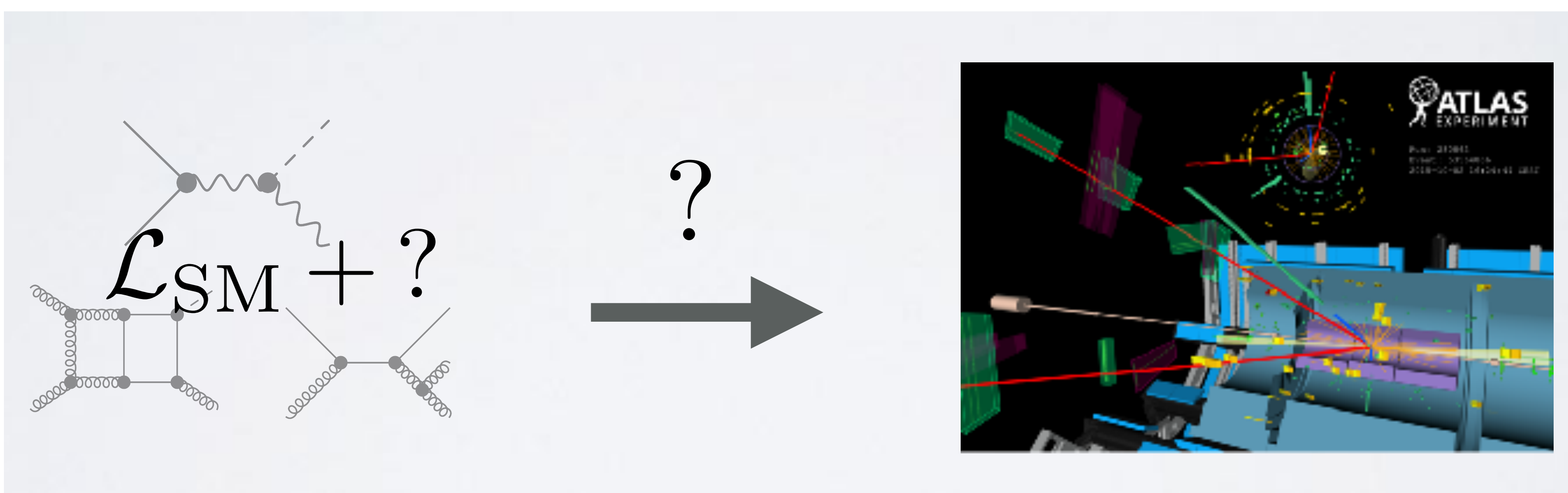
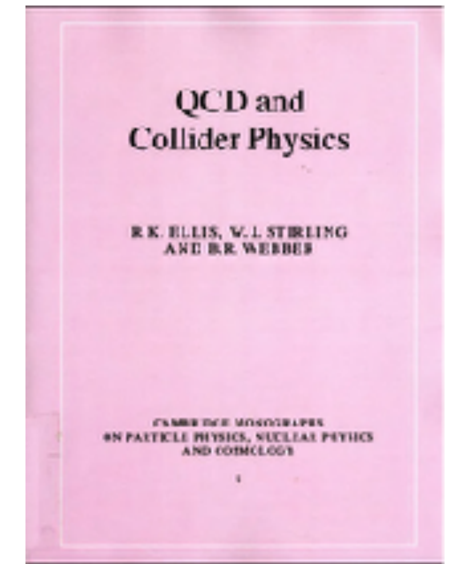
Collider Phenomenology

Lucian Harland-Lang, University of Oxford



UNIVERSITY OF OXFORD

Background Reading

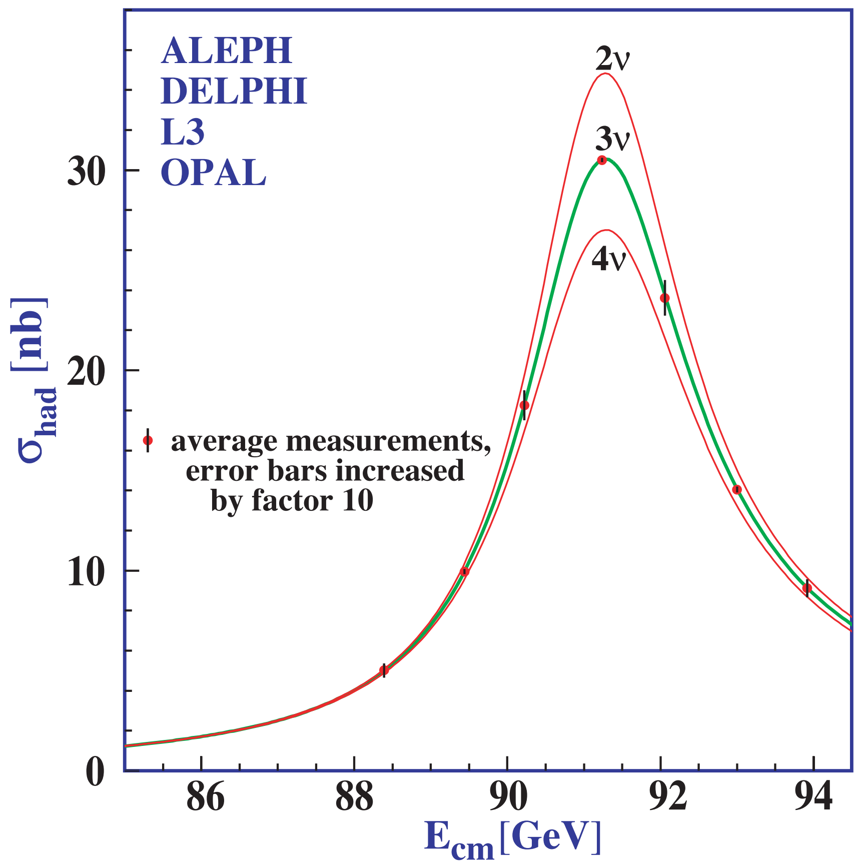


- Ellis, Stirling, Webber, “QCD and Collider Physics”, aka “The Pink Book”.

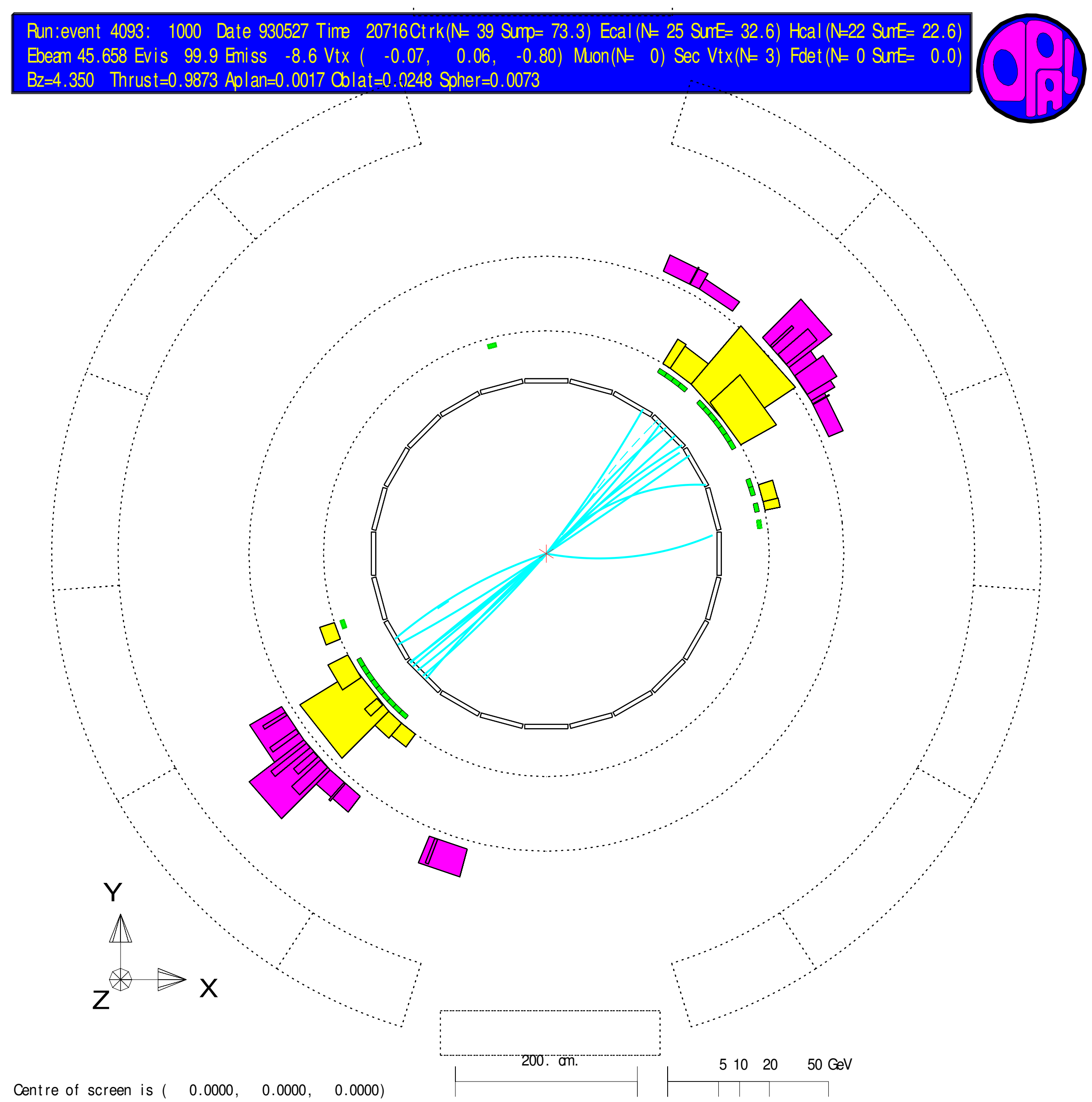
- Gunion, Kaber, Kane, Dawson, “Higgs Hunter’s Guide”
- Many nice review/lecture notes online: hep-ph/0011256, http://cds.cern.ch/record/454171, arXiv:1011.5131, arXiv:0906.1833, hep-ph/0505192, arXiv:1709.04533, arXiv:1312.5672…

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 on the board (in many cases borrowed from Simon Badger).
- May update throughout the week.



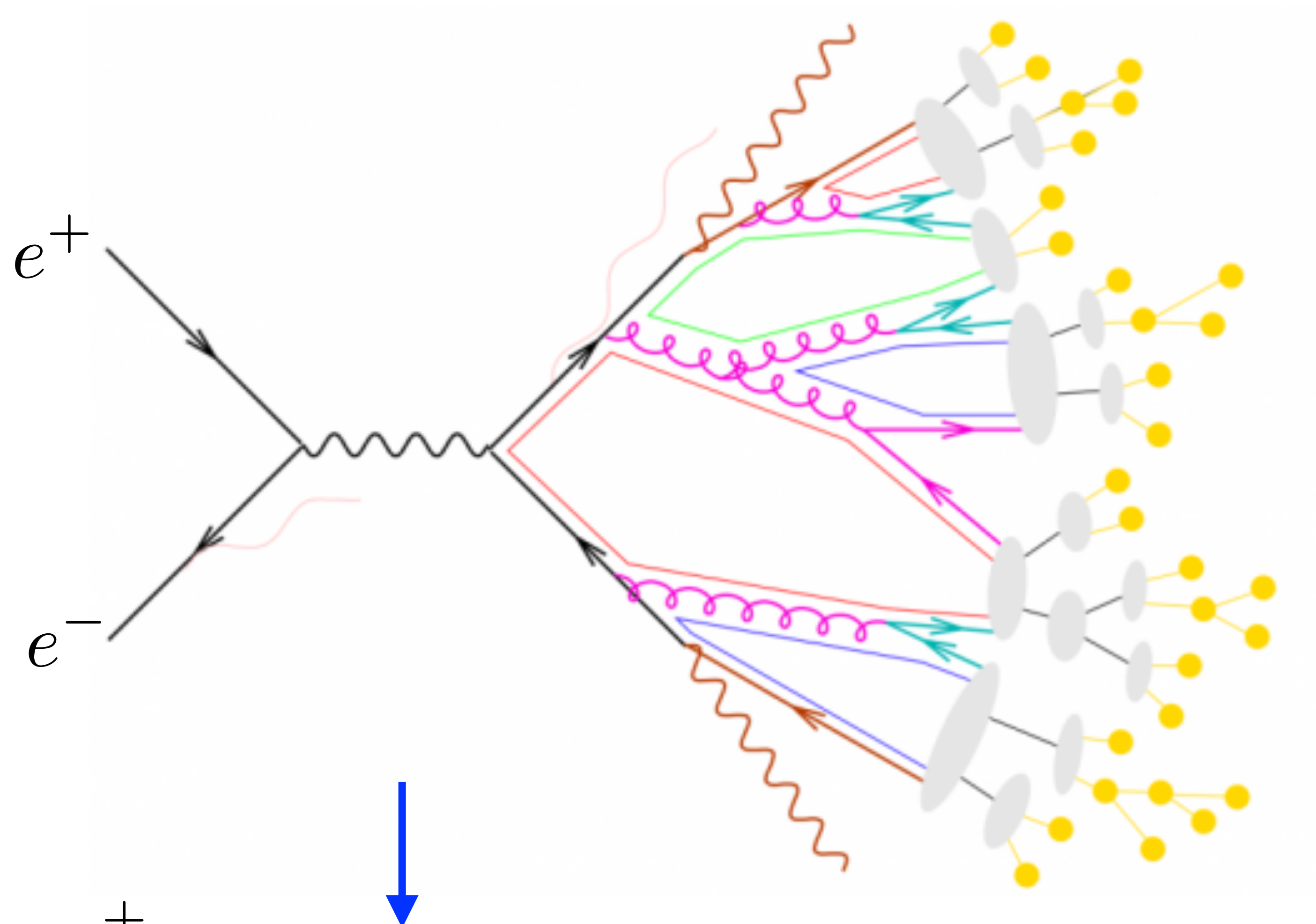
(2-jet) Event Display



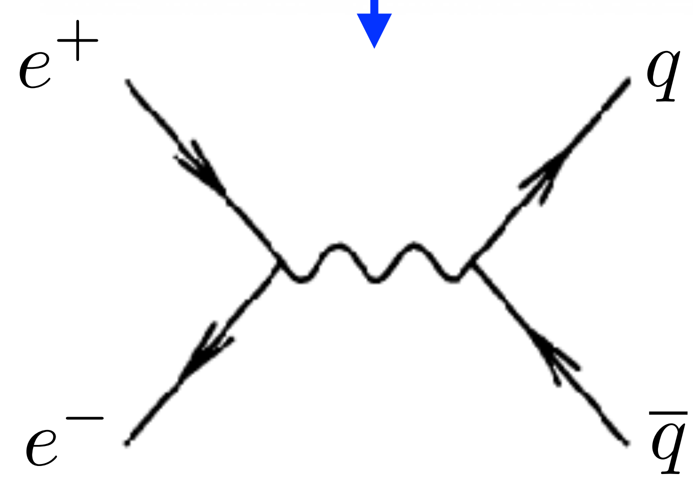
- Example event display from e^+e^- collisions.

R(hadrons/muons)

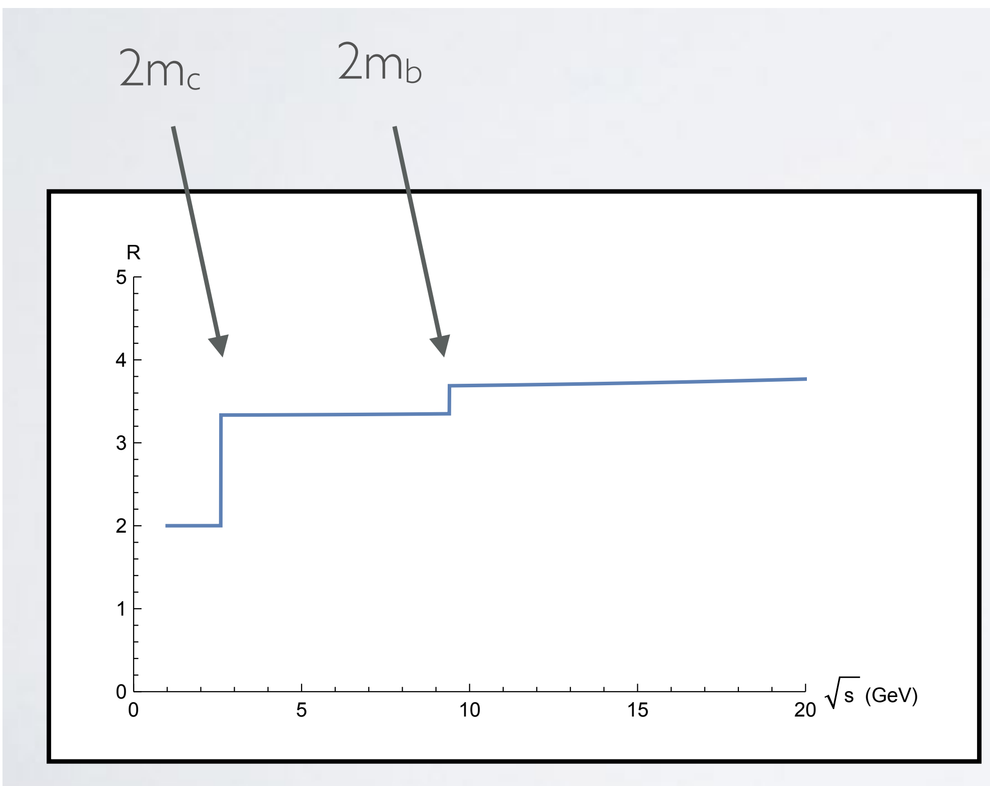
Full Event

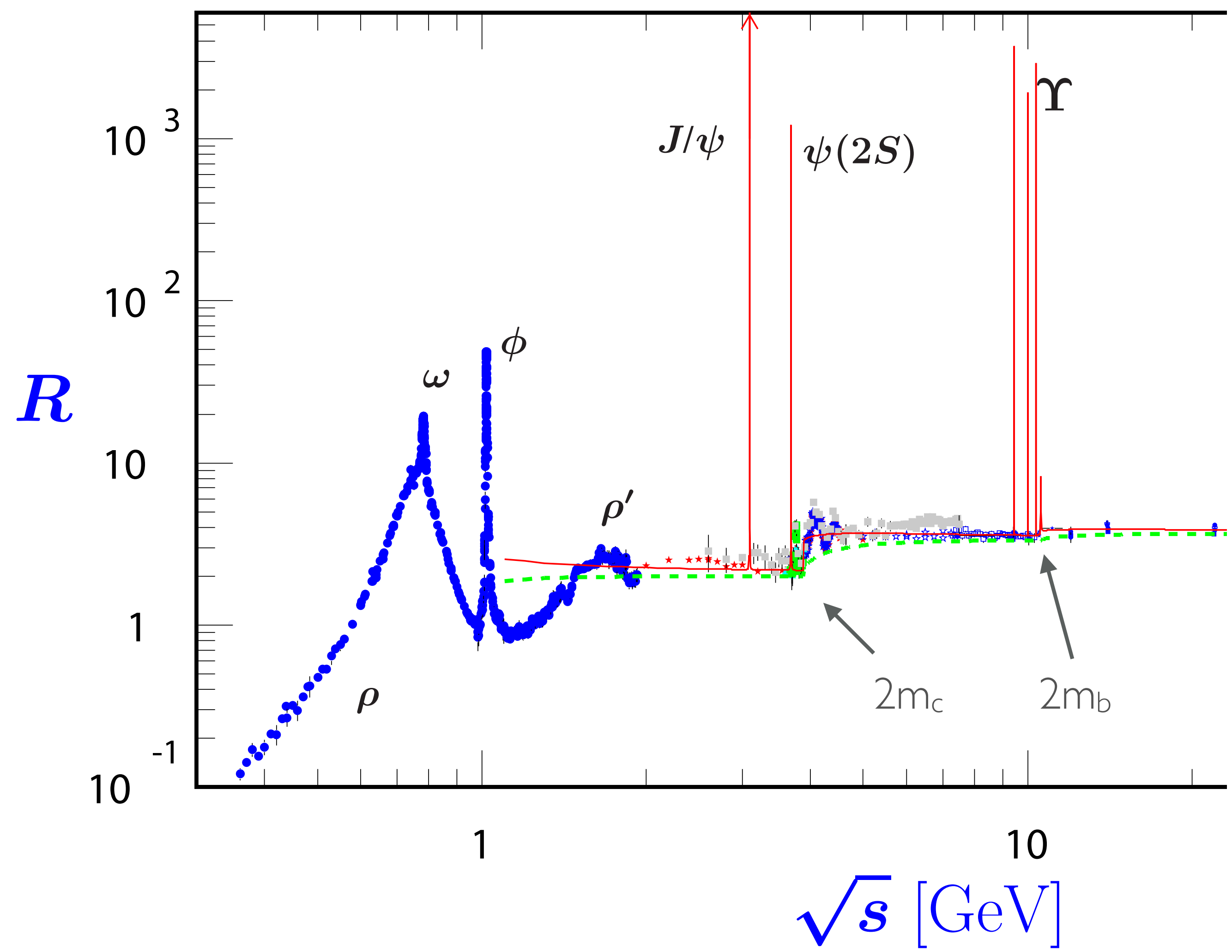


LO parton-level cross section



R(hadrons/muons)

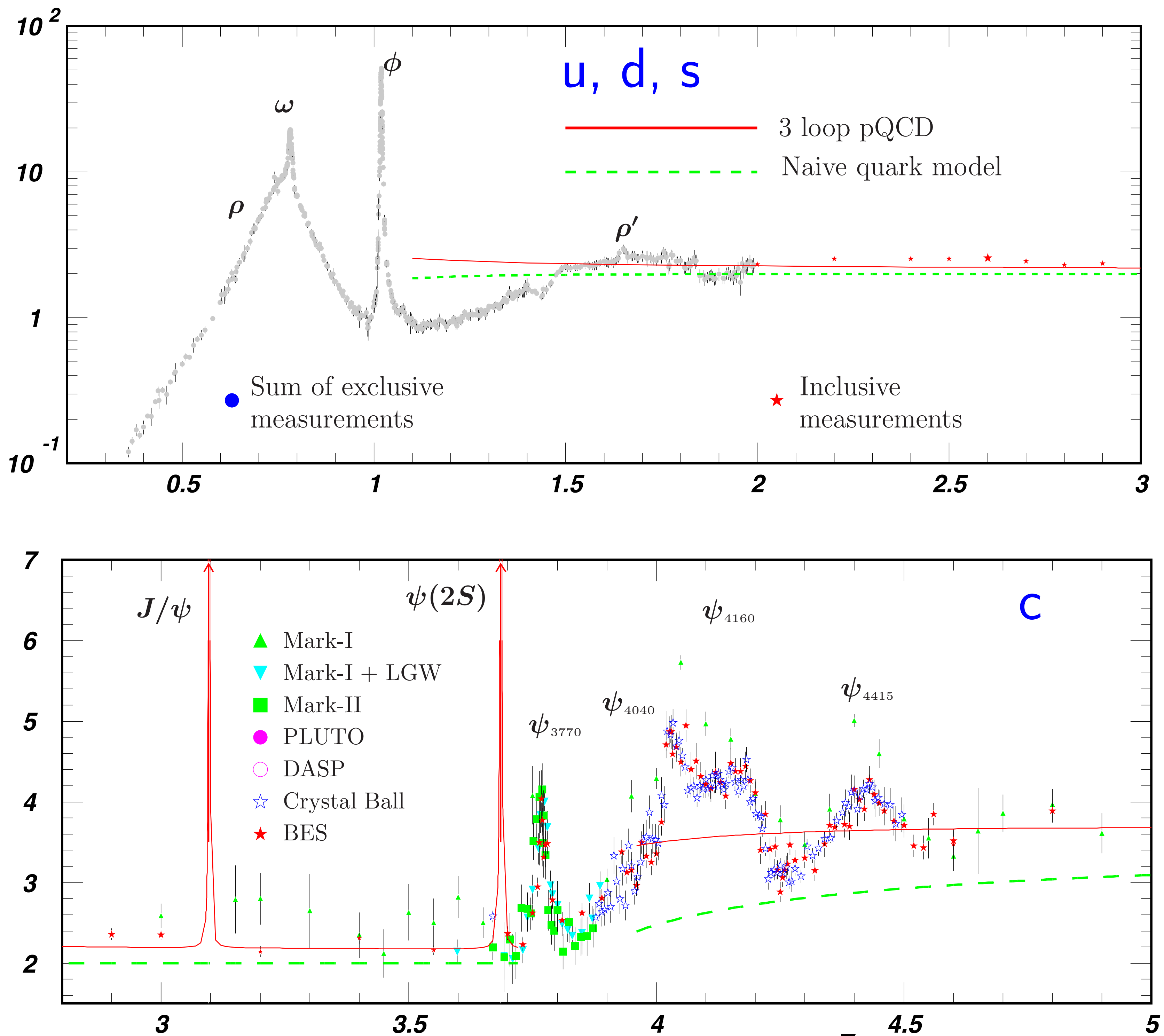




(Approx.!)
Theory

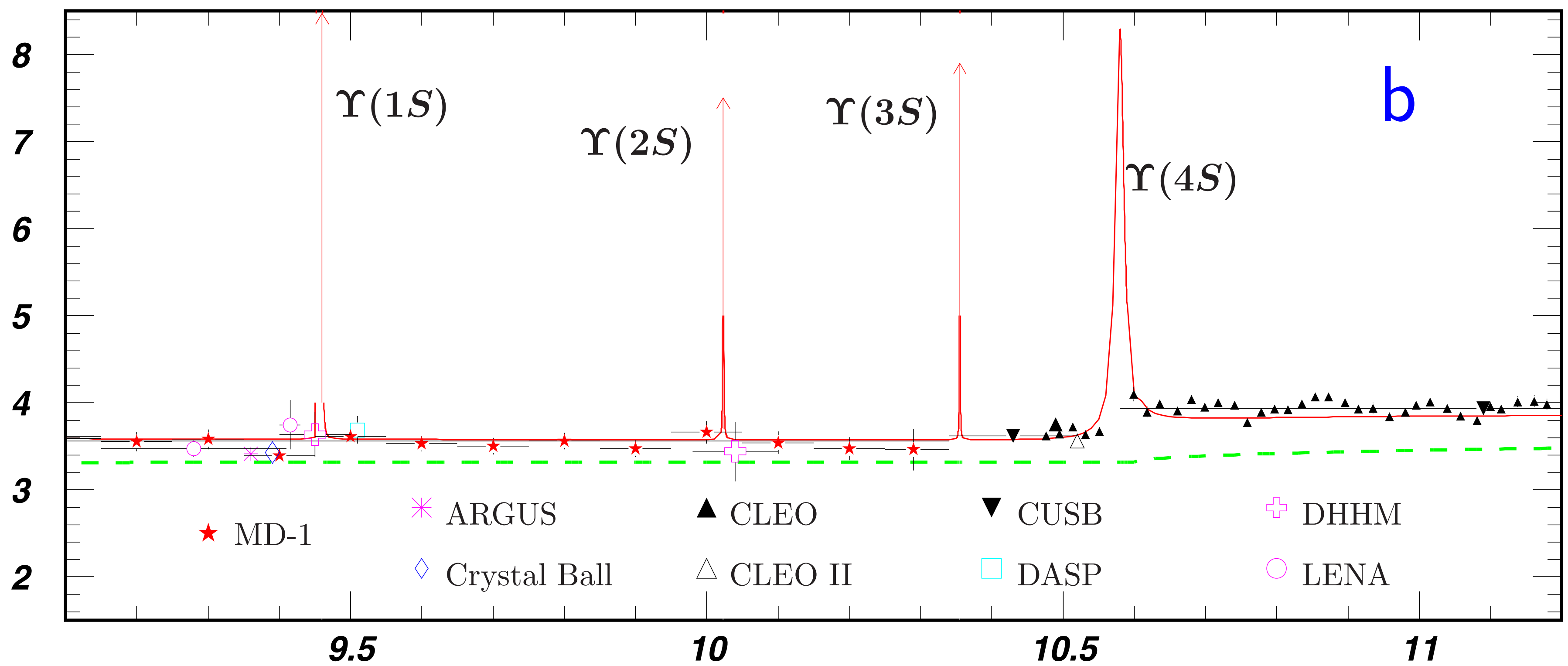
Data

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



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

- Data from last three slides:

Mark I/II @ SLAC (1974-1975)

PLUTO @ DESY (1974-1982)

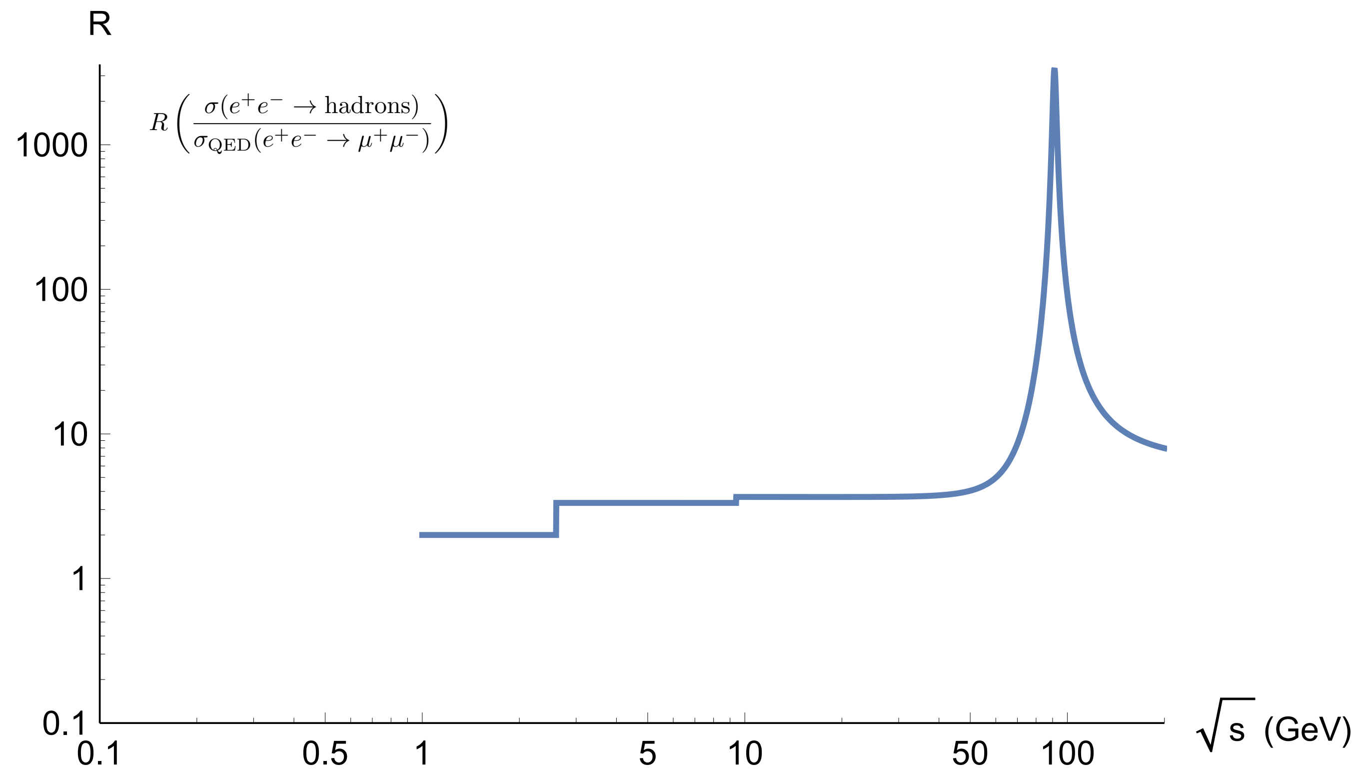
w/ DORIS I/II and PETRA

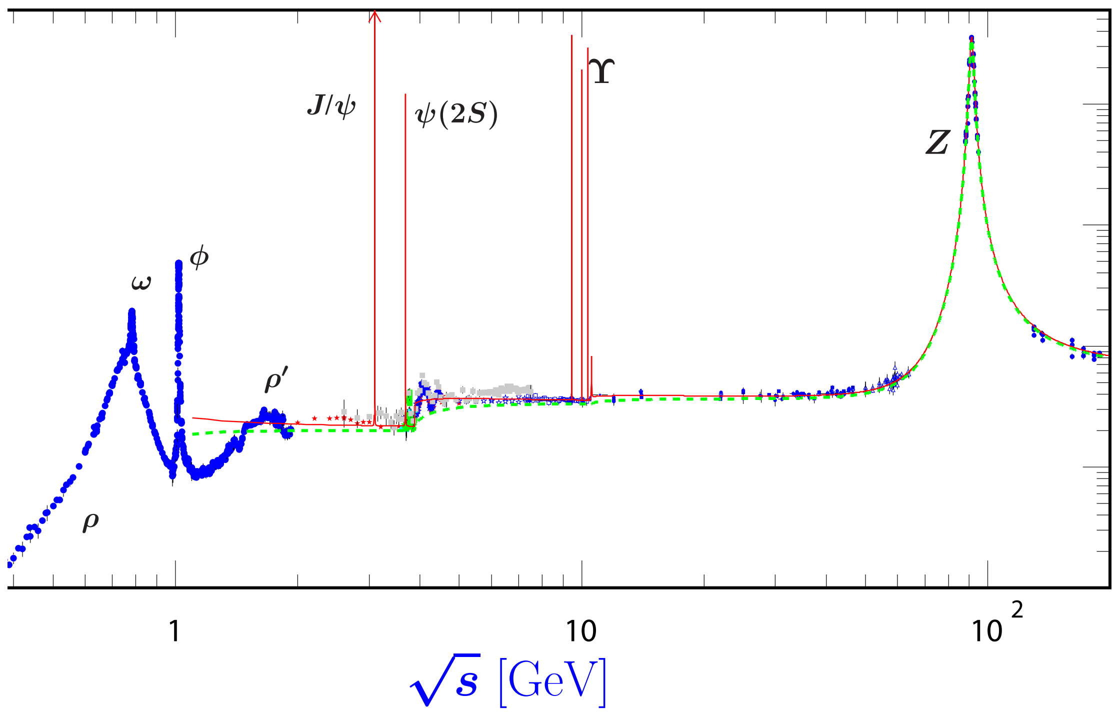
DASP @ DESY (1974-1982)

w/ DORIS I

BES @ BEPC (1995-)

R(hadrons/muons) - up to Z peak

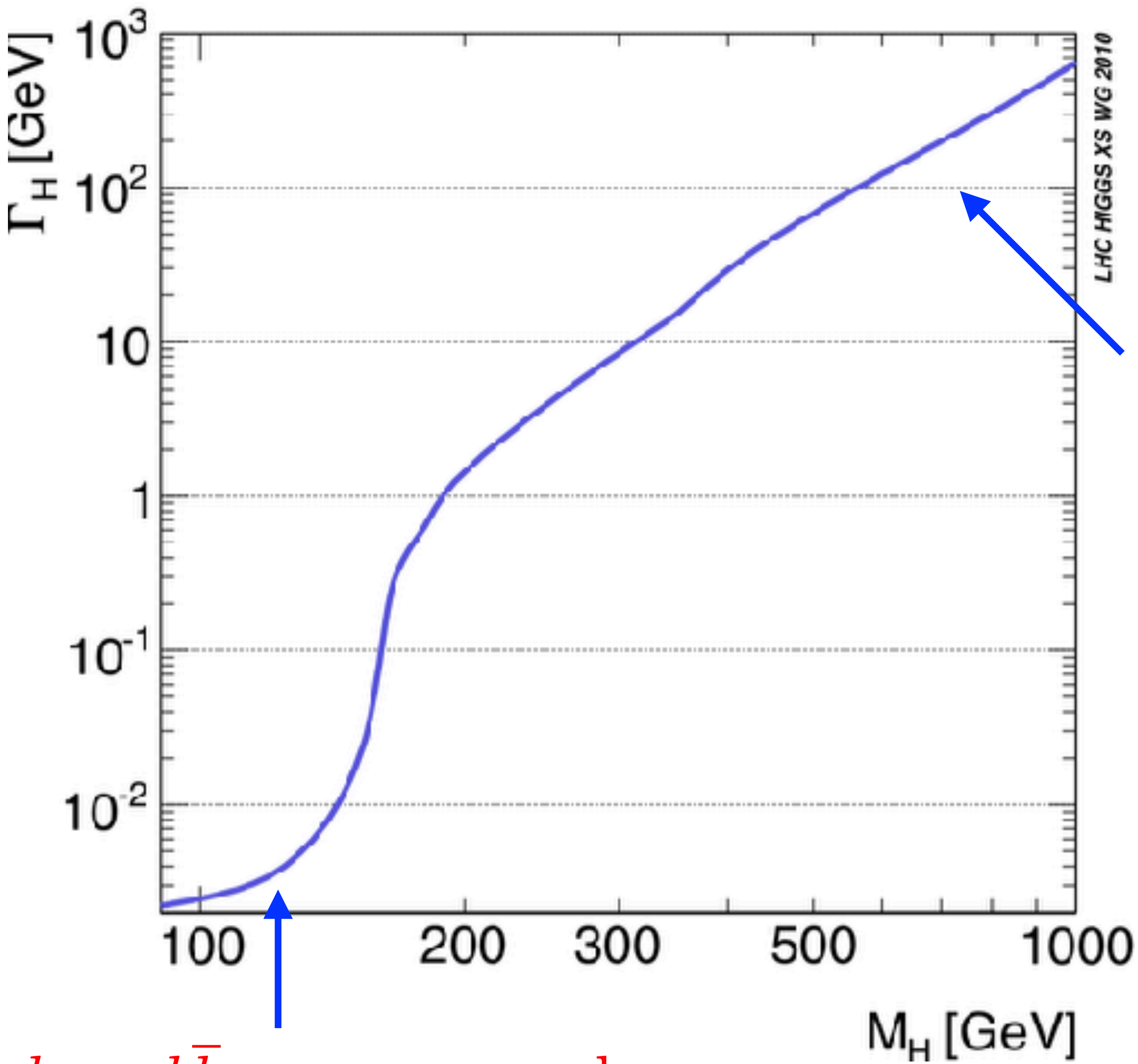




(Approx.!)
Theory

Data

Higgs Width



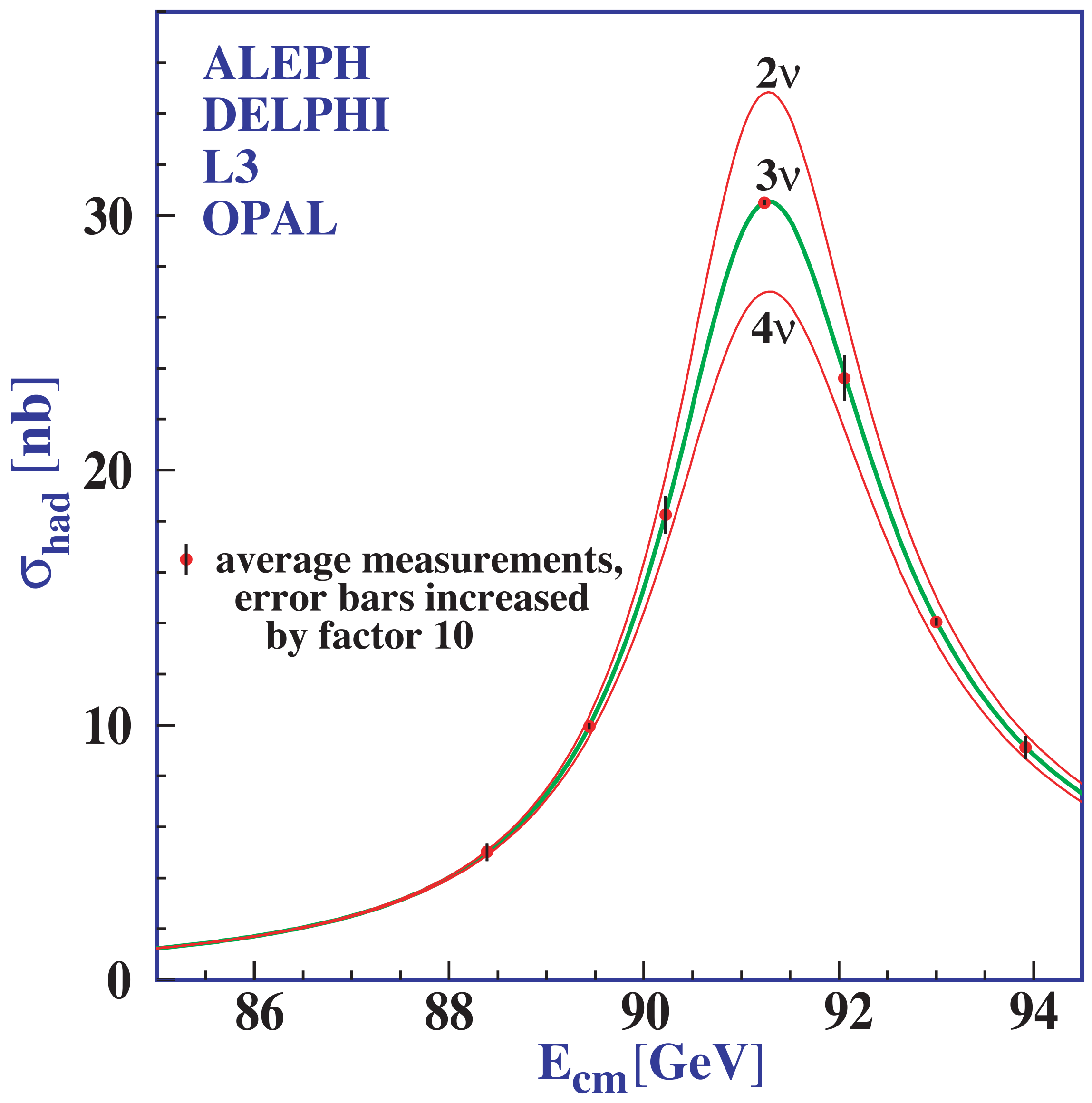
$h \to WW(ZZ)$: broad peak

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

Sigma(hadronic) - Z peak

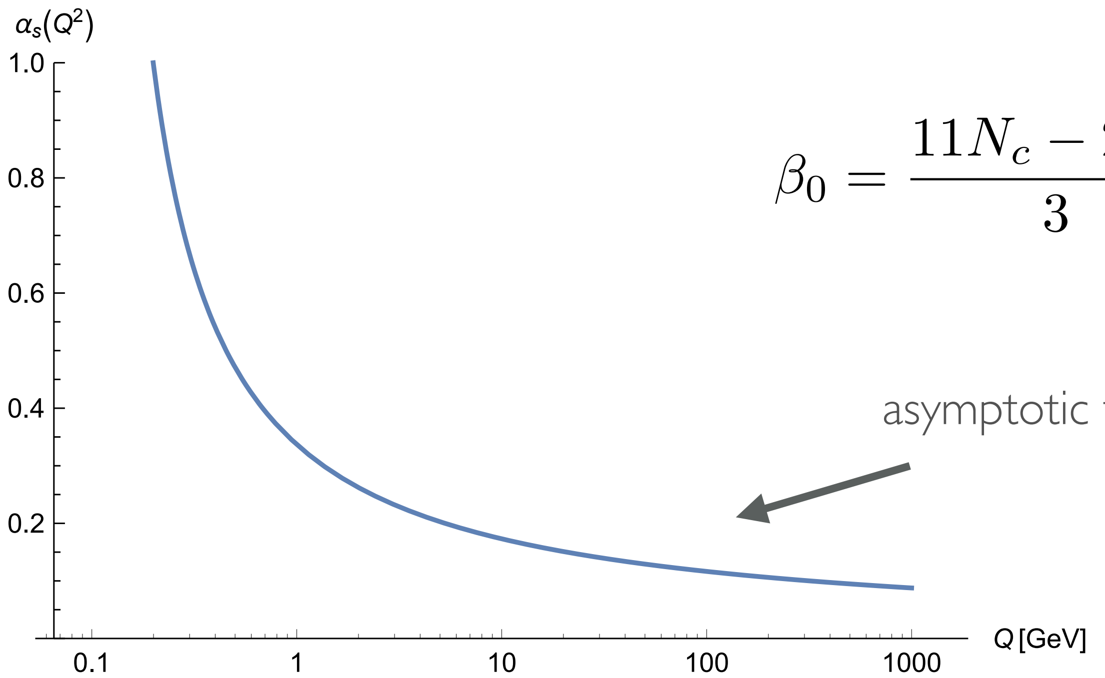
$$\sigma_Z \sim \frac{s^2}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}$$

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



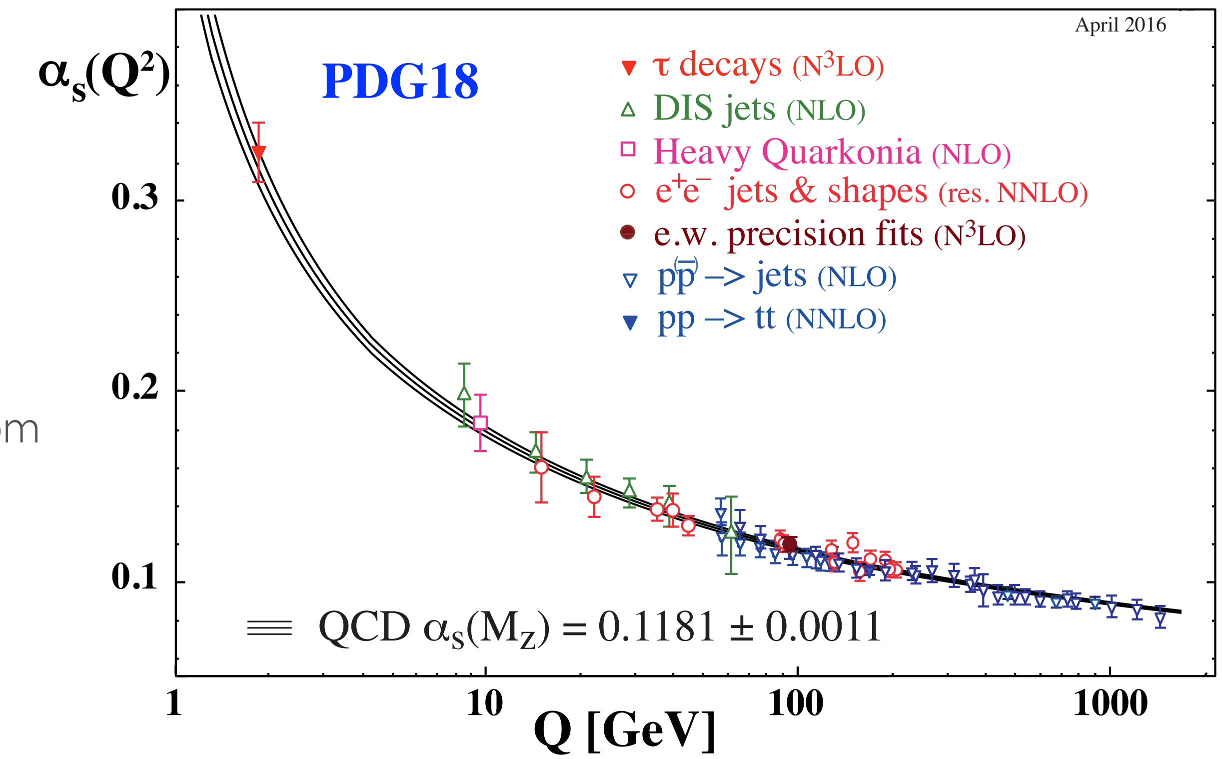
- Clear evidence for 3 light neutrino families ($2m_\nu < M_Z$).

Running (Strong) Coupling



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

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

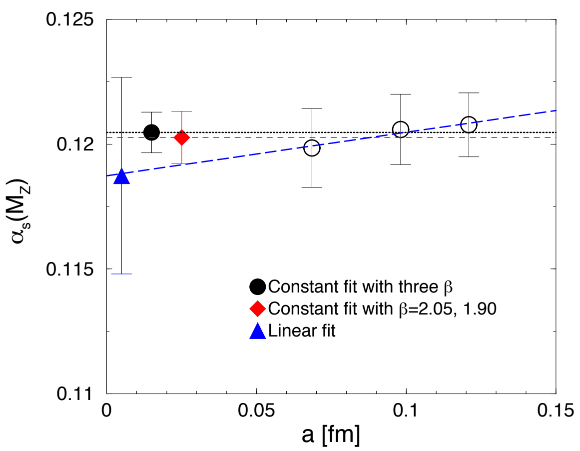


(Approx.!) Theory

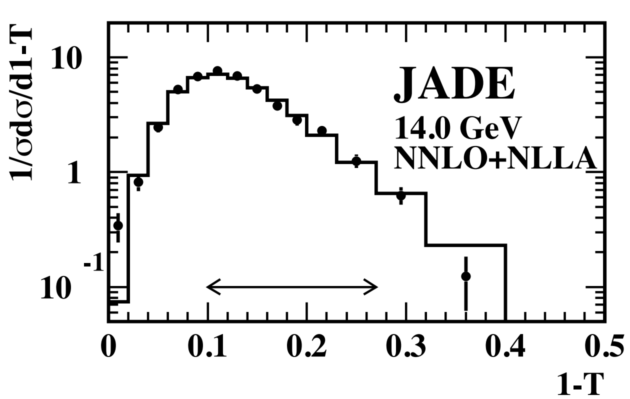
Data + Theory

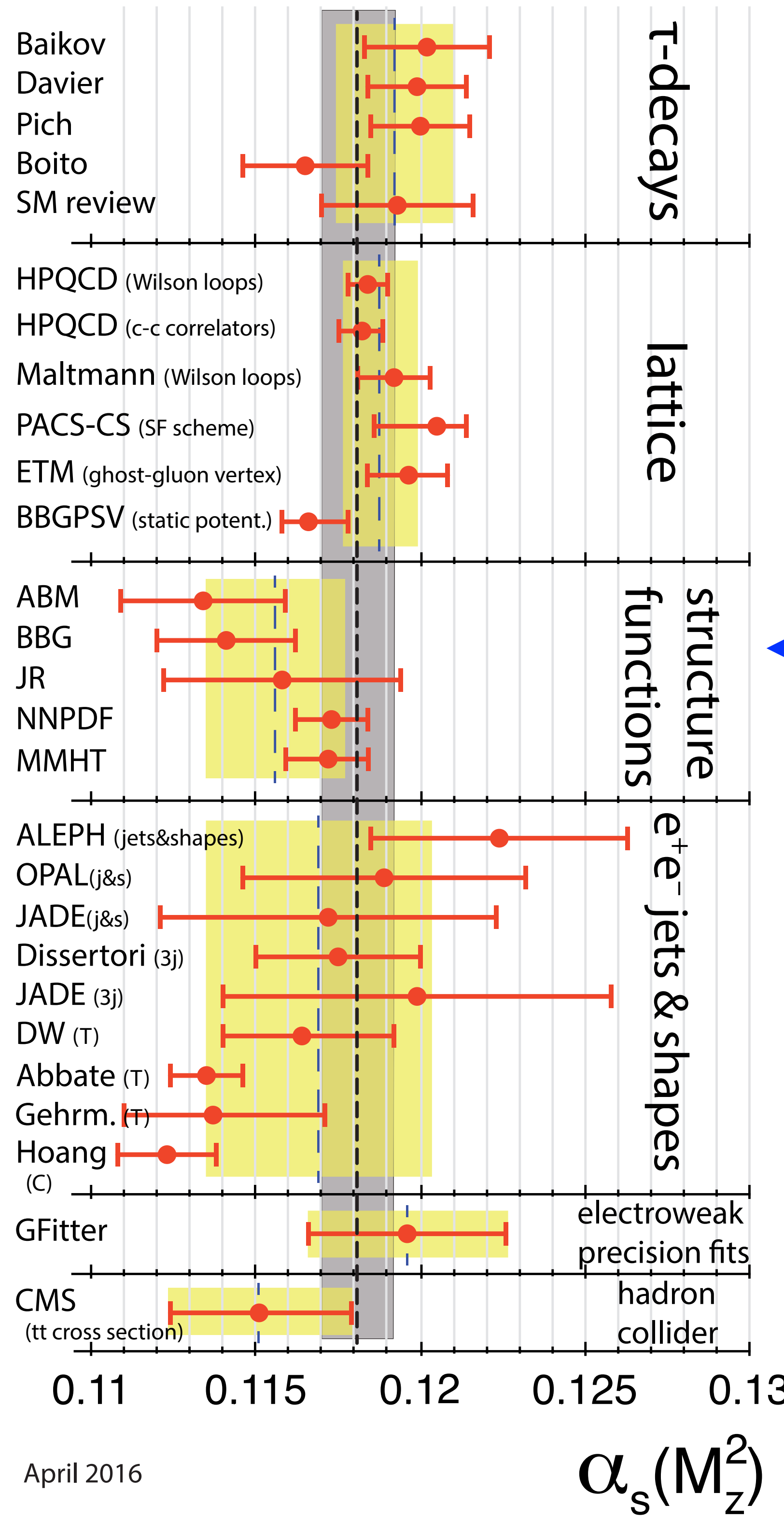
Strong Coupling Determination

arXiv:0906.3906

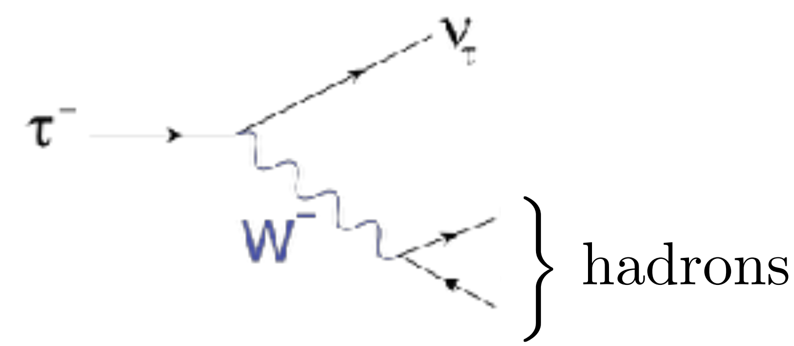


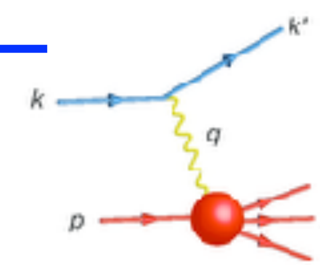
arXiv:0810.1389

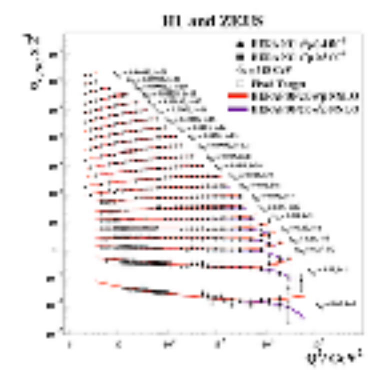




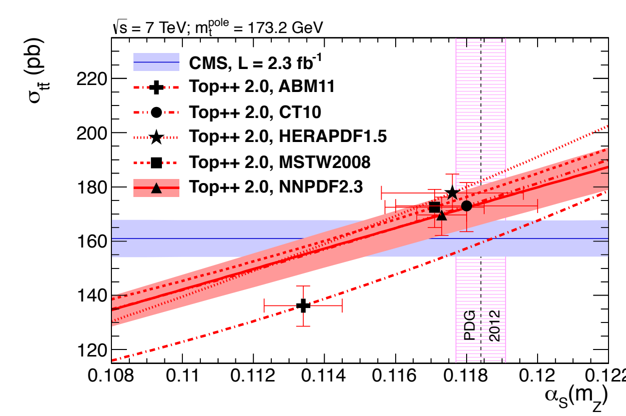
$$R_\tau \equiv \frac{\Gamma[\tau^- \to \text{hadrons}\,\nu_\tau(\gamma)]}{\Gamma[\tau^- \to e^-\overline{\nu}_e\nu_\tau(\gamma)]}$$







arXiv:1307.1907

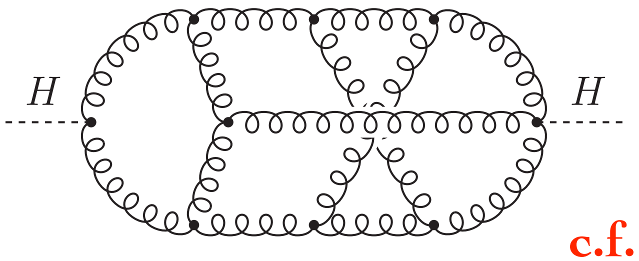


$$\alpha_s(M_Z^2) = 0.1181 \pm 0.0011$$

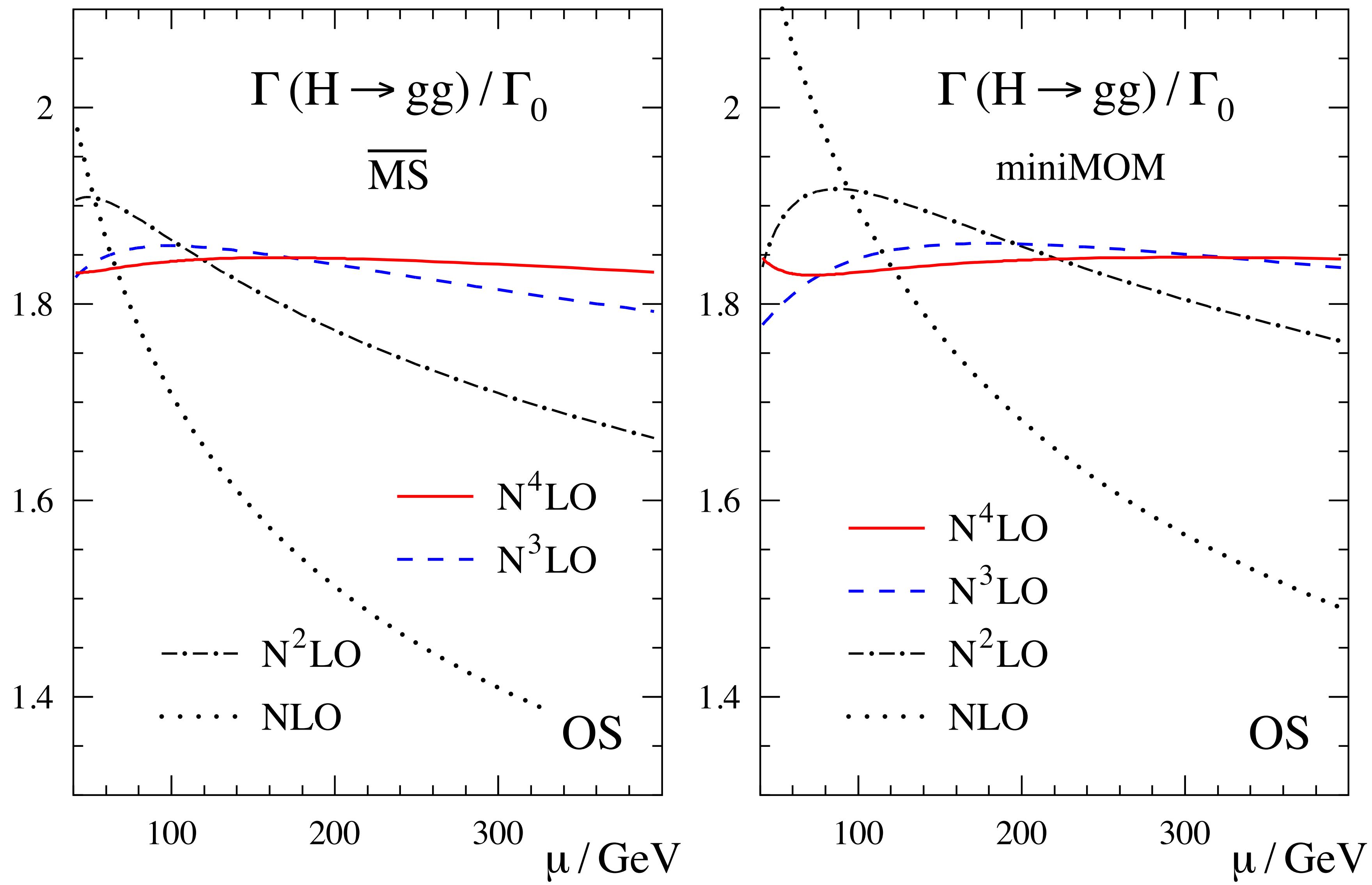
Renormalization Scale Dependence

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

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



c.f. optical theorem

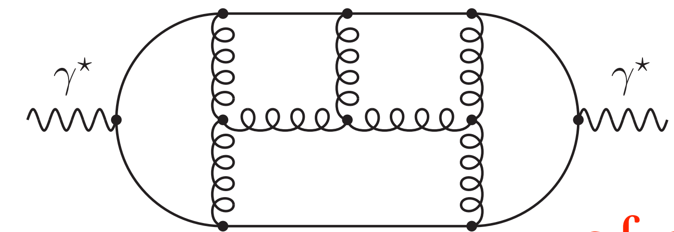


- Decreasing dependence on μ_R and scheme with increasing order.

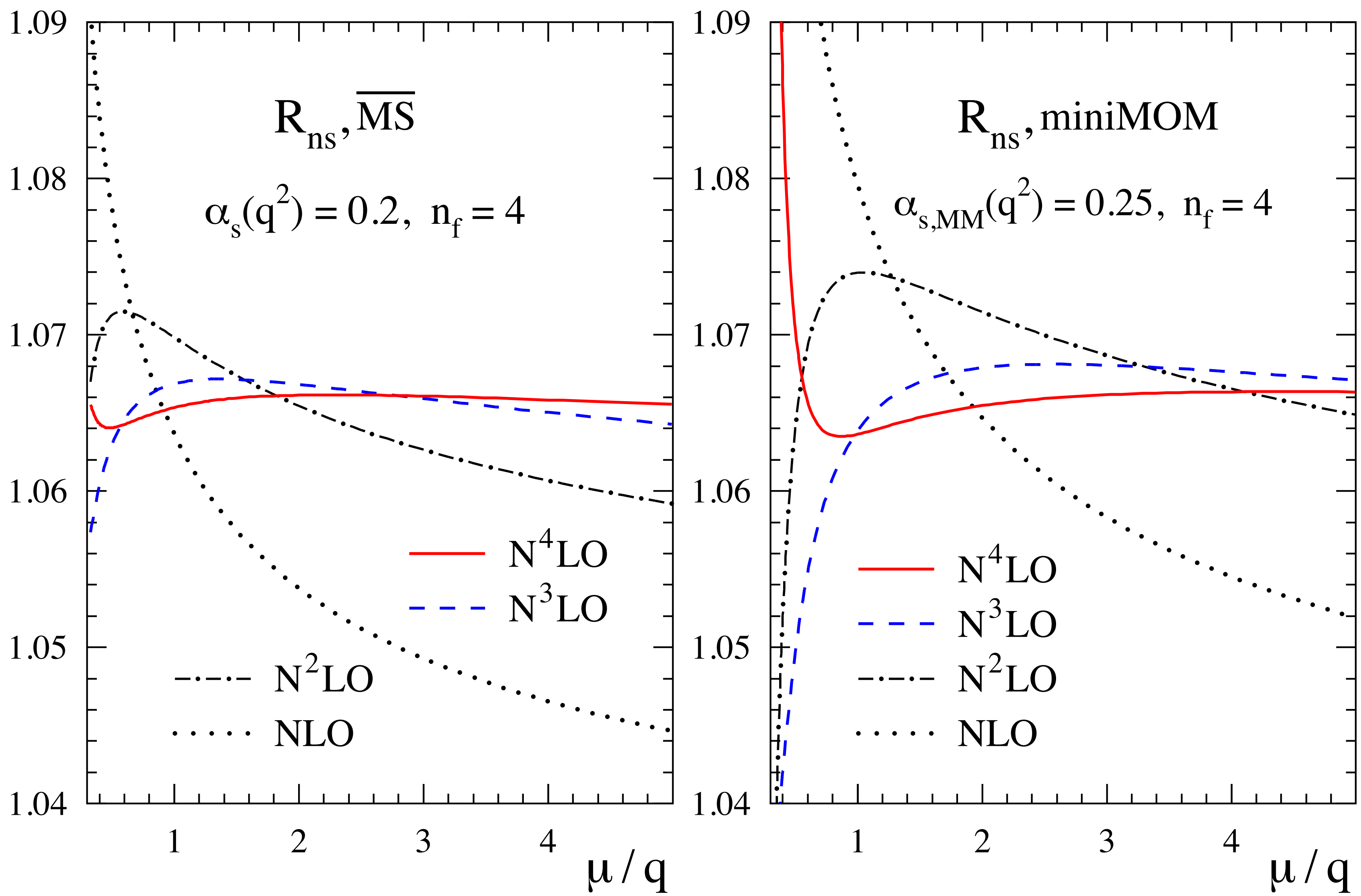
Renormalization Scale Dependence

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

Up to $O(\alpha_S^4)$ corrections to R(hadrons/muons):



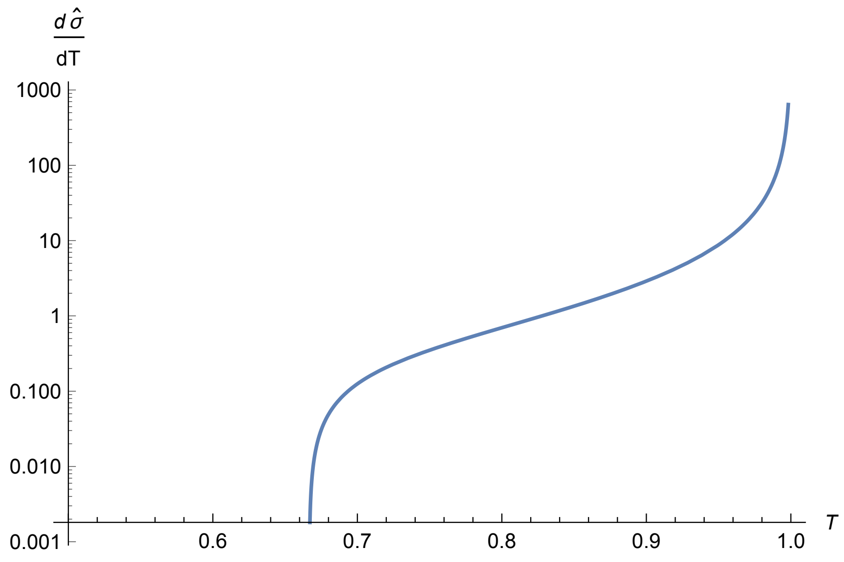
c.f. optical theorem



- Decreasing dependence on μ_R and scheme with increasing order.

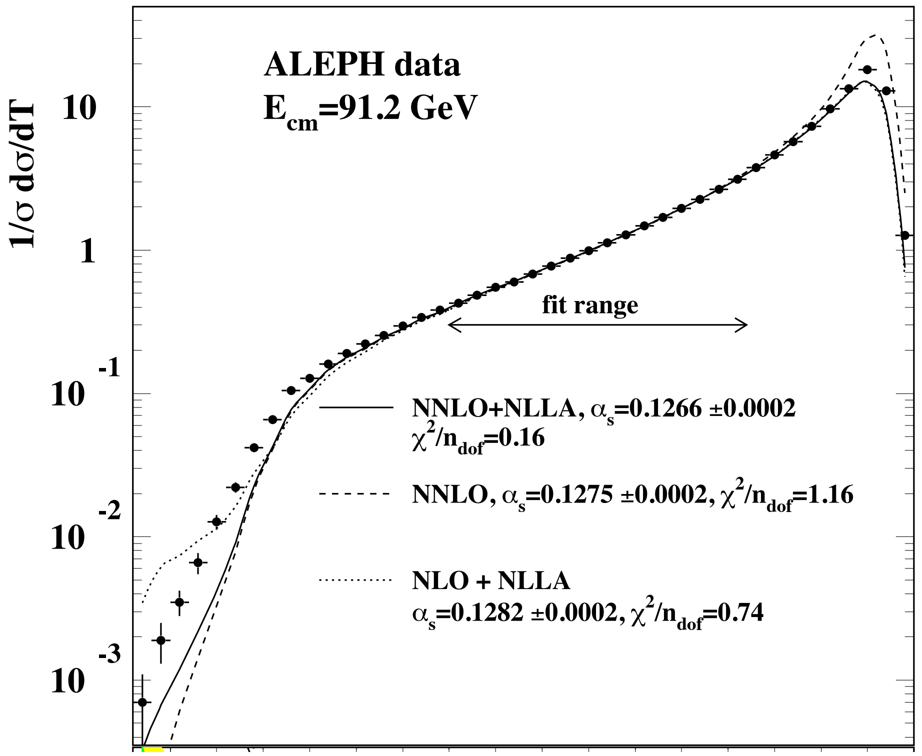
Thrust

- Basic (LO in QCD) expectation:



arXiv:0906.3436

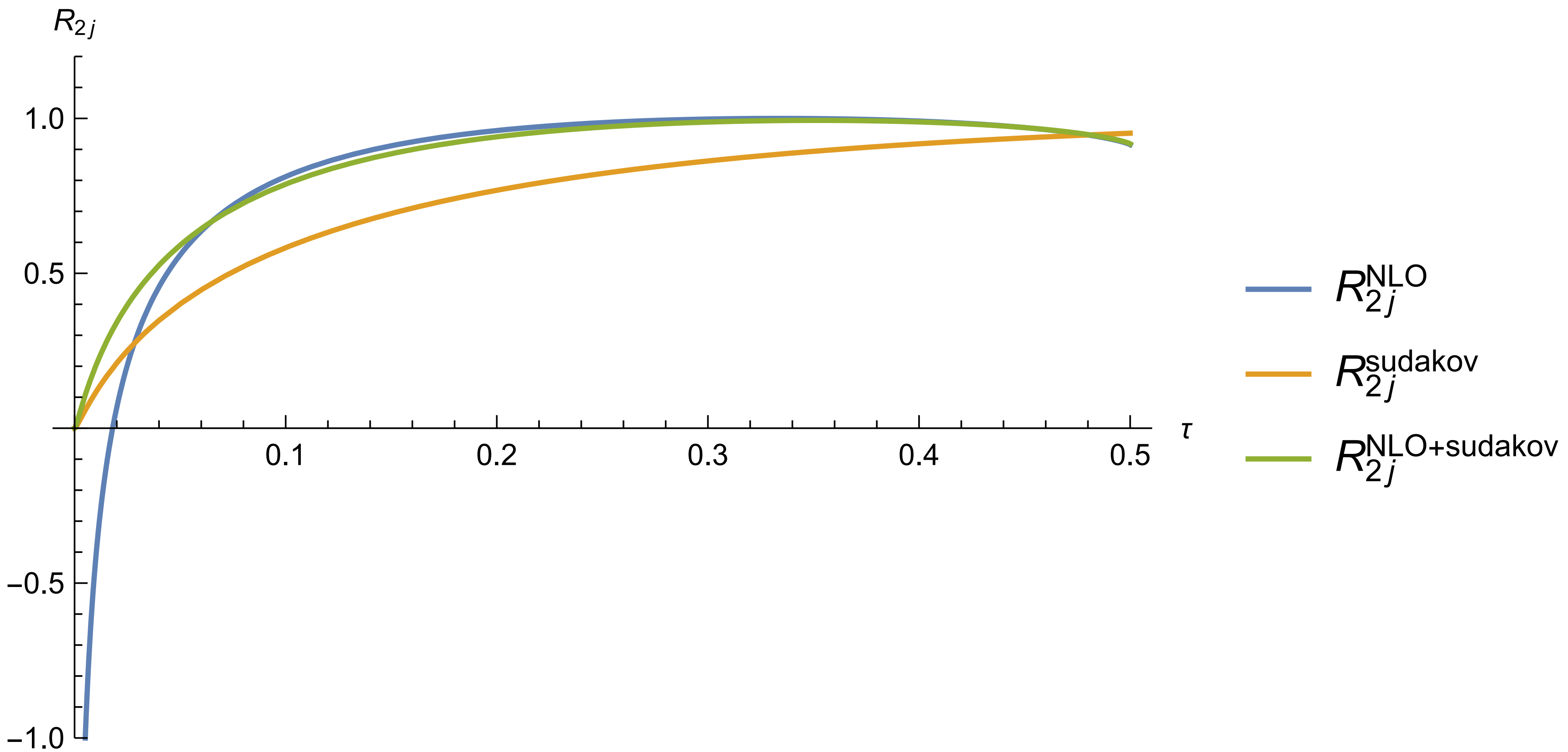
- Modern (NNLO in QCD + NLL resummation) result vs. data.



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

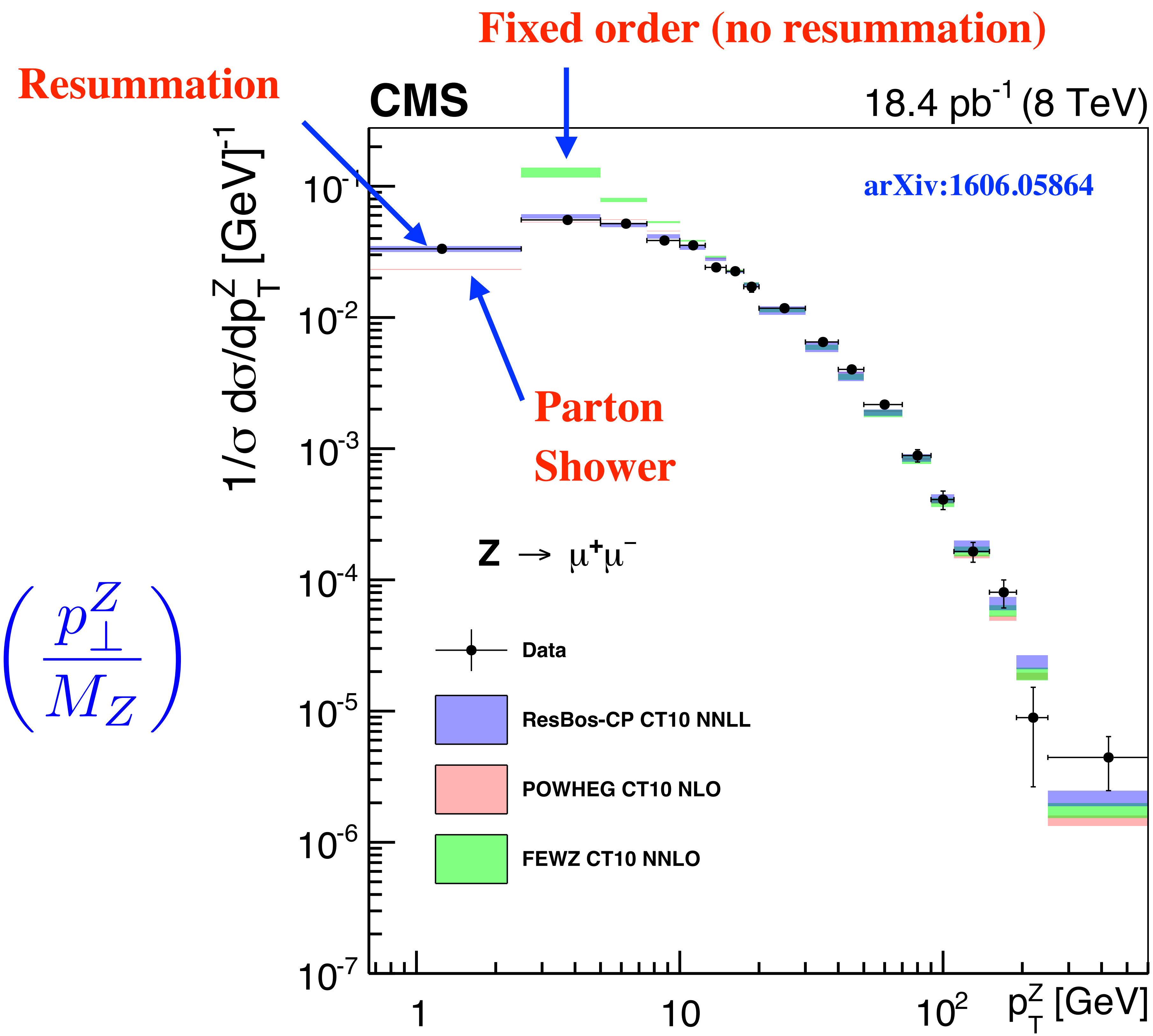
Thrust - Resummed Prediction

- Impact of resummation: including Sudakov form factor.

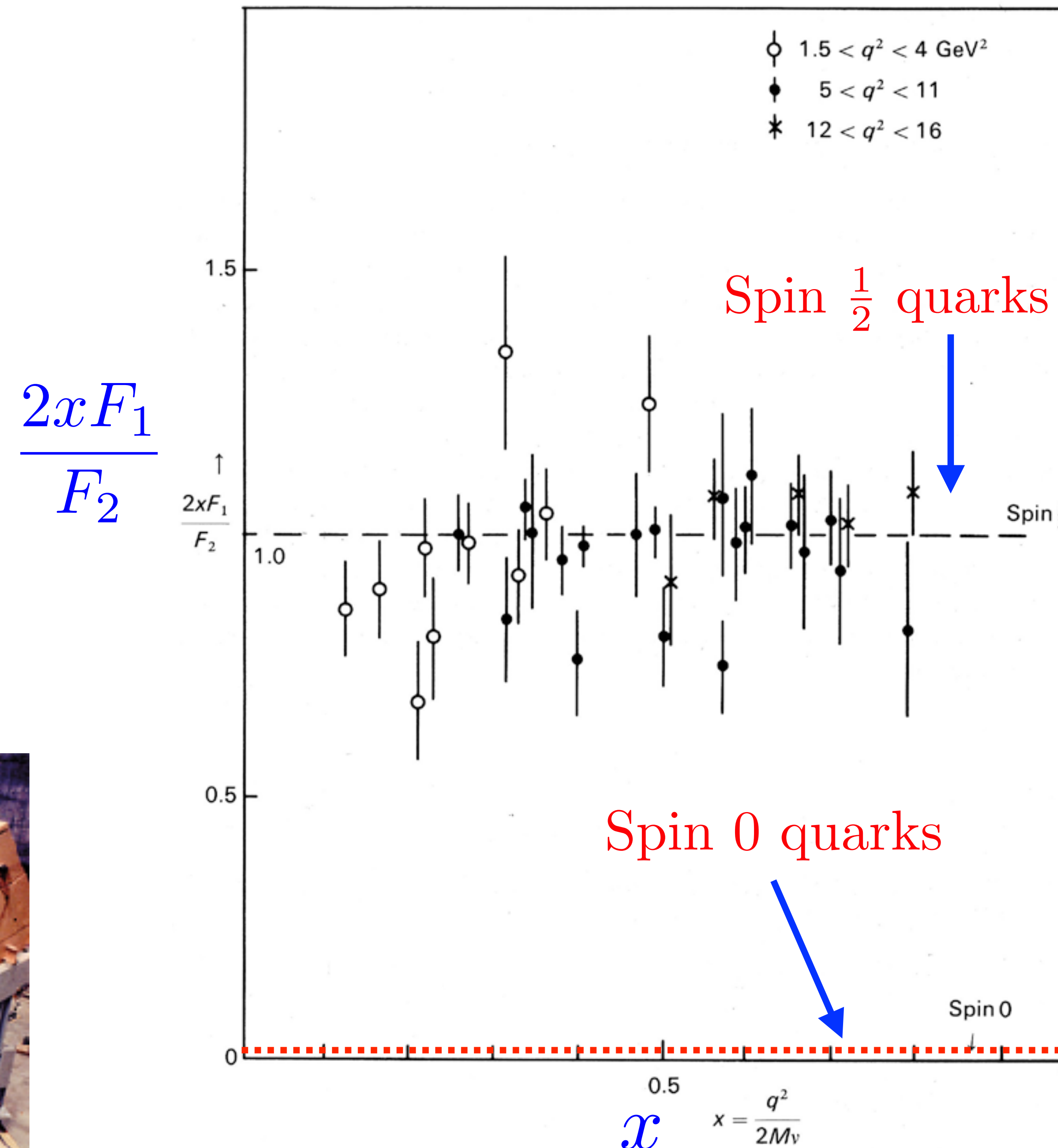


Resummation - Z transverse momentum

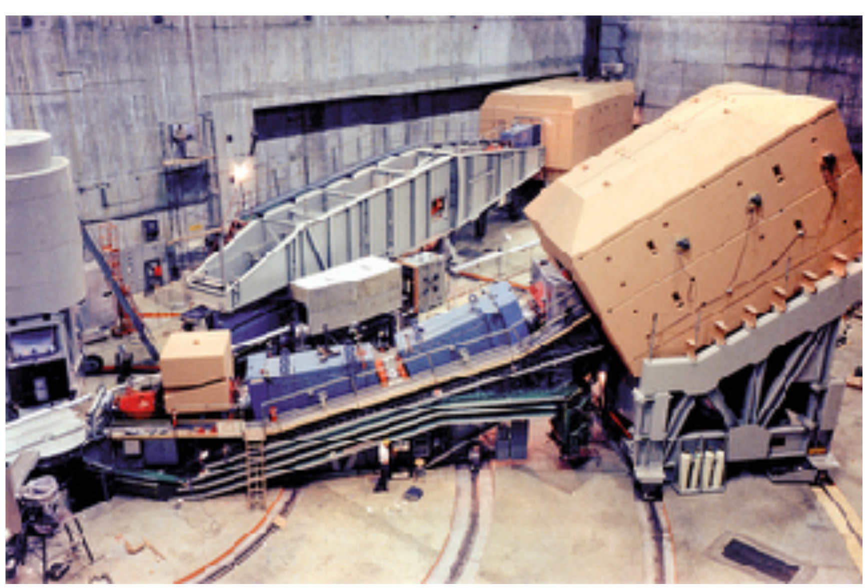
$$\sigma \sim \ln\left(\frac{p_\perp^Z}{M_Z}\right)$$



Callan-Gross Relation



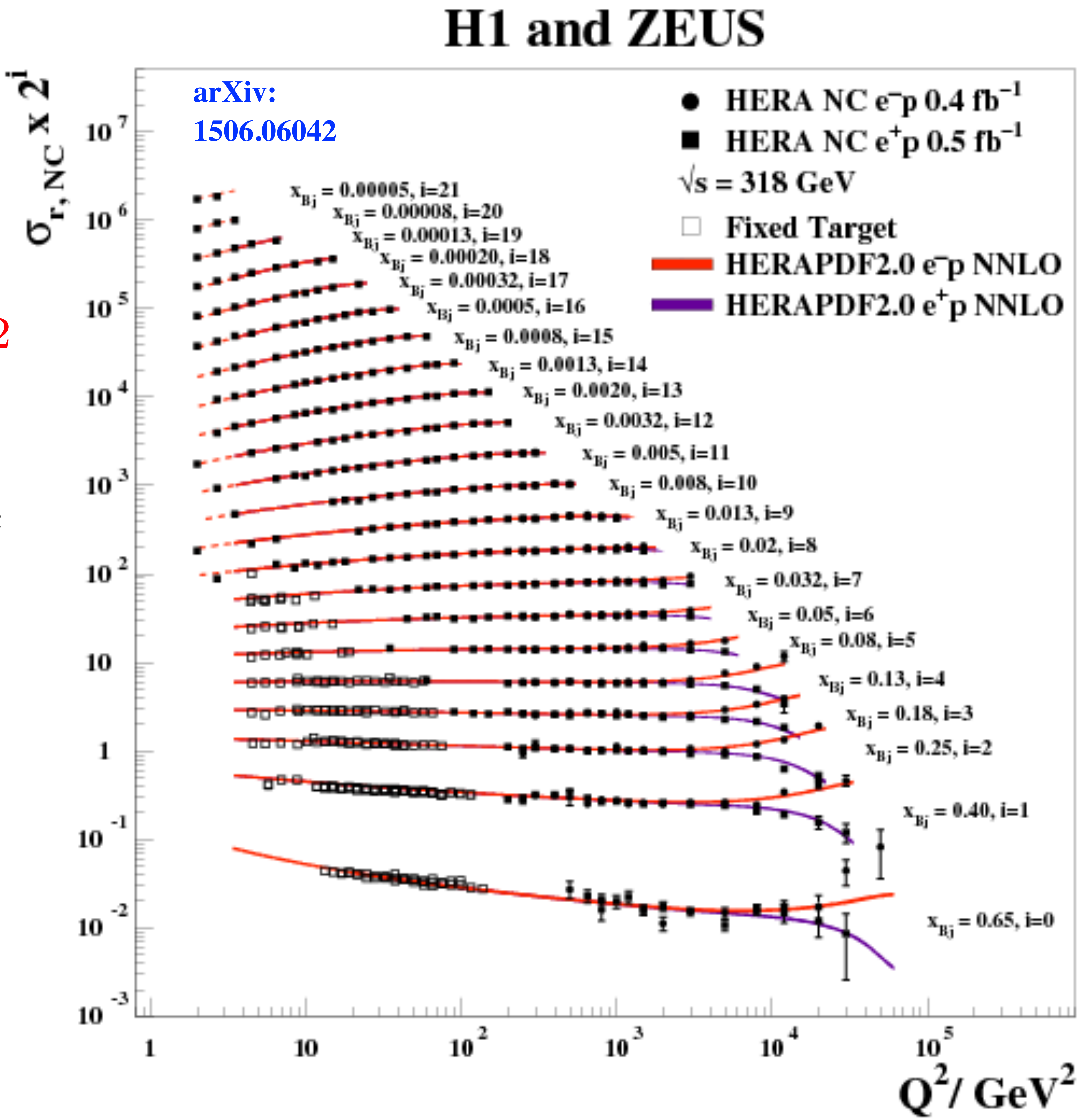
Data from SLAC



Bjorken Scaling

$\propto F_2$

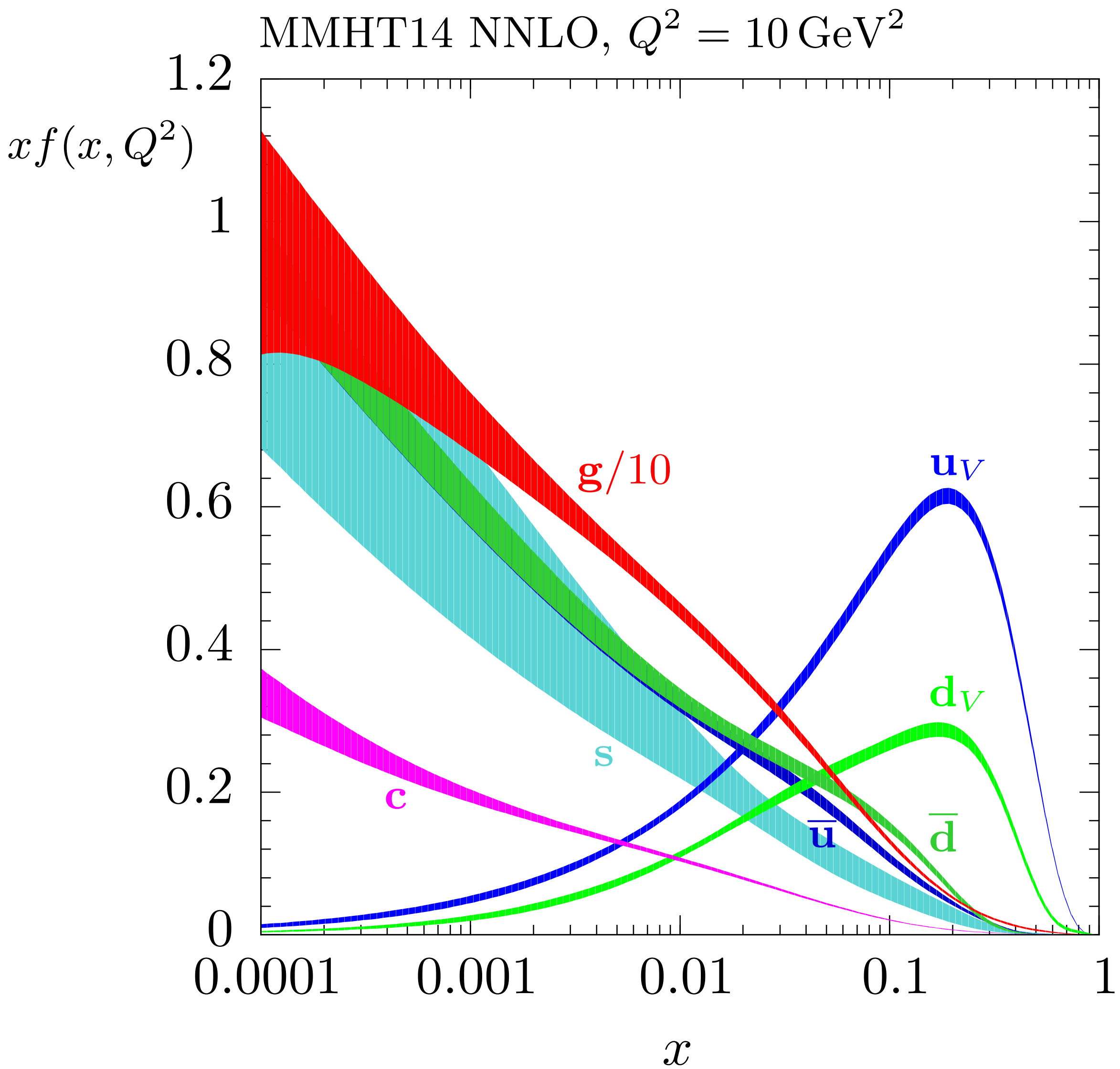
- Roughly flat with Q^2 but not exactly!

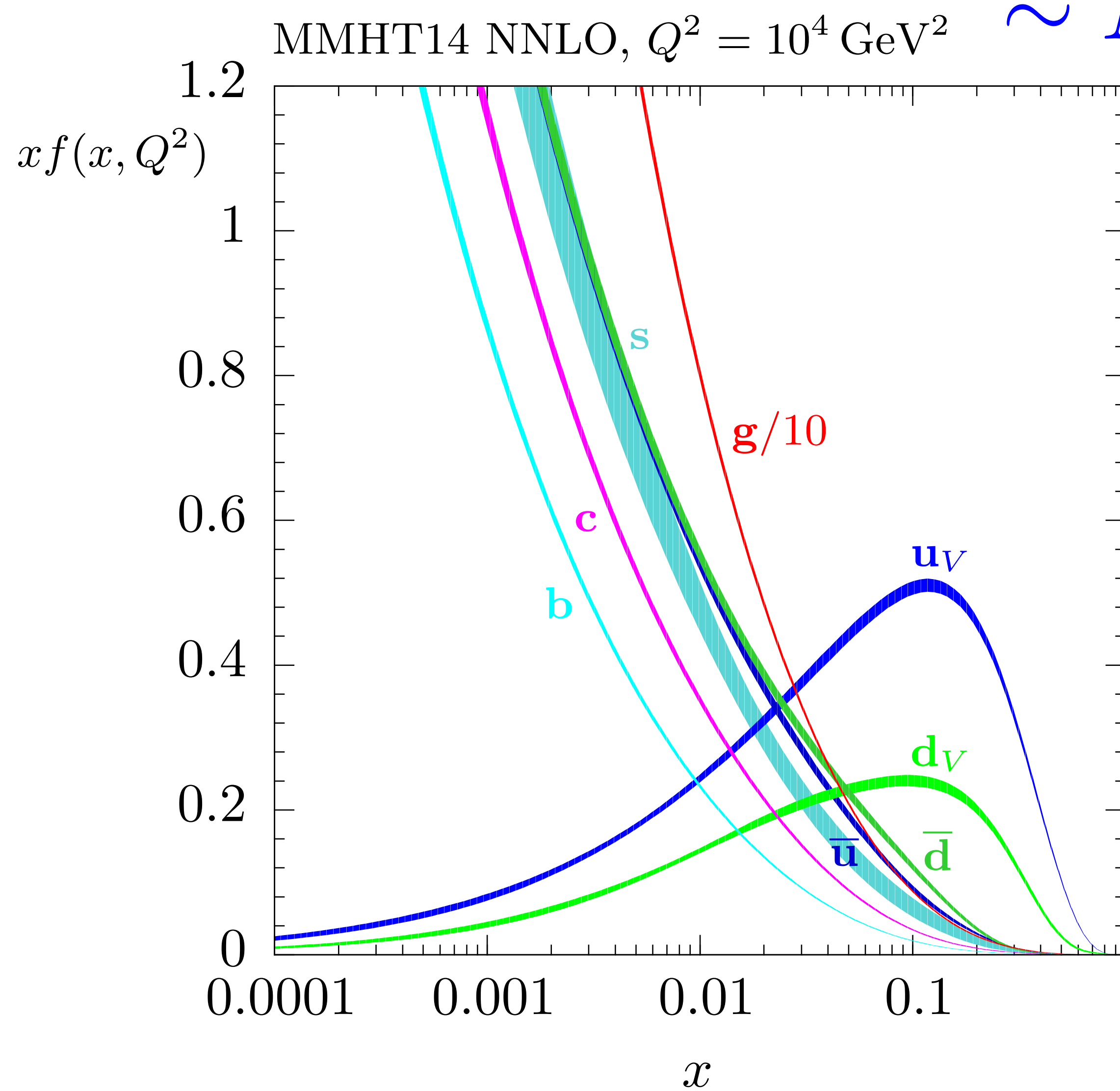


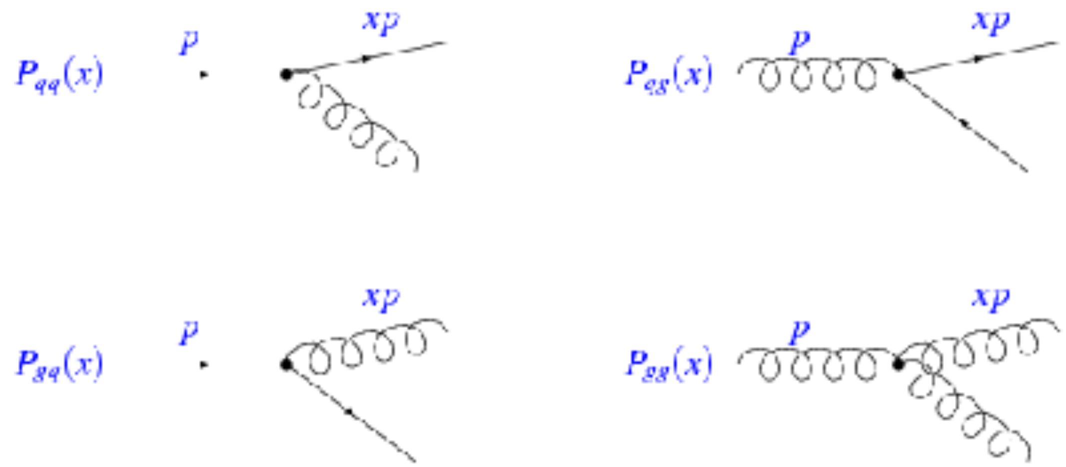
PDFs & DGLAP

Increase Scale (DGLAP) →

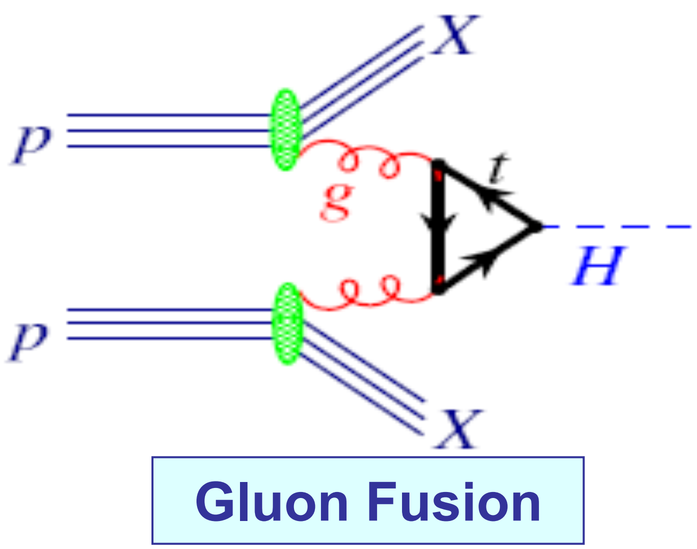
$\sim M_Z^2$

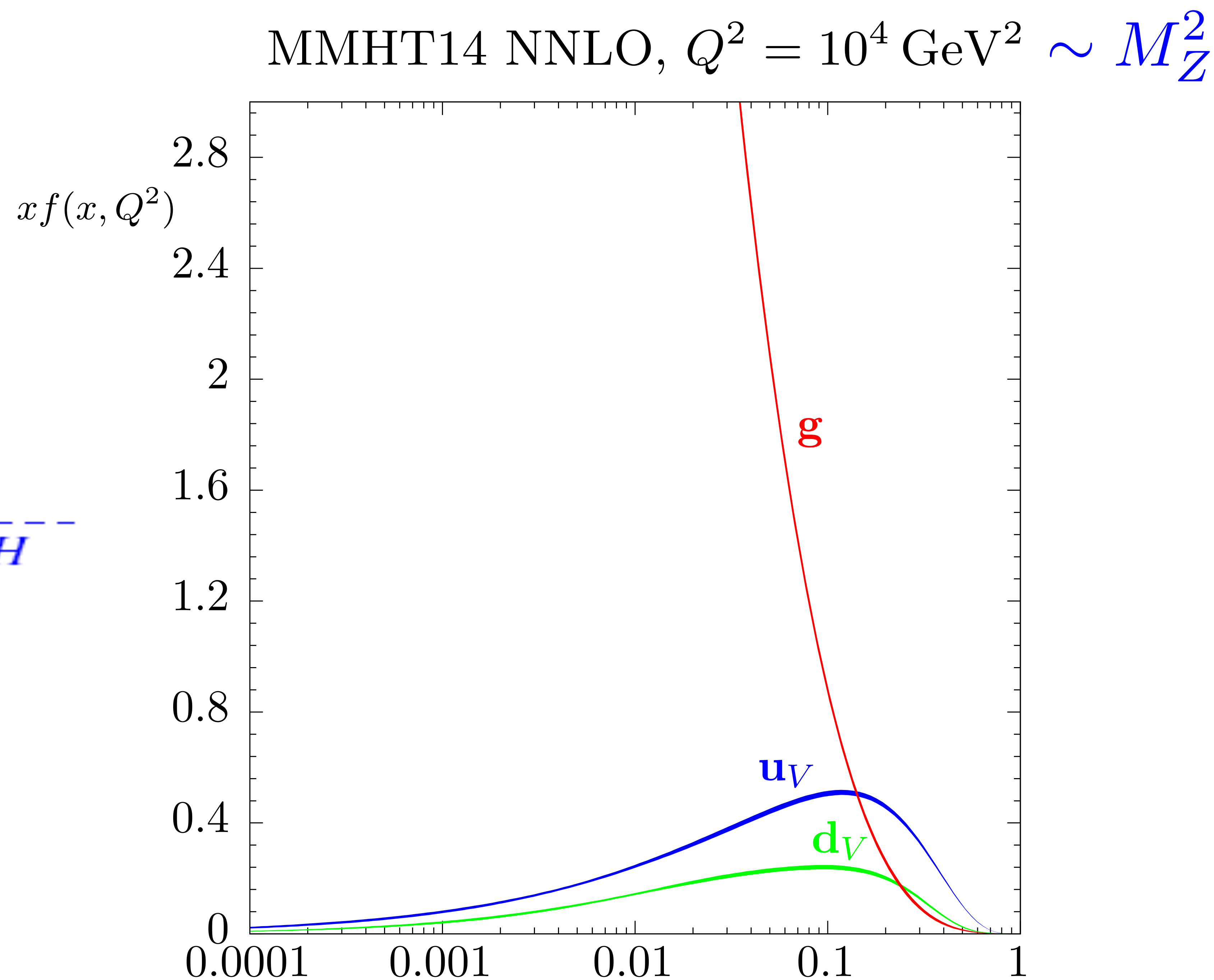






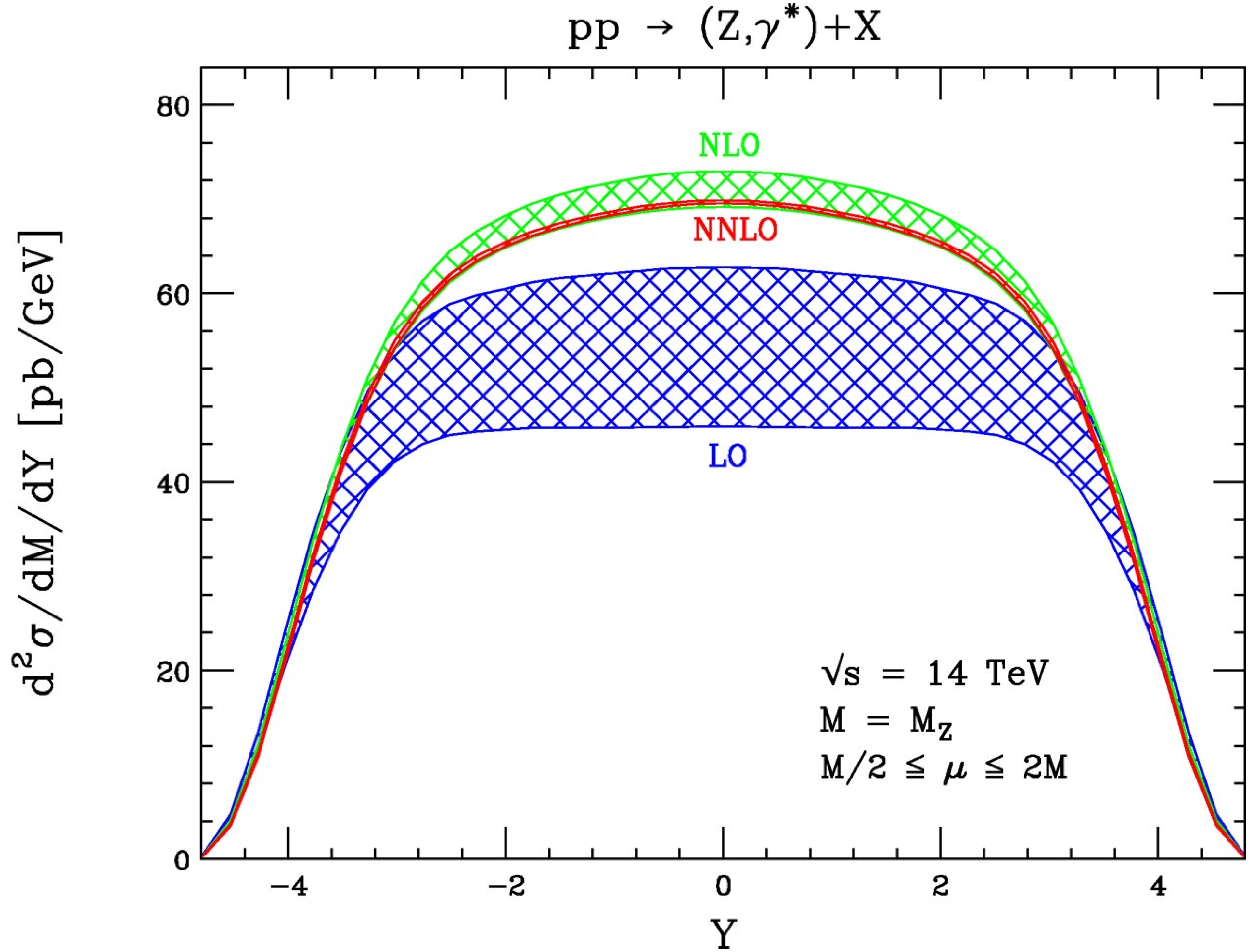
The Proton @ LHC: Mostly Gluons





(Keeping just valence quarks + gluon for clarity)

Drell-Yan



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

PDF Fits

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

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

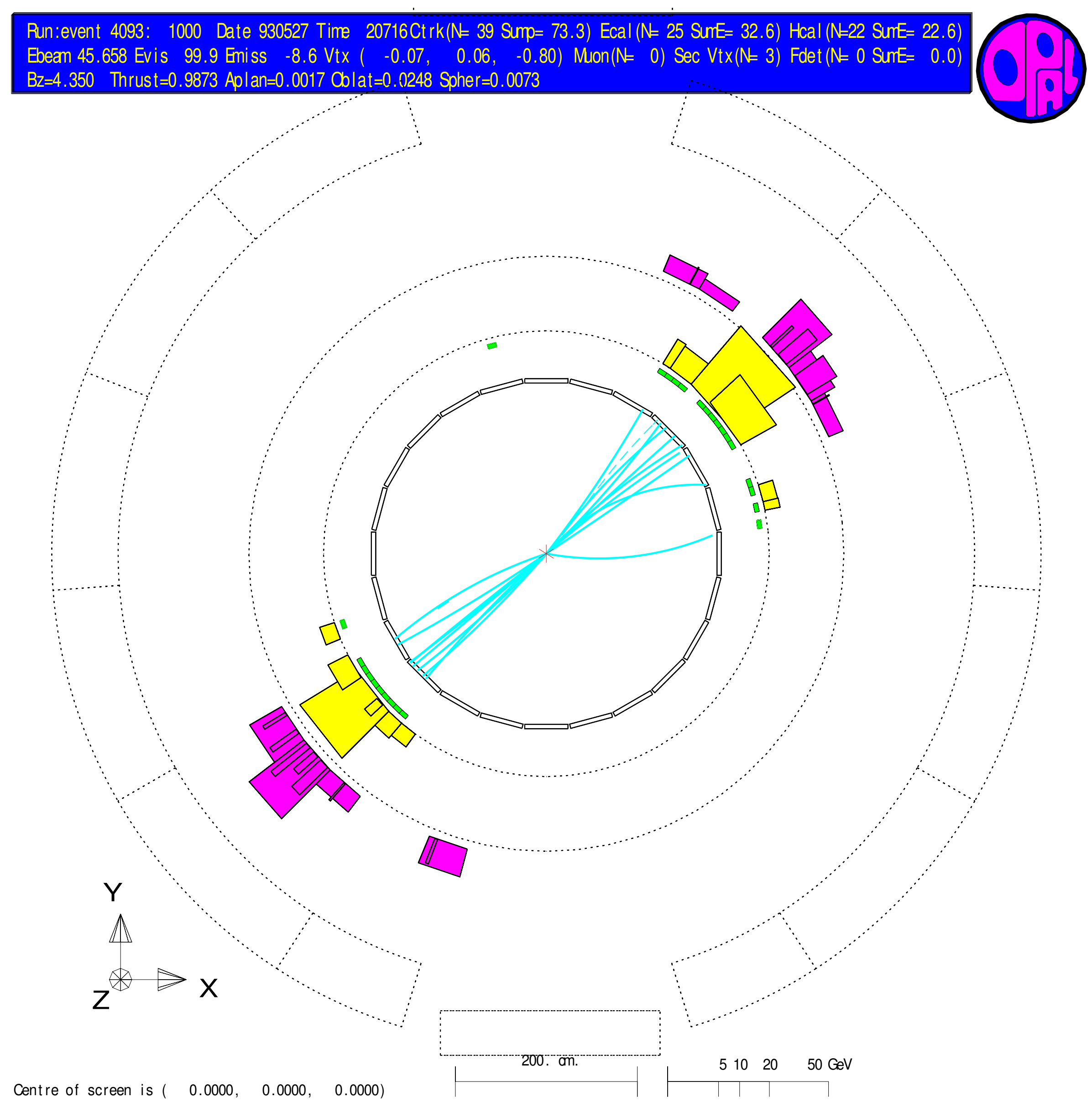
LHC

$\chi^2/\mathrm{N_{pts}} \sim 1!$

MMHT14

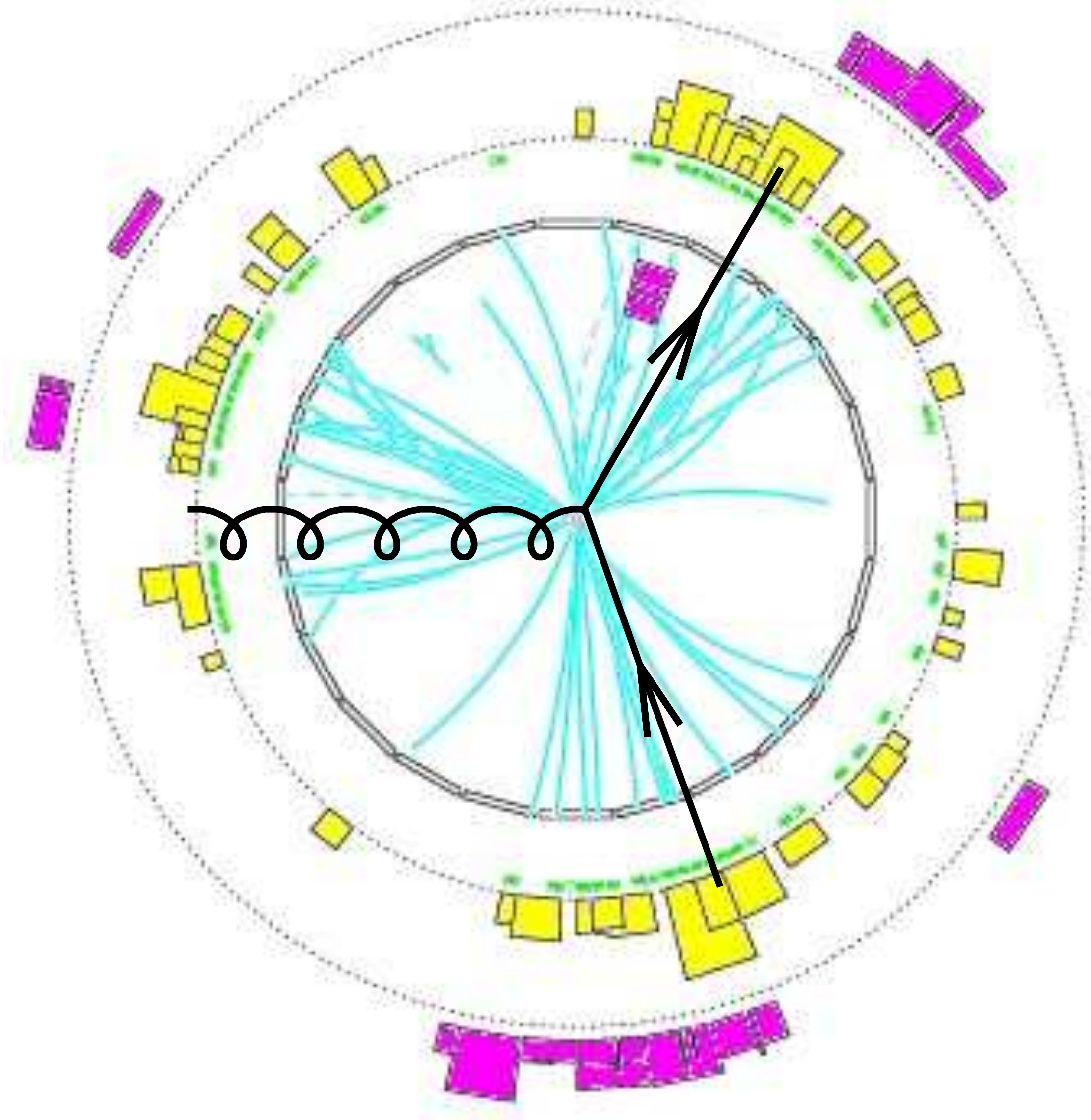
Data set	LO	NLO	NNLO
BCDMS μp F_2 [125]	162 / 153	176 / 163	173 / 163
BCDMS μd F_2 [19]	140 / 142	143 / 151	143 / 151
NMC μp F_2 [20]	141 / 115	132 / 123	123 / 123
NMC μd F_2 [20]	134 / 115	115 / 123	108 / 123
NMC $\mu n/\mu p$ [21]	122 / 137	131 / 148	127 / 148
E665 μp F_2 [22]	59 / 53	60 / 53	65 / 53
E665 μd F_2 [22]	52 / 53	52 / 53	60 / 53
SLAC ep F_2 [23, 24]	21 / 18	31 / 37	31 / 37
SLAC ed F_2 [23, 24]	13 / 18	30 / 38	26 / 38
NMC/BCDMS/SLAC/HERA F_L [20, 125, 24, 63, 64, 65]	113 / 53	68 / 57	63 / 57
E866/NuSea pp DY [88]	229 / 184	221 / 184	227 / 184
E866/NuSea pd/pp DY [89]	29 / 15	11 / 15	11 / 15
NuTeV νN F_2 [29]	35 / 49	39 / 53	38 / 53
CHORUS νN F_2 [30]	25 / 37	26 / 42	28 / 42
NuTeV νN xF_3 [29]	49 / 42	37 / 42	31 / 42
CHORUS νN xF_3 [30]	35 / 28	22 / 28	19 / 28
CCFR $\nu N \to \mu\mu X$ [31]	65 / 86	71 / 86	76 / 86
NuTeV $\nu N \to \mu\mu X$ [31]	53 / 40	38 / 40	43 / 40
HERA e^+p NC 820 GeV[61]	125 / 78	93 / 78	89 / 78
HERA e^+p NC 920 GeV[61]	479 /330	402 /330	373/ 330
HERA e^-p NC 920 GeV [61]	158/ 145	129/ 145	125 /145
HERA e^+p CC [61]	41 / 34	34 / 34	32 / 34
HERA e^-p CC [61]	29 / 34	23 / 34	21 / 34
HERA ep F_2^{charm} [62]	105 /52	72 / 52	82 / 52
H1 99–00 e^+p incl. jets [126]	77 / 24	14 / 24	—
ZEUS incl. jets [127, 128]	140/60	45 / 60	—
DØ II $p\bar{p}$ incl. jets [119]	125 / 110	116 / 110	119 / 110
CDF II $p\bar{p}$ incl. jets [118]	78 / 76	63 / 76	59 / 76
CDF II W asym. [66]	55 / 13	32 / 13	30 / 13
DØ II $W \to \nu e$ asym. [67]	47 / 12	28 / 12	27 / 12
DØ II $W \to \nu\mu$ asym. [68]	16 / 10	19 / 10	21 / 10
DØ II Z rap. [90]	34 / 28	16 / 28	16 / 28
CDF II Z rap. [70]	95 / 28	36 / 28	40 / 28
ATLAS W^+, W^-, Z [10]	94/30	38/30	39/30
CMS W asymm $p_T > 35$ GeV [9]	10/11	7/11	9/11
CMS asymm $p_T > 25$ GeV, 30 GeV[77]	7/24	8/24	10/24
LHCb $Z \to e^+e^-$[79]	76/9	13/9	20/9
LHCb W asymm $p_T > 20$ GeV[78]	27/10	12/10	16/10
CMS $Z \to e^+e^-$ [84]	46/35	19/35	22/35
ATLAS high-mass Drell-Yan [83]	42/13	21/13	17/13
CMS double diff. Drell-Yan [86]	—	372/132	149/132
Tevatron, ATLAS, CMS $\sigma_{t\bar{t}}$ [91]–[97]	53/13	7/13	8/13
ATLAS jets (2.76 TeV+7 TeV)[108, 107]	162/116	106/116	—
CMS jets (7 TeV) [106]	150/133	138/133	—
All data sets	**3706 / 2763**	**3267 / 2996**	**2717 / 2663**
	LO	**NLO**	**NNLO**

(2-jet) Event Display

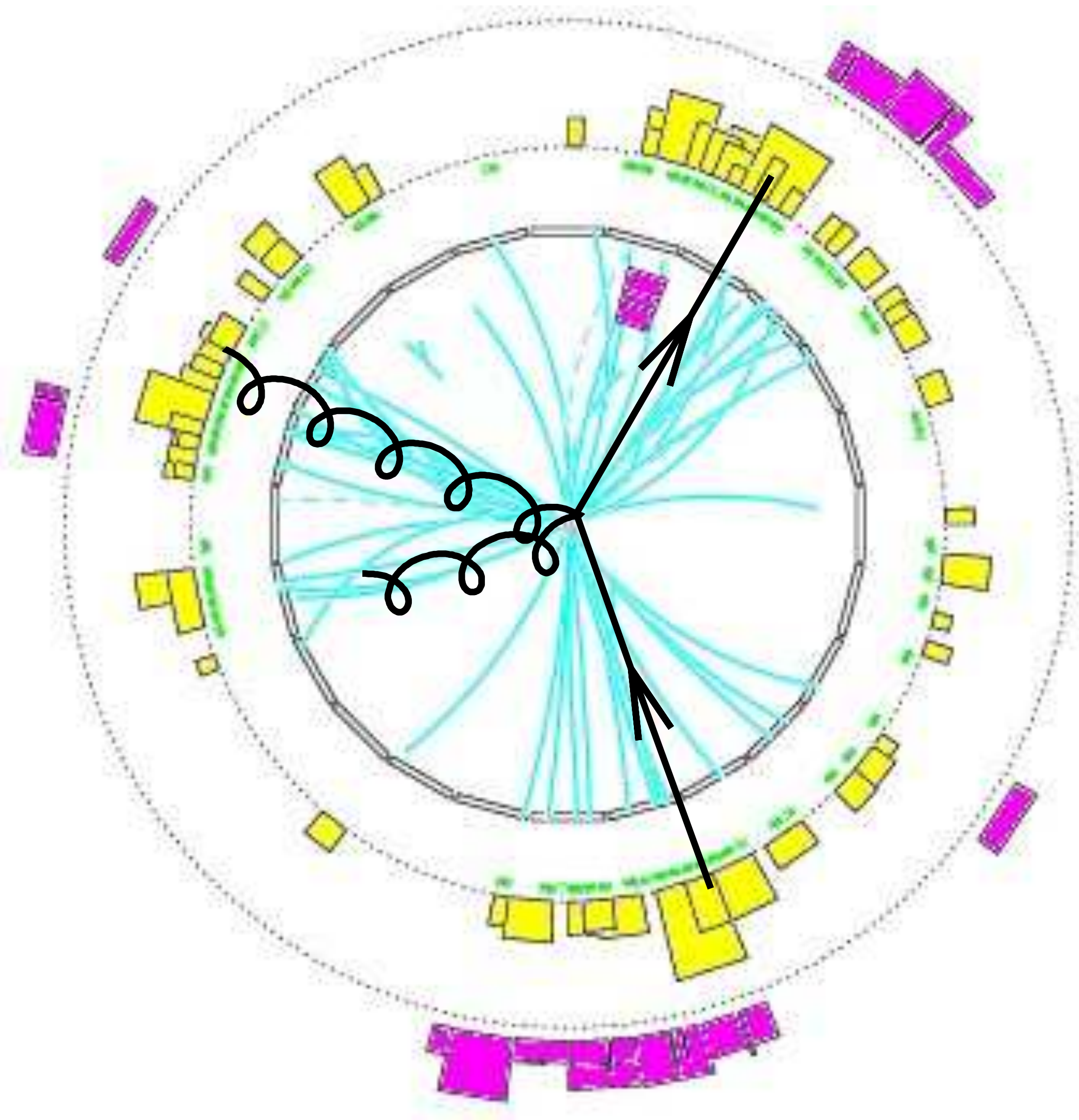


- Example event display from e^+e^- collisions.

How Many Jets?



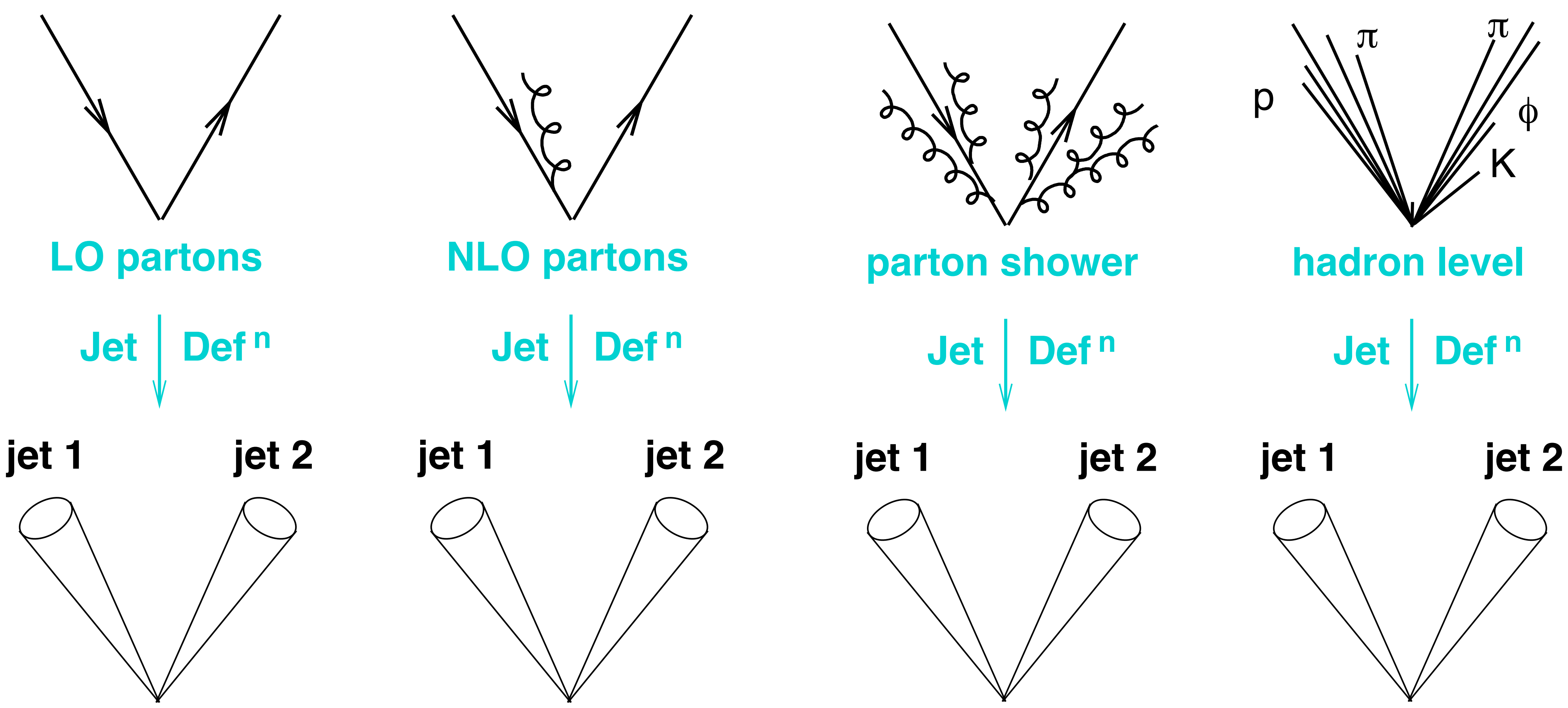
vs.



?

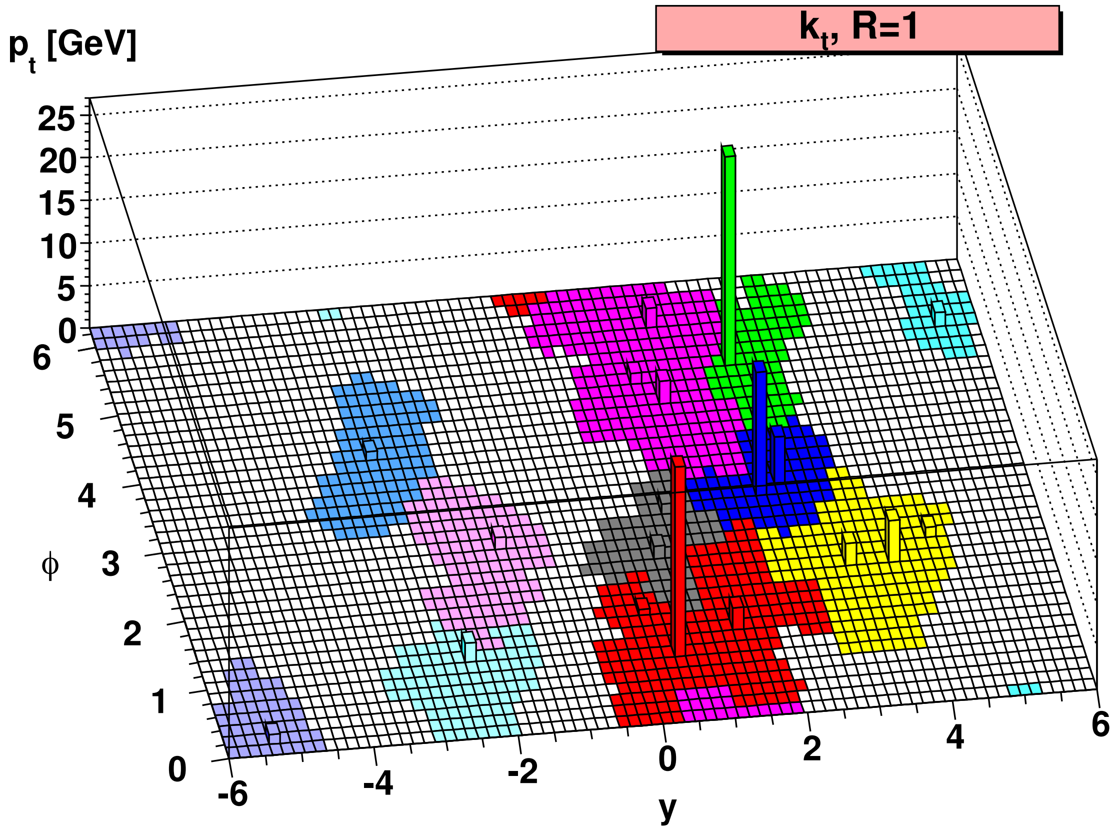
arXiv:1011.5131

Jet Algorithm: Basic Idea

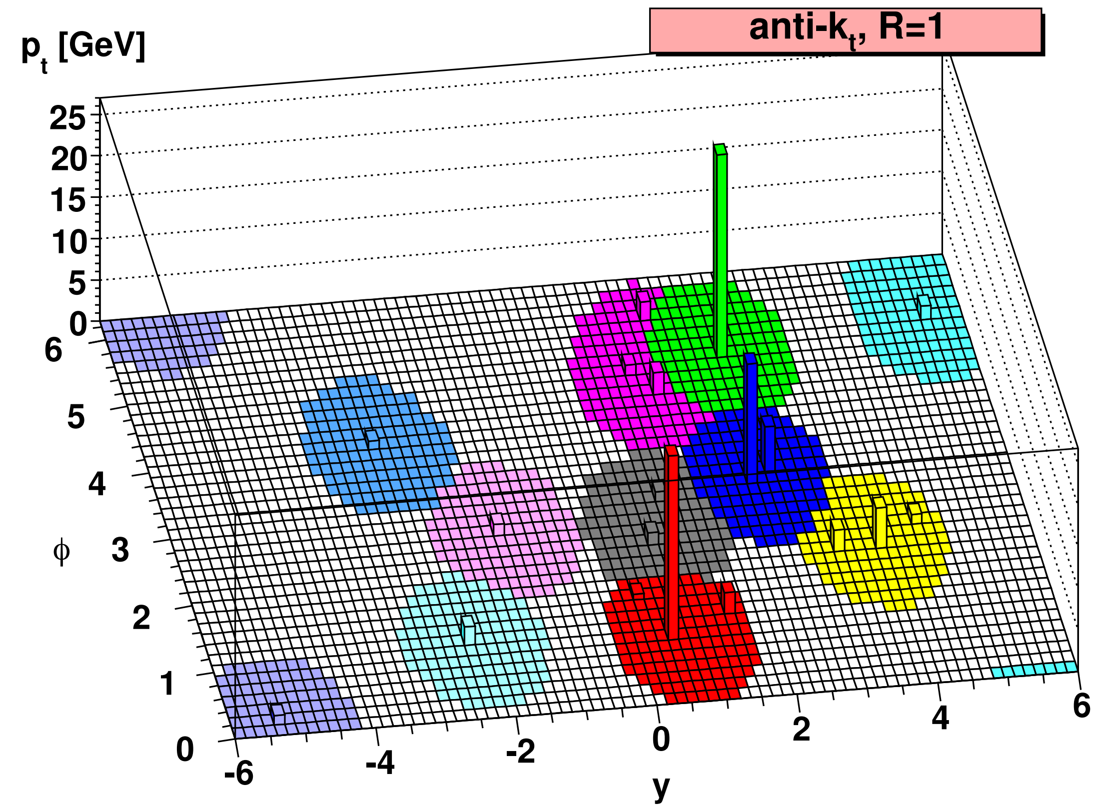


arXiv:1011.5131

Jet Algorithms

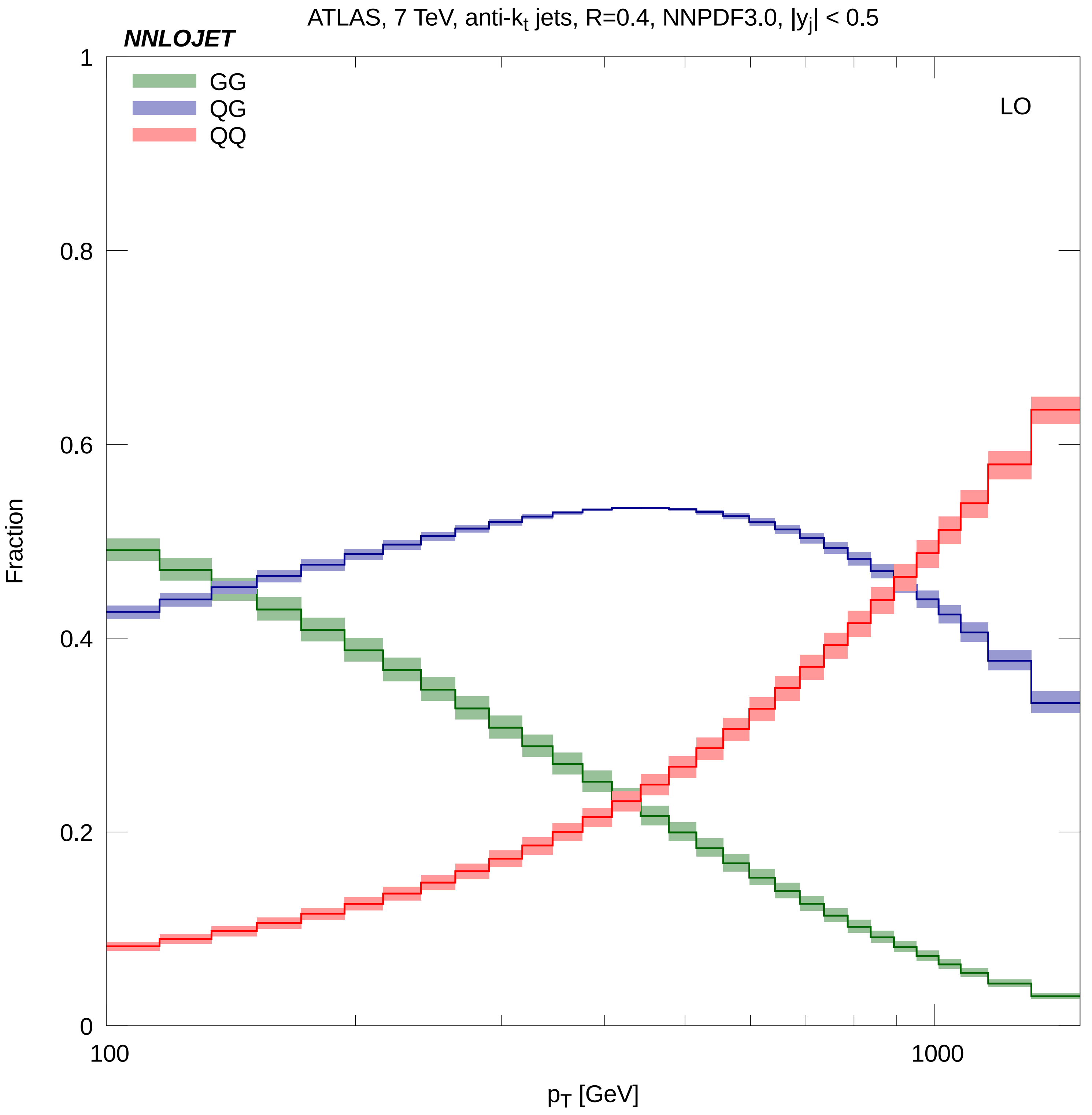


k_T

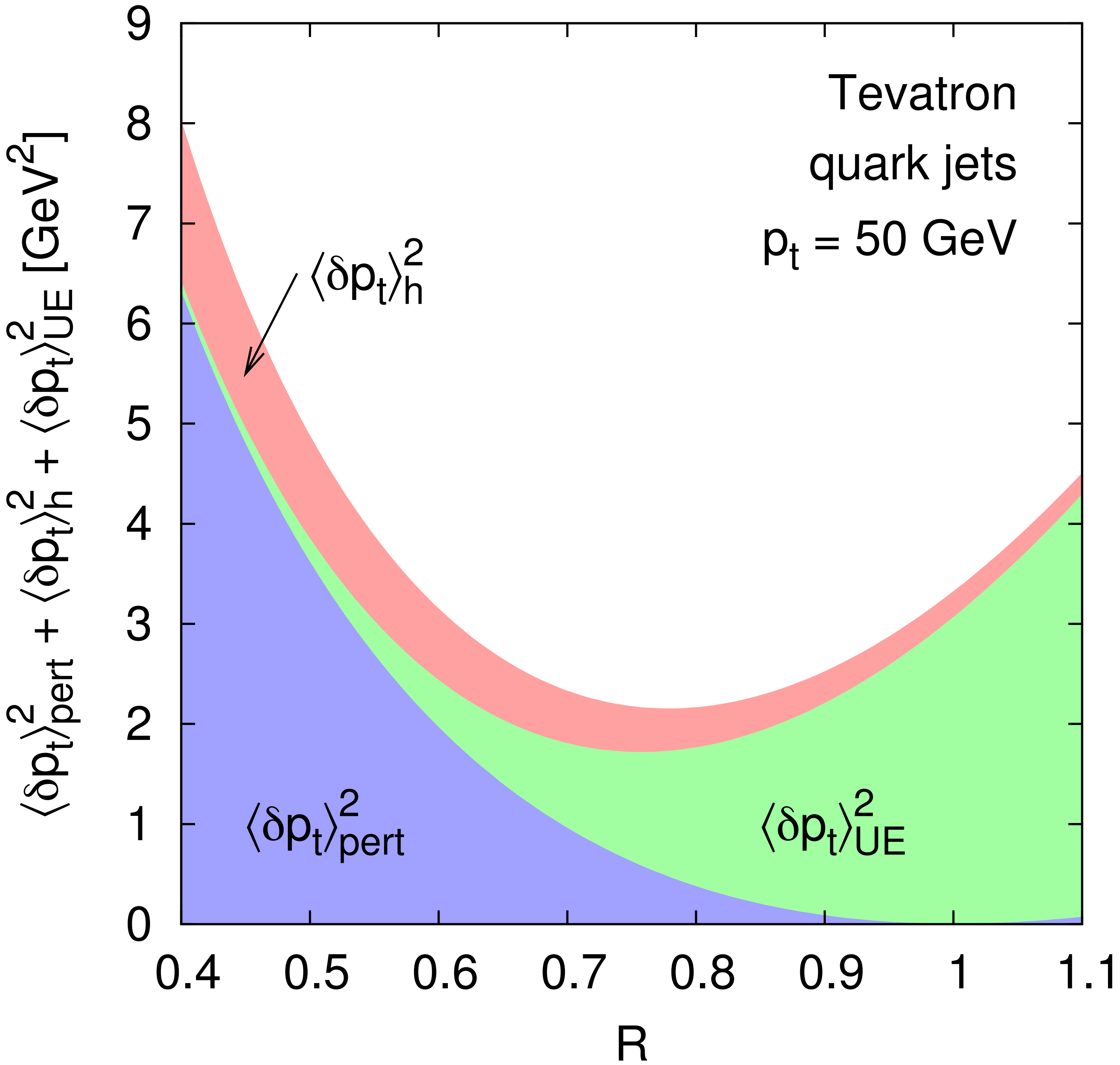


anti-k_T

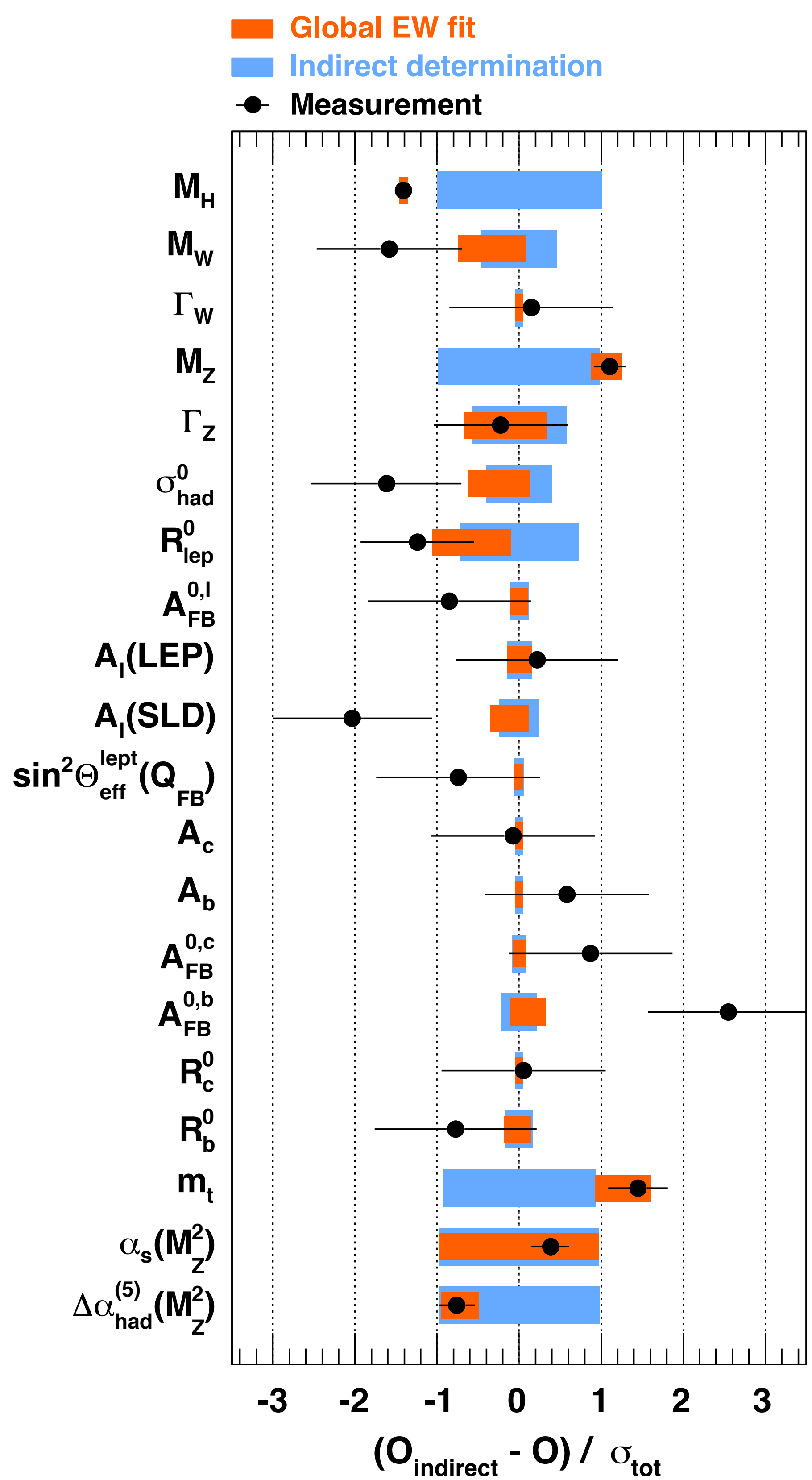
Jet Production Channels @ LHC



Jet Transverse Momentum Loss

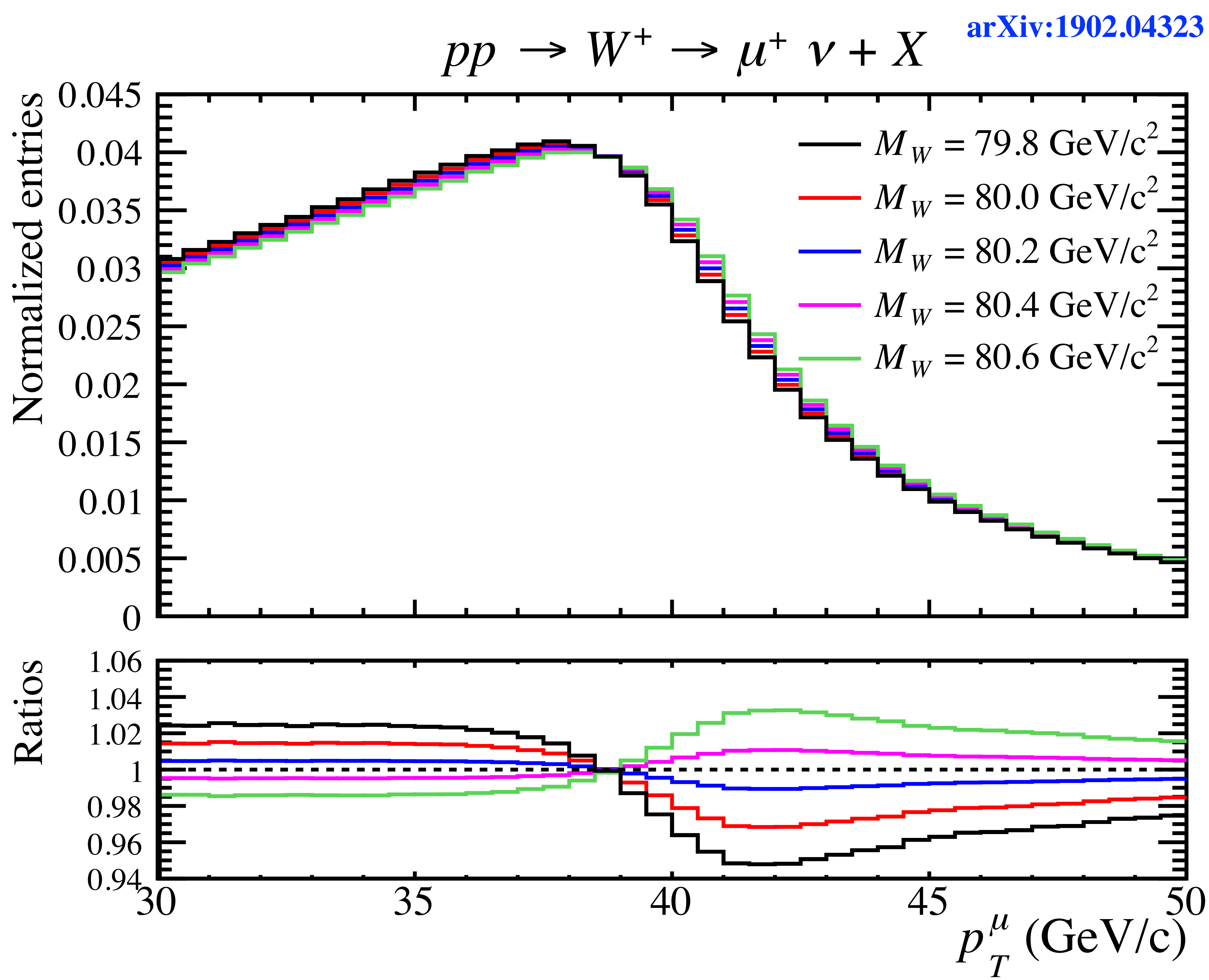


EW Precision Fits

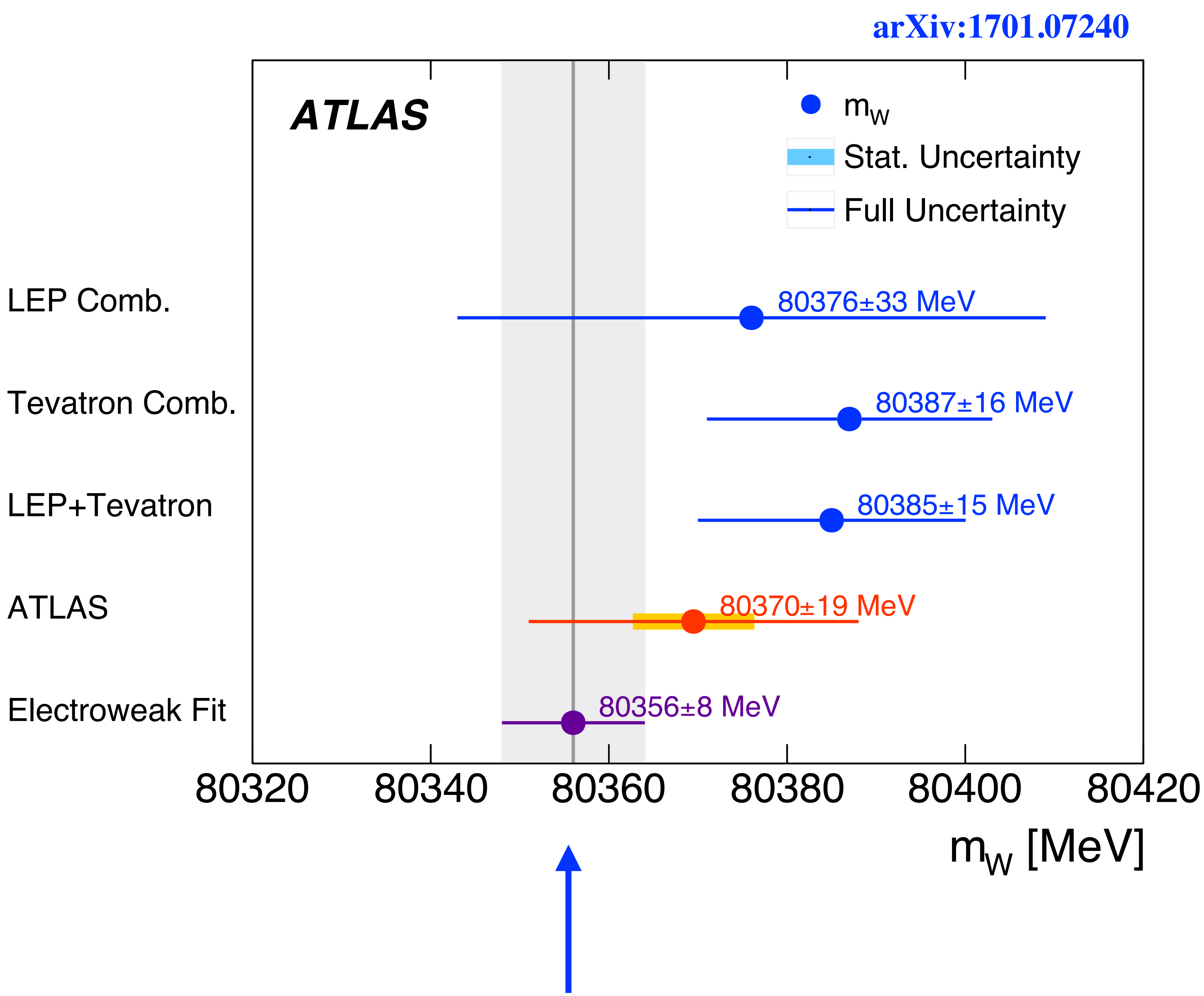


arXiv:1407.03792

W Boson Mass Determination



W Boson Mass Determination



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

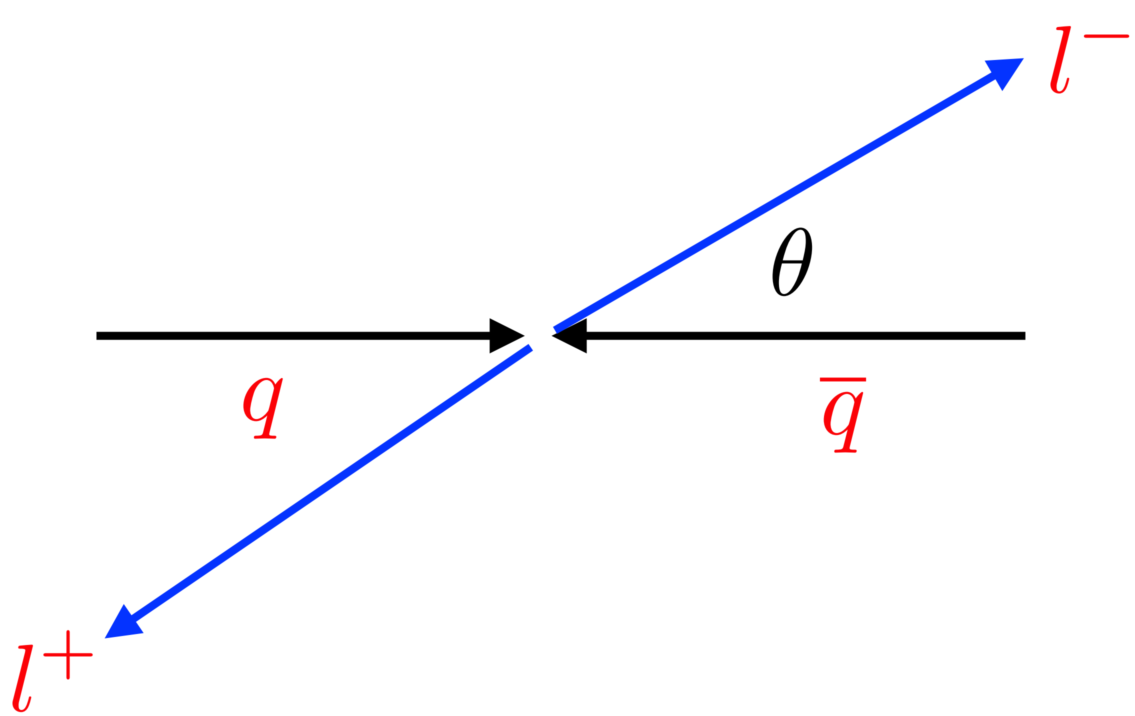
Forward Backwards Asymmetry

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

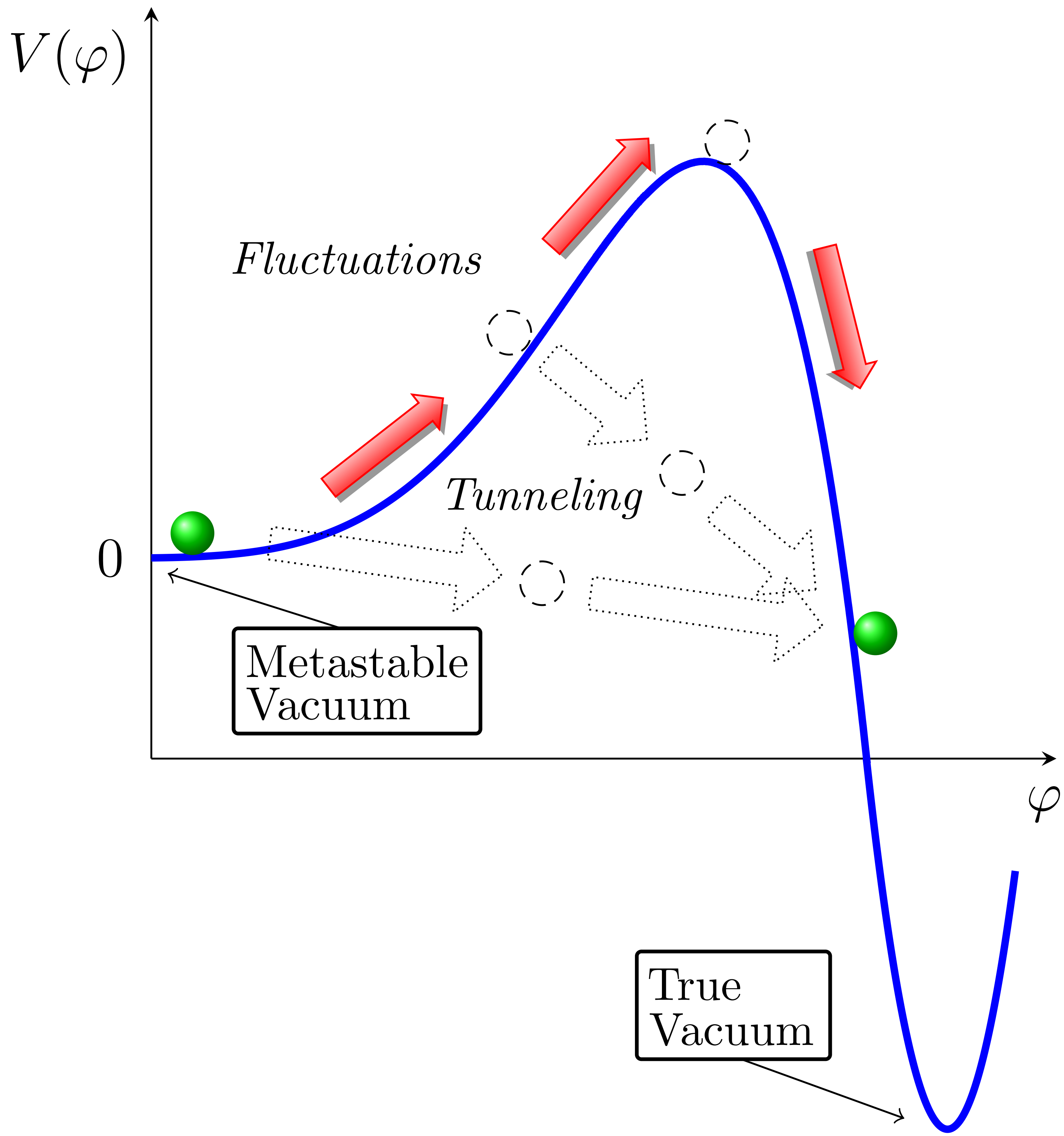
$$\left(1+\cos^2\theta\right)\left(q_f^2q_{f'}^2+\frac{g_Z^2}{4g_e^2}q_fq_{f'}v_fv_{f'}\chi_1+\frac{g_Z^4}{16g_e^4}(a_f^2+v_f^2)(a_{f'}^2+v_{f'}^2)\chi_2\right)$$

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

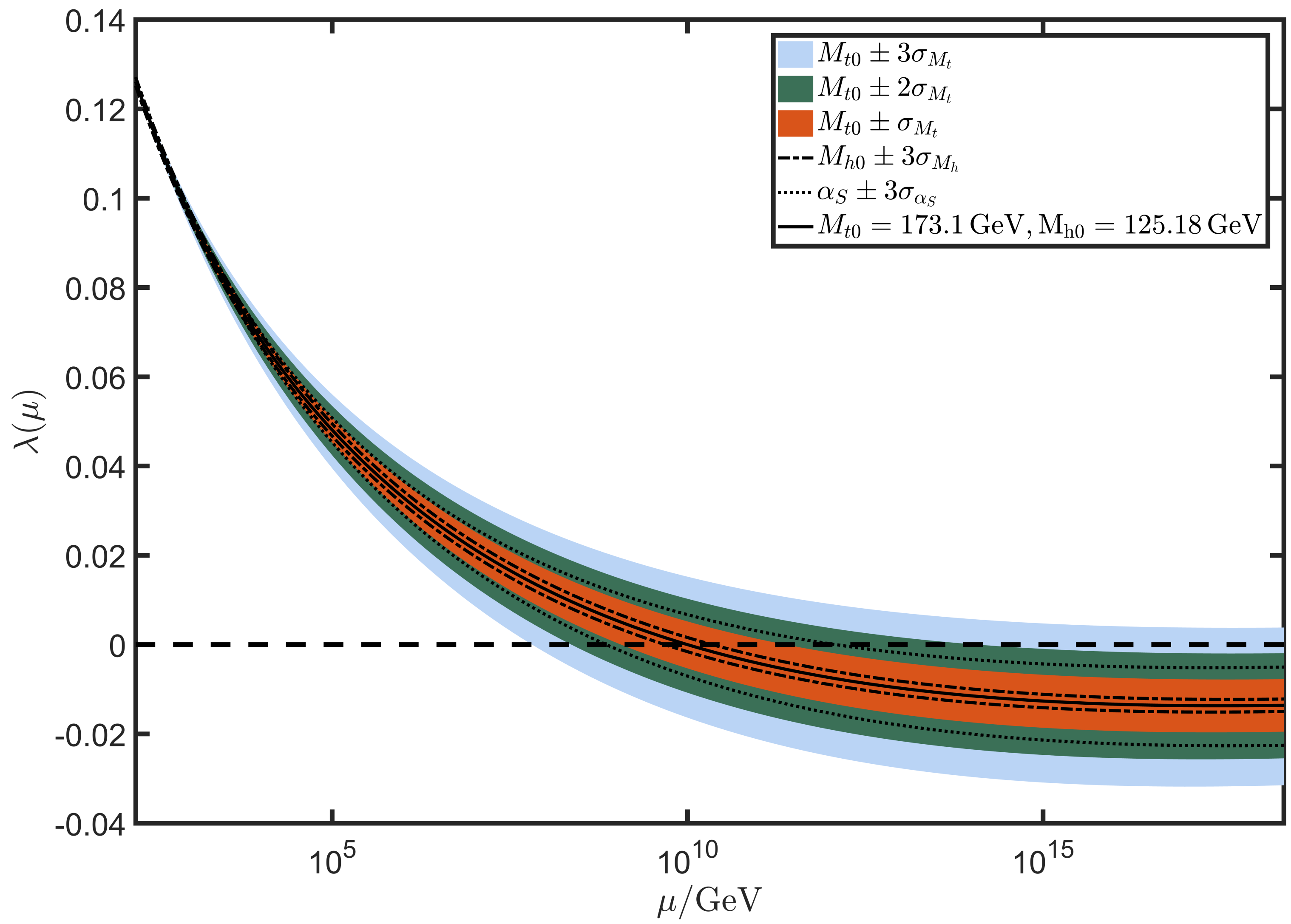
$$(v_f=T_f^3-2q_f\underline{\sin^2\theta_w})$$



Vacuum Stability of Universe



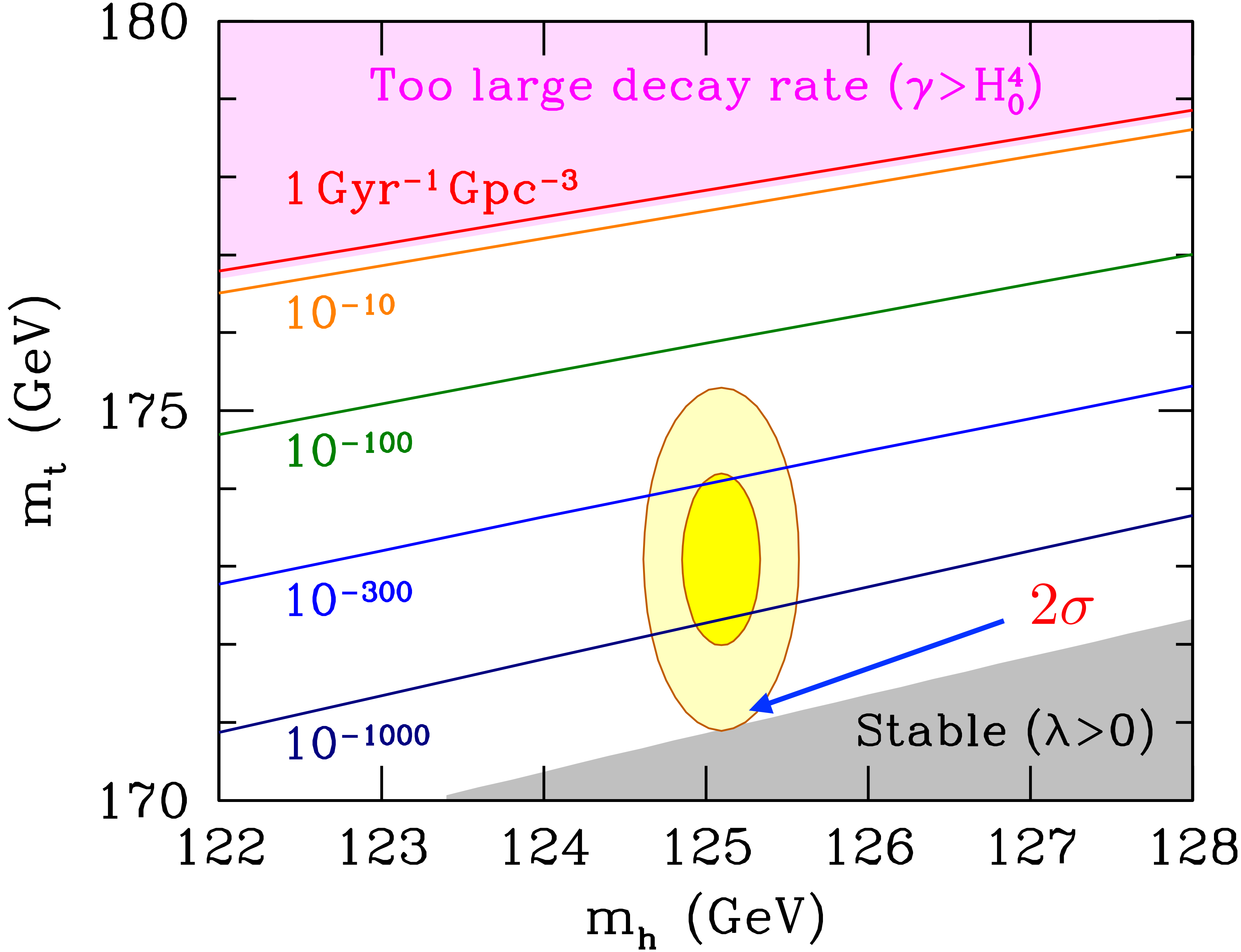
Vacuum Stability of Universe



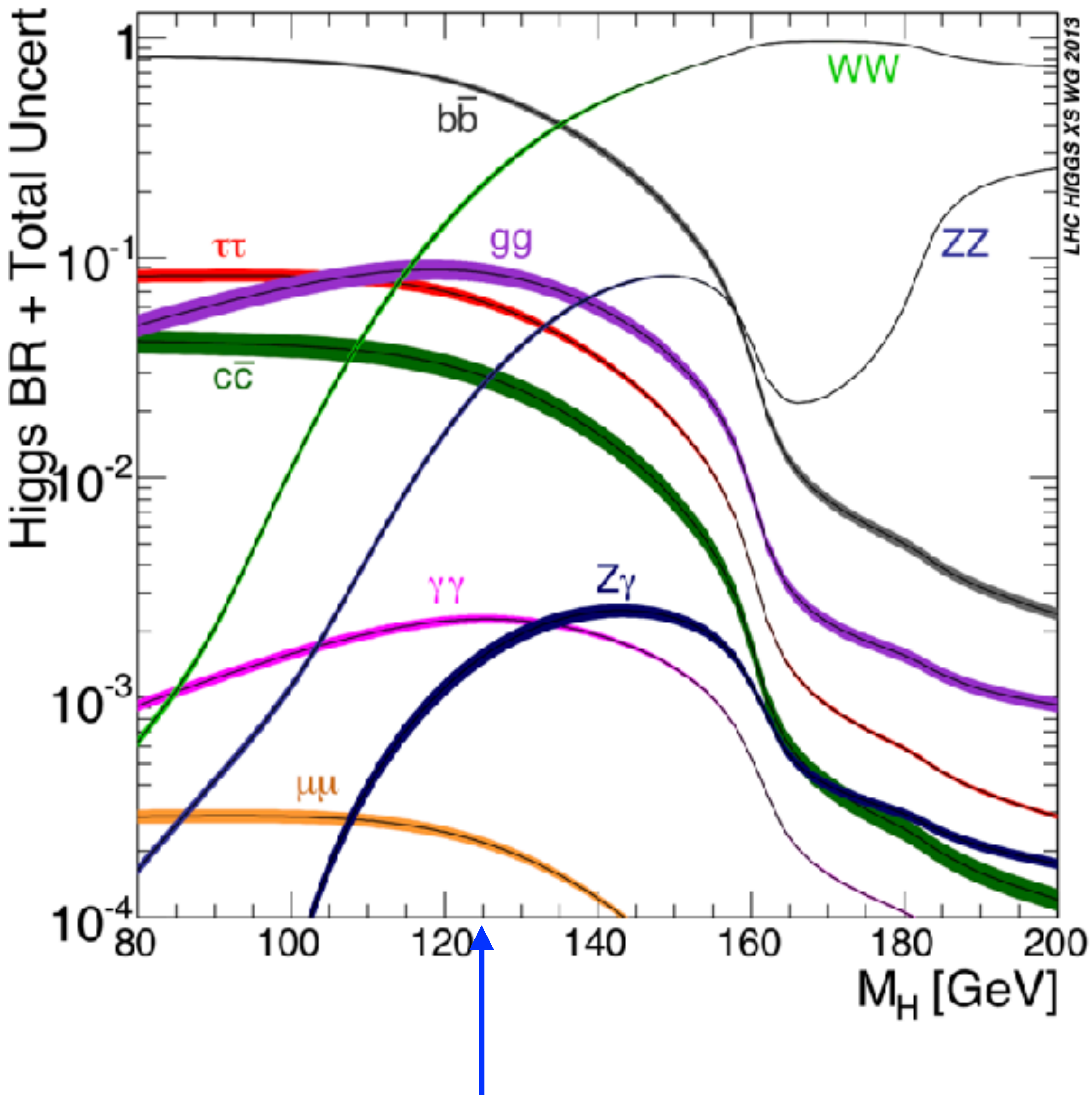
In each of them, the transition happens initially locally in a small volume, nucleating a small bubble of the true vacuum. The bubble then starts to expand, reaching the speed of light very quickly, any destroying everything in its way.

arXiv:1809.06923

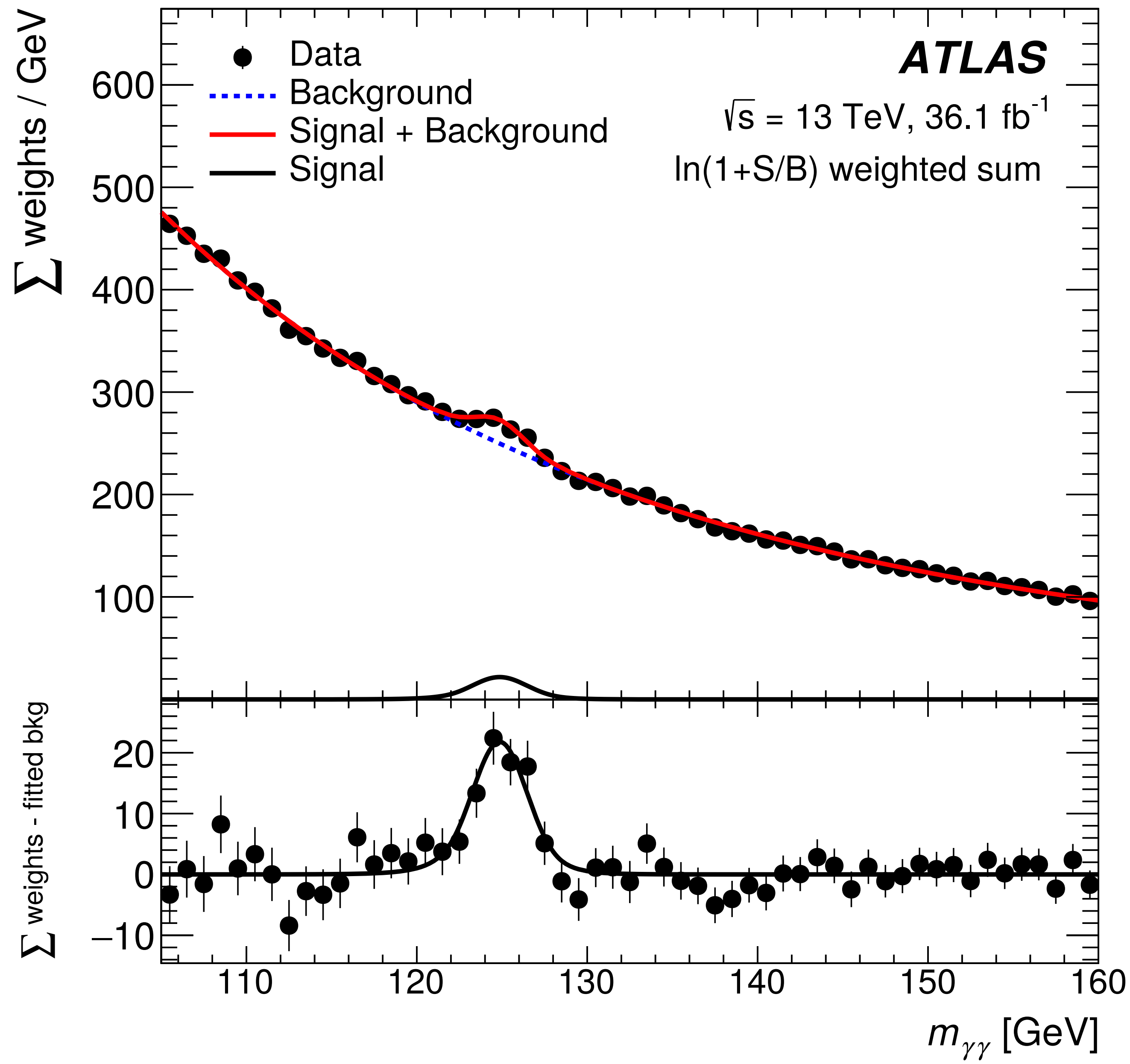
Vacuum Stability of Universe



Higgs Decays



Higgs: What Do We Know?



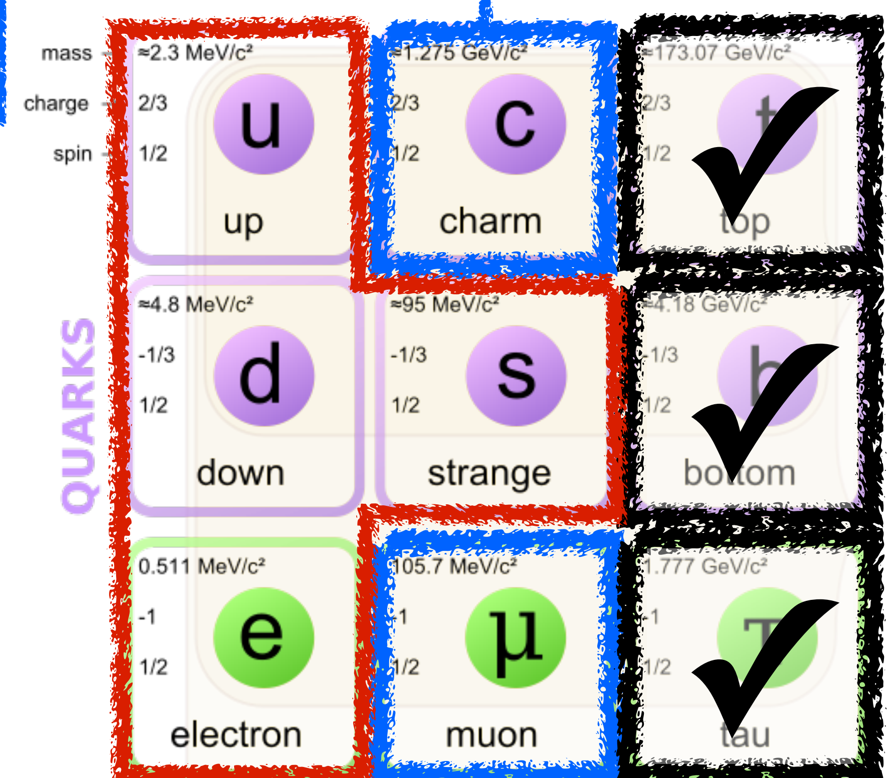
- New state there: is it Standard Model Higgs?

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

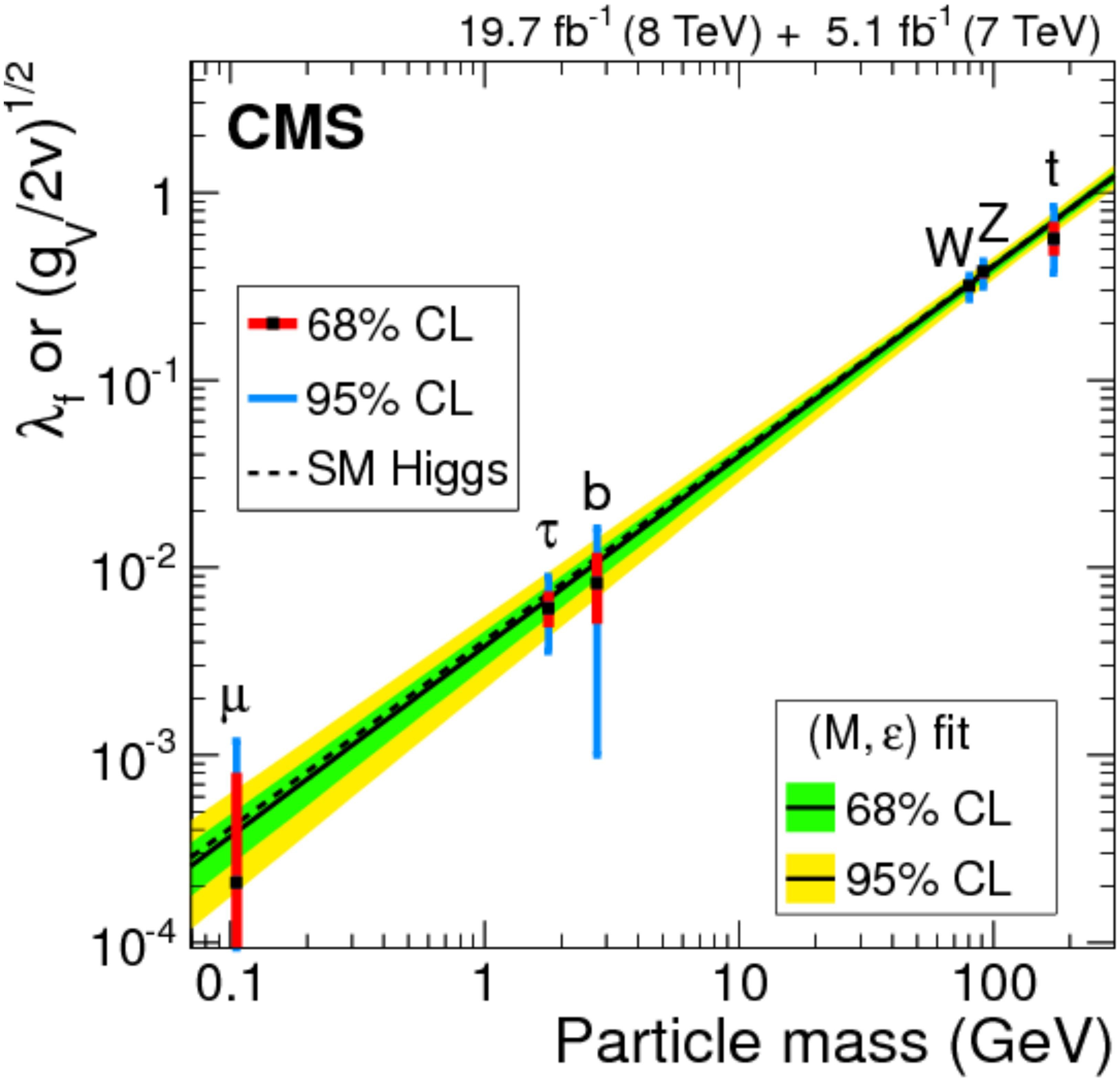


today: no evidence yet
(1 in 4000 decays)
no clear route to
establishing SM
couplings at 5σ

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

Slide Credit: Gavin Salam

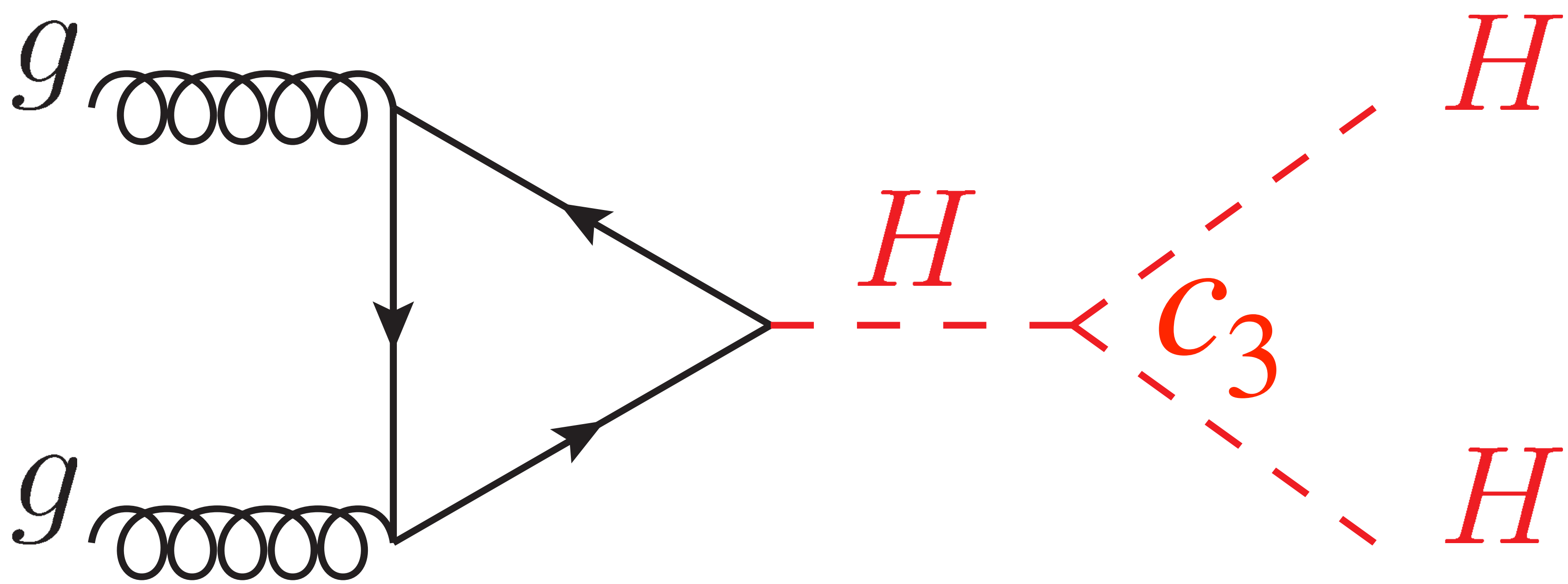
Higgs: What Do We Know?



Higgs Potential?

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

- 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

Gauge Coupling Unification + SUSY