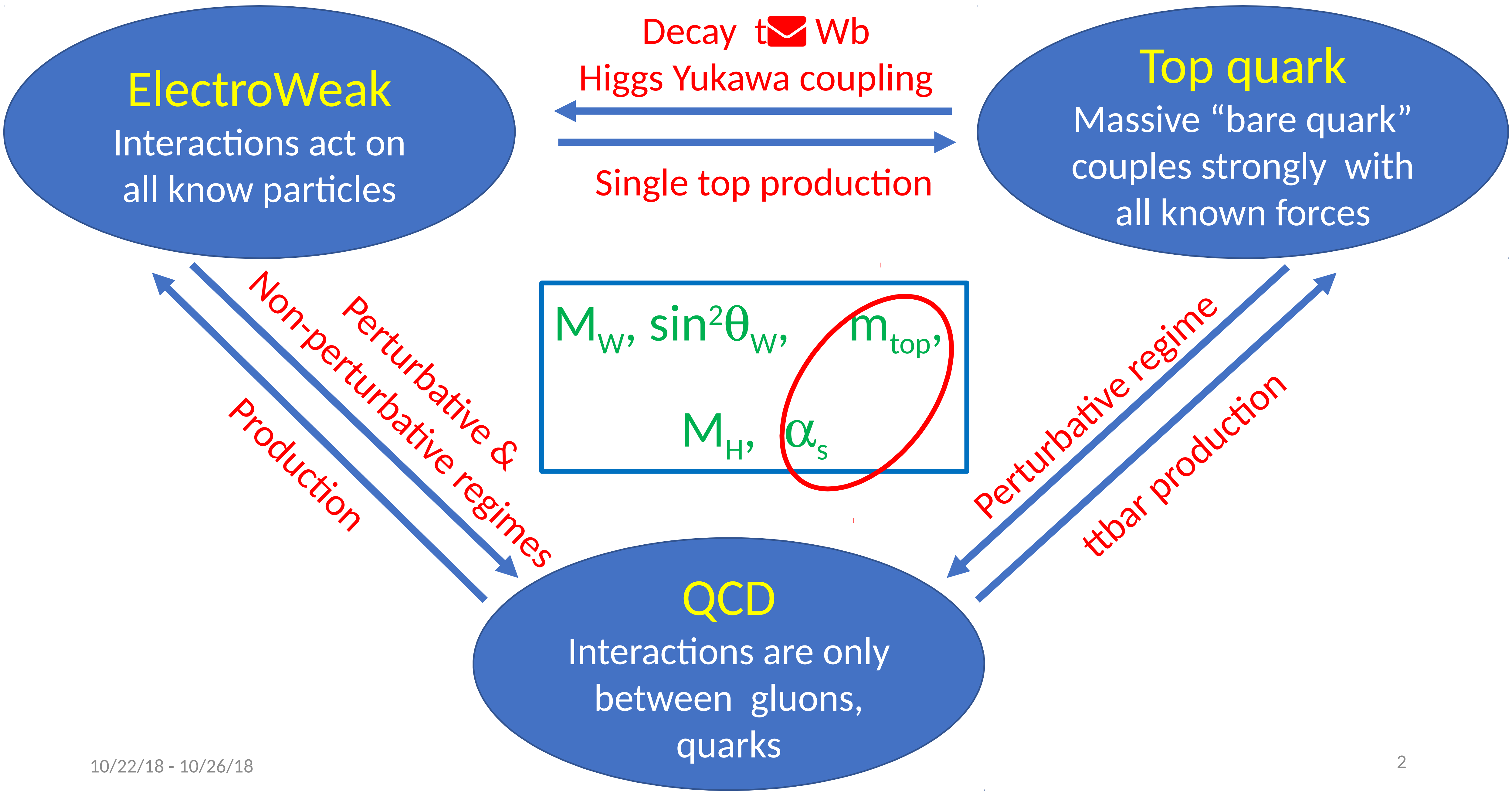
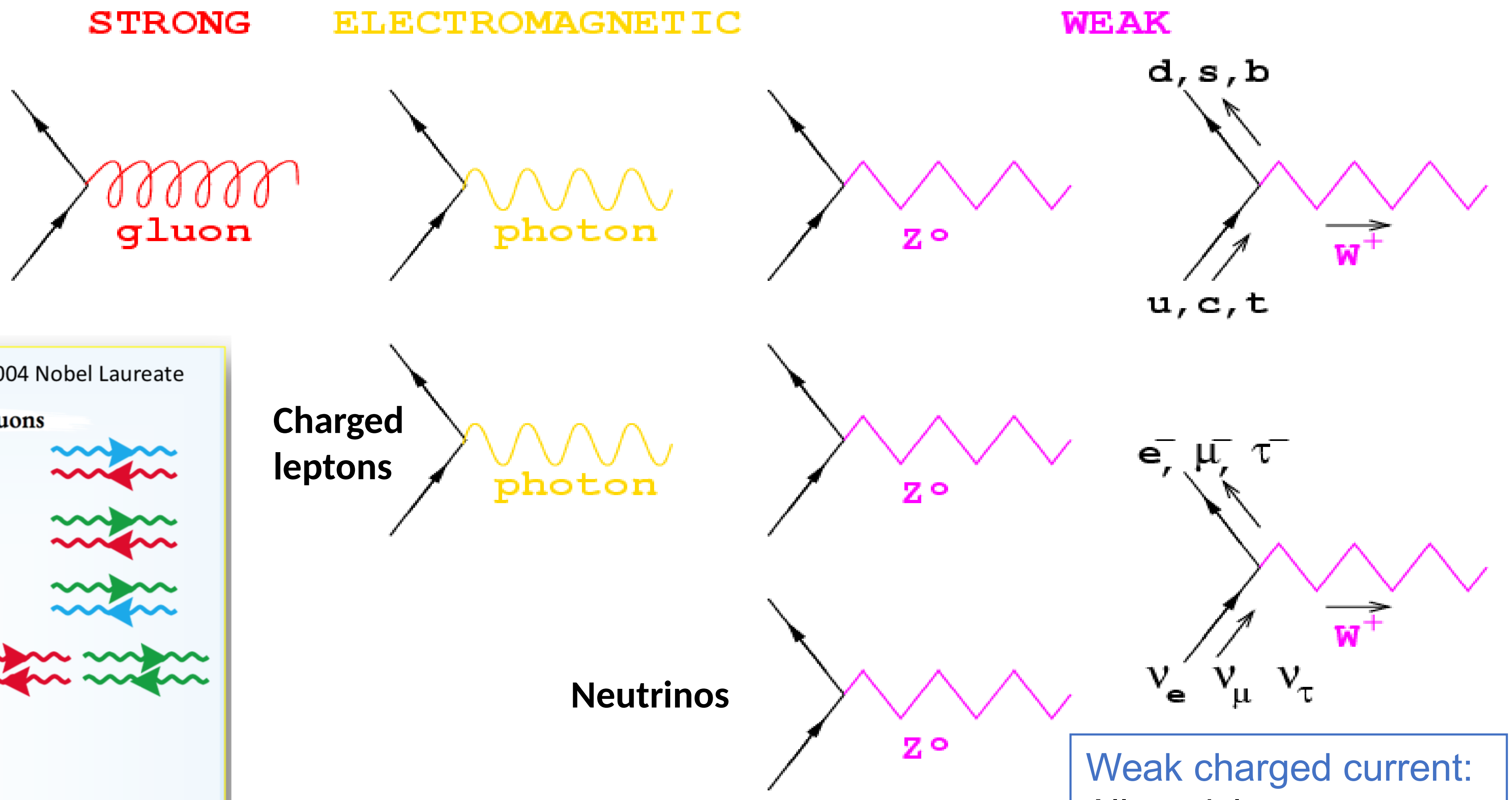
Lecture #2: XVII Mexican School of Particle Physics
2018 UNISON School of High Energy Physics

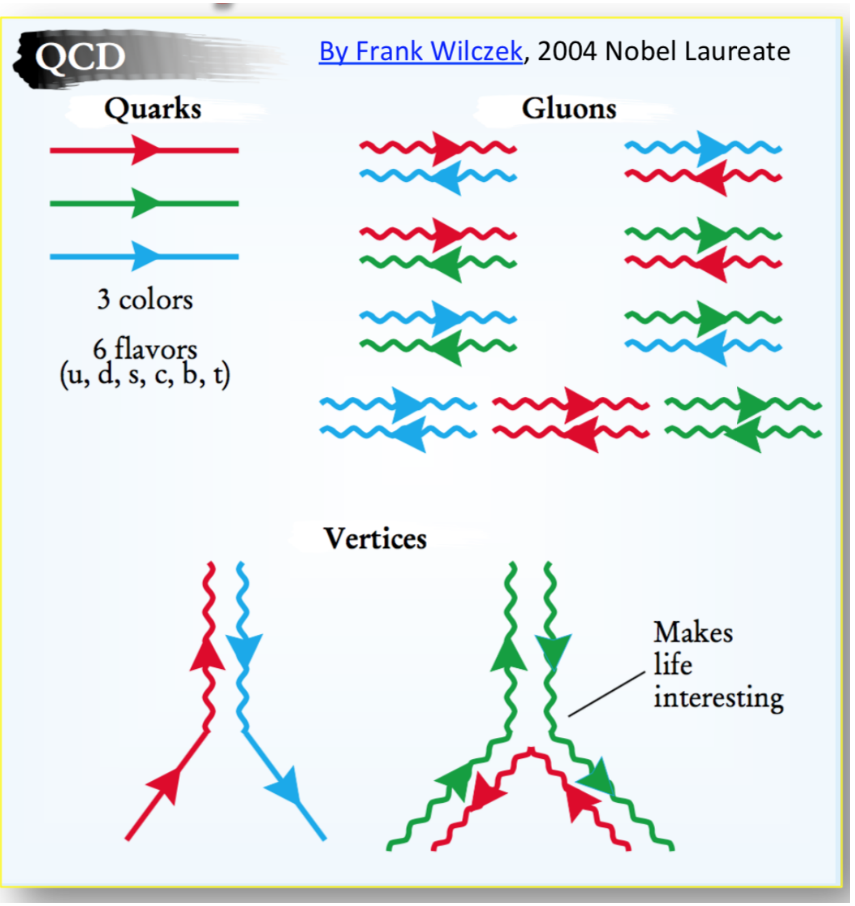
Top, ElectroWeak and QCD at the LHC

MAYDA M. VELASCO
NORTHWESTERN UNIVERSITY & COFI INSTITUTE


ElectroWeak
Interactions act on all know particles
Decay t✉Wb
Higgs Yukawa coupling
Single top production
Top quark
Massive “bare quark” couples strongly with all known forces
Perturbative & Non-perturbative regimes
Production
M_W, $\sin^2\theta_W$, m_{top},
M_H, α_s
Perturbative regime
ttbar production
QCD
Interactions are only between gluons, quarks

Quarks





Weak neutral current:
All particles
No change of flavour

Weak charged current:
All particles
Flavour changes

GIM mechanism

Historical overview of the top quark

Once the b-quark was found in 1977, it becomes evident that another 3^{rd} generation quark must exist!

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Because:
- $I_3 = -^1/_2$ was measured for the b-quark forward backward asymmetry
- $I_3 = 0$ will violate the GIM mechanism

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- I_3=-0 will violate the GIM mechanism

Also Br(Z → gg) must be equal to zero and without the top-quark a triangular anomaly will be introduced giving a non-zero value

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Quarks

			I_3	Y	$Q = I_3 + Y/2$
$\begin{bmatrix} u \\ d \end{bmatrix}_L$	$\begin{bmatrix} c \\ s \end{bmatrix}_L$	$\begin{bmatrix} t \\ b \end{bmatrix}_L$	+1/2 −1/2	+1/3 +1/3	+2/3 −1/3
u_R d_R	c_R s_R	t_R b_R	0 0	+4/3 −2/3	+2/3 −1/3

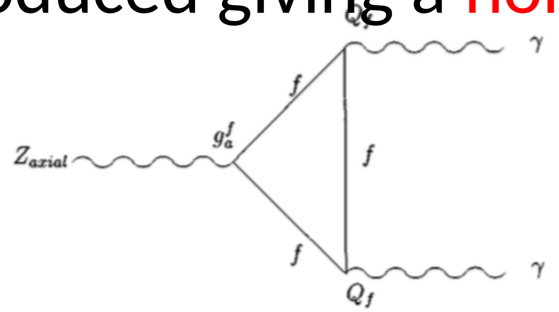
Leptons

$\begin{bmatrix} \nu_e \\ e \end{bmatrix}_L$	$\begin{bmatrix} \nu_\mu \\ \mu \end{bmatrix}_L$	$\begin{bmatrix} \nu_\tau \\ \tau \end{bmatrix}_L$	+1/2 −1/2	−1 −1	0 −1
e_R	μ_R	τ_R	0	−2	−1

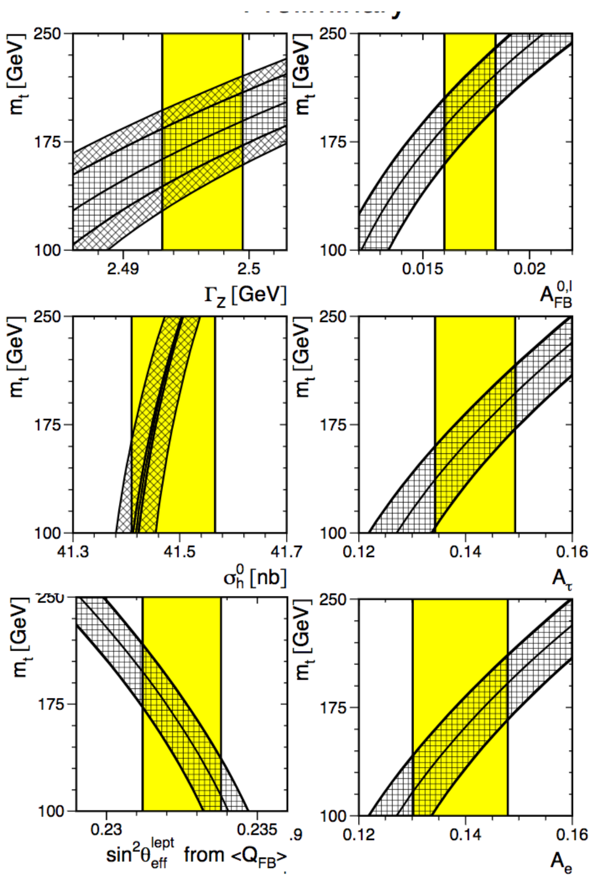
$$\bar{f}\,\gamma_\mu(g_V - g_A\gamma_5)Z^\mu f,$$

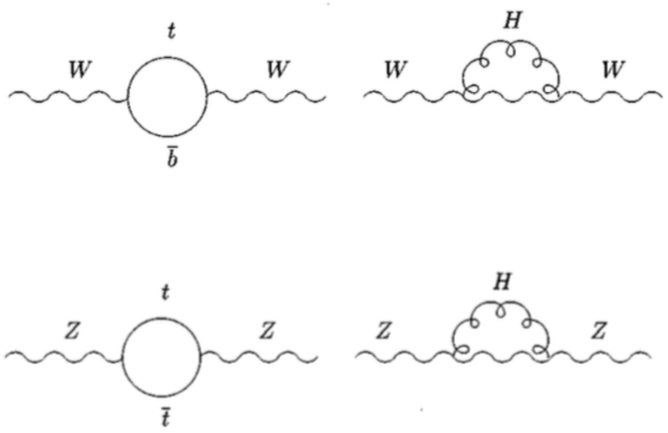
$$g_V = \frac{I_3 - 2Q\sin^2\theta_W}{2\sin\theta_W\cos\theta_W},$$

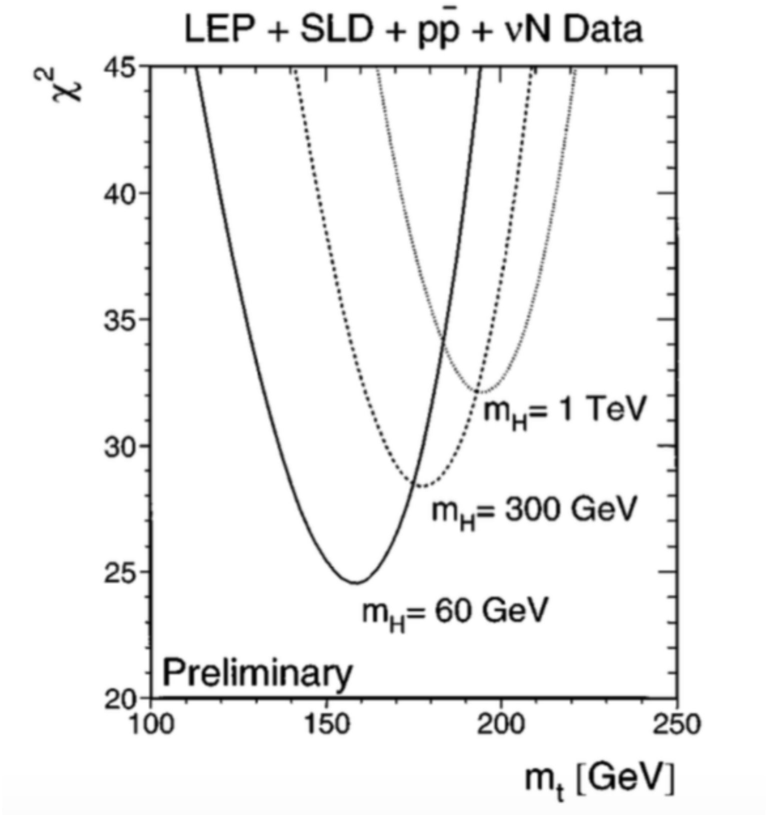
$$g_A = \frac{I_3}{2\sin\theta_W\cos\theta_W},$$



Historical overview of the top quark



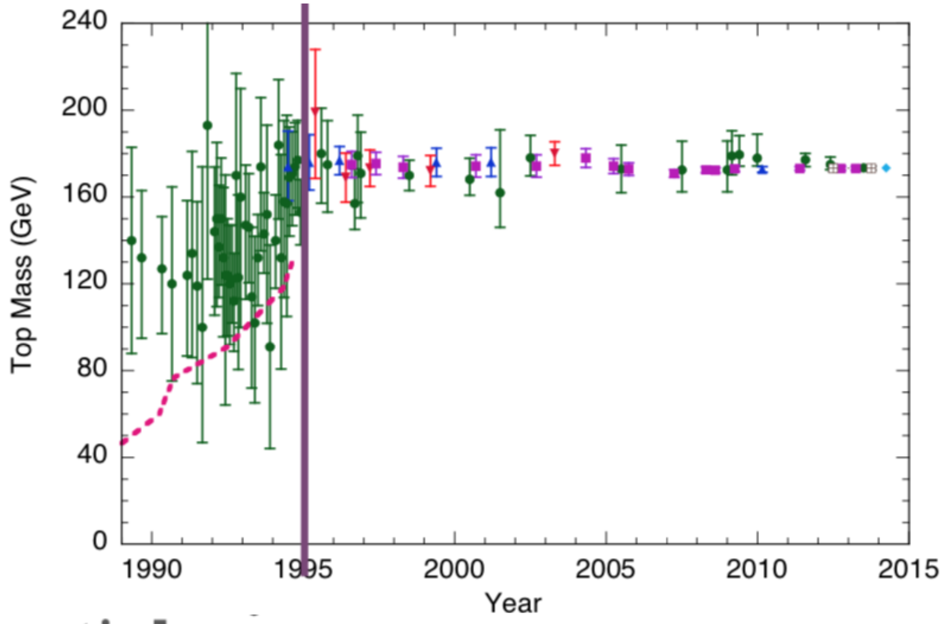




Our knowledge of Electroweak parameters in the early 1990's allowed us to predict the top-quark mass as a function of the Higgs boson mass and other SM parameters

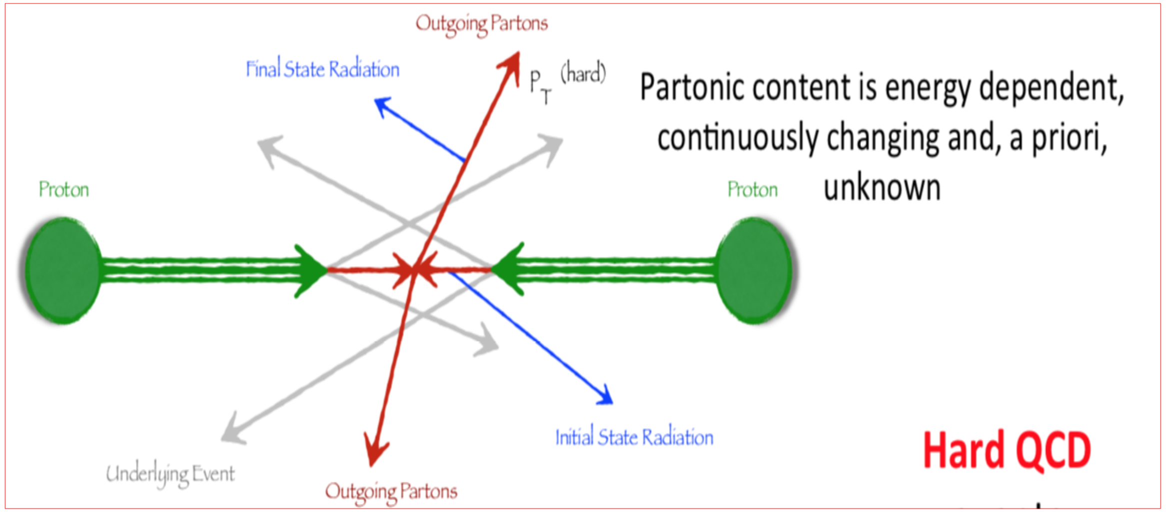
Top quark is "old" enough to legally drink

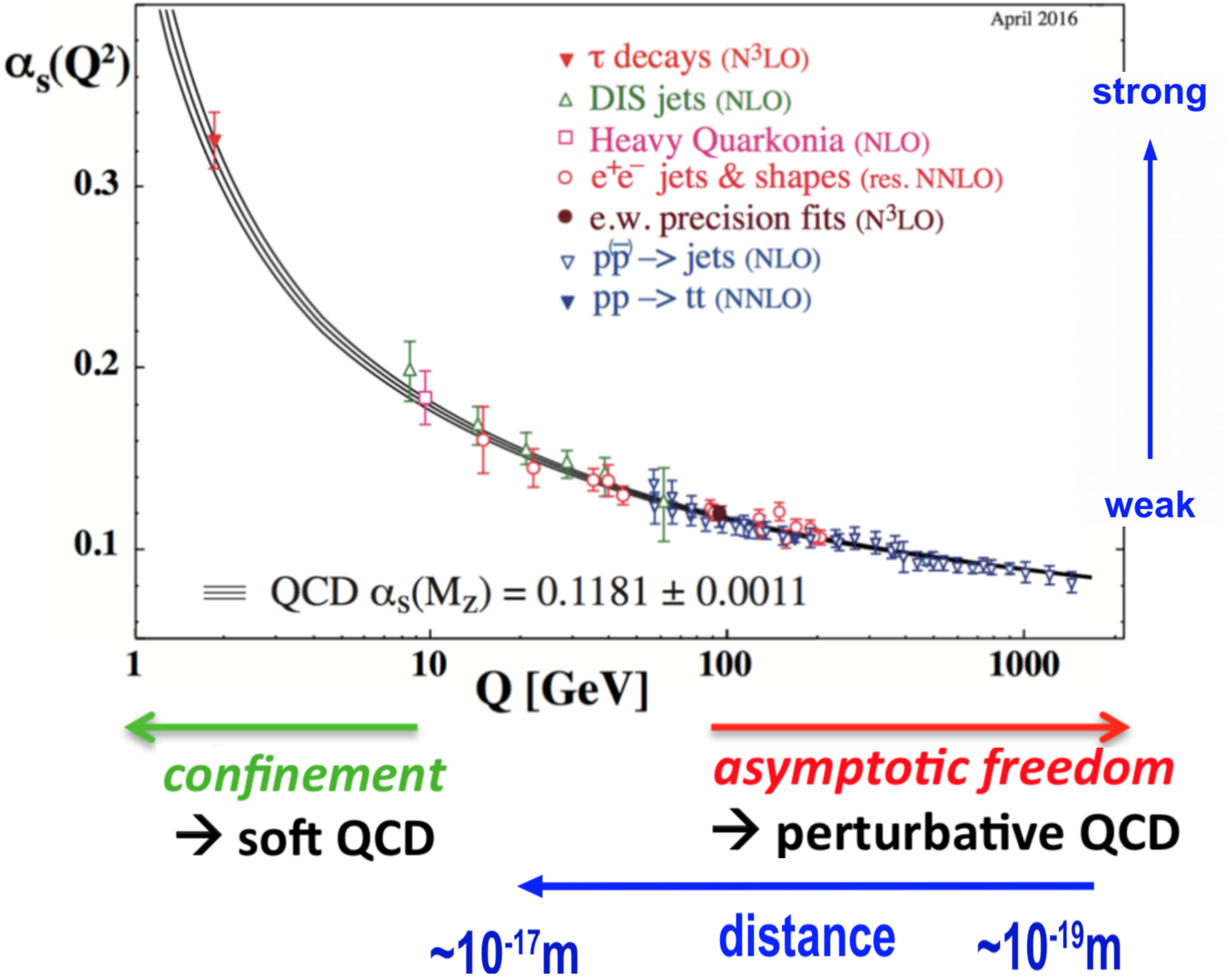
- 2015 was the 20th anniversary of the discovery
  - CDF: PRL74 2626-2631 (1995)
  - D0: PRL74 2632-2637 (1995)



- It completes the SM 3 family structure
  - top is the weak-isospin partner of the b-quark
  - spin = ½ & charge = + ⅔|e|
- Top quark is the heaviest known fundamental particle
  - $m_t = 173.34 \pm 0.76$ GeV [World comb.(2014), arXiv:1403.4427]
  - $m_t = 172.99 \pm 0.91$ GeV [ATLAS Combination (March 2015)]
  - $m_t = 172.44 \pm 0.48$ GeV [CMS Combination (Sept. 2015)]
- Top decays (almost exclusively) through $t \rightarrow bW$, $BR(t \rightarrow bW) \sim 100\%$
  - $BR(t \rightarrow sW) \leq 0.18\%$, $BR(t \rightarrow dW) \leq 0.02\%$

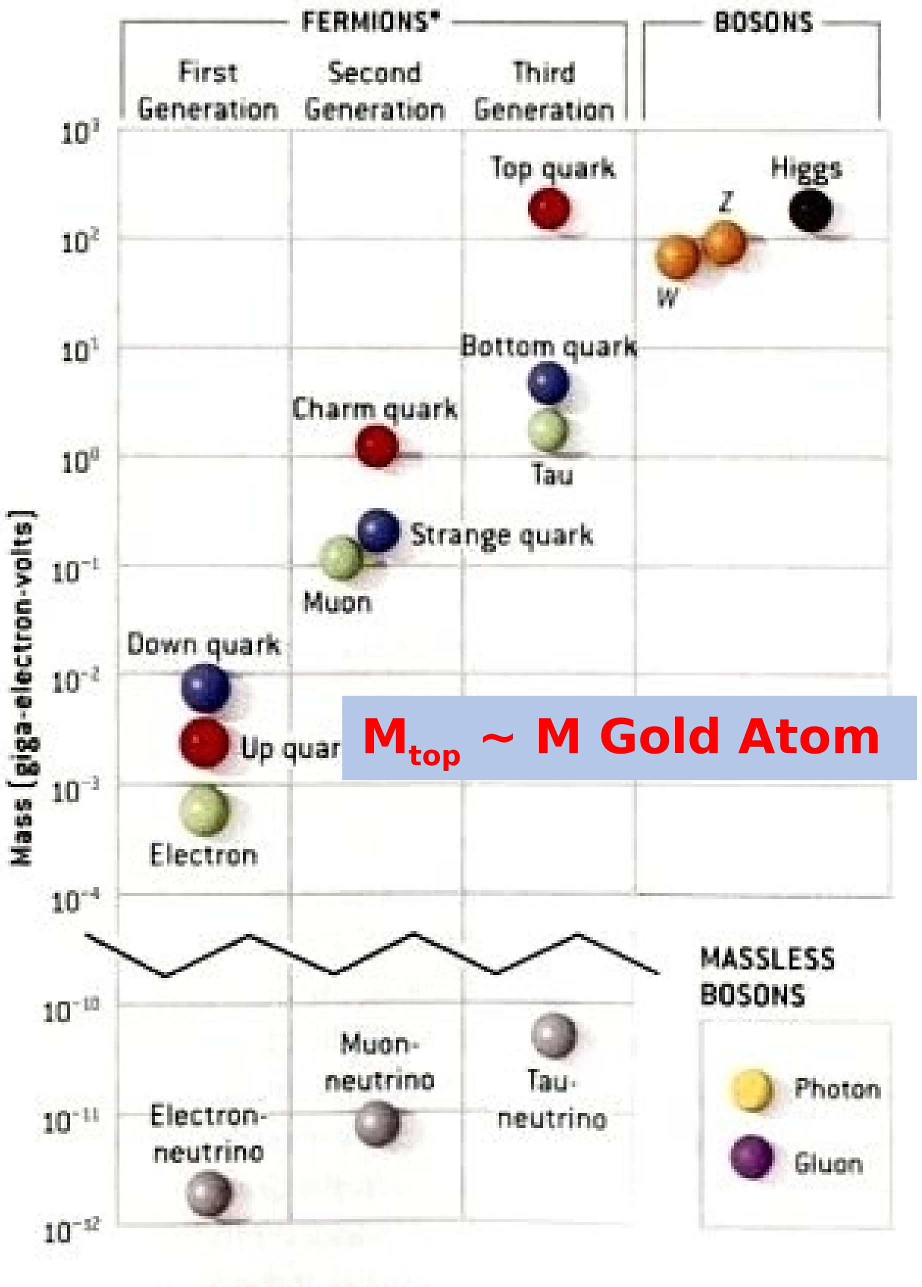
Top quark is providing a great opportunity to study both the Pertubative & Soft QCD regime





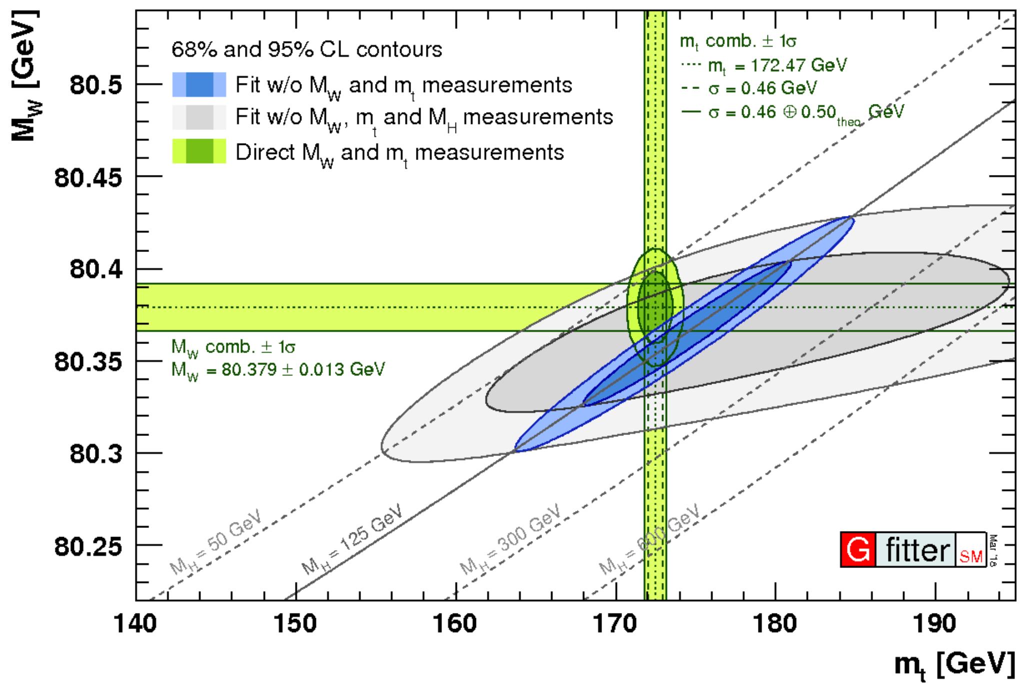
Compared to the electromagnetic force, which is infinite in range and obeys to the inverse square law, the **strong force** has a **very short range.** The restriction of the strong force to subatomic distances is related to two features called

Other reasons to study the top



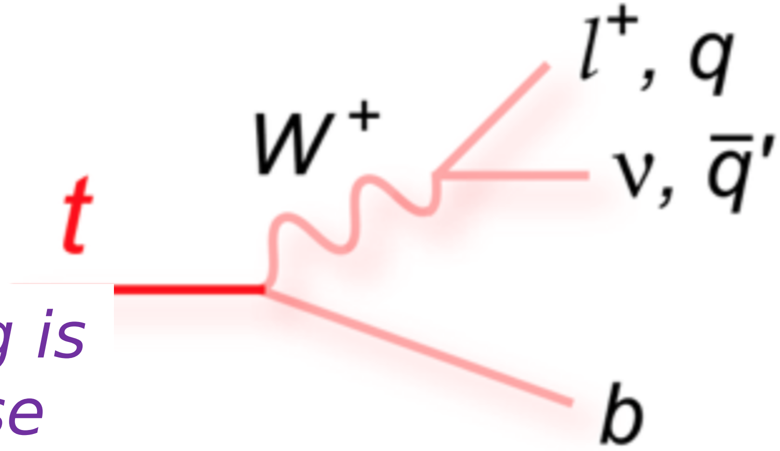
M_{top} ~ M Gold Atom

Top-quark is the most massive known **constituent** of matter



Largest Yukawa coupling to the Higgs providing more information on whether the Higgs Boson is truly a SM-like

More reasons to study the top quark in detail

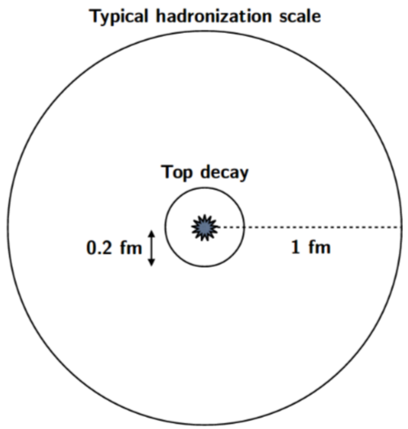


Mass of top-quark is so large that strong coupling is small that as already mentioned allows us to use perturbation theory , but more important is the fact that:

- **Decays weakly**
  - **t→Wb~BR(99%)**
  - **Γ_{top} ~1.32 GeV**

⇨ **"lives" less than "time to make hadrons" less than "time to decorrelate spins"**

$1/m_t$	<	$1/\Gamma_t$	<	$1/\Lambda$	<	m_t/Λ^2
Production time	<	Lifetime	<	Hadronization time	<	Spin decorrelation time



No top-antitop meson is observed , **spin information is preserved** in decay products

The LHC is a "Top Factory"

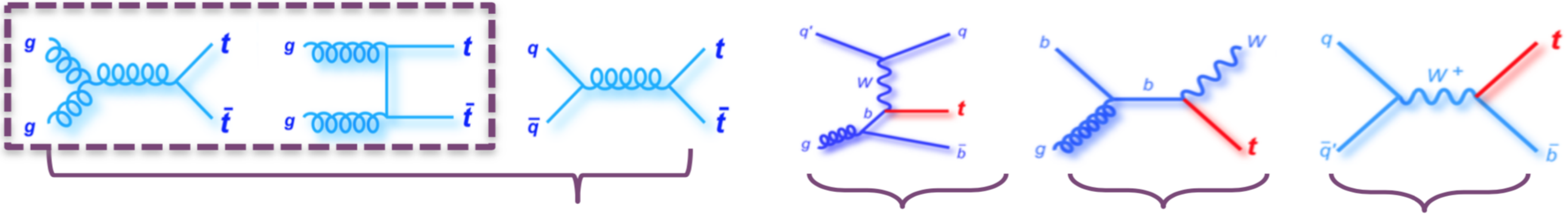
At the LHC:

- 1 ttbar event per sec
- top quarks are mainly produce in ttbar pairs
- At a lower rate: single top quark

➔Strong Interactions

➔Weak Interactions

@LHC ~ 90% of total rate



@ NLO

σ [pb]*	ttbar	t-channel	tW	s-channel
Tevatron (1.96TeV)	7.08	2.08	0.22	1.046
LHC @ 7 TeV	177.31	63.89	15.74	4.29
LHC @ 8 TeV	252.89	84.69	22.2	5.24
LHC @ 13 TeV	831.76	216.99	71.2	10.32

* m_t=172.5 GeV

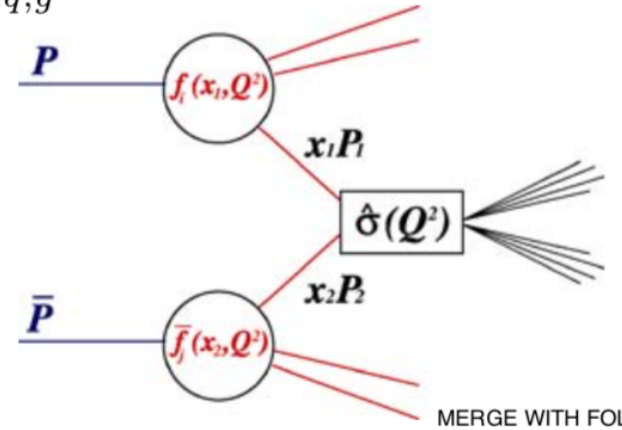
t-channel: $\sigma_{top} \neq \sigma_{Anti\text{-}top}$

s-channel: $\sigma_{top} \neq \sigma_{Anti\text{-}top}$

Additional information on ttbar cross section

ρ ≡ 4m²/s

$$\sigma^{t\bar{t}}(\sqrt{s}, m_t) = \sum_{i,j=q,\bar{q},g} \int dx_i\, dx_j\, f_i(x_i,\mu^2)\, \bar{f}_j(x_j,\mu^2)\; \hat{\sigma}^{ij\to t\bar{t}}(\rho, m_t^2, x_i, x_j, \alpha_s(\mu^2), \mu^2)$$



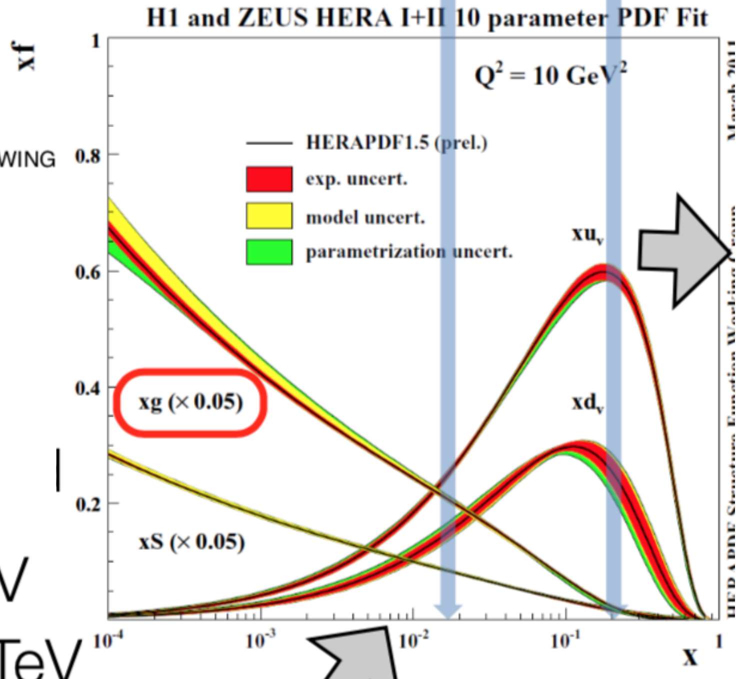
	LHC(14)	LHC(7)	Tev(1.9)
gg	**~90%**	**~85%**	**~10%**
qq	**~10%**	**~15%**	**~90%**

MERGE WITH FOLLOWING

To produce $t\bar{t}$

~massless partons

$$\hat{s} \geq 4m_t^2 \Rightarrow x_i x_j = \hat{s}/s \geq 4m_t^2/s.$$



$$\Rightarrow x \approx \frac{2m_t}{\sqrt{s}} =$$

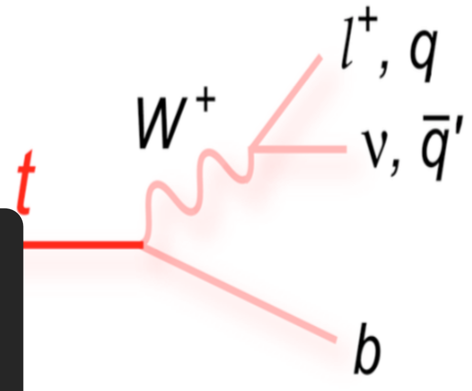
0.19 @ Tevatron √s=1.8 TeV

0.18 @ Tevatron √s=1.96 TeV

(0.048, 0.043, 0.026) @ LHC with √s=(7, 8,13) TeV

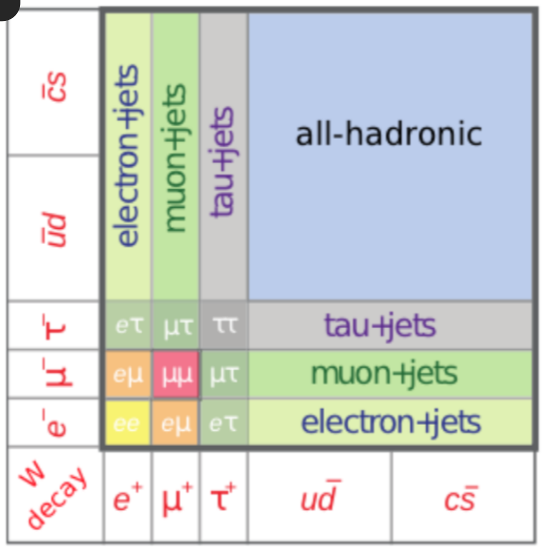
ttbar: Basic

Top – AntiTop topology

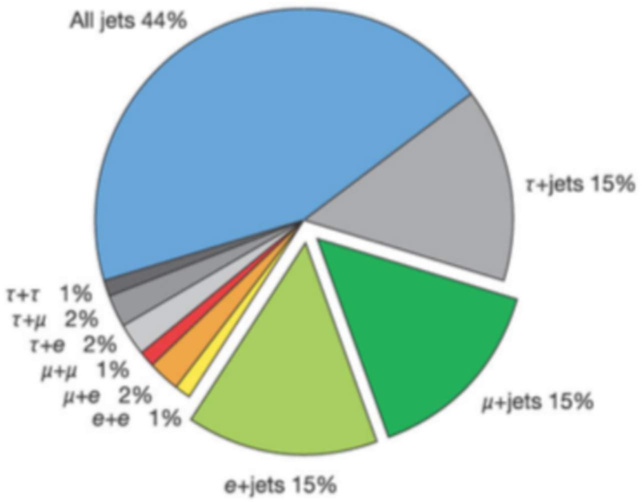


(not inc. τ)	BR	background
dilepton	~5%	low
lepton + jets	~30%	moderate
all hadronic	~44%	high

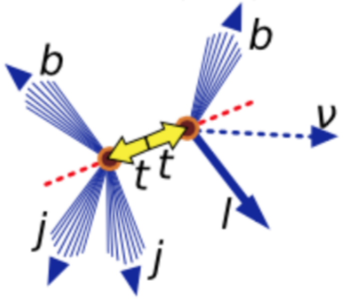
Top pair decay channels



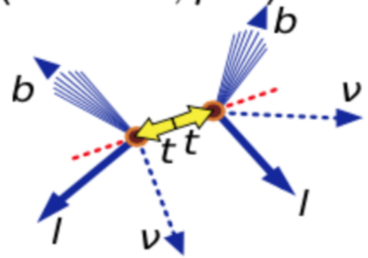
Top pair branching fractions



$\Longrightarrow$ Lepton+jets ($\sim$ 30%): ($\ell = e^{\pm}, \mu^{\pm}$)



$\Longrightarrow$ Dilepton ($\sim$ 5%): ($\ell = e^{\pm}, \mu^{\pm}$)



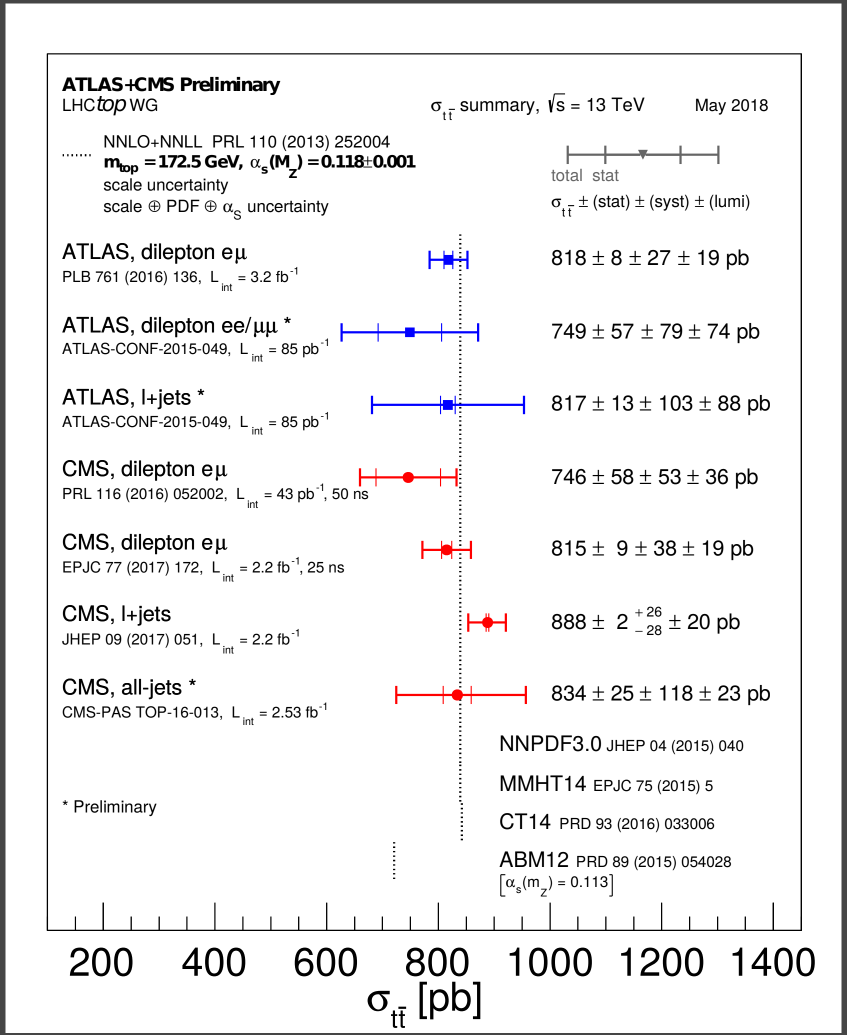
700

800

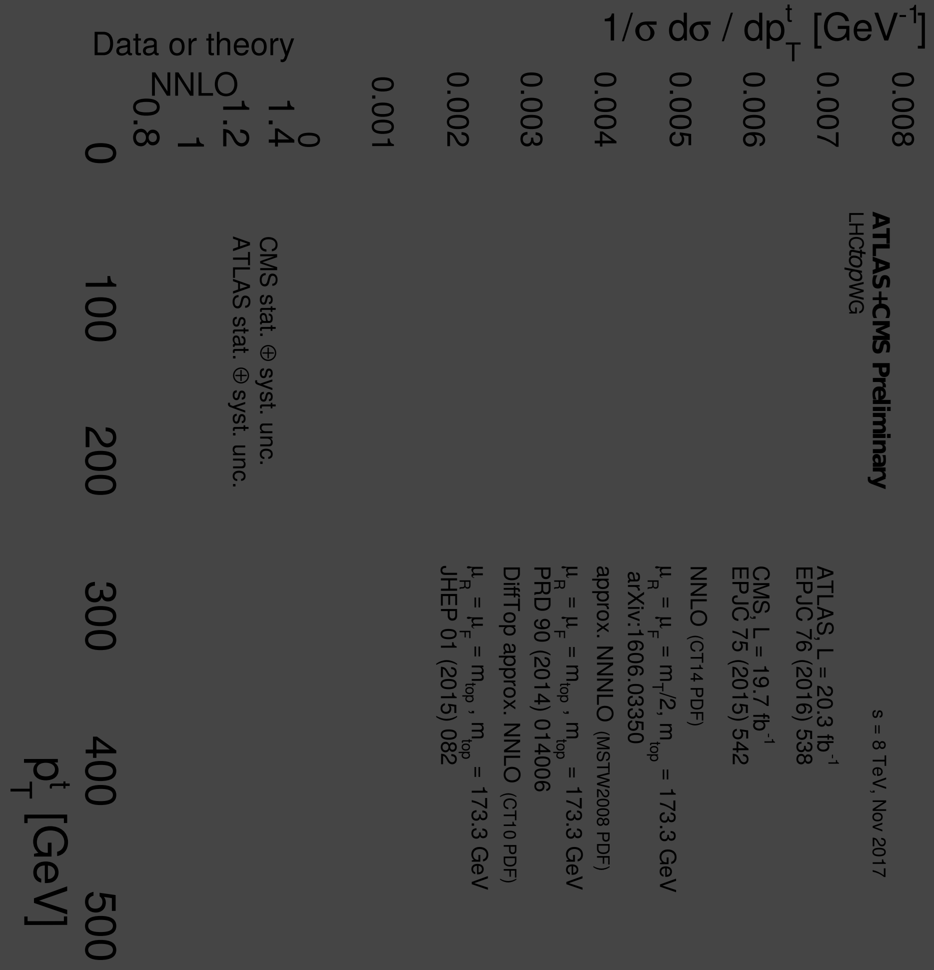
900

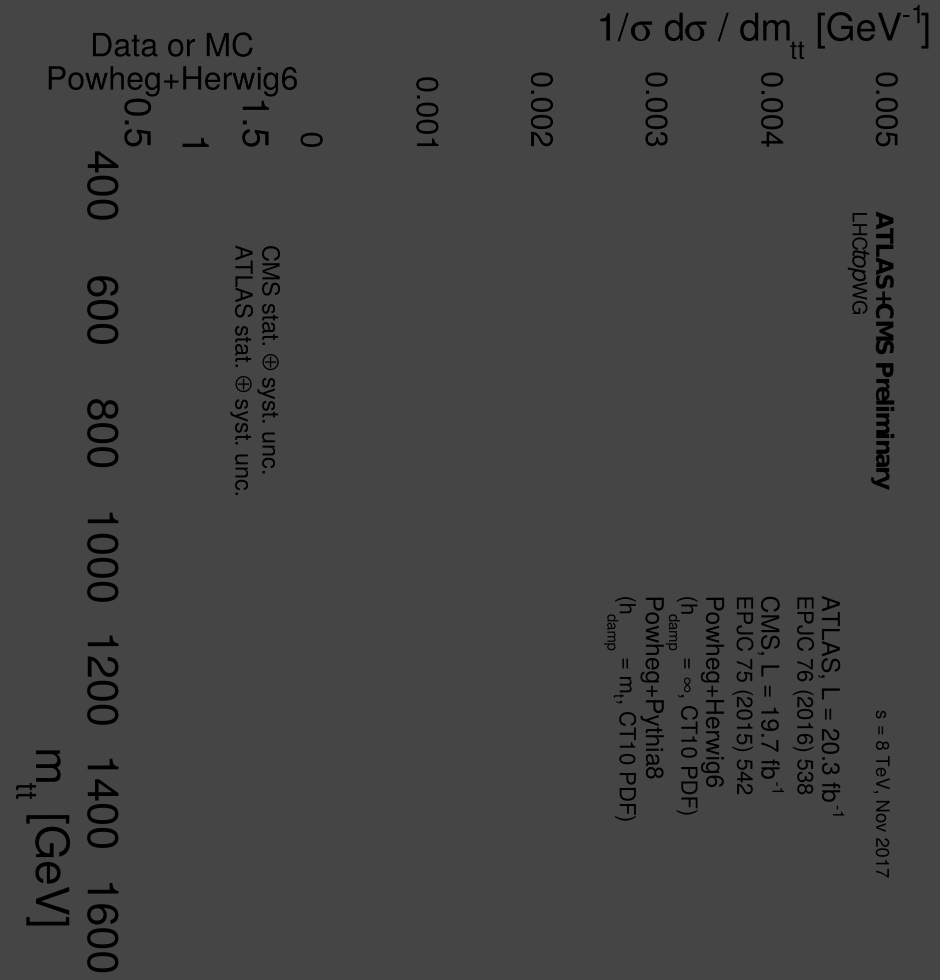
13

s [TeV]



ttbar Cross Section Measurements





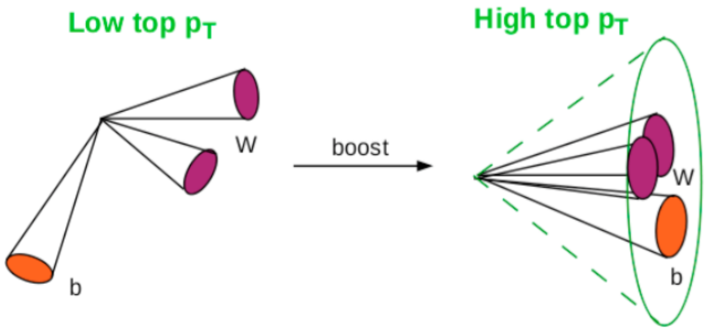
ttbar Differential Cross Section Measurements

Top mass measurements

We still need to improve M_{top} :

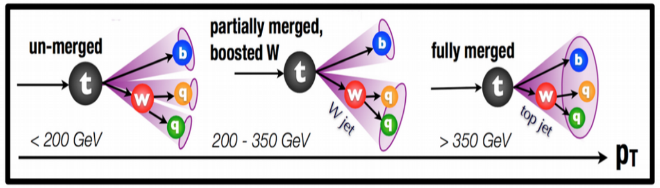
the recent shift on the world average of the top mass resulted in a lowering of 3 GeV on the predicted Higgs mass

Future top mass measurements could come from the boosted topology with W's decaying hadronically

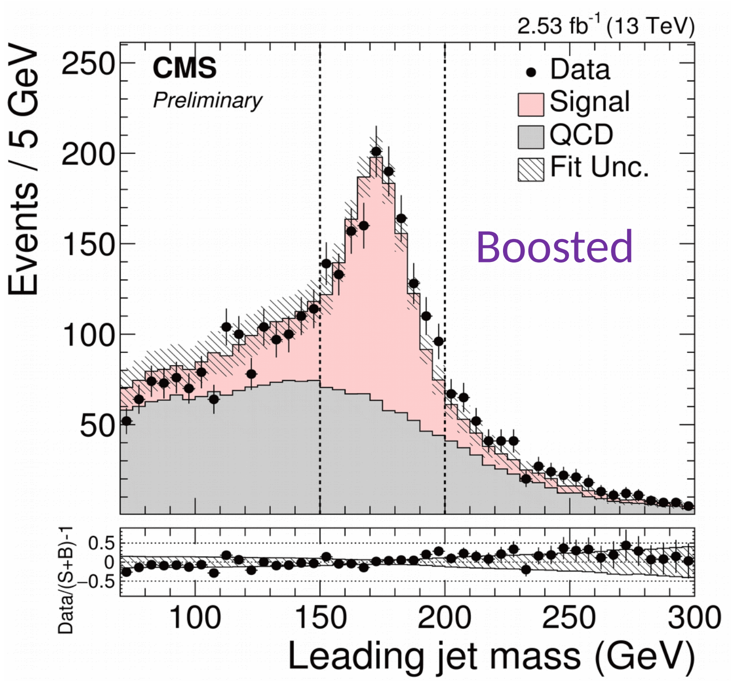


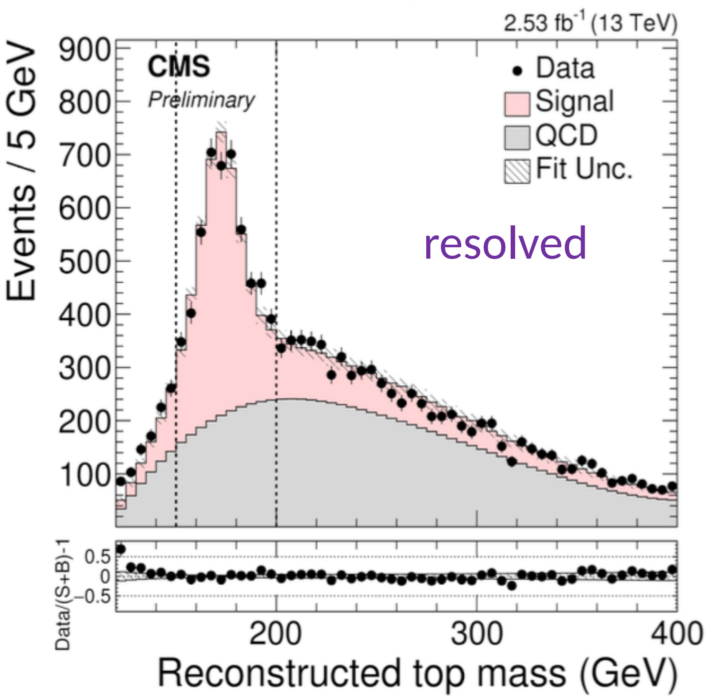
Resolved: decay products are measured individually
Boosted: top-quark decay is contained in a large radius jet

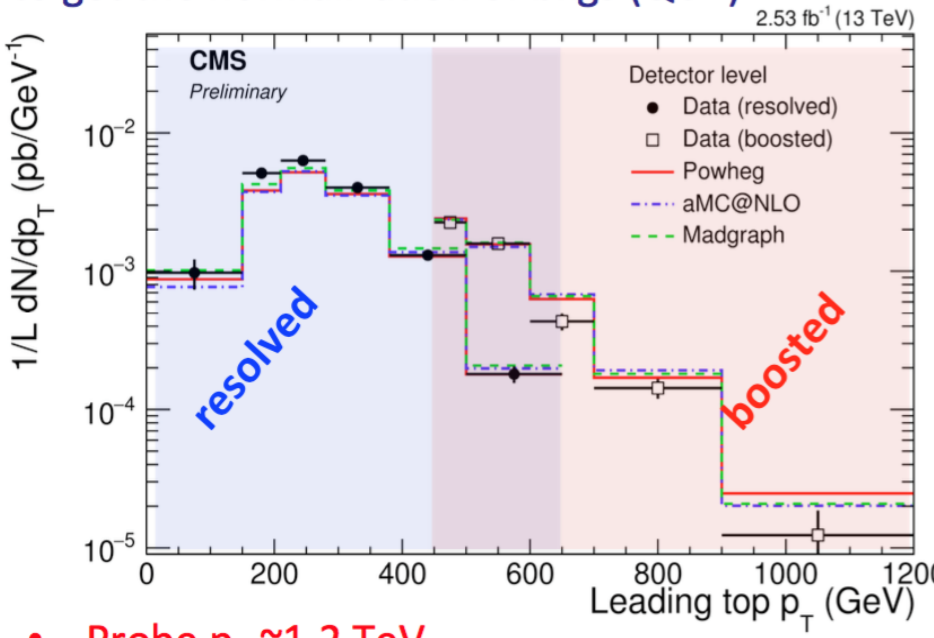
→ Jet substructure techniques (top-tagging)



- Fully hadronic decays: 6 jets, 2 bjets
- QCD background shape from 0-bjet region
- Fit measured top mass distribution to get the normalization of bkgs (QCD)







CMS-PAS-TOP-16-013

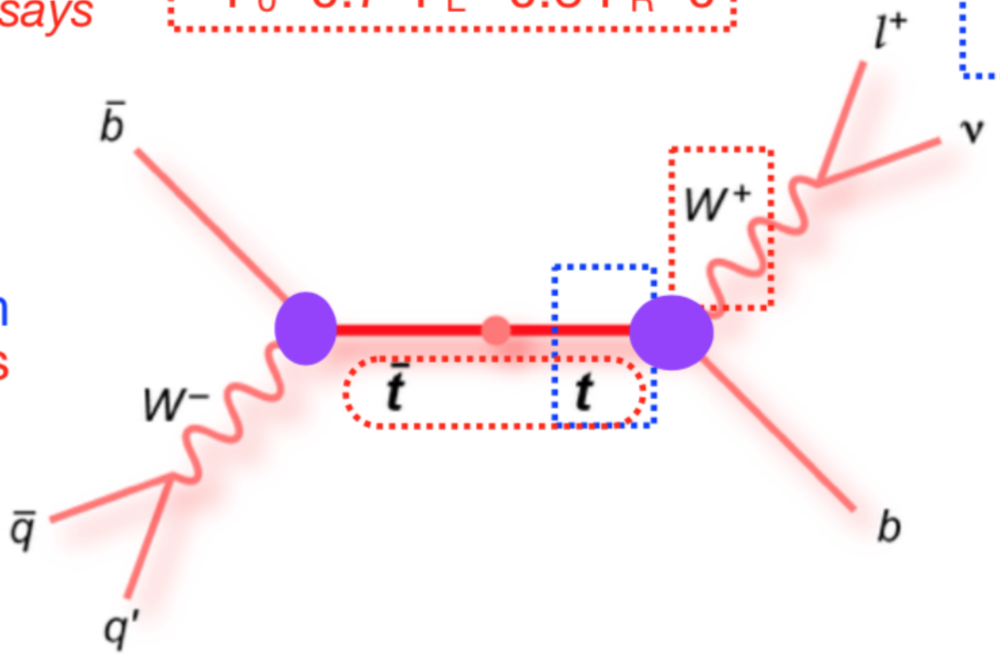
- Probe p_T ~1.2 TeV
- Main systematics, btag, JES, theoretical

So far, all angular properties measured at the LHC are found to be consistent with SM

- W helicity in Wtb vertex? SM says $F_0 \sim 0.7$ $F_L \sim 0.3$ $F_R \sim 0$

- *is top polarised in single top production? SM says YES*

- is top quark unpolarised in pp→ $t\bar{t}$ production? SM says yes



- are t and anti-t angular distribution different ? SM says yes @NLO

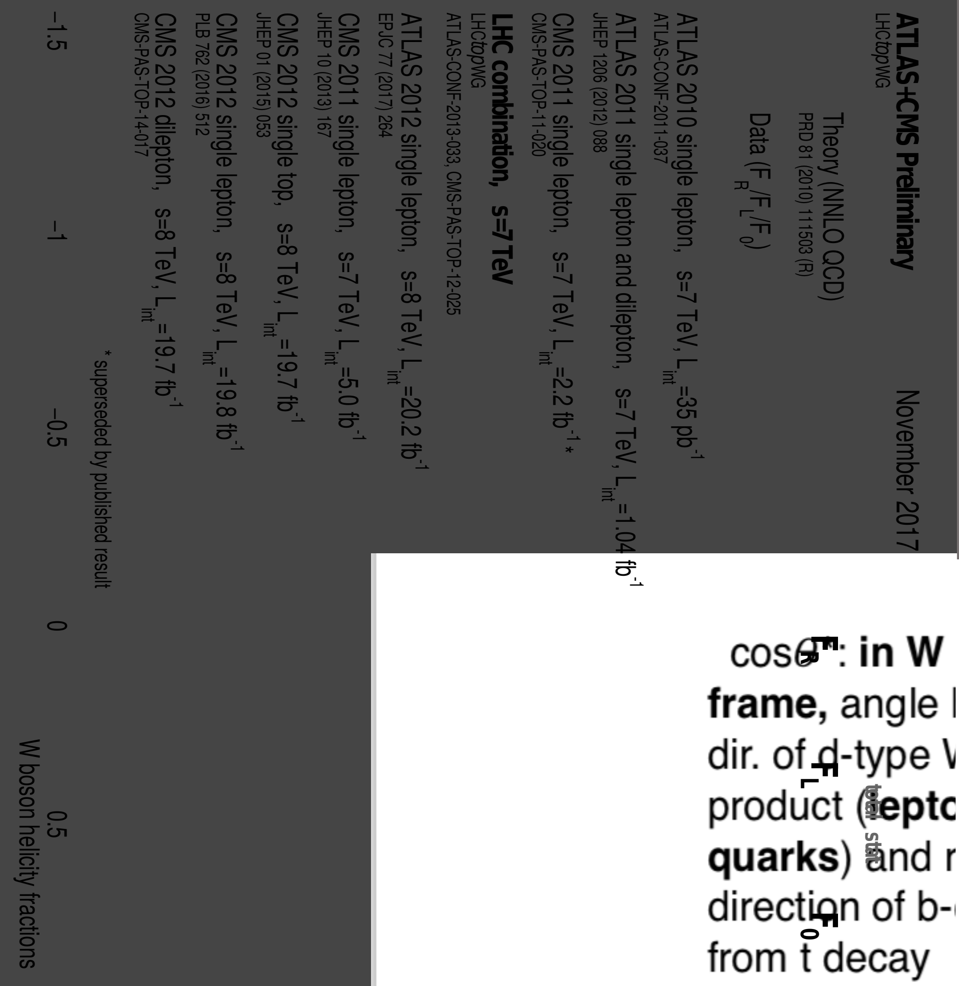
- Are $t\bar{t}$ spins correlated in pp → $t\bar{t}$ production? SM says YES

- is CP violation visible in b-decay from $t\bar{t}$? SM says yes at $<10^{-2}$

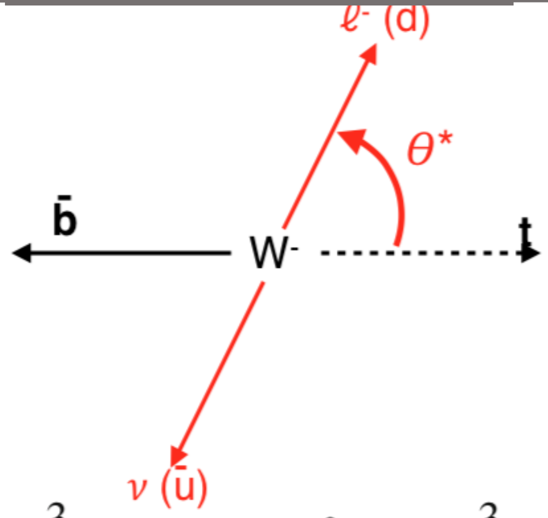
- Wtb vertex ? SM says V-A: i.e. **spin density matrix** as foreseen in combination of $t\bar{t}$ production and decay?

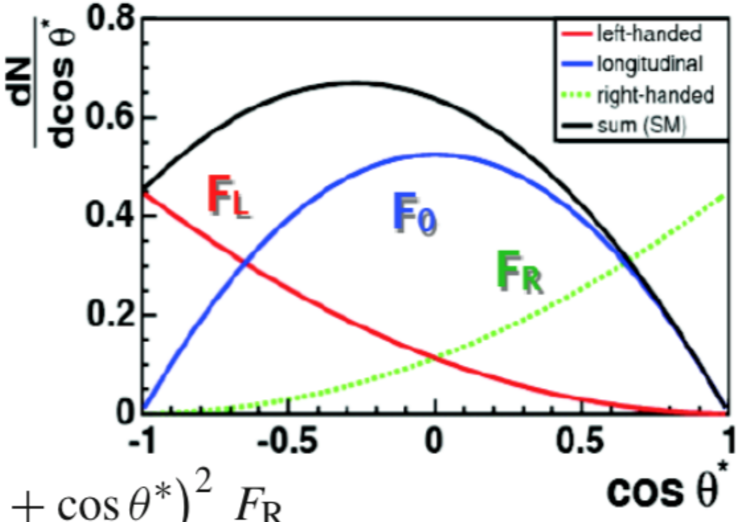
W polarization in Top Decays measurements

The longitudinal polarization state of the *W* is directly connected with the breaking of electroweak symmetry



cosθ^*: **in W frame,** angle b/w dir. of d-type W decay product (**leptons, quarks**) and reversed direction of b-quark from t decay



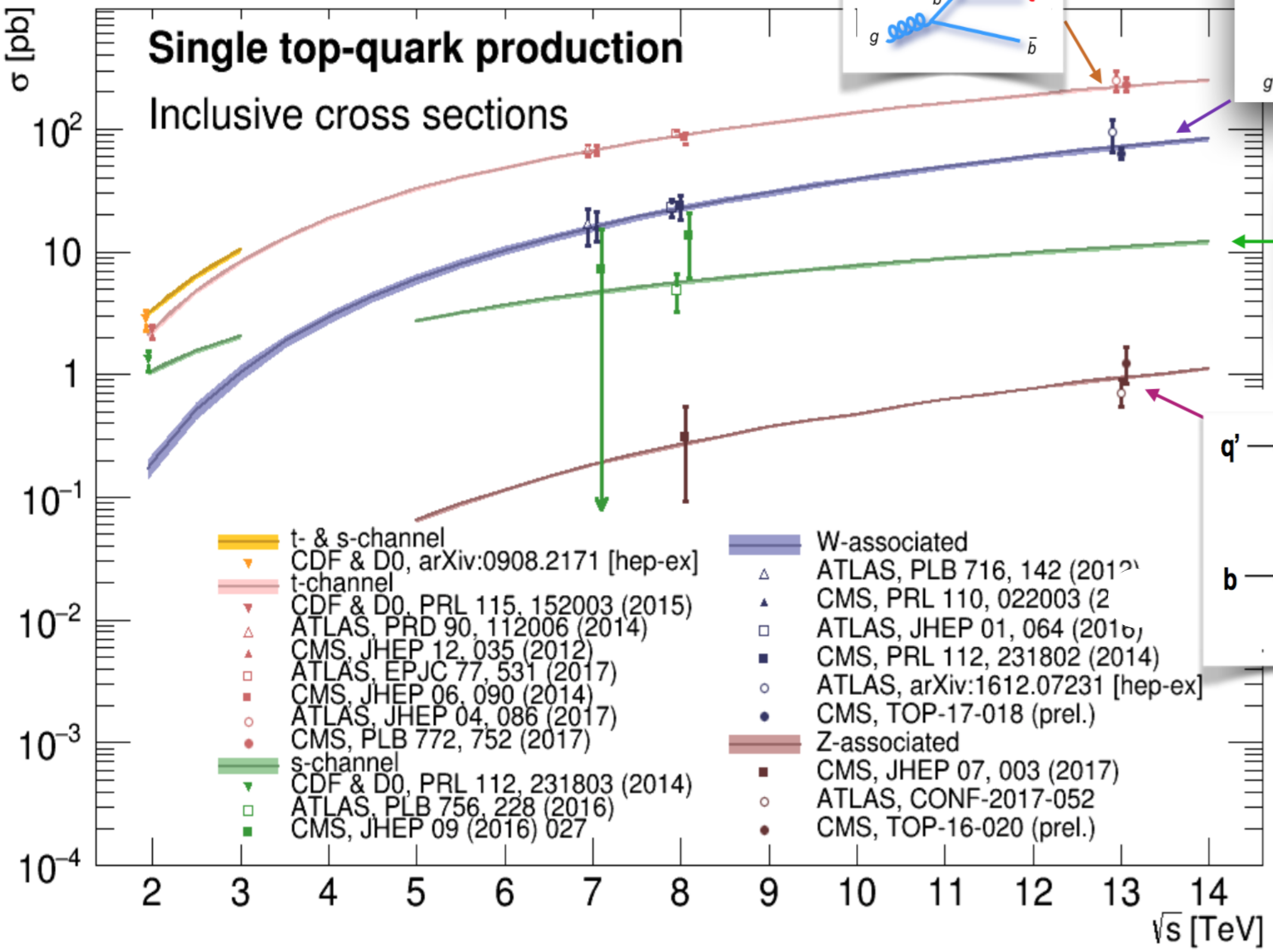


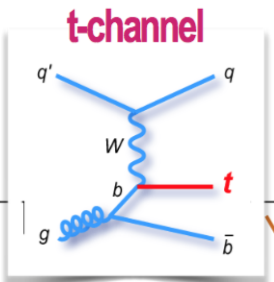
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

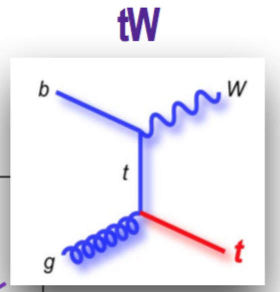
SM (@NNLO, % rel unc.) ~0.687 ~0.311 ~0.0017

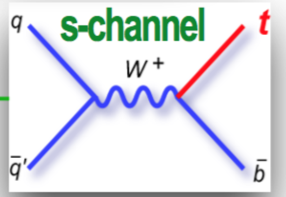
Single-Top Quarks

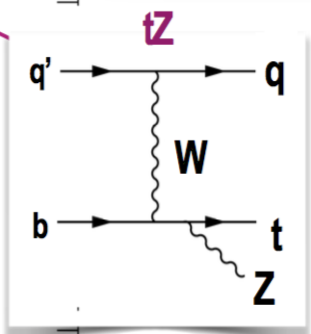
Picture from upcoming paper (A. Giammanco & R. Schwienhorst),
Theory curves: N. Kidonakis (t, tW, s, @ NLO+NNLL) & J. Andrea (tZ @ NLO)



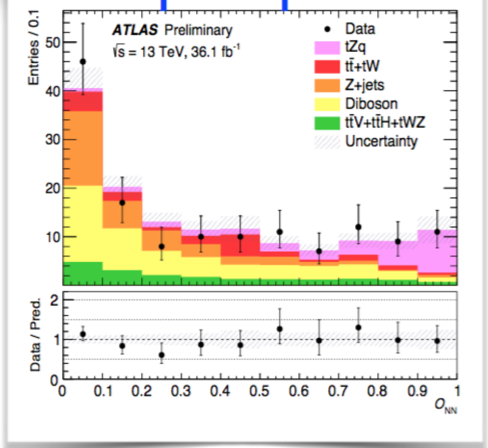




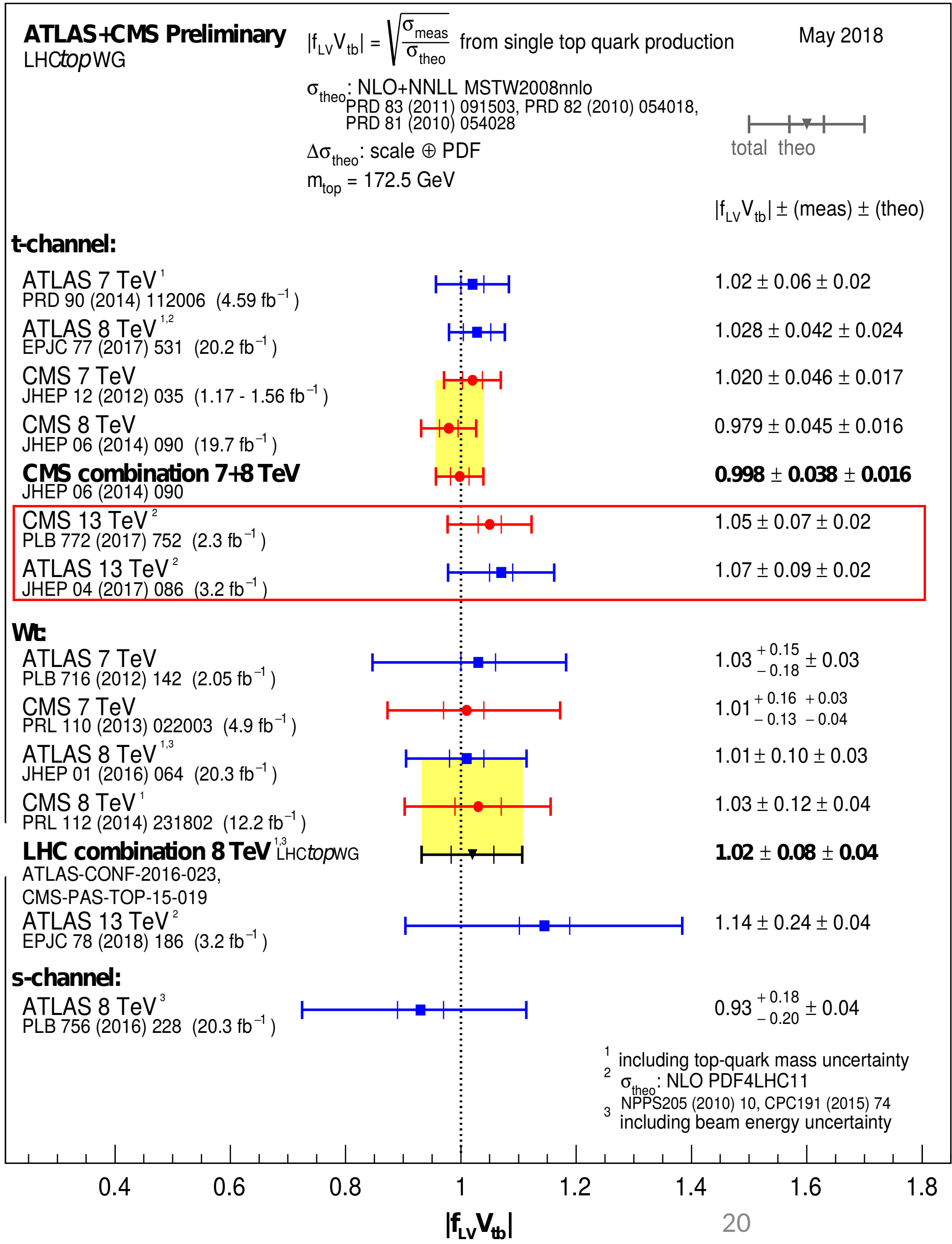




tZq template fit



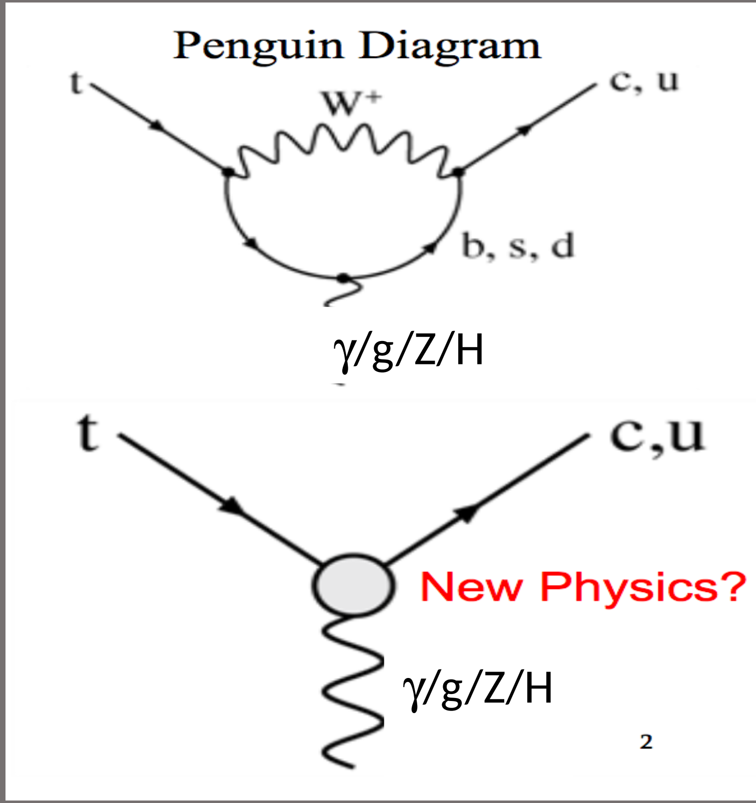
➡ Many new results!
➡ SM predictions 😀

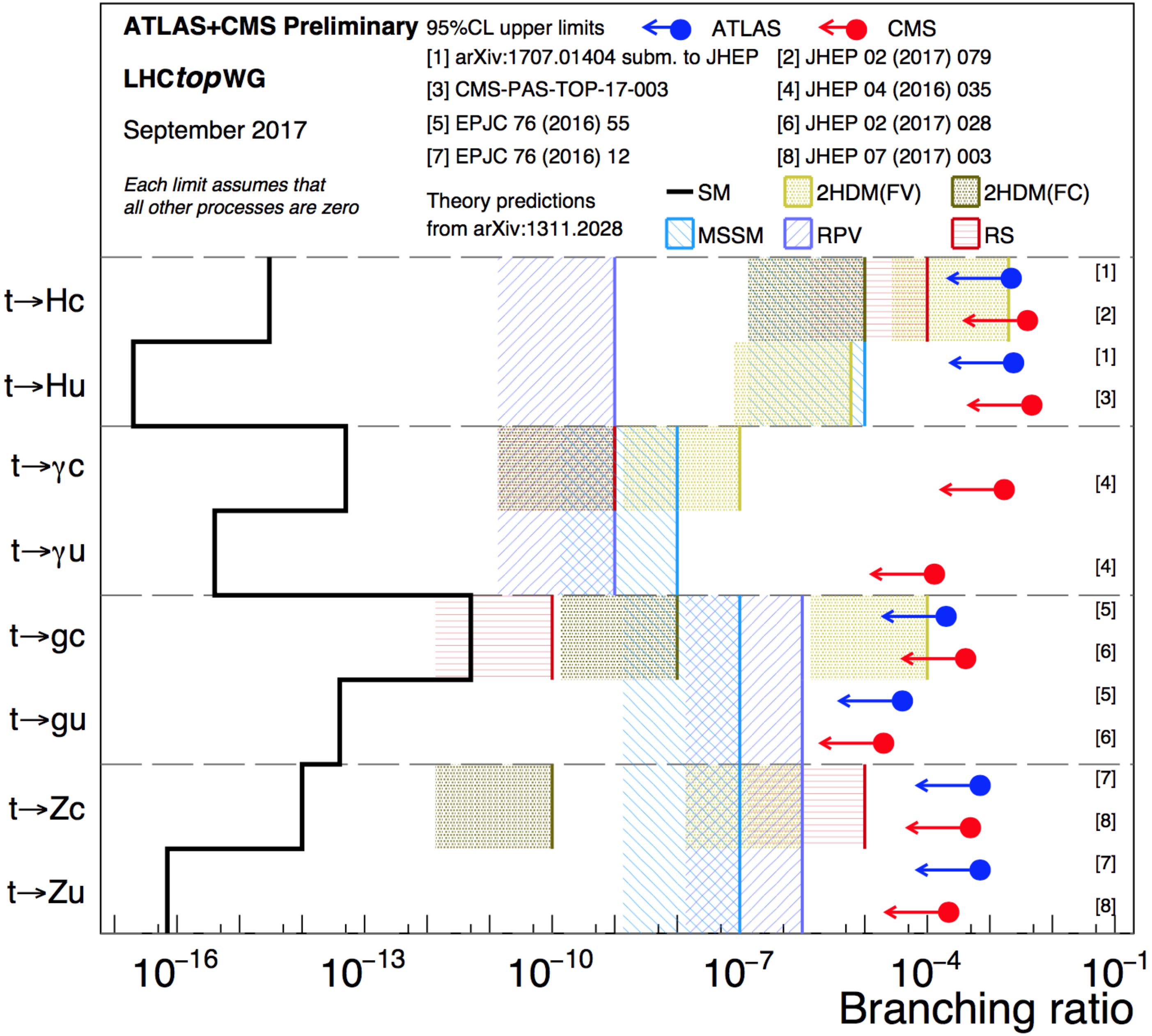


Single top V_{tb} at 1-2% level* will be possible with the full 13 TeV data compared to 4% at 8 TeV

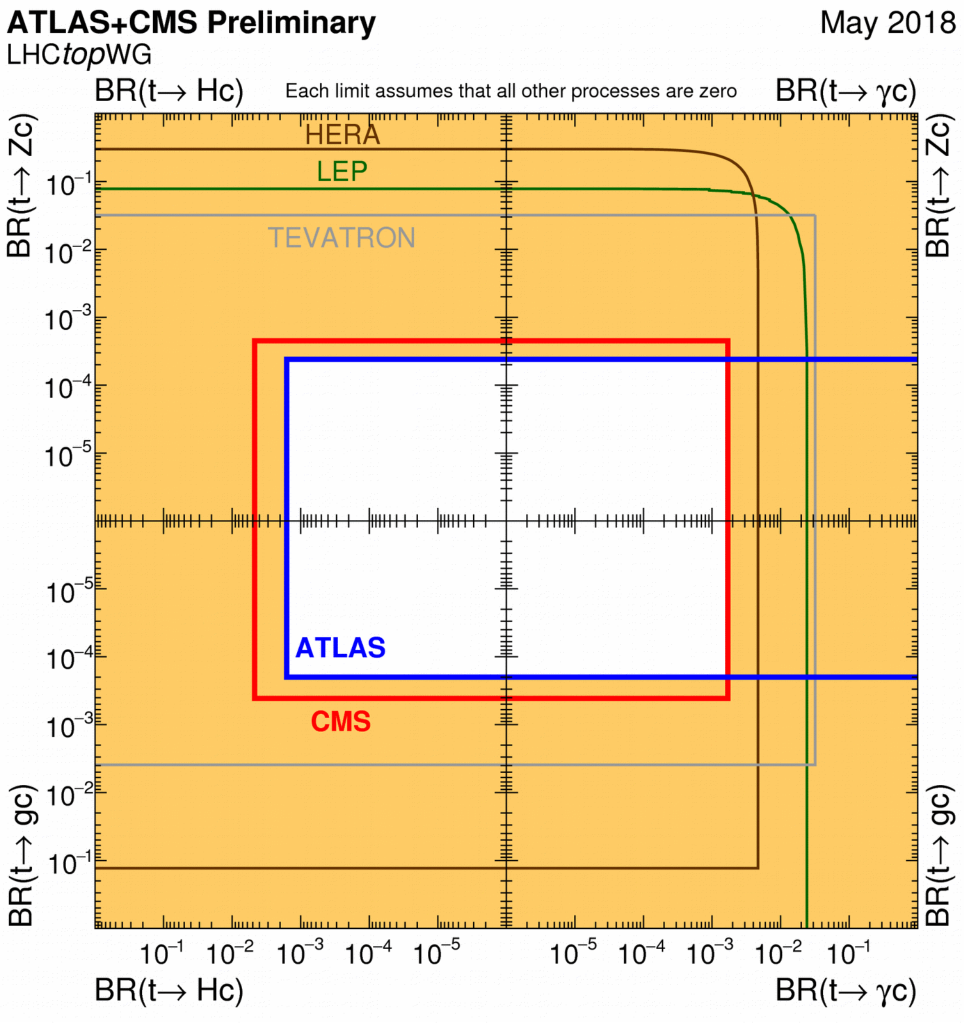
* Assuming the theoretical error will go down

Searches for Flavor-Changing-Neutral Currents in top decays… Decay into real Z's & Higgs boson kinematically possible





Reducing the allowed window with all channels combined



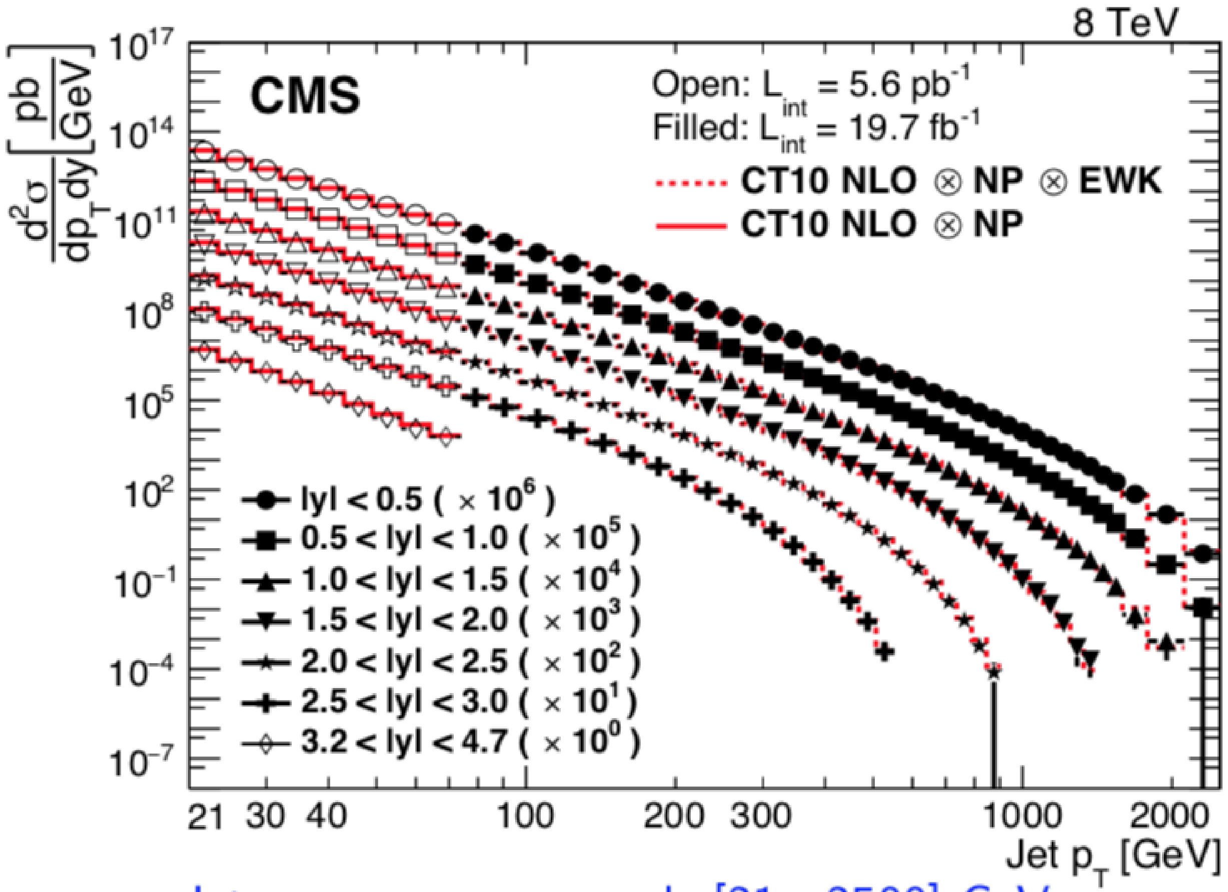
FCNC in top decays

Jet based measurements

Inclusive Jet Cross Section Measurement

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon\mathcal{L}} \frac{N_j}{\Delta p_T \Delta y}$$

Predictions are in very good agreement with data!



Jet p_T range measured: [21 , 2500] GeV

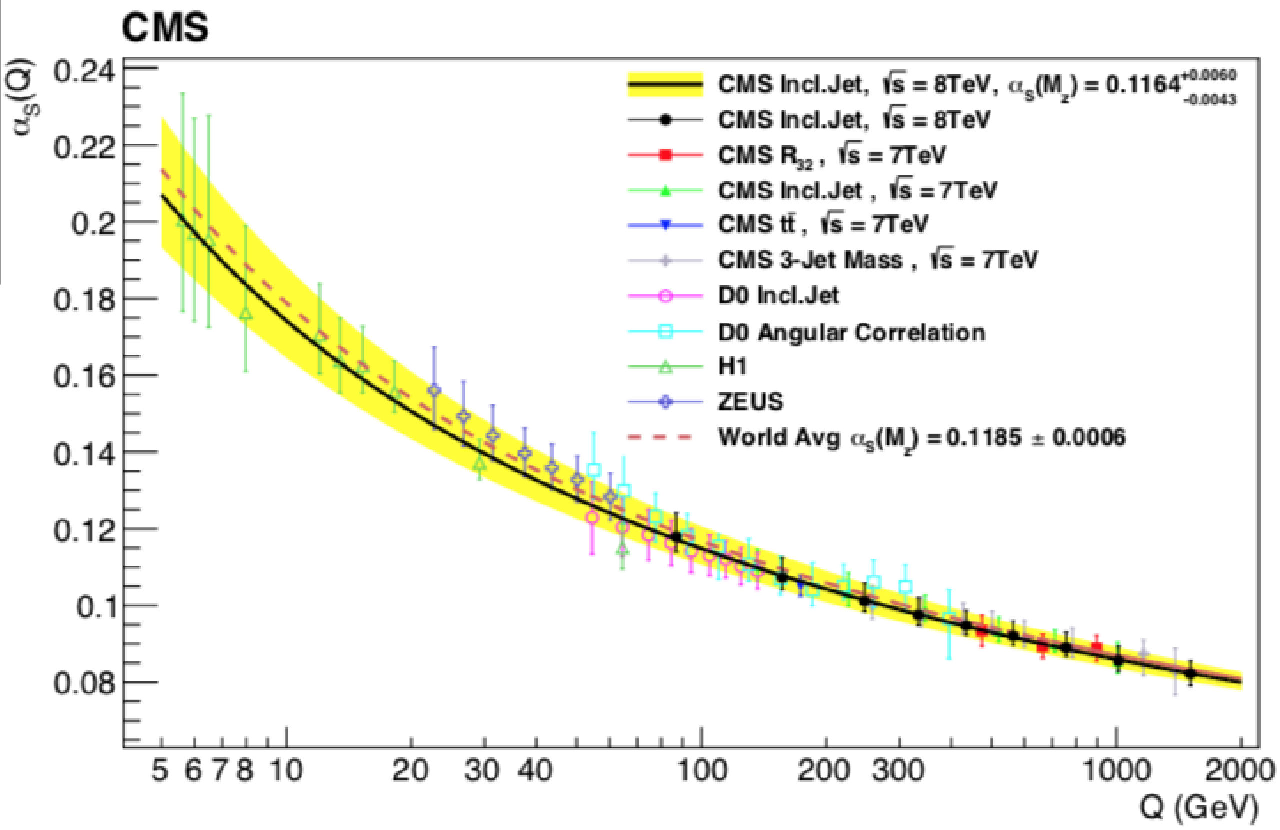
Double differential inclusive jet cross sections compared to NLO predictions

Examples of extraction of the strong coupling α_s from inclusive Jet Cross Section Measurement

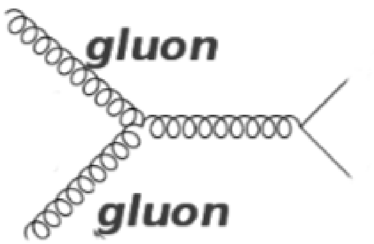
CMS jet measurements allow extraction of value of α_S:

$$\alpha_S(M_Z) = 0.1164^{+0.0029}_{-0.0025}\ \text{(PDF)}\ ^{+0.0053}_{-0.0028}\ \text{(scale)}\ ^{+0.0014}_{-0.0015}\ \text{(exp.)}$$

CMS data from jet measurements add points to the running of α_S up to 2 TeV



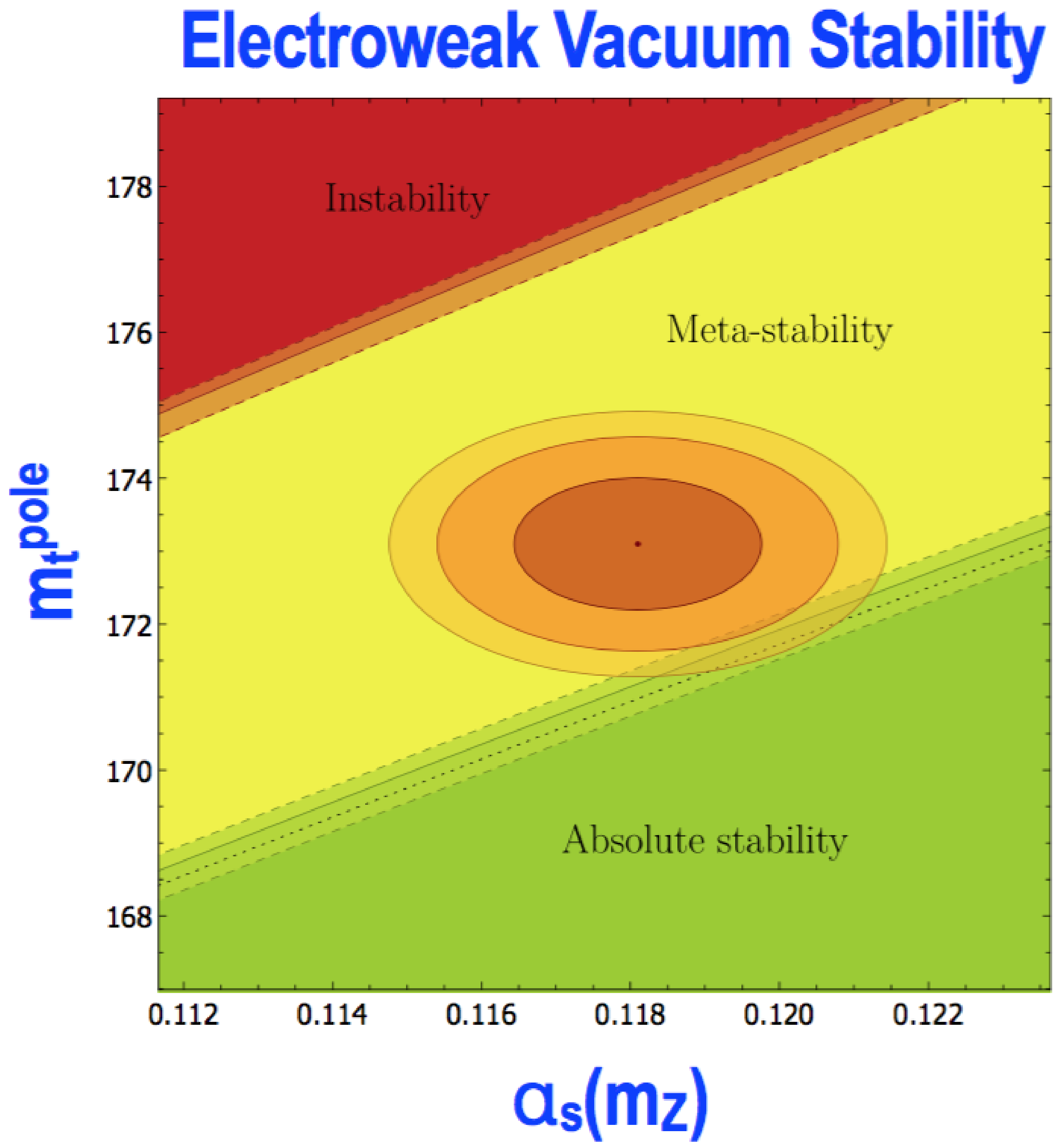
$$\frac{d\sigma}{dp_T dy} \propto \alpha_S^2$$



→ α_S **measurement dominated by theory uncertainties!**

Why are we obsessed with Top mass and α_s?

10/22/18 - 10/26/18



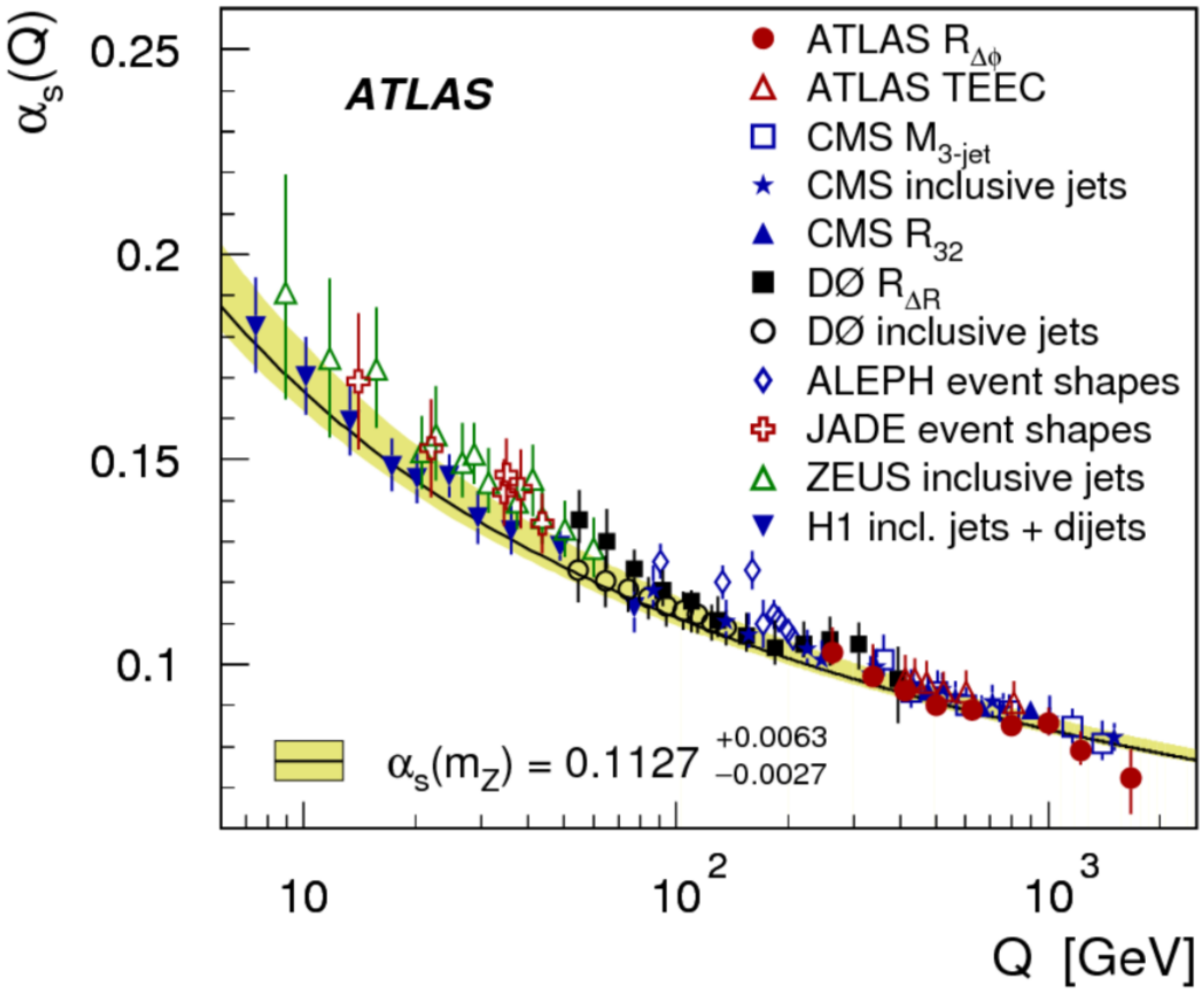
arXiv:1707.08124

arXiv:1805.04691

Similarly for ATLAS using decorrelations in dijet events

- Calculate running with renormalisation group equation
- 1 σ below world average $\alpha_S^{\text{PDG}} = 0.1181 \pm .0011$
- Highest measured $\alpha_S(Q)$ value to date

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

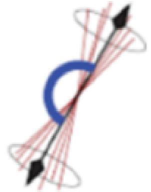


PDF uncertainties cancel out

More on Multi-jet correlations

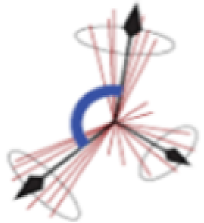
For more than one jet in the event, one can measure the azimuthal correlation between the two leading jets

At LO in pQCD the two final-state partons are produced back-to-back in transverse plane.



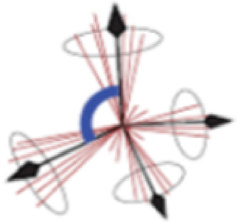
$\Delta\varphi_{\text{dijet}} = \pi$

The production of a third jet leads to a decorrelation in azimuthal angle.



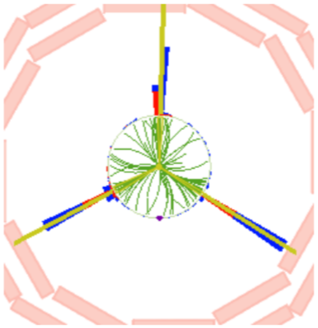
$2\pi/3 \leq \Delta\varphi_{\text{dijet}} < \pi$

If more than three jets are produced, the azimuthal angle between the two leading jets can approach zero.

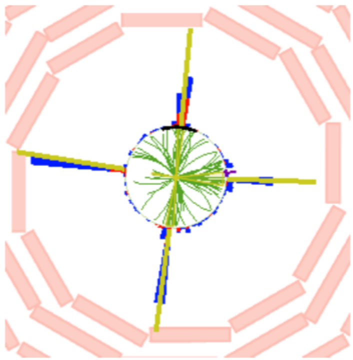


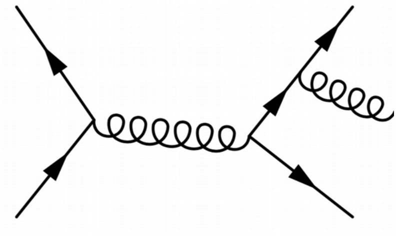
$0 < \Delta\varphi_{\text{dijet}} \ll \pi$

$2\pi/3$, 3 jets



$\pi/2$, 4 jets



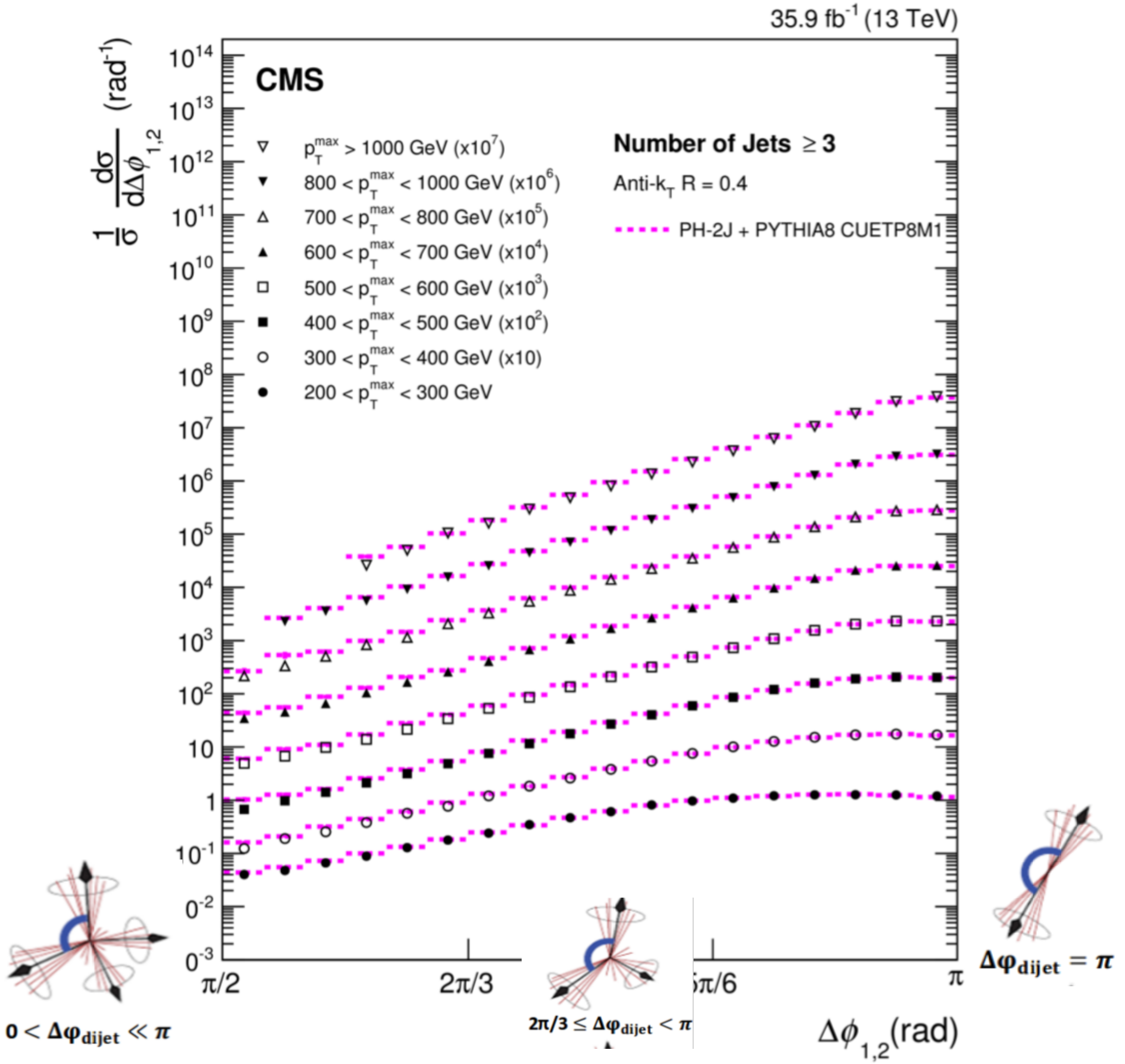


- Azimuthal angles between jets are sensitive to ISR, FSR
- Testing ground for pQCD, MC tunes

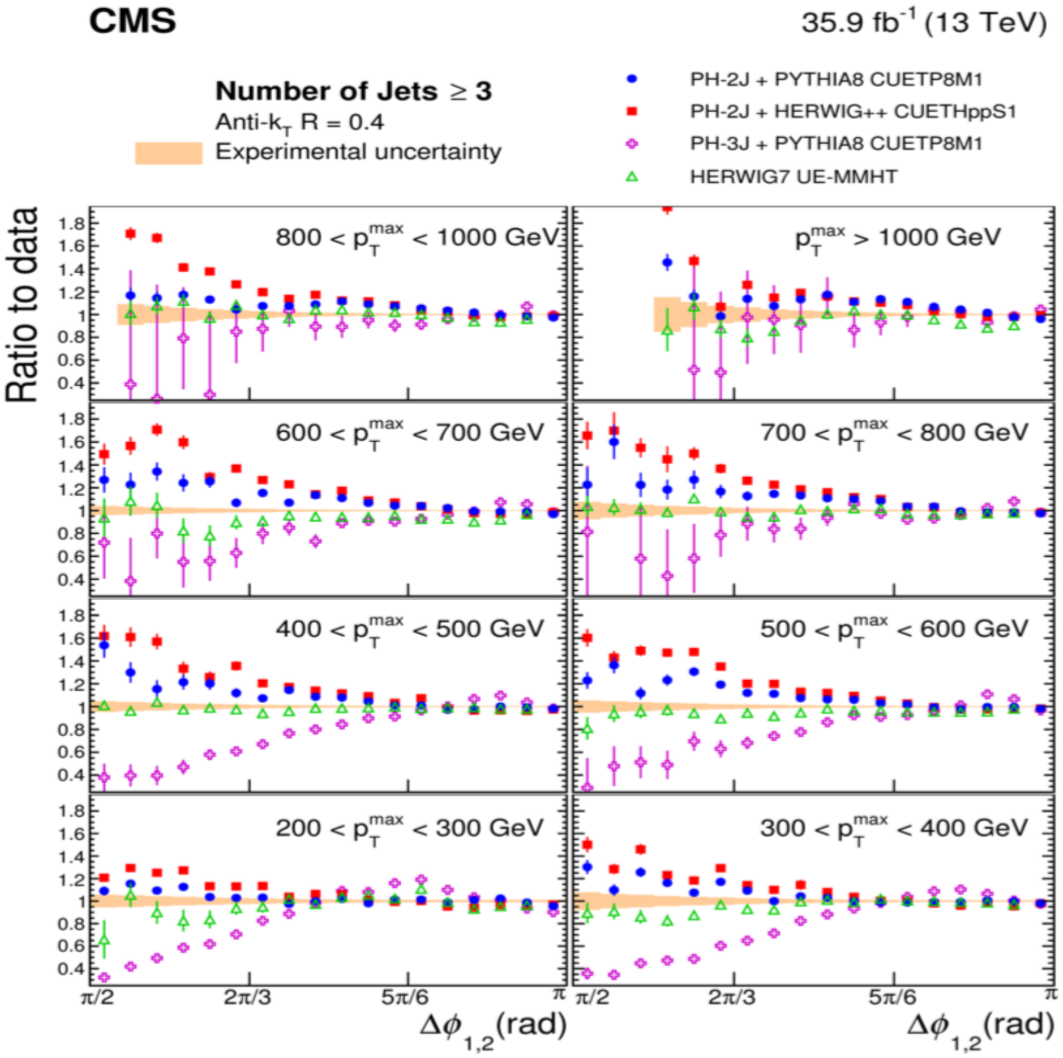
Azimuthal Correlations

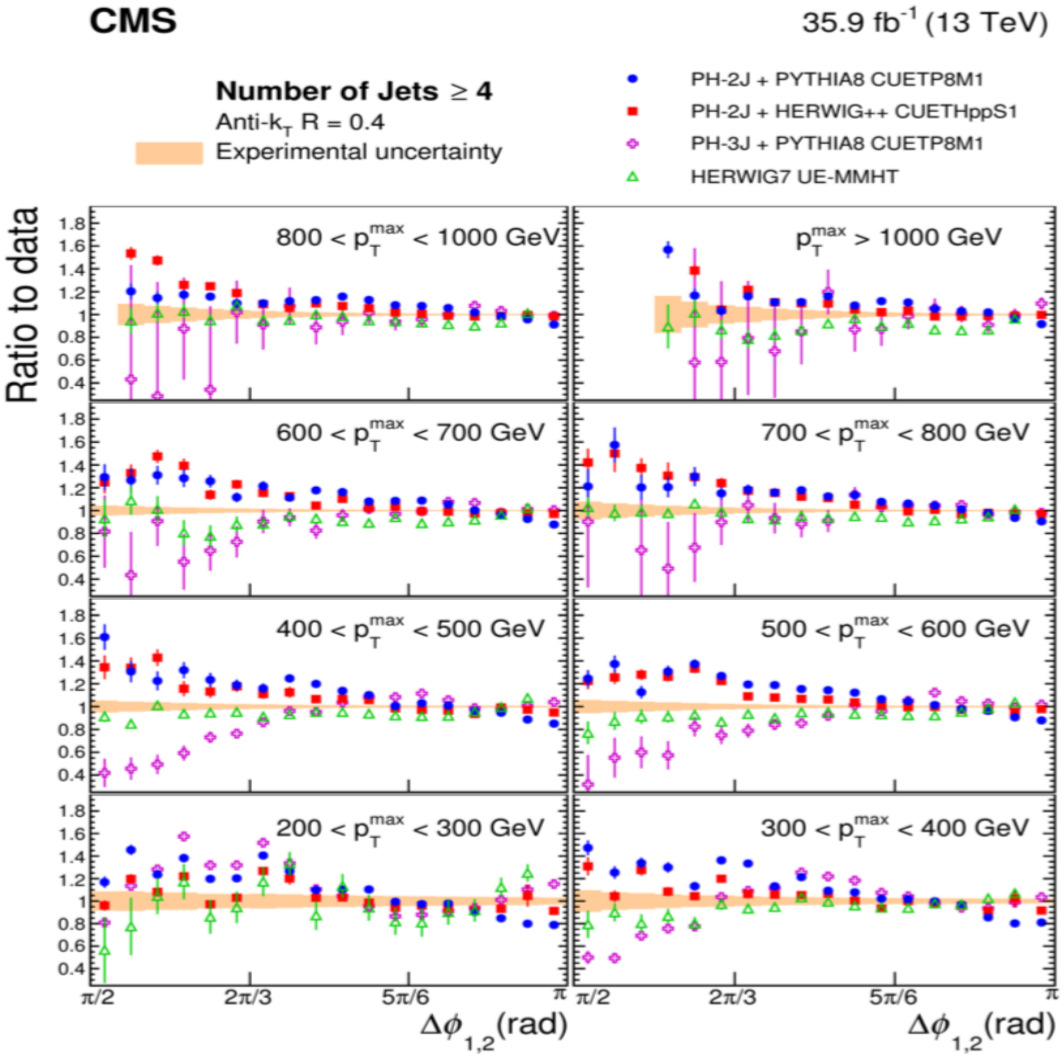
- Exclude Δφ < π/2: large $t\bar{t}$ and W/Z + jet backgrounds

- Best overall description given by MC@NLO



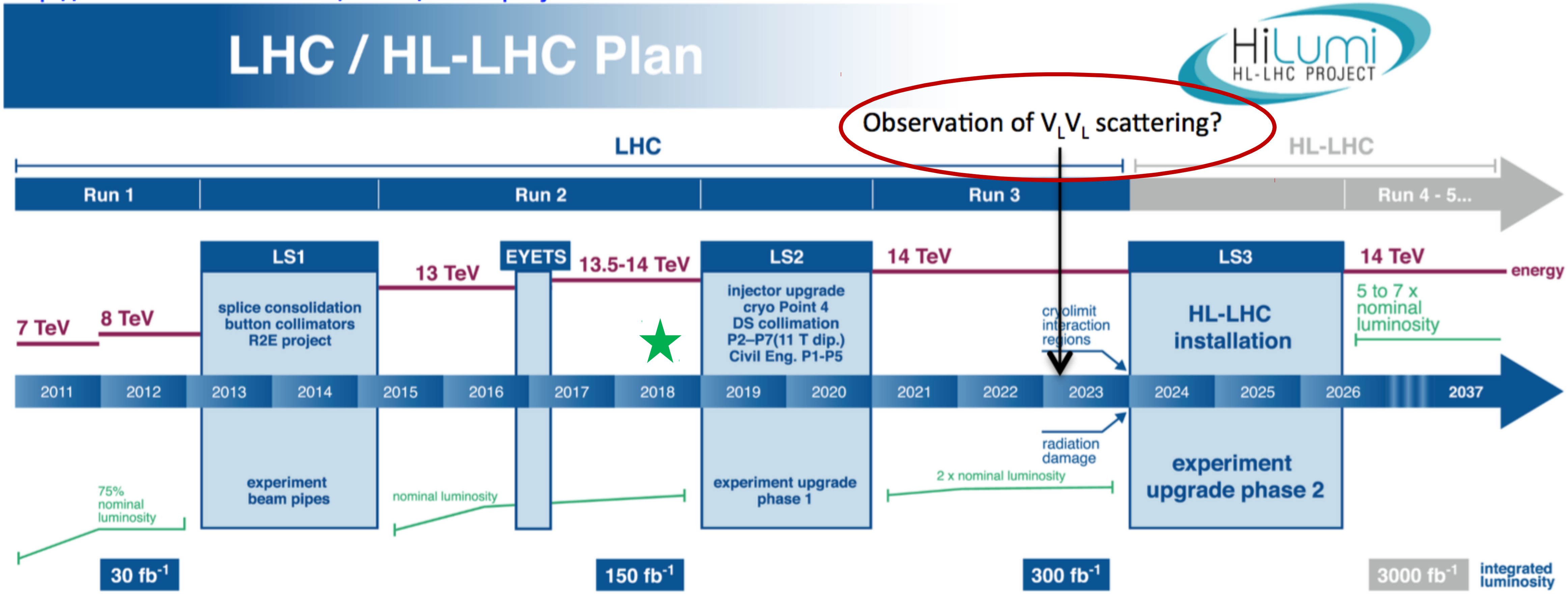
Azimuthal Correlations





arXiv:1712.05471

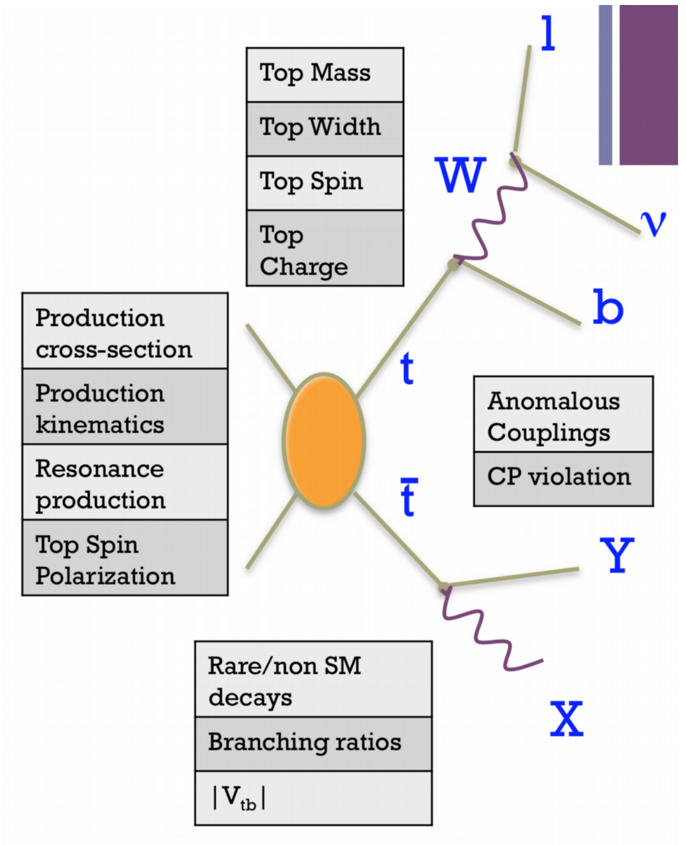
http://hilumilhc.web.cern.ch/about/hl-lhc-project



Preparing the ground for the scattering of longitudinal W's

Already have 150 fb^{-1}/experiment

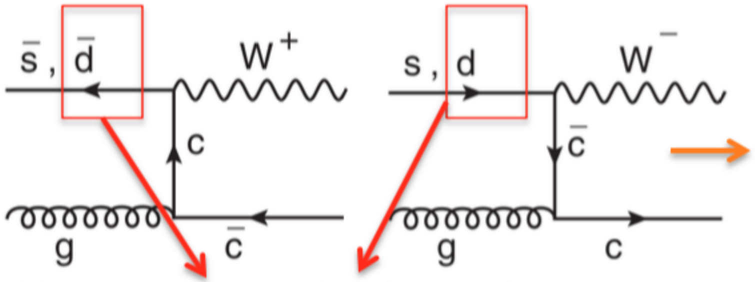
- Precision test of both QCD and EWK
  - Strong coupling to Higgs
- Sensitive to Physics Beyond the SM
- Can be used to measure important parameters like α_s, m_t etc.
- Mayor background to important searches
- Interesting playground to develop new analysis techniques



Conclusions
Top properties makes it a great probe … and jets too

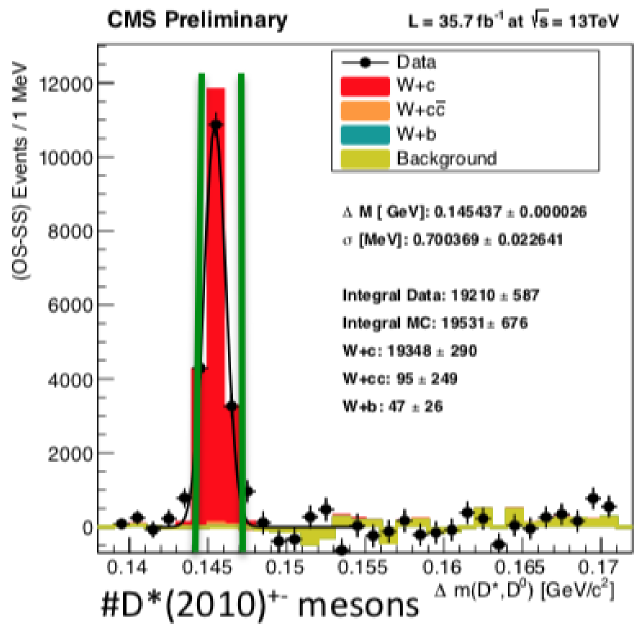
BACKUP

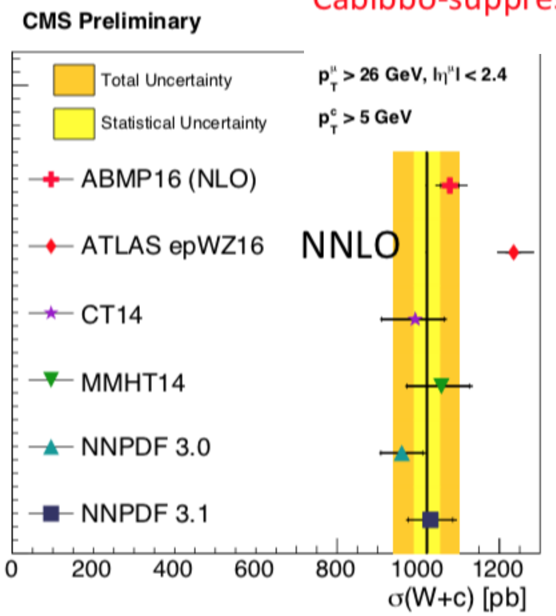
Some controversies to be solve… W+Charm



Cabibbo-suppressed, only a few % of the W+c-jets xs

W+c opposite sign events

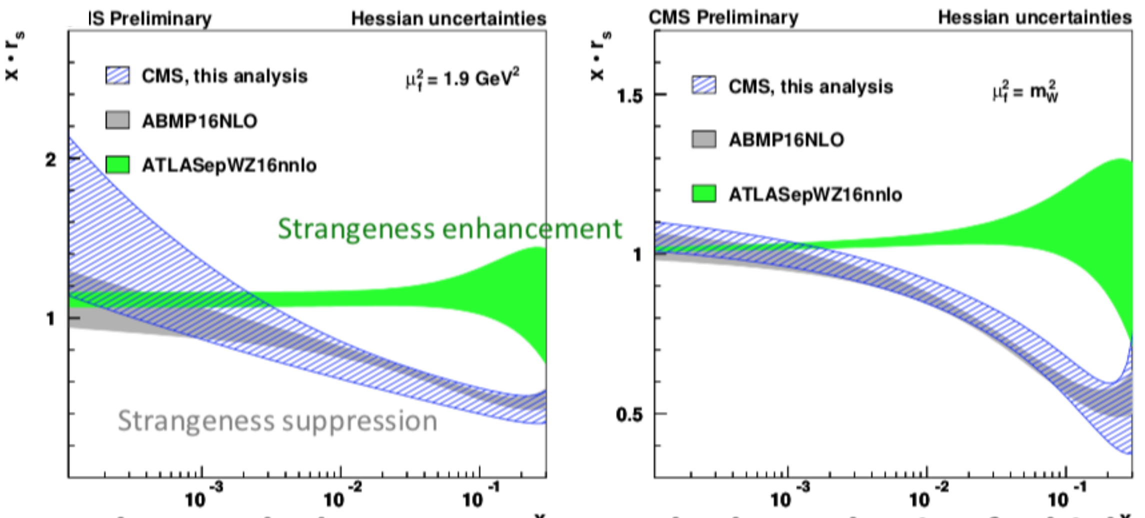




$$\sigma(\mathrm{W+c}) = 1026 \pm 31\ (\mathrm{stat})\ ^{+76}_{-72}\ (\mathrm{syst})\ \mathrm{pb}$$

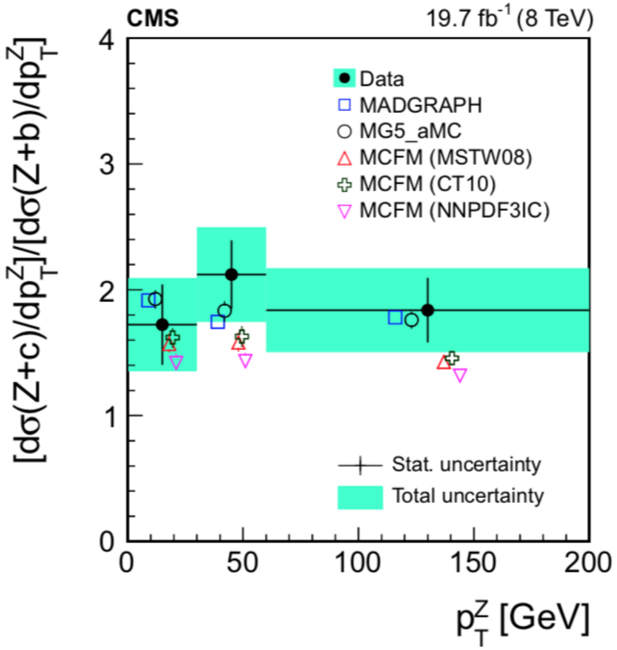
$$\frac{\sigma(\mathrm{W^+ + \bar{c}})}{\sigma(\mathrm{W^- + c})} = 0.968 \pm 0.055\ (\mathrm{stat})\ ^{+0.015}_{-0.028}\ (\mathrm{syst})$$

$$r_s = \frac{s+\bar{s}}{2\bar{d}}$$



The result does not support the hypothesis of a high strange quark contribution in the proton quark sea

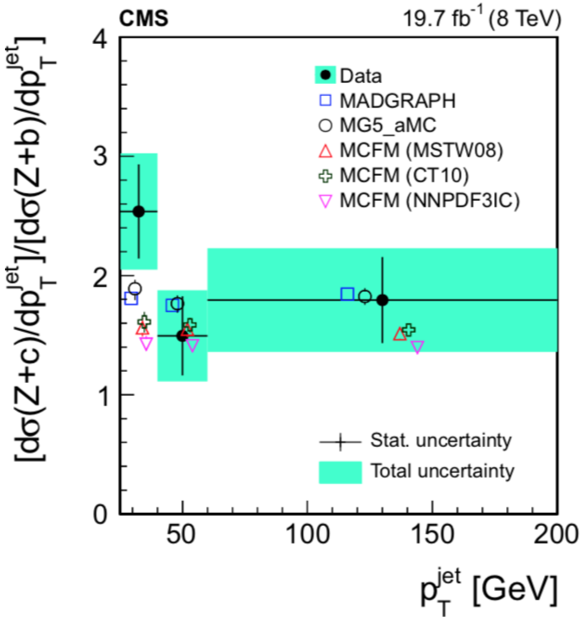
No evidence found for intrinsic charm in the nucleon from Z + c (b)

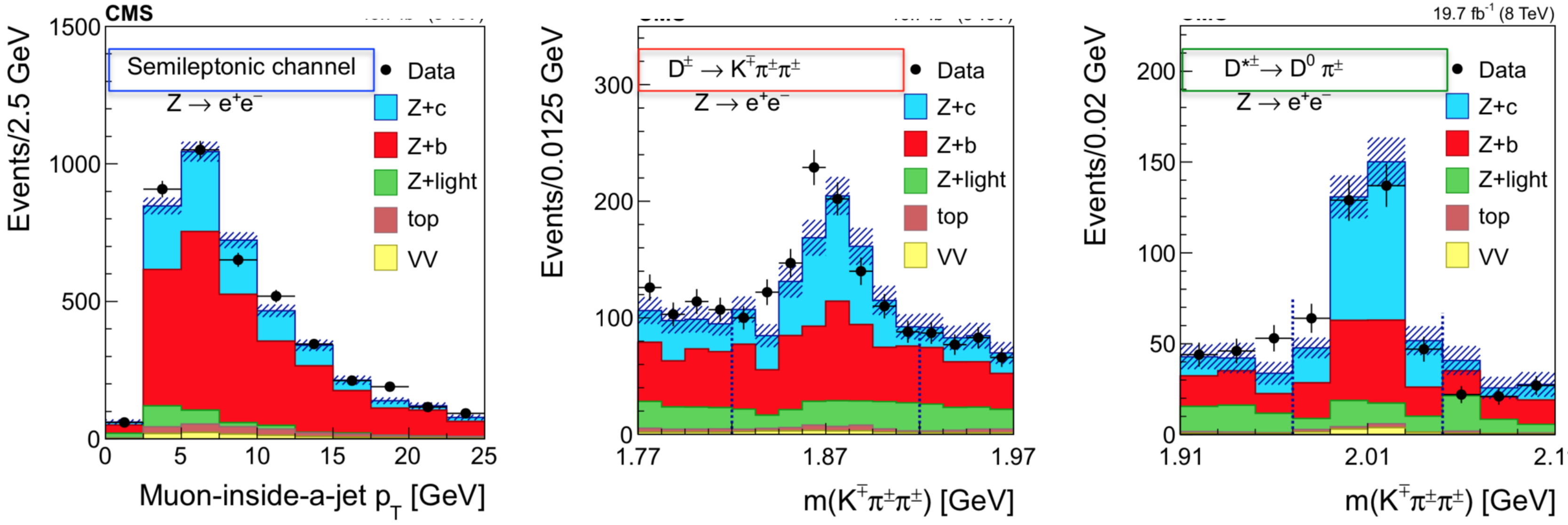


- Possibility to look at **Intrinsic Charm** component in the nucleon would enhance Z+c production, in particular **at high Z and c-jet p_T**

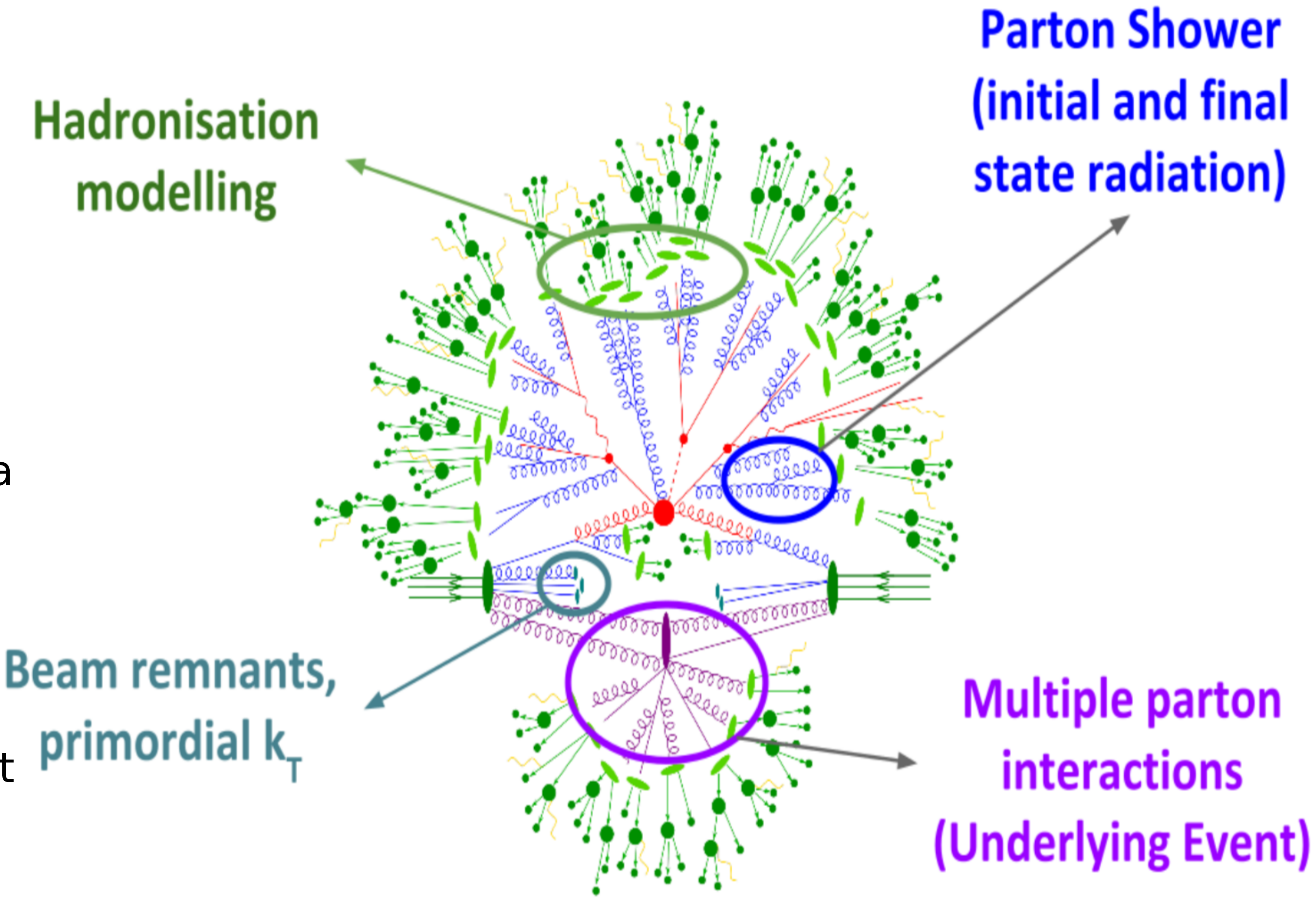
Semi-leptonic decay mode, ratio

$$\sigma(Z+c)/\sigma(Z+b) = 2.0 \pm 0.2\,(\text{stat}) \pm 0.2\,(\text{syst})$$





A hard ***pp*-collision** at the LHC can be interpreted as a hard scattering between partons, accompanied by the underlying event (UE) consisting of the 4 components illustrated in this drawing… not just what is labeled as UE



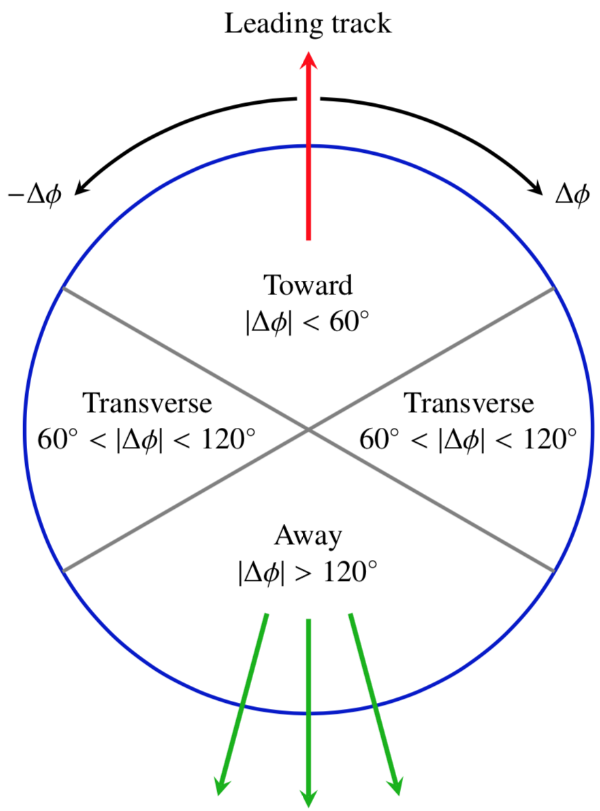
From Frank Siegert

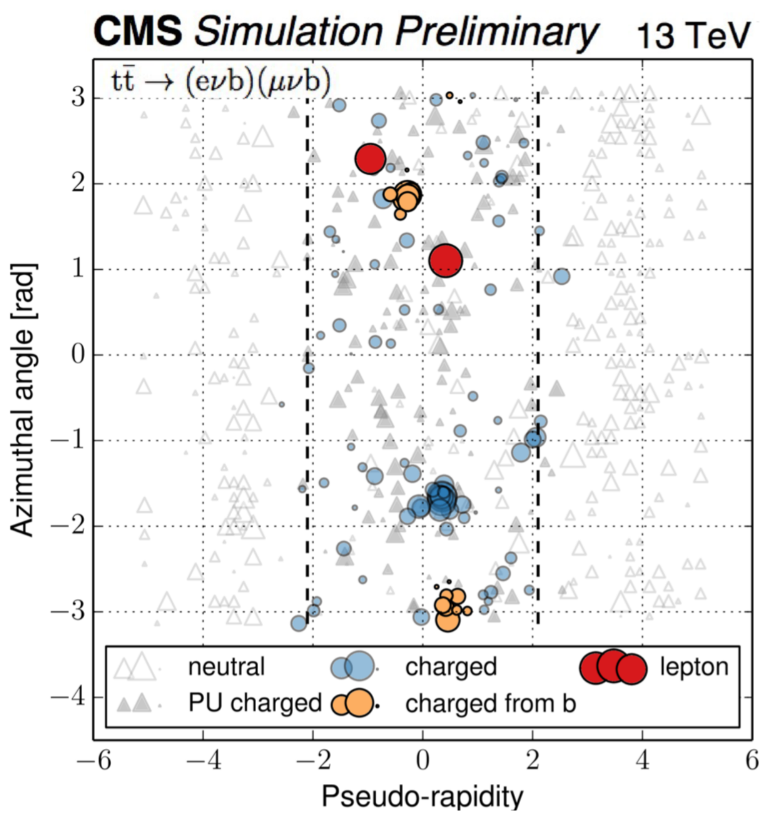
Many processes are included in the nomenclature "UE" at

Double Parton Scattering (DPS), Diffractive processes, Semi-hard multiparton interactions

Initial measurements from Minimum bias, DY, etc.

In event generators a lot of parameters need to be adjusted (tuned) to describe data





Measuring UE properties at $\mu_R,\mu_F \approx 2m_t$

Comparisons with a range of generators, tunes and settings