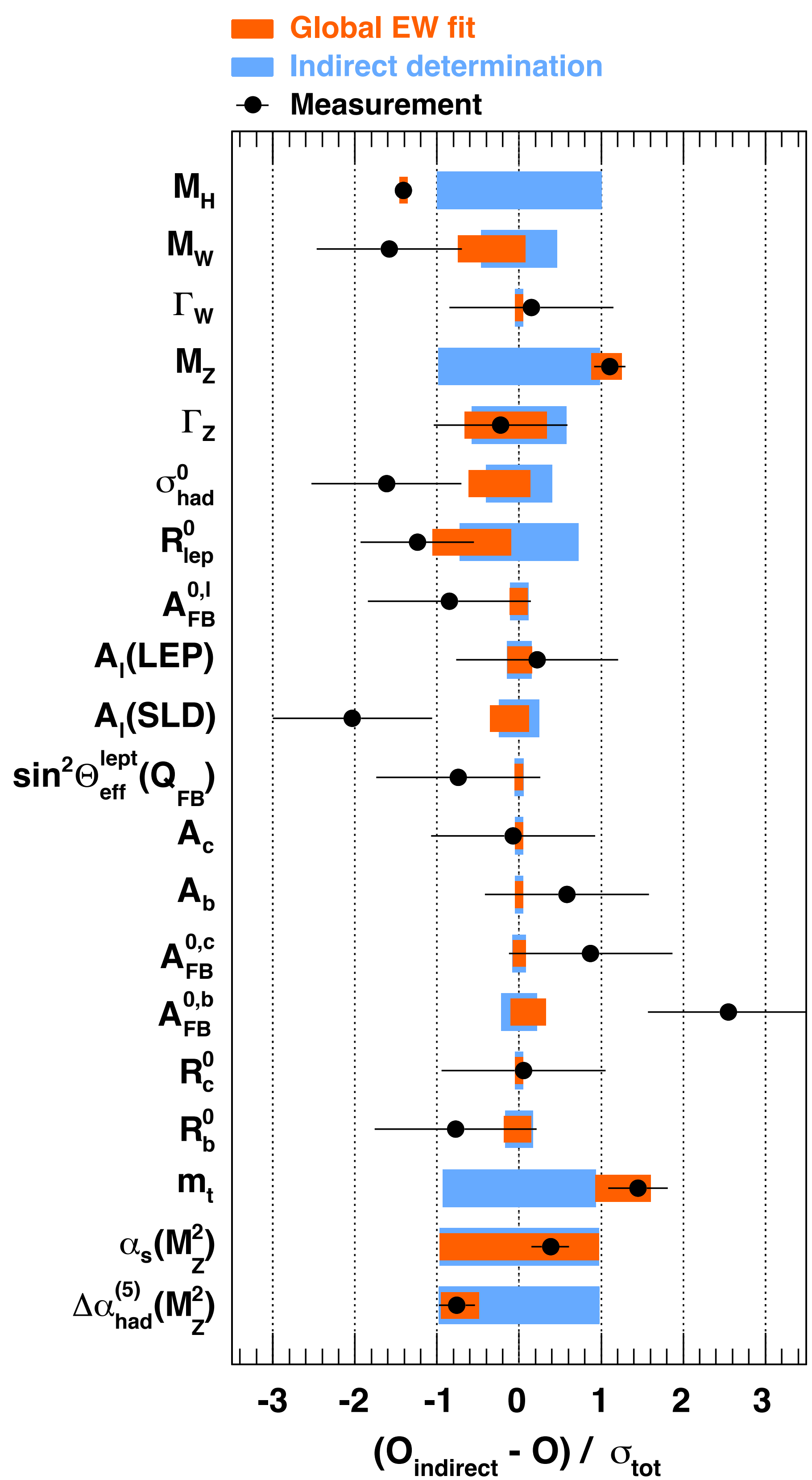
Jet Production Channels @ LHC



Jet Transverse Momentum Loss

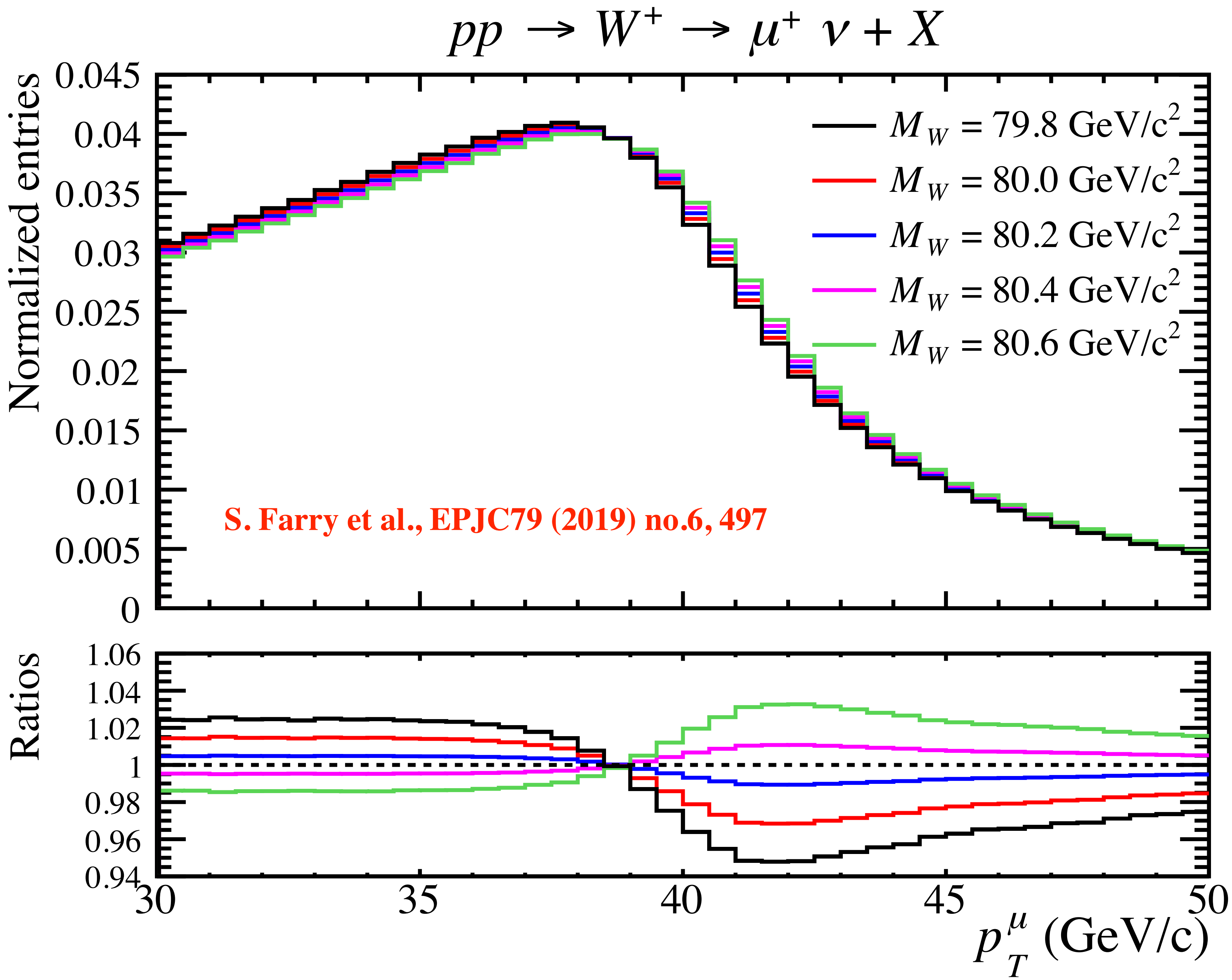


EW Precision Fits



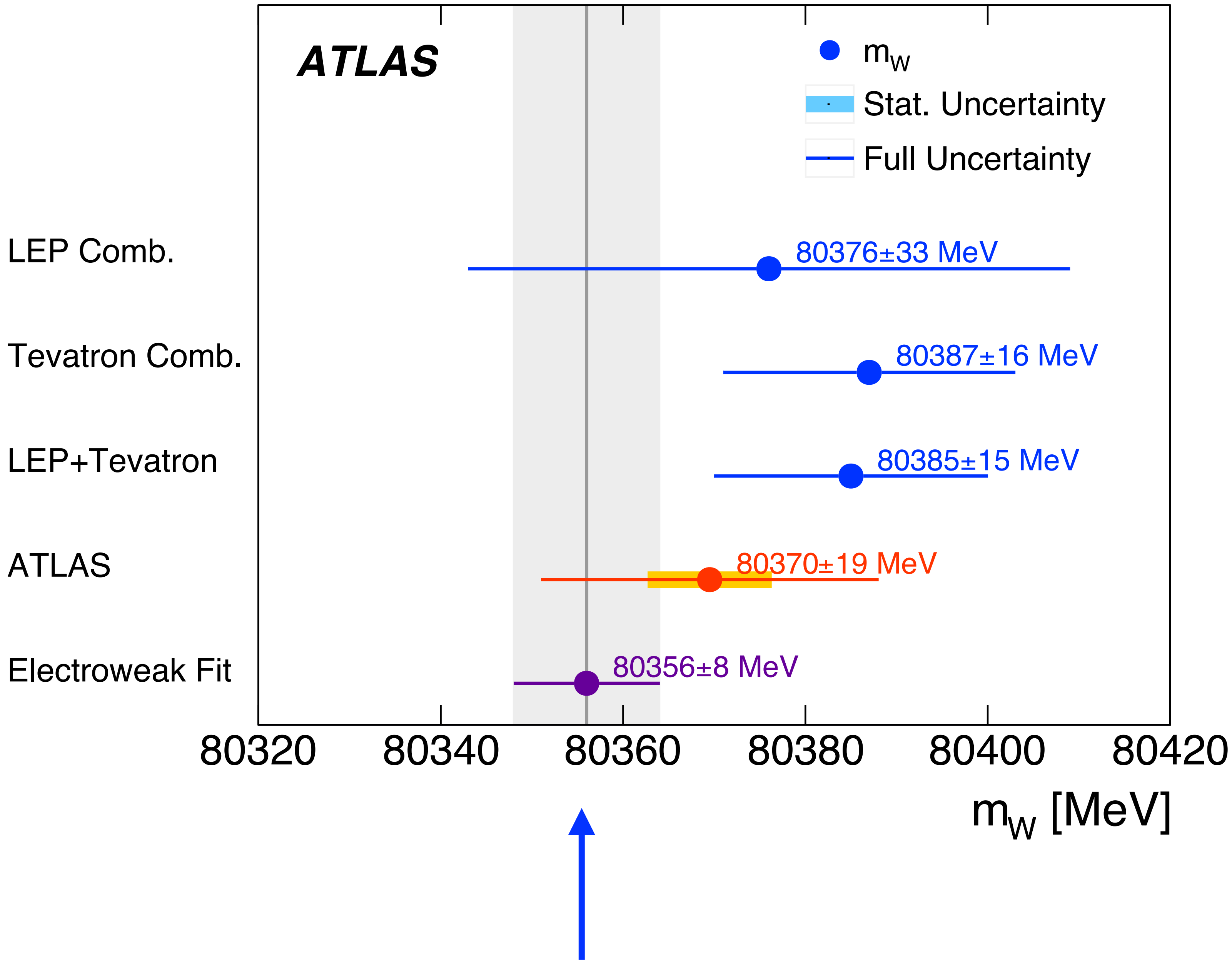
arXiv:1407.03792

W Boson Mass Determination



W Boson Mass Determination

ATLAS Collab., Eur.Phys.J.C 78 (2018) 2



- Uncertainty on indirect EW fit ~ 8 MeV. Natural target for direct LHC measurements.

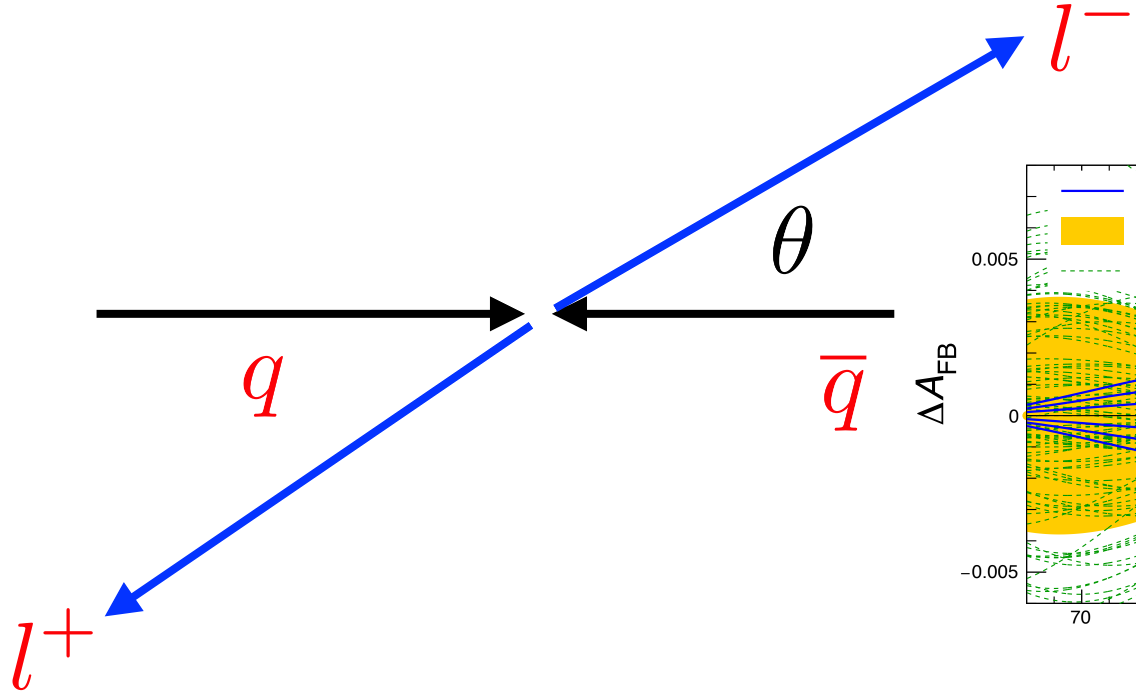
Forward Backwards Asymmetry

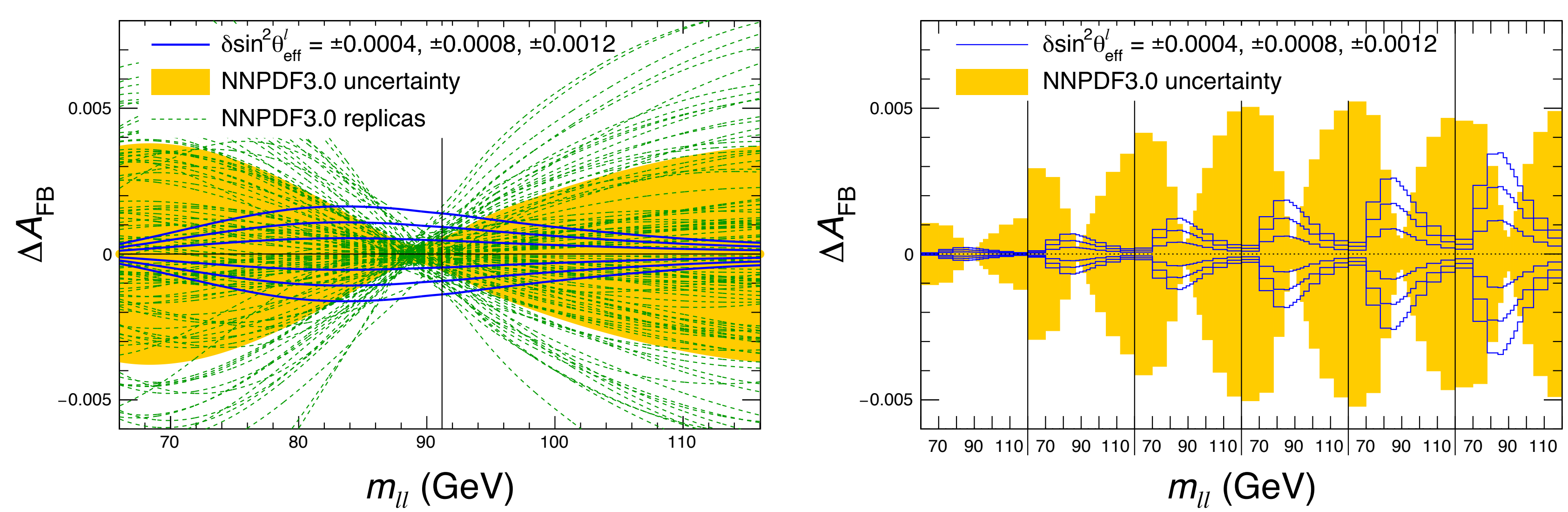
$$\sigma\left(f\bar{f}\to f'\bar{f}'\right)=\alpha^2\frac{\pi}{2s}\int_{-1}^{1}d(\cos\theta)\Bigg\{$$

$$\left(1+\cos^2\theta\right)\left(q_f^2q_{f'}^2+\frac{g_Z^2}{4g_e^2}q_fq_{f'}v_fv_{f'}\chi_1+\frac{g_Z^4}{16g_e^4}(a_f^2+v_f^2)(a_{f'}^2+v_{f'}^2)\chi_2\right)$$

$$+\cos\theta\left(\frac{g_Z^2}{2g_e^2}a_fa_{f'}v_fv_{f'}\chi_1+\frac{g_Z^4}{2g_e^4}a_fa_{f'}v_fv_{f'}\chi_2\right)\Bigg\}$$

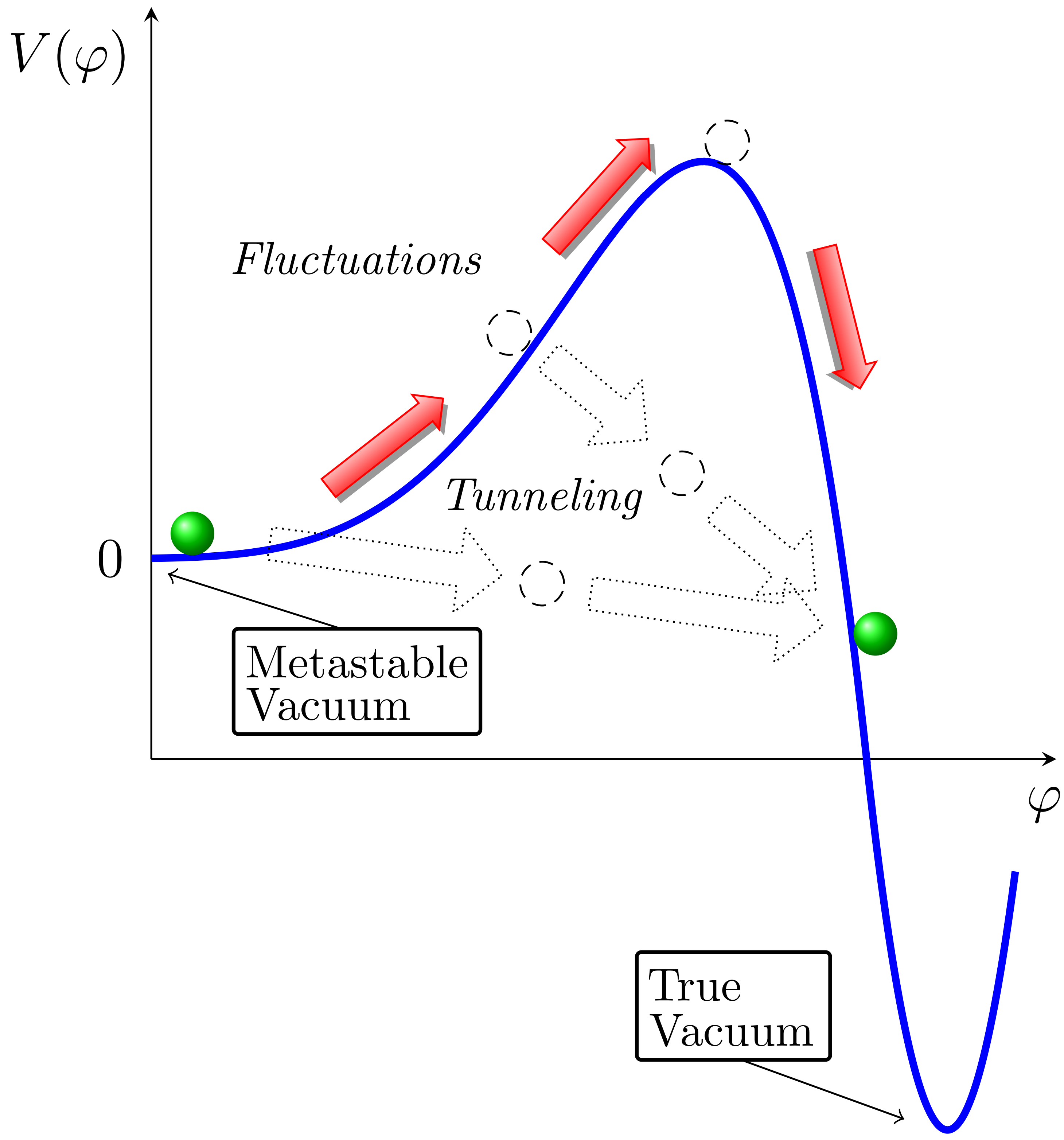
$$\left(v_f=T_f^3-2q_f\sin^2\theta_w\right)$$



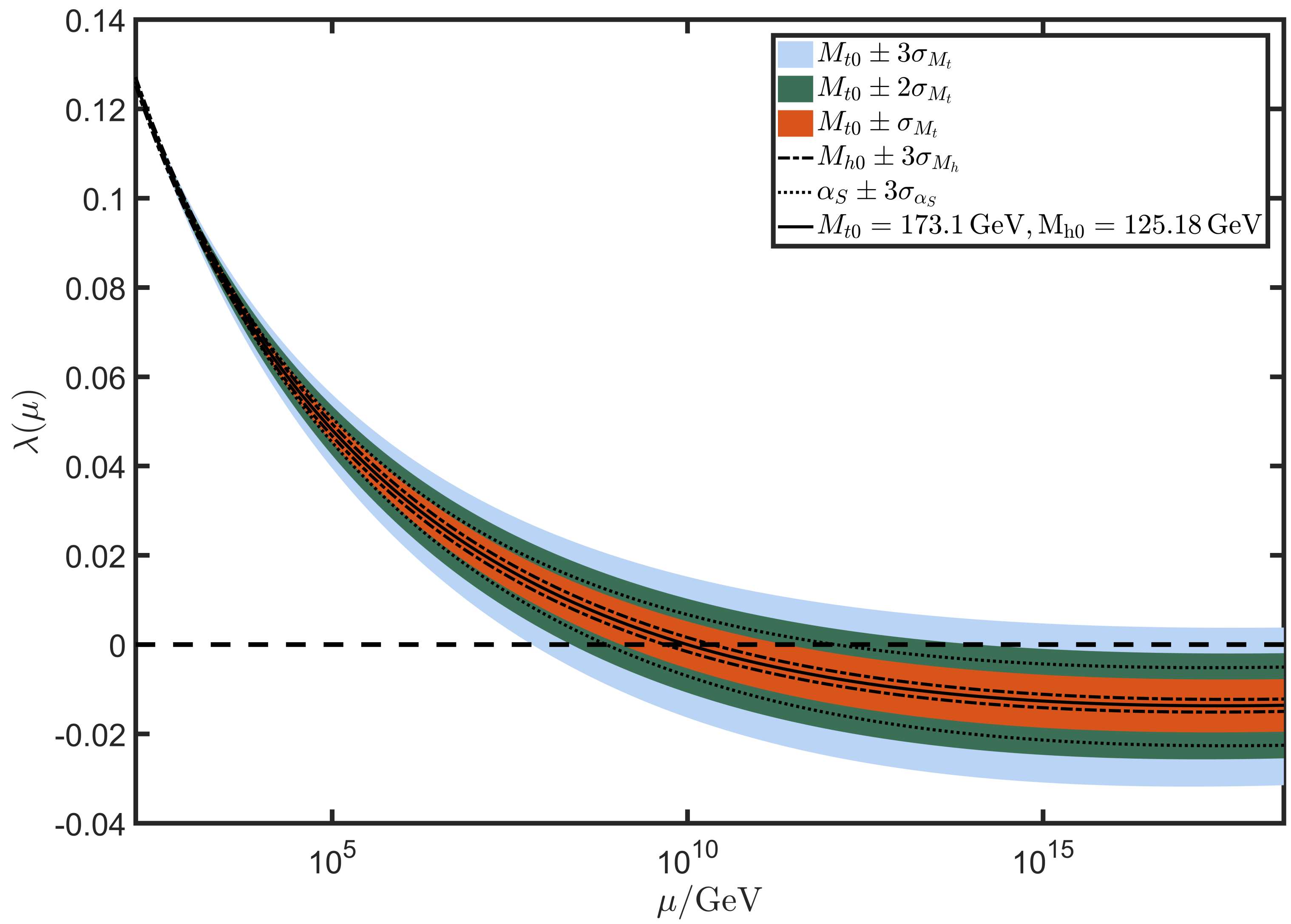


CMS Collab., *Eur.Phys.J.C* 78 (2018) 9, 701

Vacuum Stability of Universe



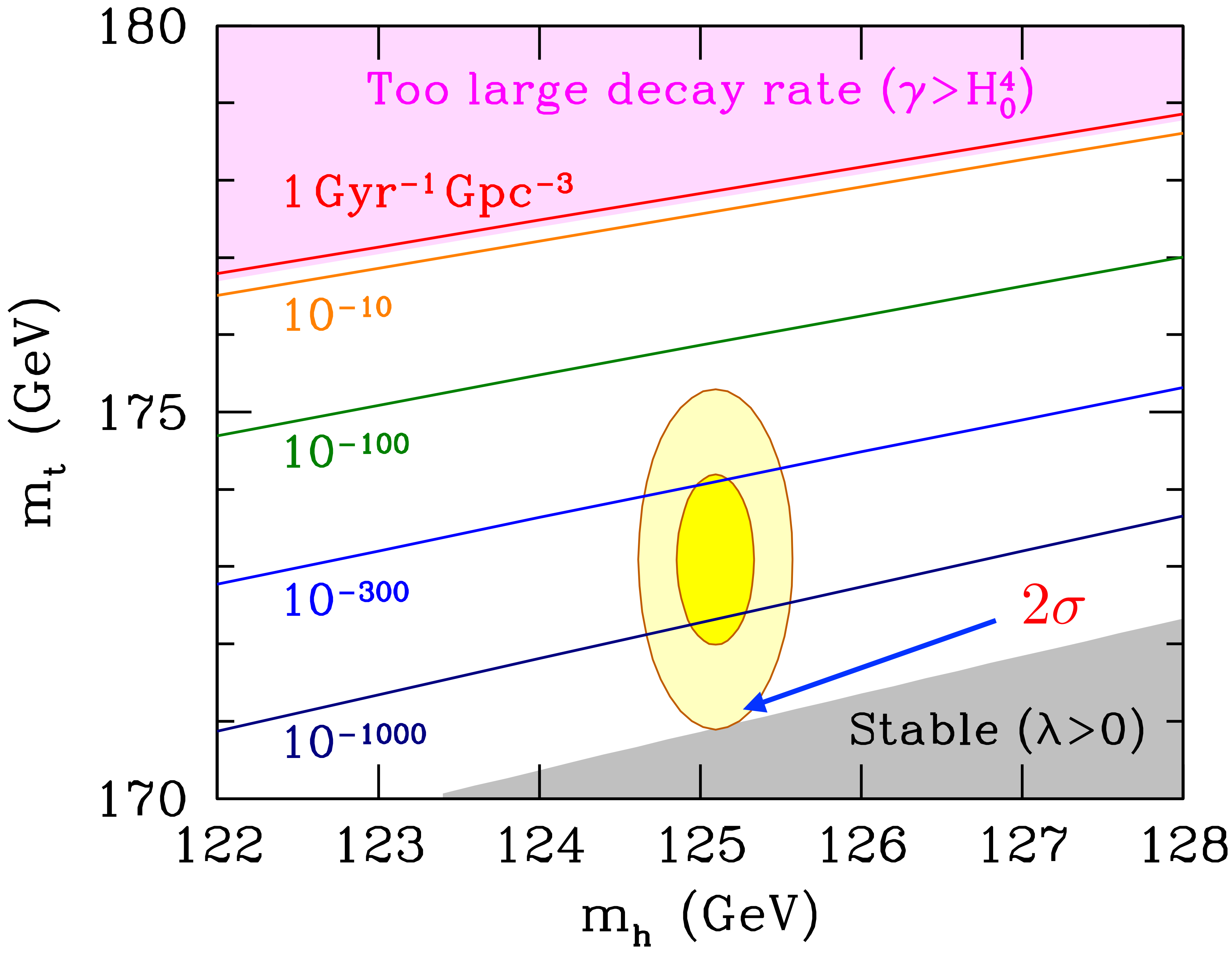
Vacuum Stability of Universe



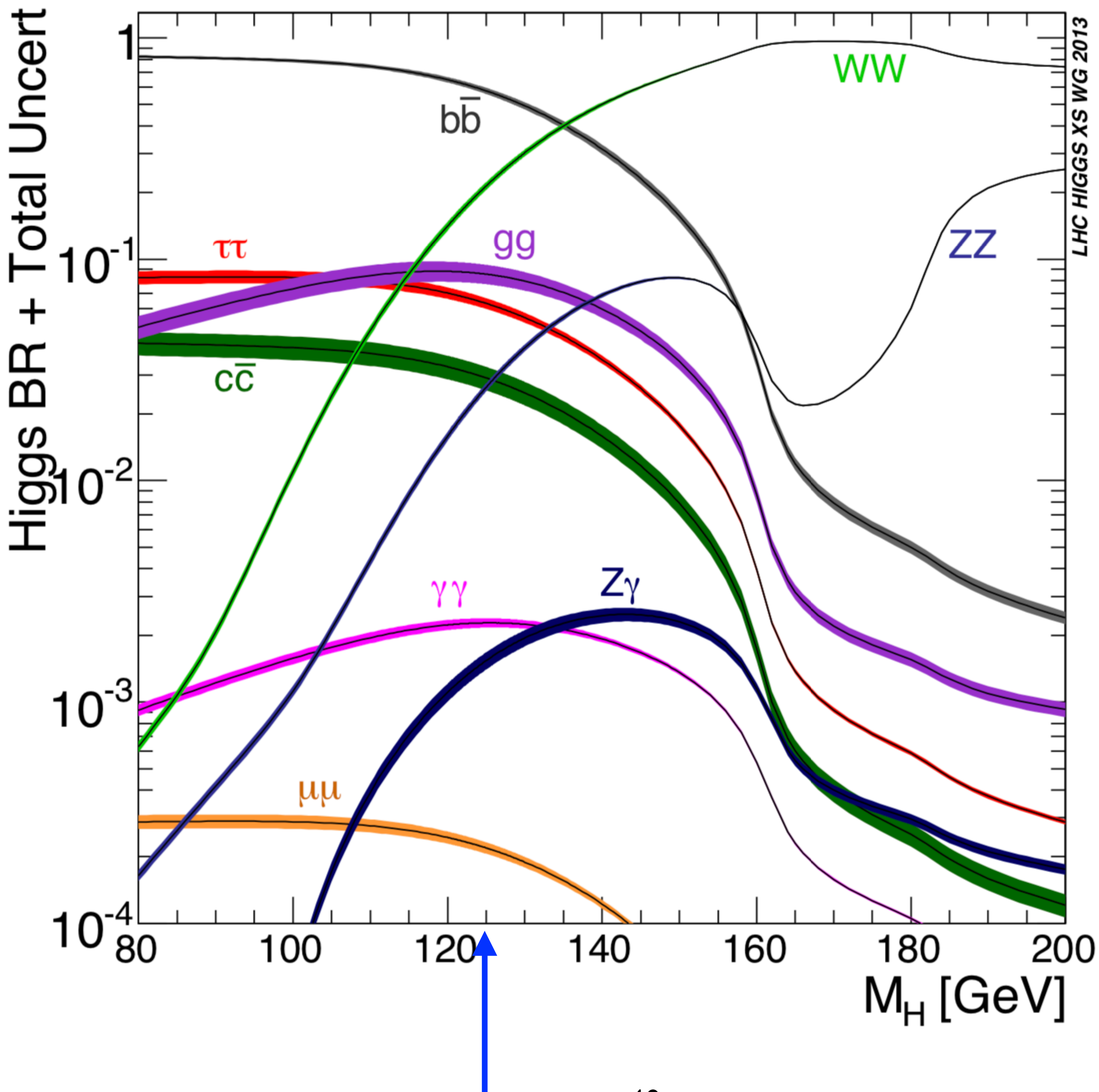
In each of them, the transition happens initially locally in a small volume, nucleating a small bubble of the true vacuum. The bubble then starts to expand, reaching the speed of light very quickly, any destroying everything in its way.

arXiv:1809.06923

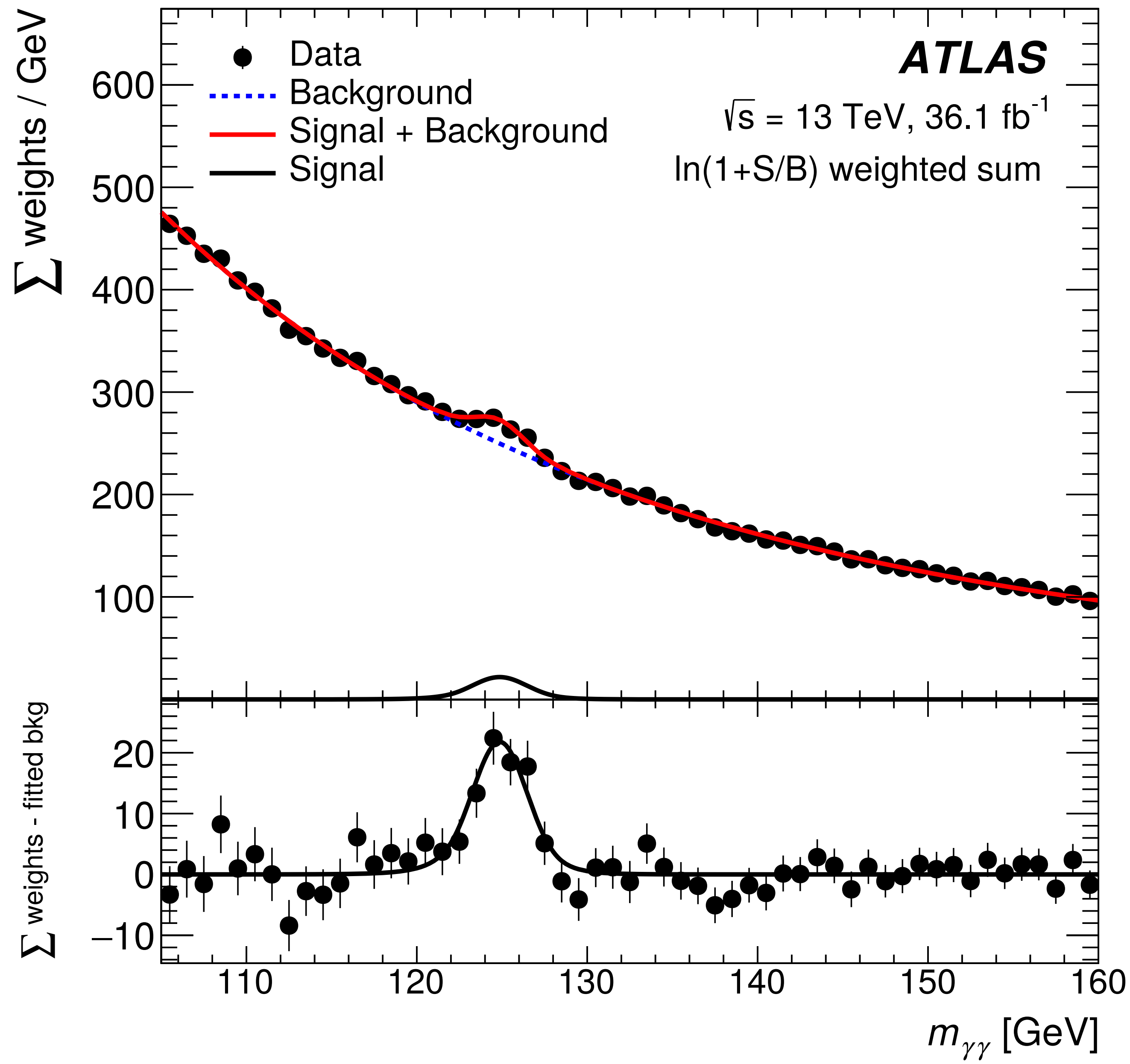
Vacuum Stability of Universe



Higgs Decays



Higgs: What Do We Know?



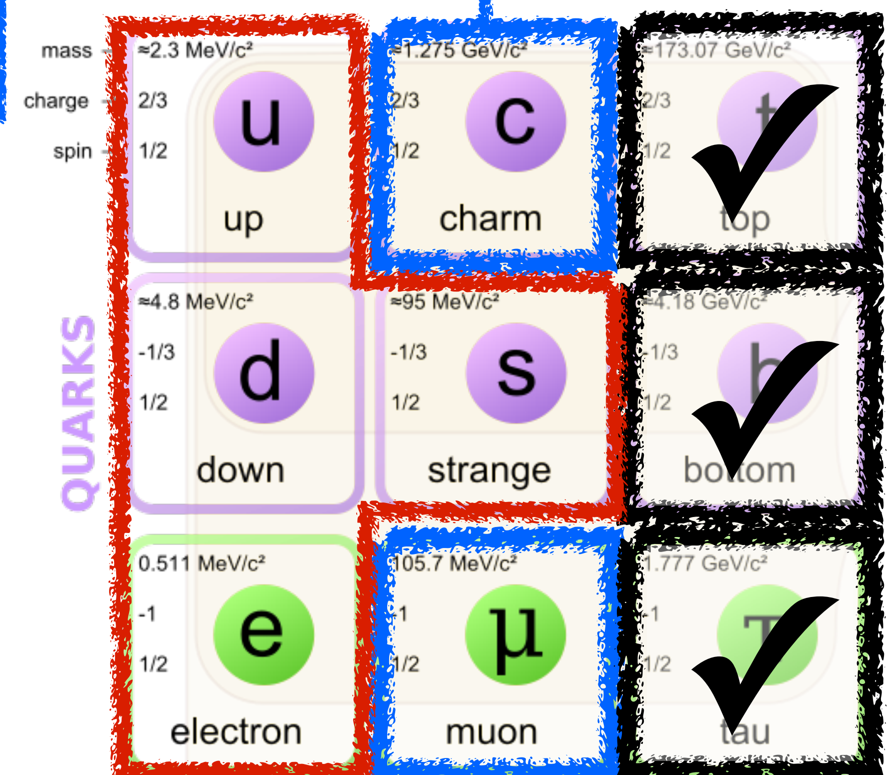
- New state there: is it Standard Model Higgs?

Higgs: What Do We Know?

Yukawas

today: no evidence yet
(1 in 35 decays)
needs an e^+e^-
or ep collider

overall normalisation
(related to Higgs width):
needs an e^+e^- collider



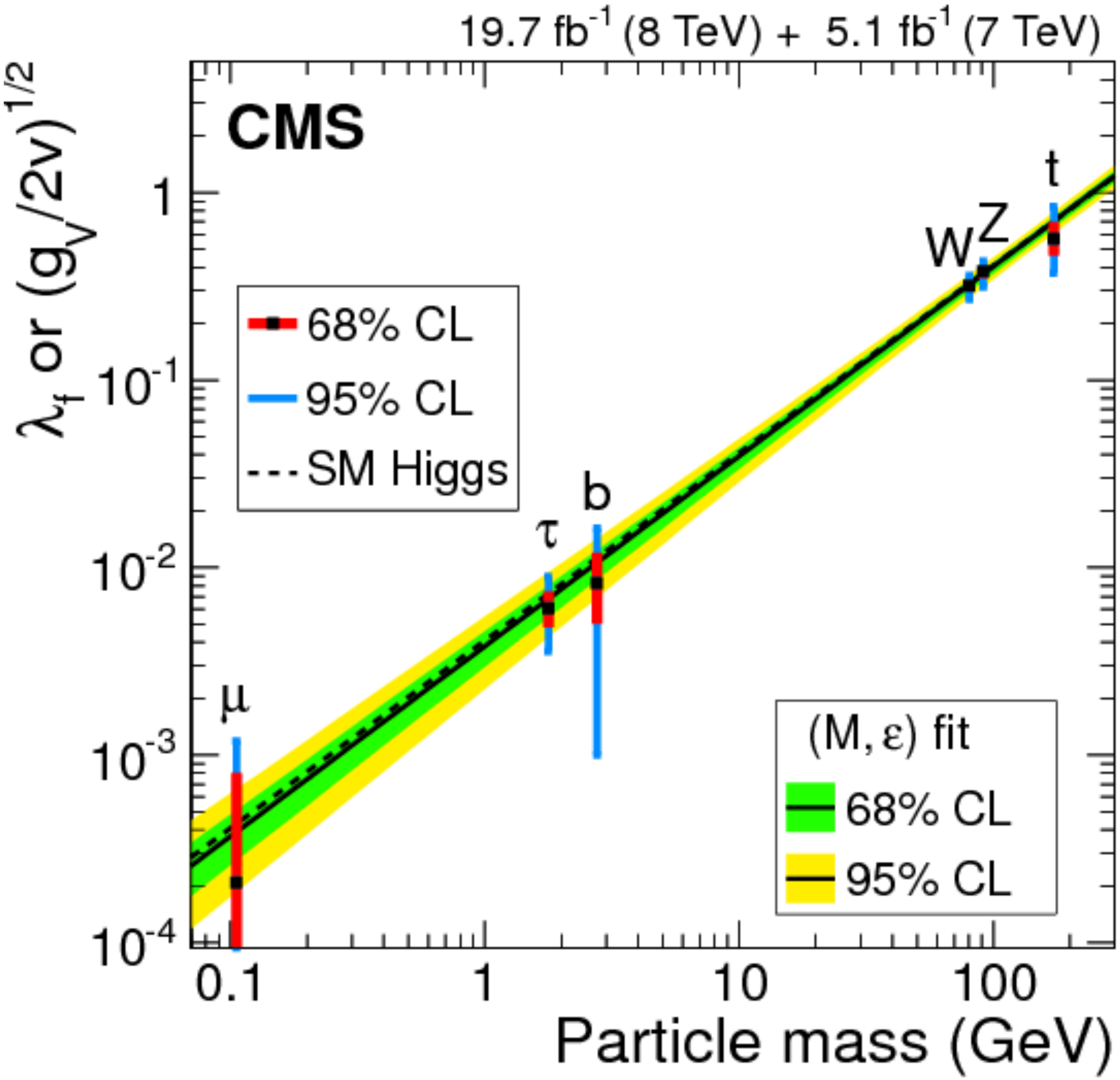
today: no evidence yet
(1 in 4000 decays)
no clear route to
establishing SM
couplings at 5σ

today: no evidence yet
(1 in 4570 decays)
observable at the LHC
within about 10 years.

40

Slide Credit: Gavin Salam

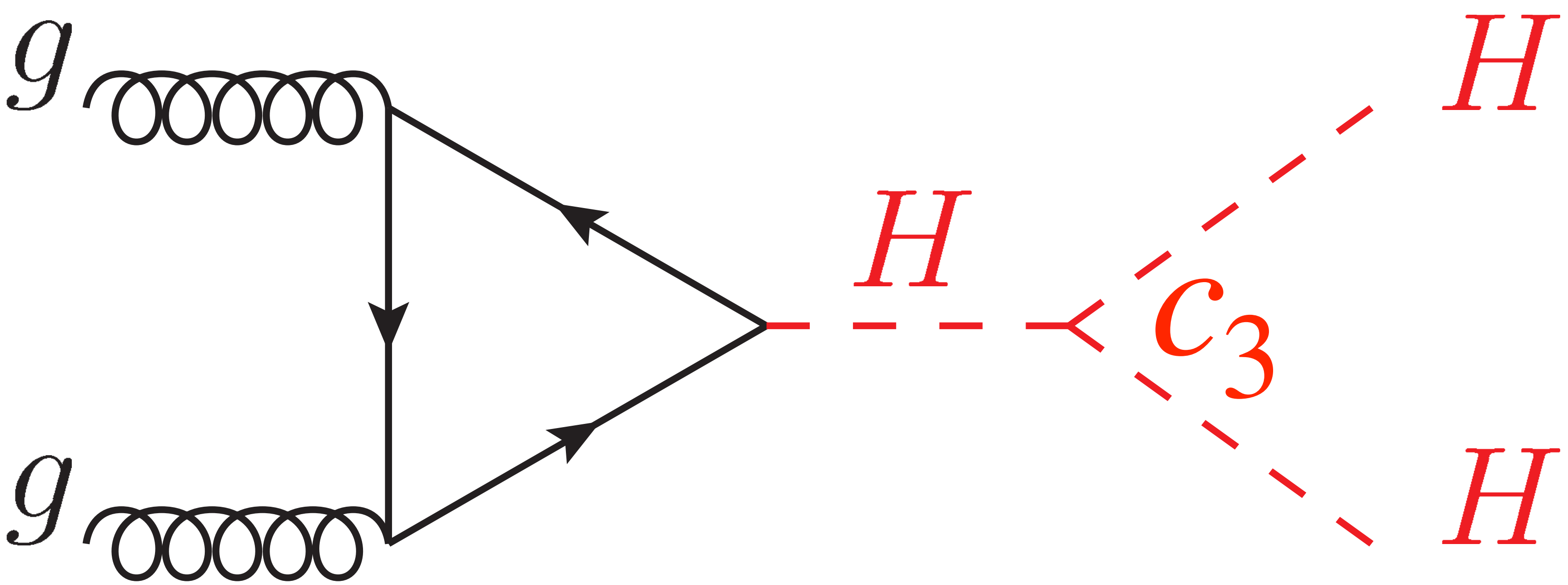
Higgs: What Do We Know?



Higgs Potential?

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4 \quad \textbf{?}$$

- So far this has only been seen in textbooks - not measured.



- Challenge (suppressed rate), currently ~ 50% precision at HL-LHC. Real precision needs new collider (or other breakthrough…).

Slide Credit: Gavin Salam