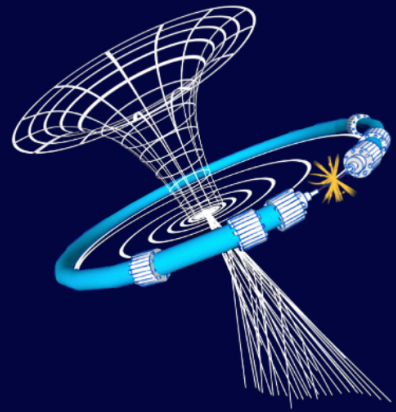


15th IDPASC
Summer School

20 - 29 July 2026

Natal, Brazil



Collider Physics

The energy frontier

July 24, 2026

15th IDPASC Summer School

Oscar Éboli

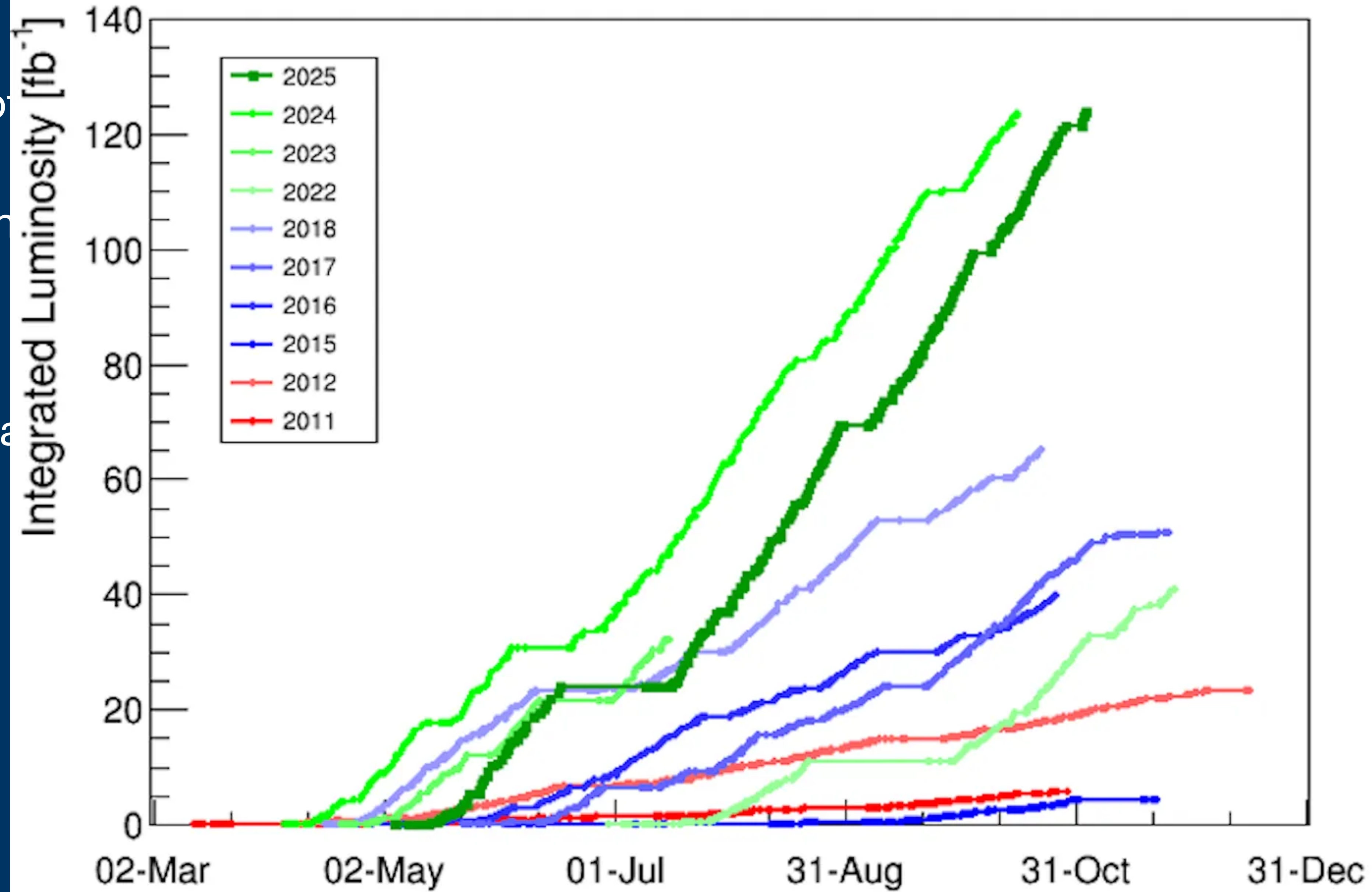


Scenarios

- Particle physics frontiers:
 1. The intensity frontier
 2. The cosmic frontier
 3. The energy frontier
- Intensity frontier: high statistics to look for small effects, e.g. $\mu^- \rightarrow e^- \gamma$
- Cosmic frontier: uses astronomical/cosmological data.
- Energy frontier: colliders are used to test the SM and look for BSM

Collider parameters

- Center-of-mass energy
- Instantaneous luminosity
- Beams and beam dynamics



p_2

thumb:

$$\Rightarrow \mathcal{L} \propto s$$

e^+e^- colliders

e^+e^- colliders

Advantages

- e^+e^- colliders are precision machines: interactions are well understood
- Initial charges are zero
- Scattering kinematics is well understood/constrained
- All CM energy is available to produce new states
- It is possible to polarize the beams

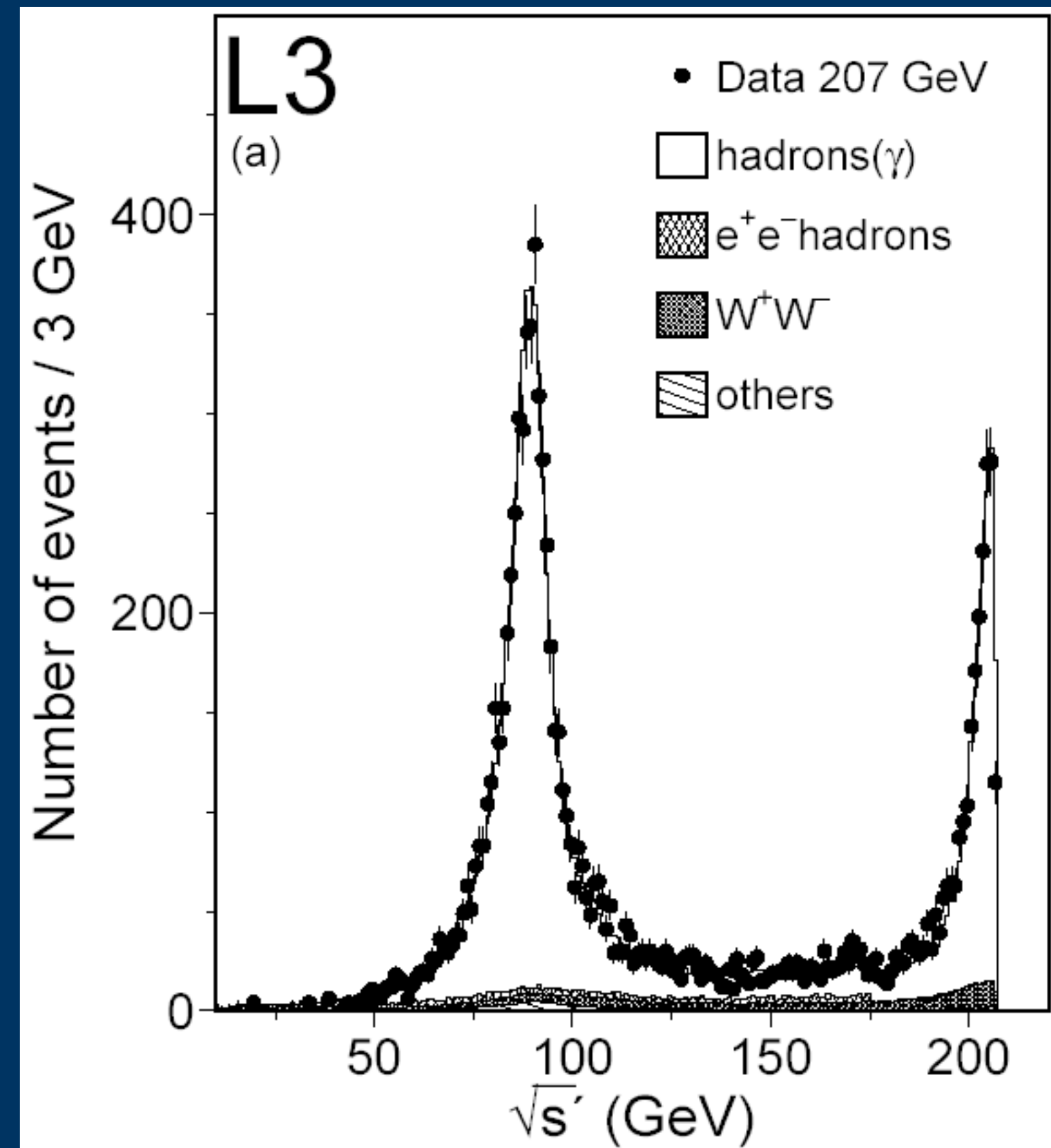
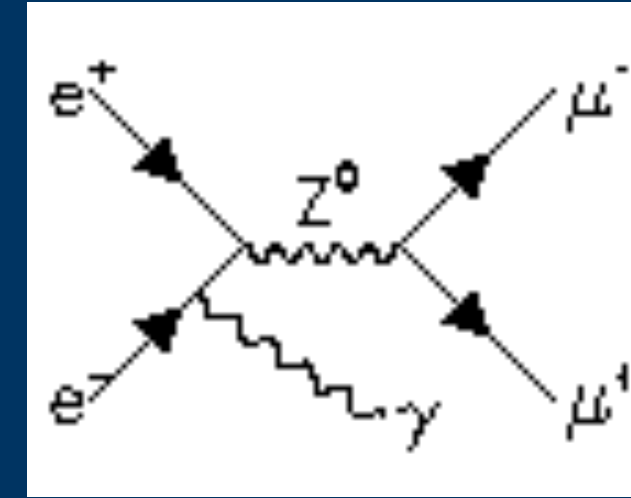
Disadvantages

- Large synchrotron radiation
- Energy losses by bremstrahlung/beamstrahlung

- Need to take into account the energy spread: $\int \frac{d\mathcal{L}}{d\tau} \sigma(\hat{s})$ with $\tau = \frac{\sqrt{\hat{s}}}{\sqrt{s}}$

e^+e^- colliders

- ISR can lead to large effects



hadron colliders

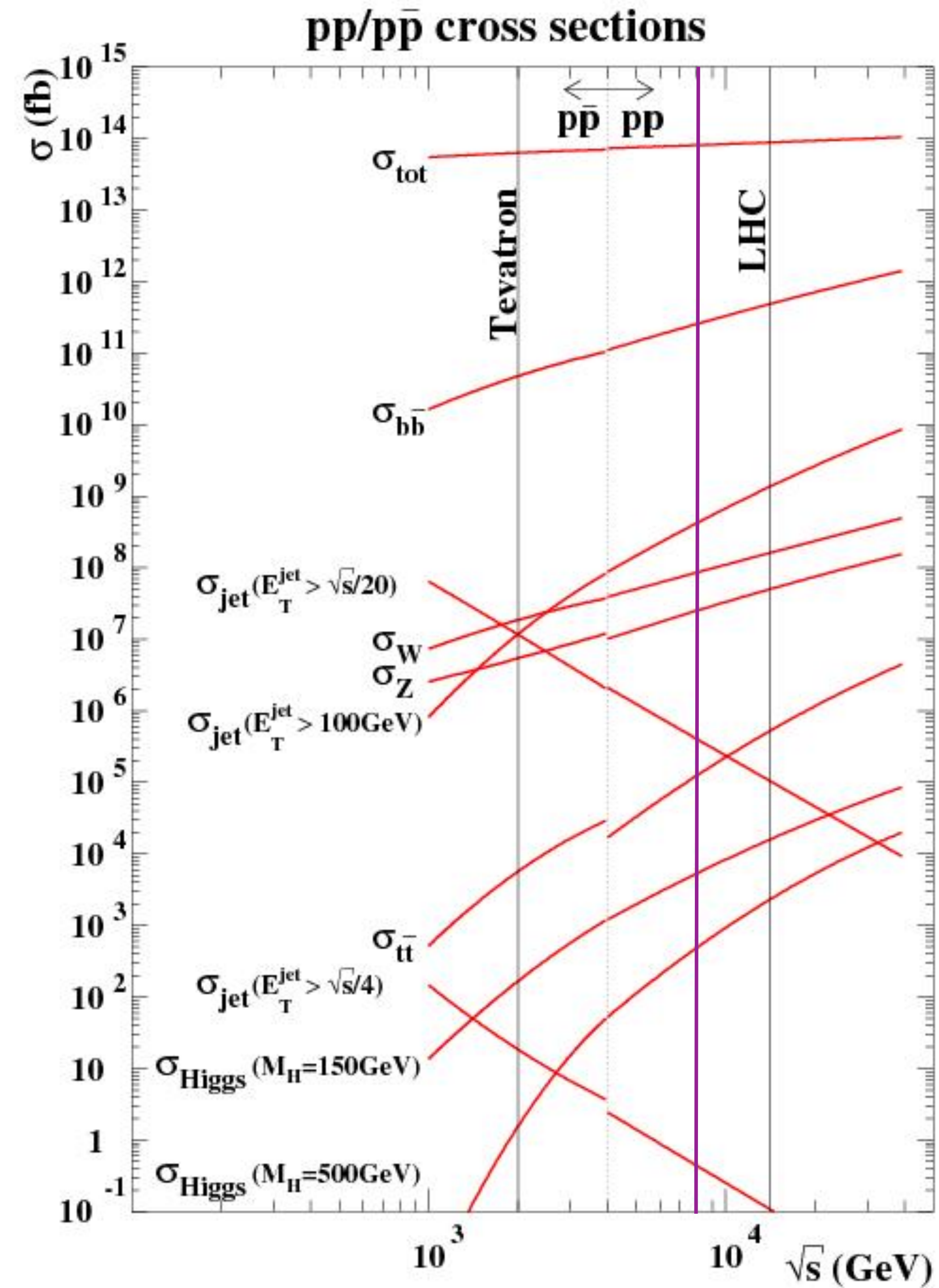
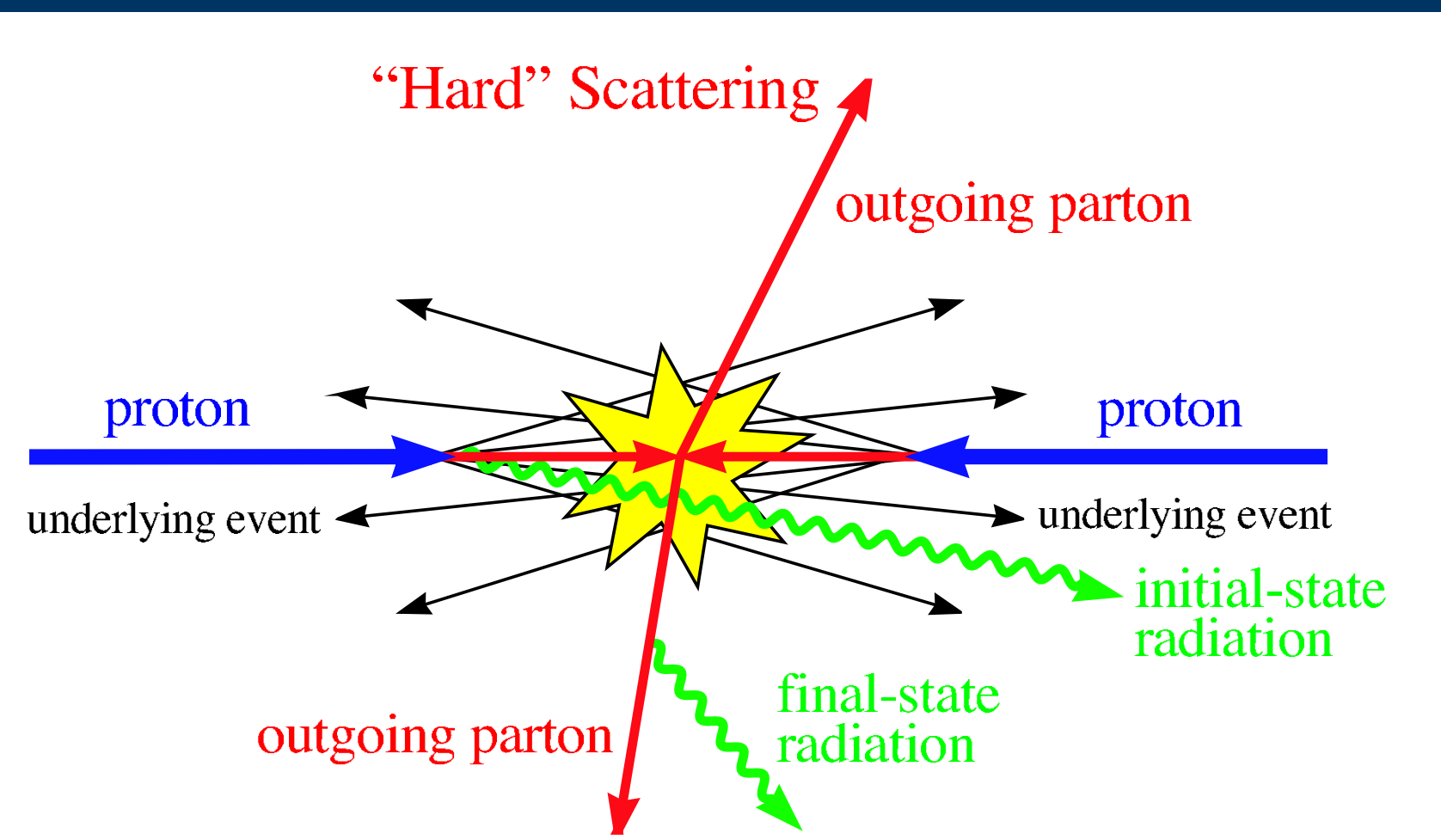
Hadron colliders

Advantages

- $m_p \gg m_e \implies$ higher CM energies
- Higher luminosities

Disadvantages

- Fewer kinematics constraints due to protons being
- Protons are strongly interacting: collisions are messy
- Strong interactions $\implies$ large cross sections σ_{total}



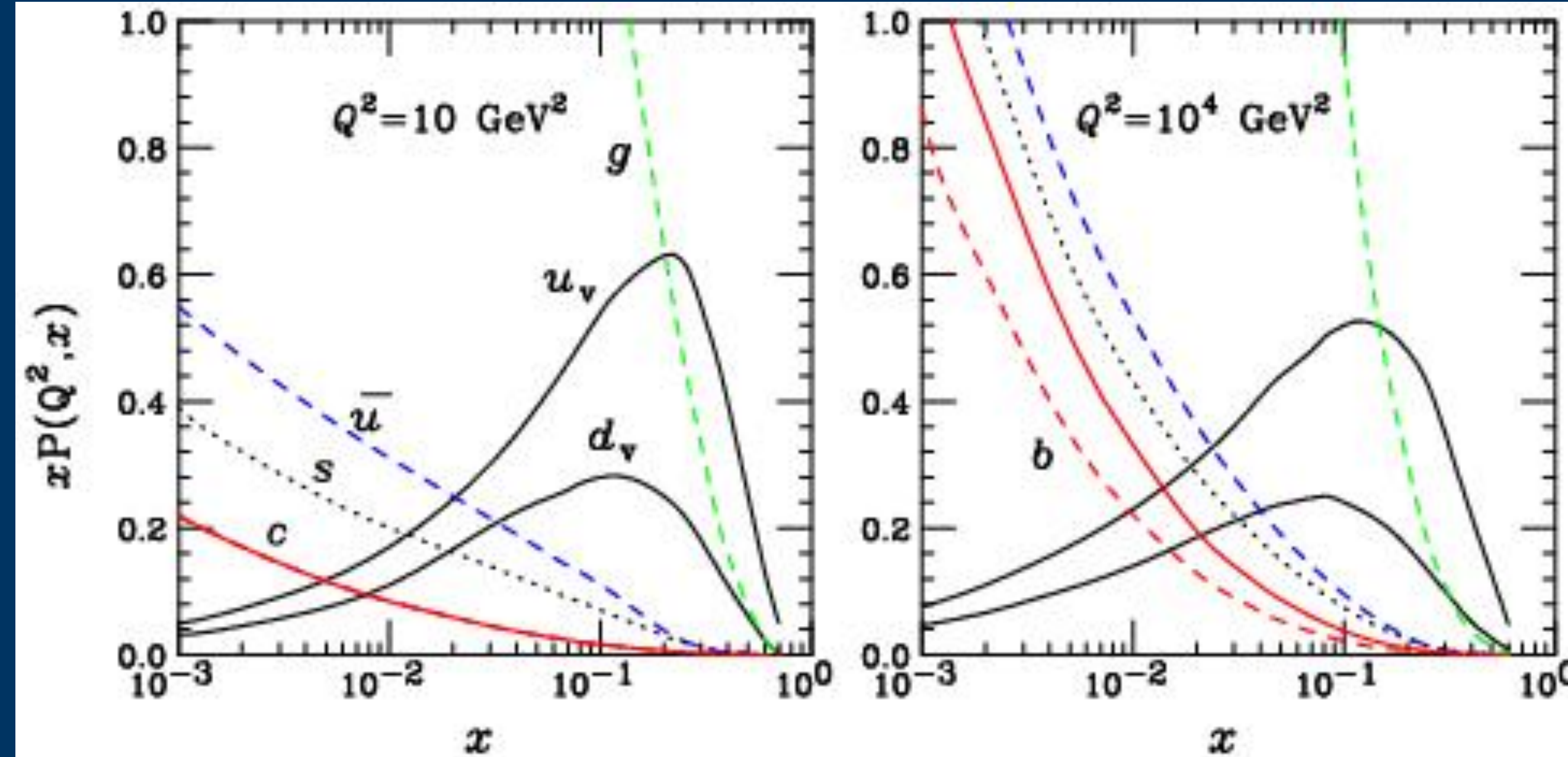
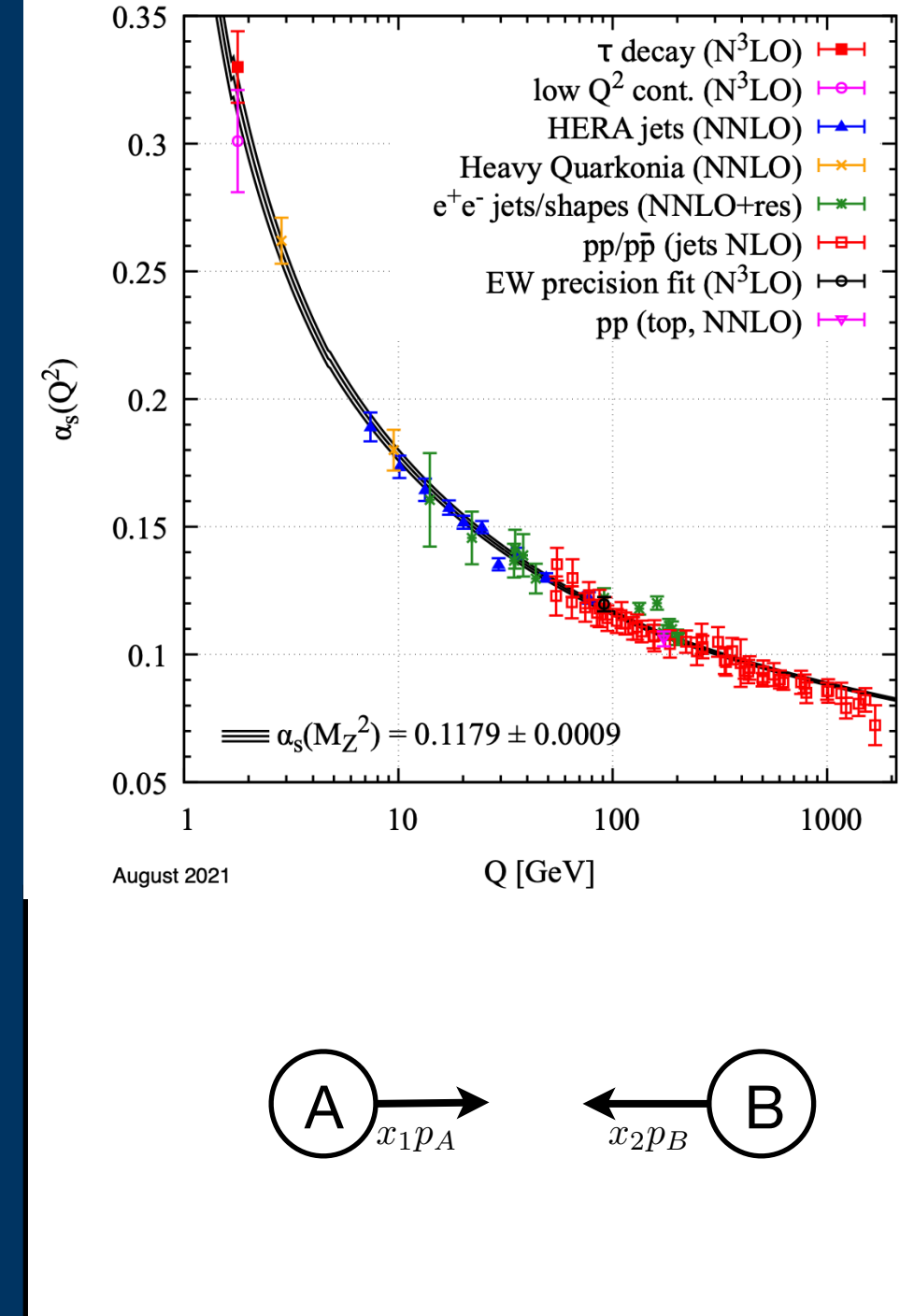
Hadron colliders

- QCD factorization theorem: for large transfer momentum we have

$$\sigma(AB \rightarrow F X) = \sum_{a,b} \int dx_1 dx_2 f_{a/A}(x_1, Q^2) f_{b/B}(x_2, Q^2) \hat{\sigma}(ab \rightarrow F)$$

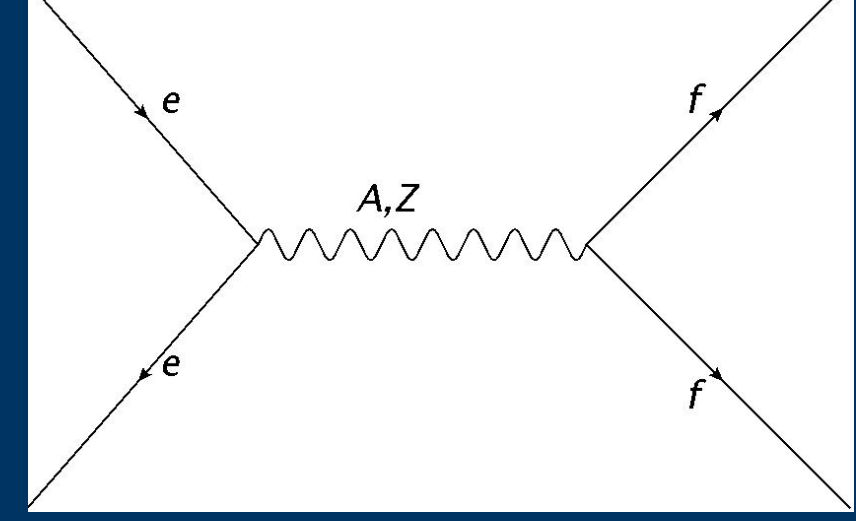
inclusive
distribution functions
parton-parton scattering

- $f_{b/B}(x, Q^2)$ is the b parton density in hadron B carrying x of its momentum
- Q^2 is a characteristic scale



LEP 1 Physics

e^+e^- colliders: LEP 1



- LEP 1 studied in detail the Z . At tree level $\Gamma(Z \rightarrow f\bar{f}) = \frac{\alpha}{3 \sin^2 \theta_W \cos^2 \theta_W} M_Z (g_V^2 + g_A^2) N_c$

- Born amplitude for $e^+e^- \rightarrow f\bar{f}$: $\mathcal{M}_{born} \simeq \frac{1}{s} J_{\gamma e}^\alpha \otimes J_\alpha^{\gamma f} + \frac{1}{s - M_Z^2 + i s \Gamma_Z / M_Z} J_{Z e}^\alpha \otimes J_\alpha^{Z f}$

- Close to the Z resonance :

$$\frac{d\sigma}{d\Omega} = \frac{3}{16\pi} (1 + \cos^2 \theta + 2A_e A_f \cos \theta) \sigma(e^+e^- \rightarrow f\bar{f})$$

Some observables:

$$m_Z, \Gamma_Z, \sigma_{had}, R_\ell = \frac{\Gamma_{had}}{\Gamma_\ell}$$

$$A_e \equiv \frac{2g_V^e g_A^e}{(g_V^e)^2 + (g_A^e)^2} \quad A_f \equiv \frac{2g_V^f g_A^f}{(g_V^f)^2 + (g_A^f)^2}$$

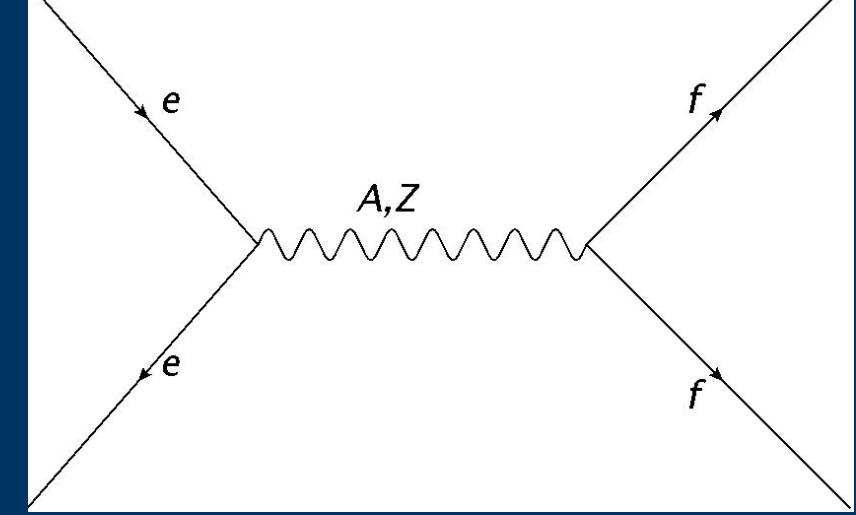
$$R_b = \frac{\Gamma_b}{\Gamma_{had}}, R_c = \frac{\Gamma_c}{\Gamma_{had}}$$

$$\sigma(e^+e^- \rightarrow f\bar{f}) = \frac{s}{M_Z^2} \frac{12\pi\Gamma_e\Gamma_f}{(s - M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2}$$

$$g_V^f = T_f^3 - 2Q_f \sin^2 \theta_W \quad \text{and} \quad g_A^f = T_f^3$$

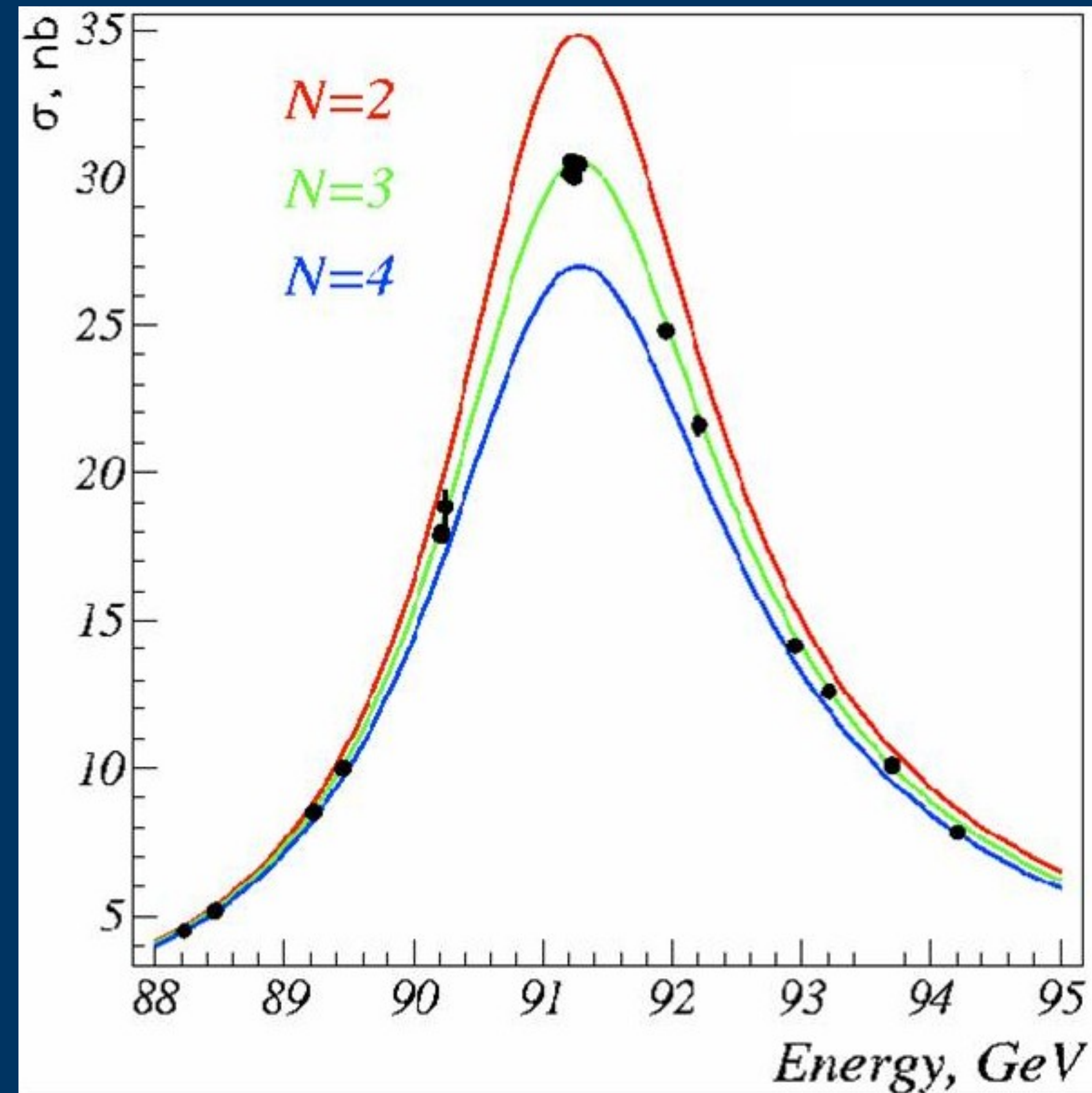
e^+e^- colliders: LEP 1

- Varying $\sqrt{s}$ near the Z mass



$$\sigma \propto \frac{1}{(s - M_Z)^2 + s^2 \Gamma_Z^2 / M_Z^2}$$

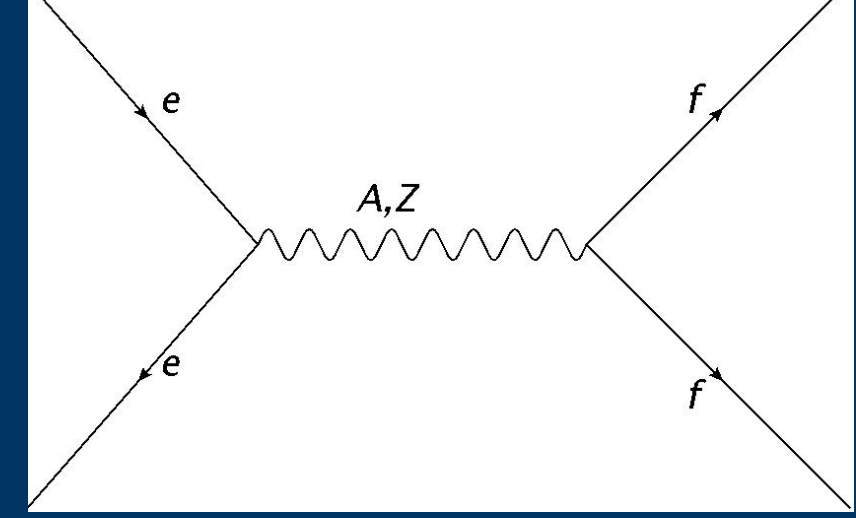
$$\Rightarrow \Gamma_Z$$



$$\text{From } \Gamma_Z = \Gamma_\ell + \Gamma_q + \Gamma_\nu$$

$$N_\nu = 2.9840 \pm 0.0082$$

e^+e^- colliders: LEP 1



- Additional observables:

- Forward-backward asymmetry

$$A_{FB} \equiv \frac{\sigma(\cos \theta > 0) - \sigma(\cos \theta < 0)}{\sigma(\cos \theta > 0) + \sigma(\cos \theta < 0)} = \frac{3}{4} A_e A_f$$

- SLAC could polarize the e^- beam

$$A_{LR}^e \equiv \frac{\sigma(e_L^-) - \sigma(e_R^-)}{\sigma(e_L^-) + \sigma(e_R^-)} = A_e = \frac{2g_V^e g_A^e}{(g_V^e)^2 + (g_A^e)^2}$$

- τ polarization

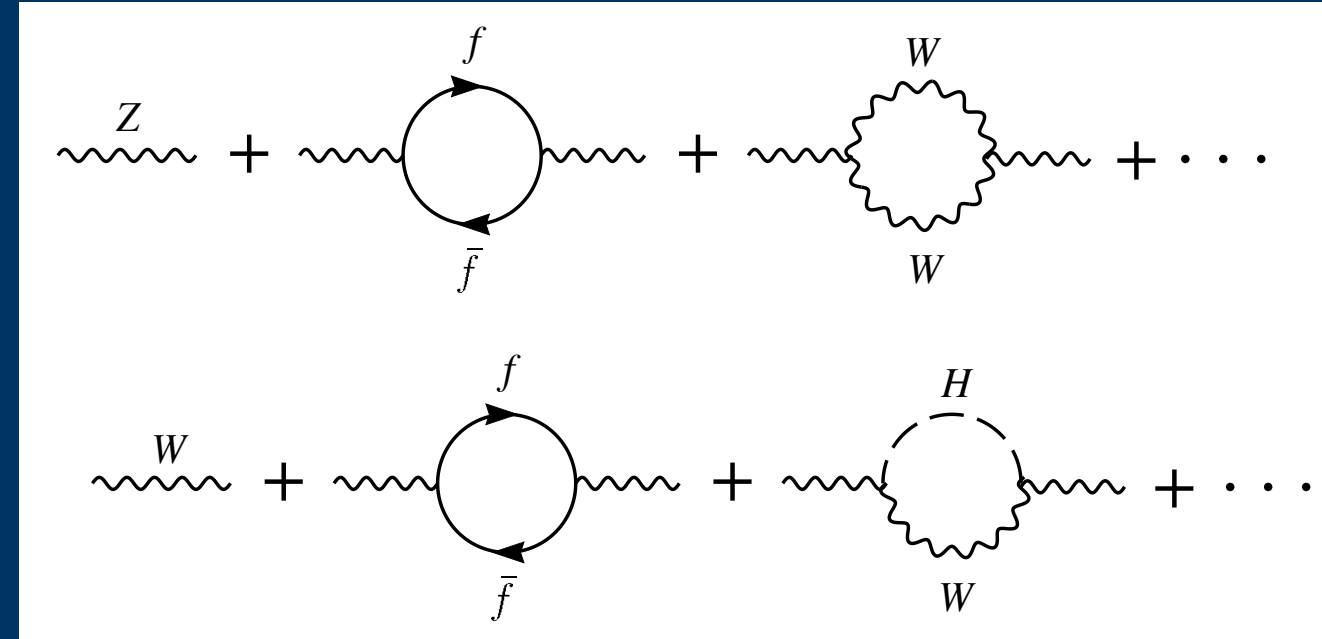
$$P^\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -A_\tau$$

- $\sin^2 \theta_W$ can be extracted

$$g_V^f = T_f^3 - 2Q_f \sin^e \theta_W \quad \text{and} \quad g_A^f = T_f^3$$

e^+e^- colliders: LEP 1

- It is mandatory the inclusion of higher order corrections
- First task: define the input parameters and their definitions
- Radiative corrections modify tree level relations



$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

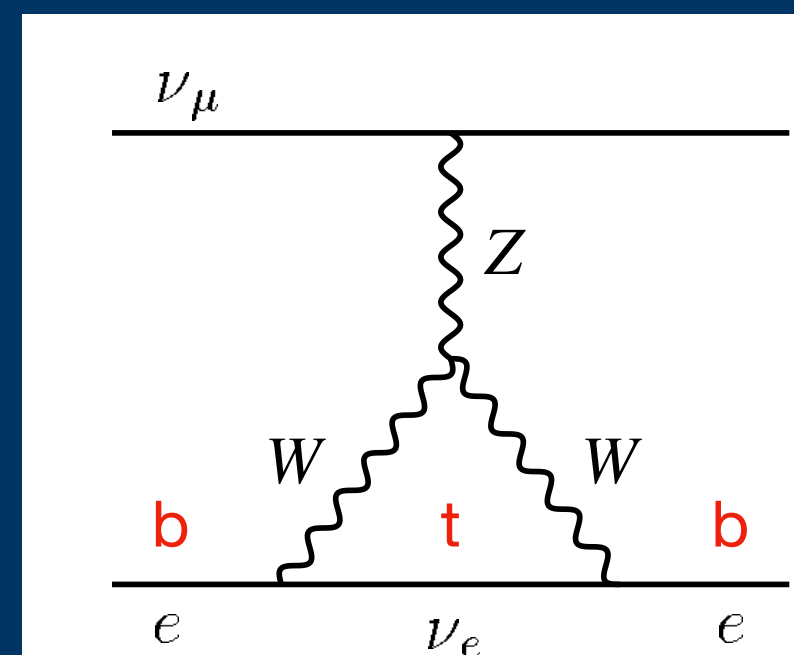
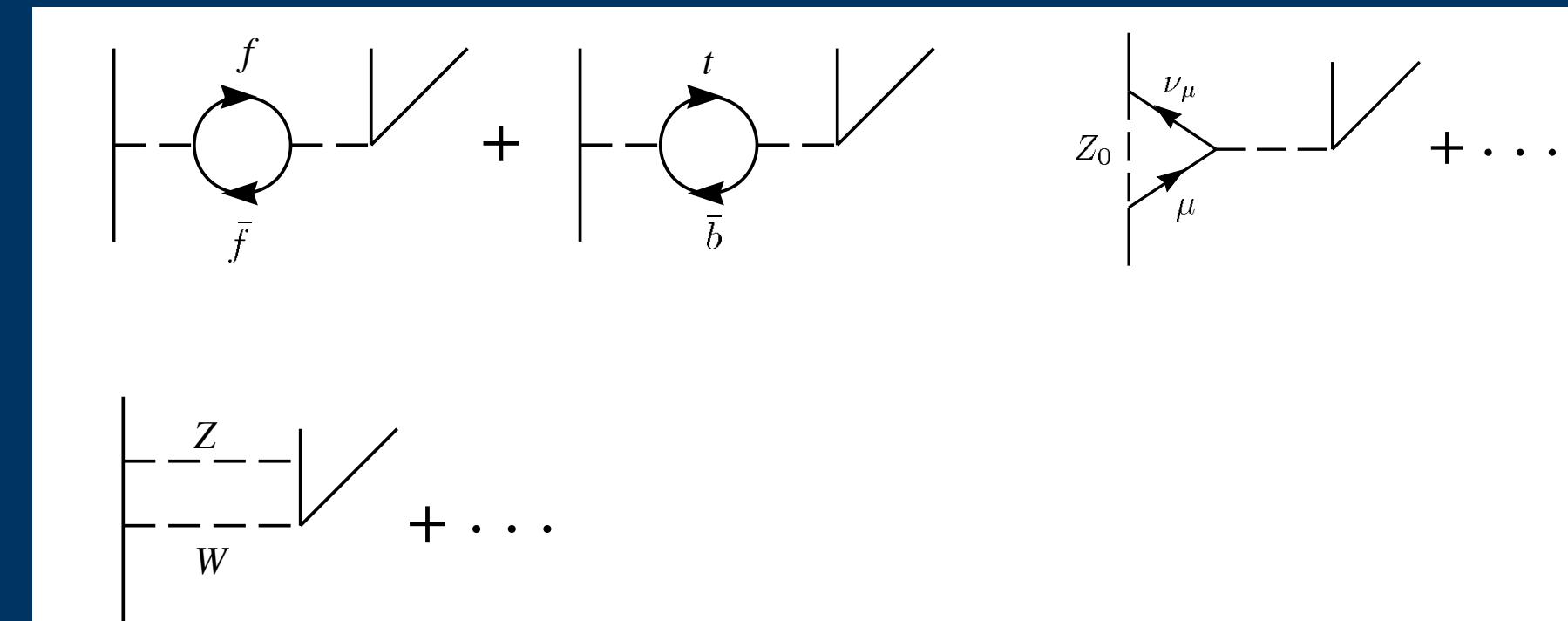
$$\frac{\sigma(\nu_\mu e)}{\sigma(\bar{\nu}_\mu e)} = \frac{3 - 12s_W^2 + 16s_W^4}{1 - 4s_W^2 + 16s_W^4}$$

$$\frac{\pi\alpha}{\sqrt{2}G_F} \frac{1}{M_W^2} = s_W^2$$

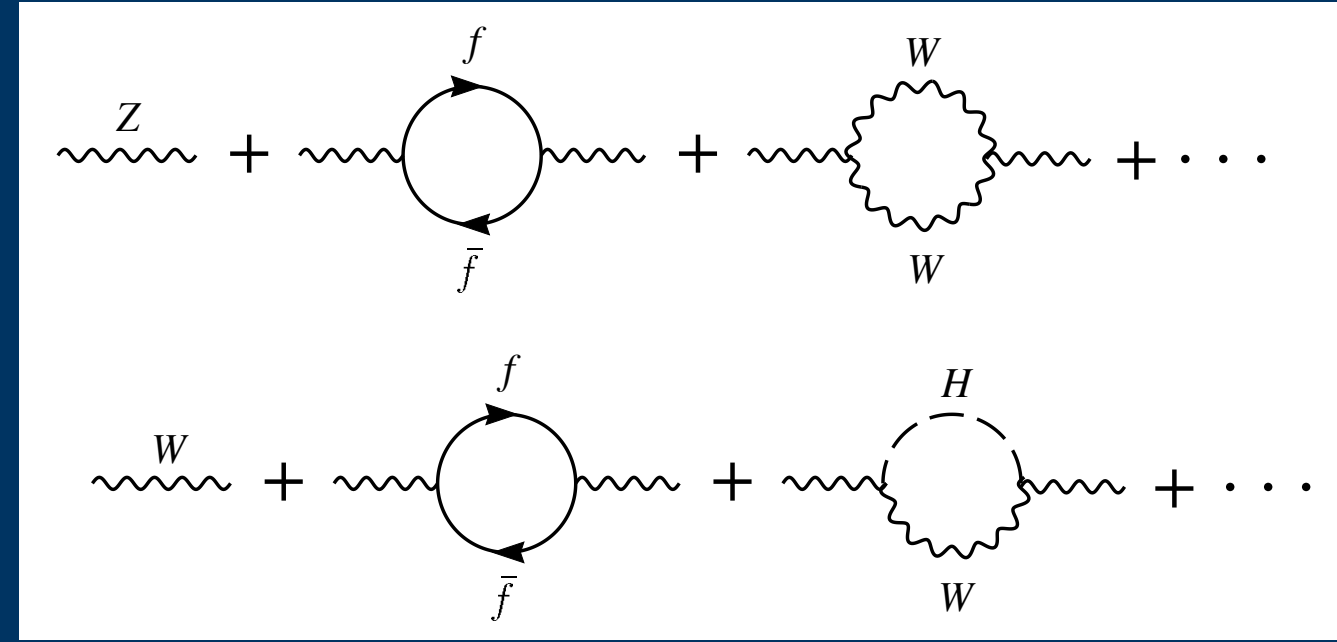
$$\frac{\Gamma(Z \rightarrow f\bar{f})}{M_Z} = N_c \frac{\alpha_{em}}{16s_W^2 c_W^2} [(g_V^f)^2 + (g_A^f)^2]$$

$$P^\tau = -\frac{2g_V^\tau g_A^\tau}{(g_V^\tau)^2 + (g_A^\tau)^2}$$

- Example: $(\alpha_{em}, m_f, M_W, M_Z, M_H)$ and $\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$



e^+e^- colliders: LEP 1

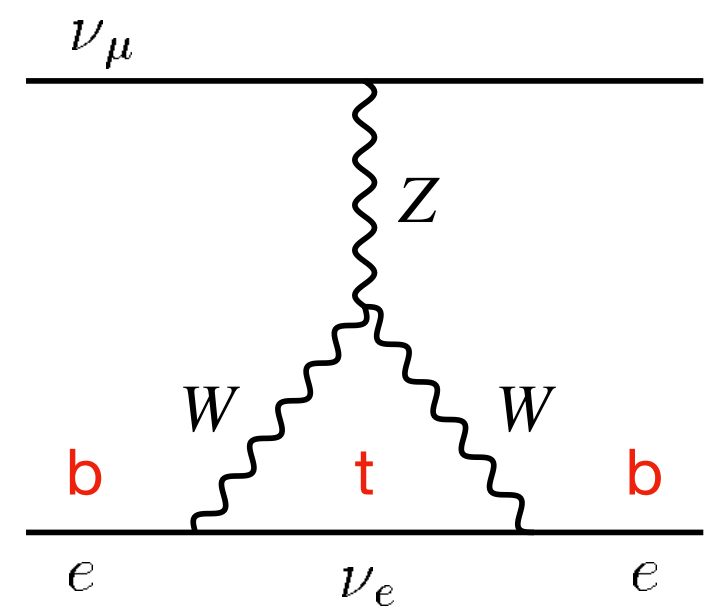


- It is mandatory the inclusion of higher order corrections

- The $Zf\bar{f}$ coupling: $(\sqrt{2}G_F M_Z^2)^{1/2} \sqrt{\rho_f} \left[\left(T_f^3 - 2Q_f \sin^2 \theta_W \kappa_f \right) \gamma^\mu - T_f^3 \gamma^\mu \gamma^5 \right] Z_\mu$

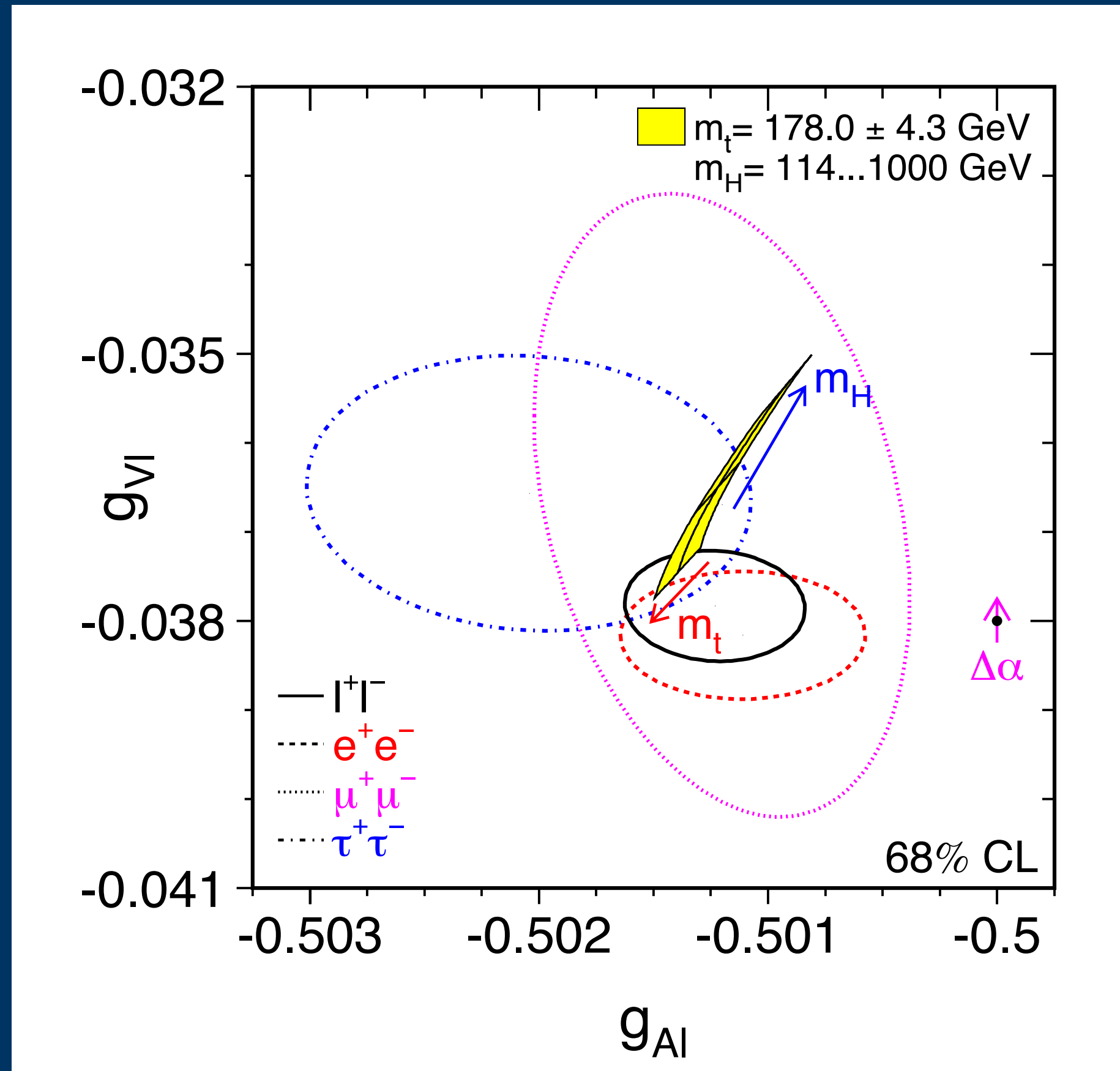
- Definition $\sin^2 \theta_{\text{eff}} = \kappa_f \sin^2 \theta_W$

- The main contributions come from gauge boson self-energies and they are **universal**

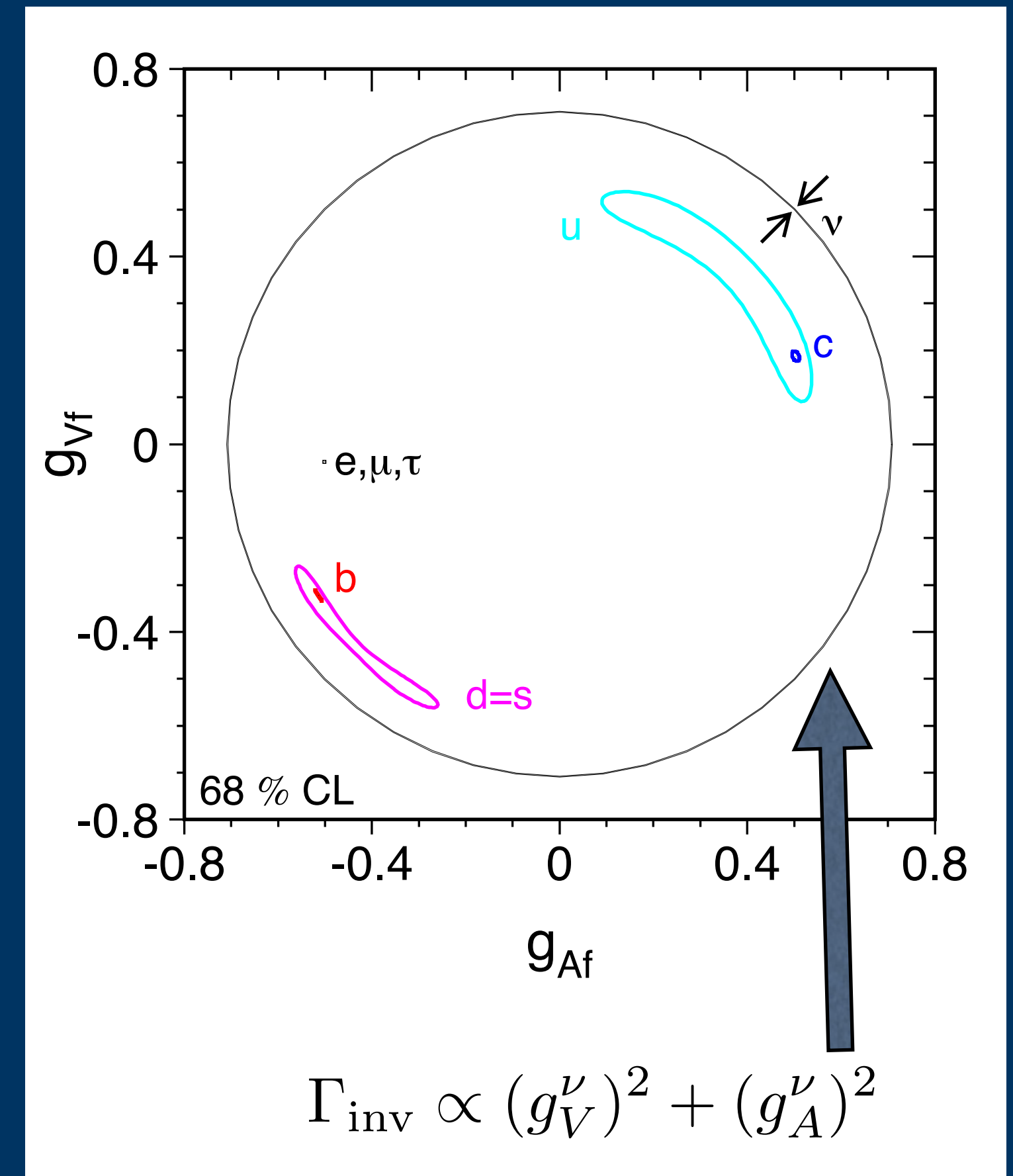


e^+e^- colliders: LEP 1

- Testing lepton universality



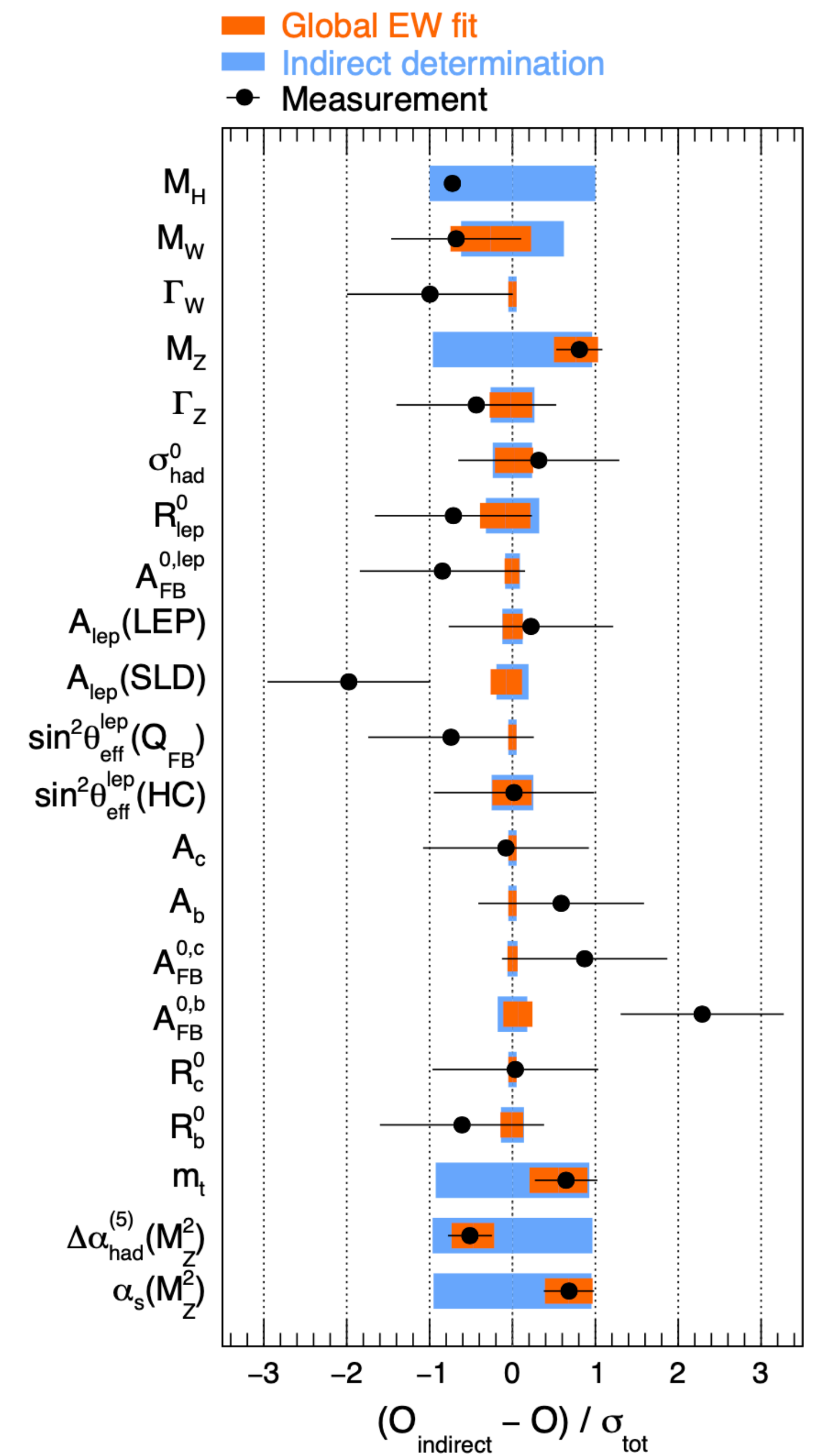
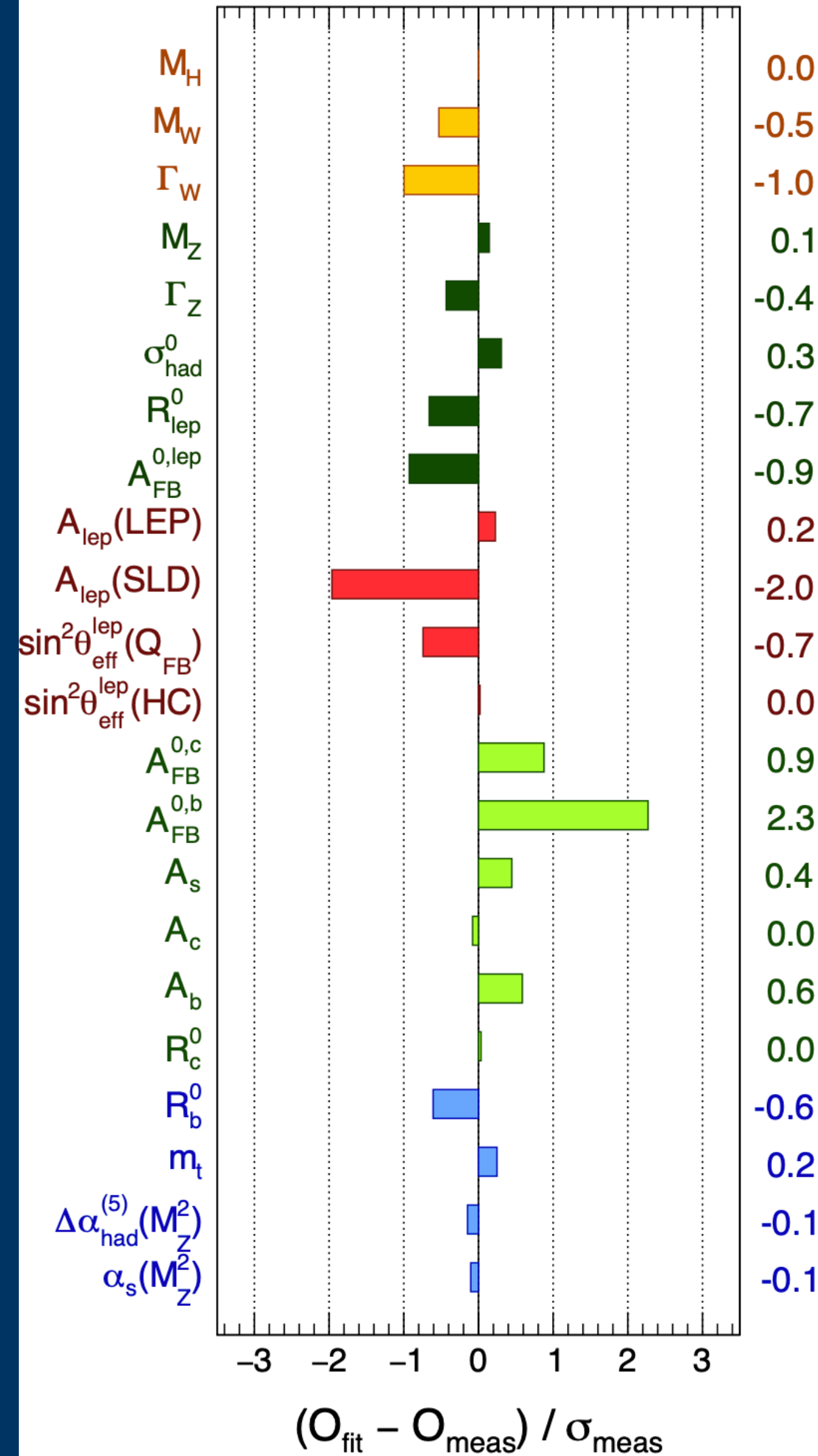
- all fermion couplings



- Running of α is not enough!

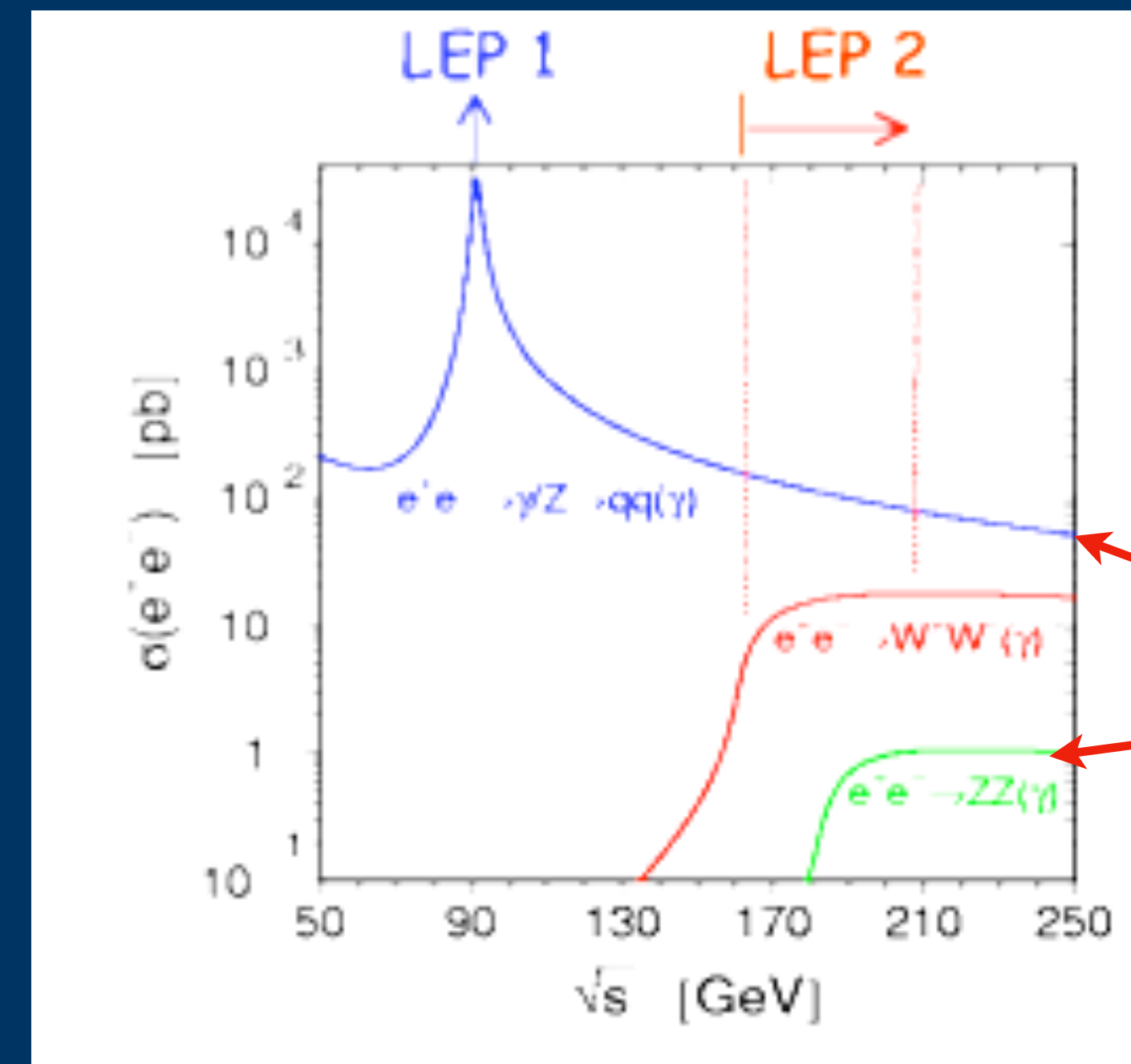
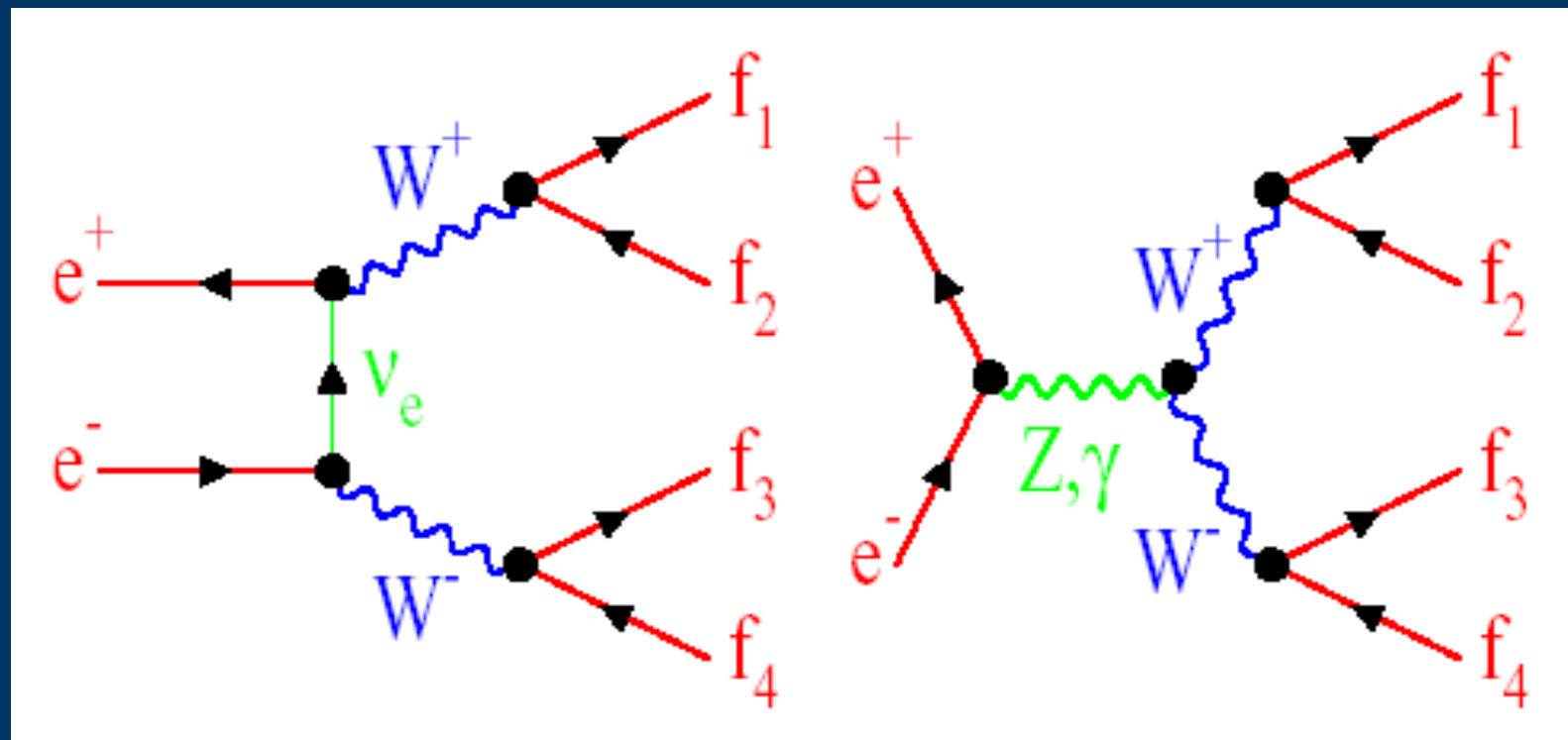
e^+e^- colliders: LEP 1

- Inputs and results to the fits
- Global fit
- The SM is doing very well



e^+e^- colliders: W mass at LEP 2

- W mass from its decay products



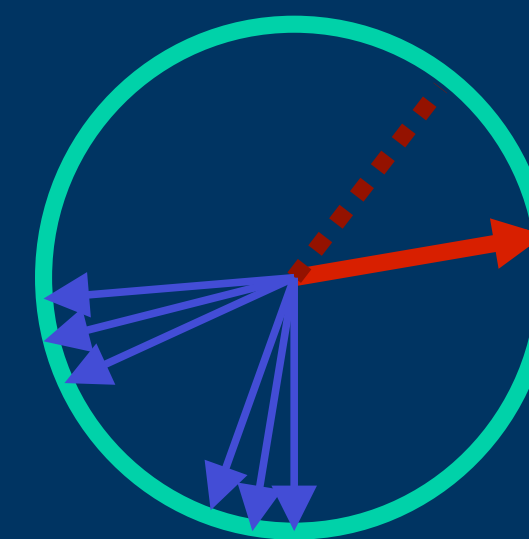
backgrounds

- Main channels: $WW \rightarrow qqqq$ (46%)



- Requiring 4 jets
- efficiency 85%
- purity 80%

- $W \rightarrow qq\ell\nu$ (44%)



- Requiring 2 jets, e/muon, missing pt
- efficiency 85%
- purity 90%

CMS Preliminary

LEP combination

Phys. Rep. 532 (2013) 119

D0

PRL 108 (2012) 151804

CDF

Science 376 (2022) 6589

LHCb

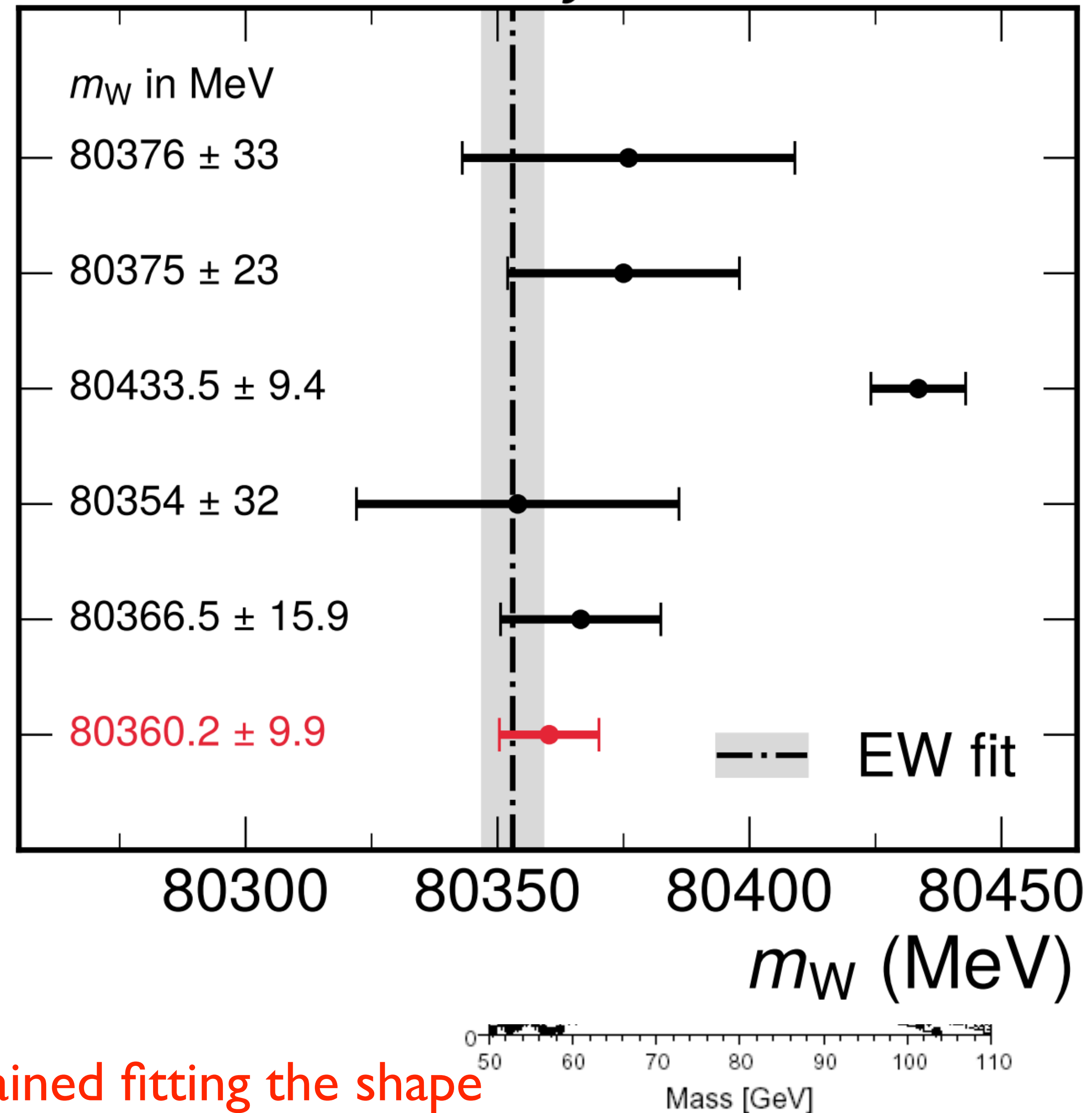
JHEP 01 (2022) 036

ATLAS

arxiv:2403.15085, subm. to EPJC

CMS

This Work

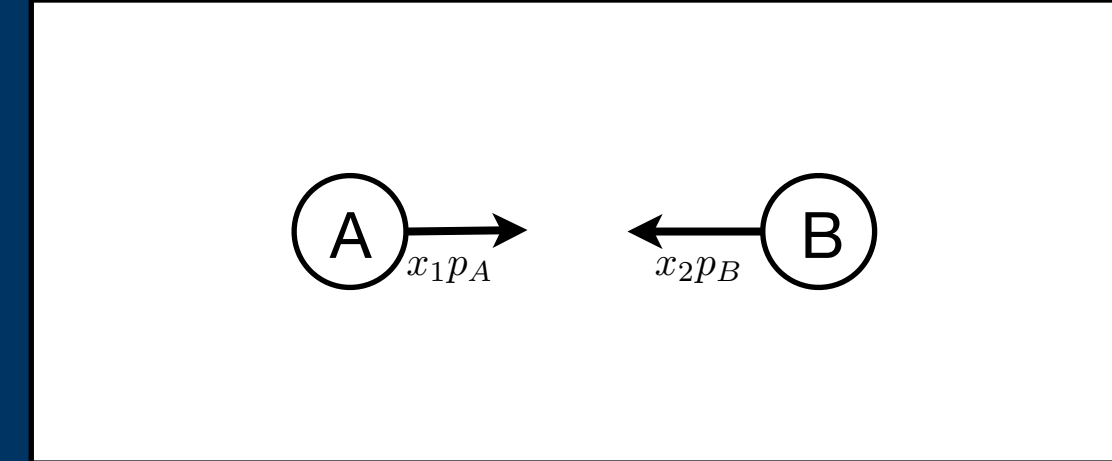
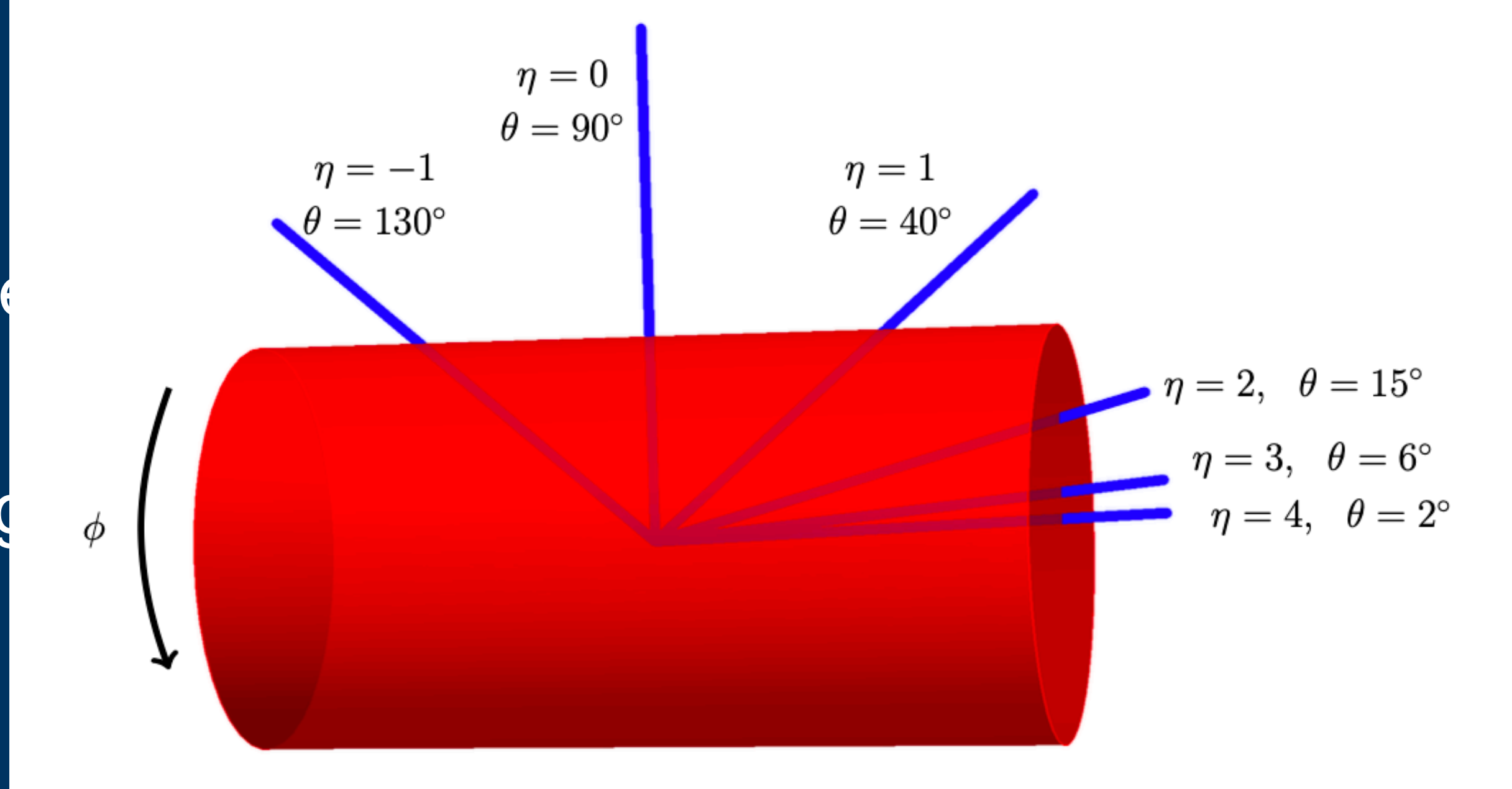


- Mass and width obtained fitting the shape

Large Hadron Collider

LHC: kinematics

- Subprocess CM frame
- Subprocess CM energy



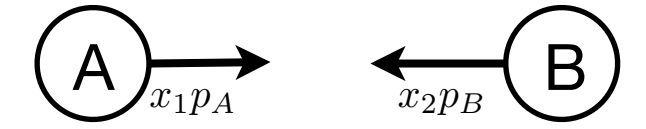
$$\hat{s} = x_1 x_2 s$$

- Rapidity/pseudorapidity: $p^\mu = E (1, \beta \sin \theta \cos \varphi, \beta \sin \theta \sin \varphi, \beta \cos \theta)$

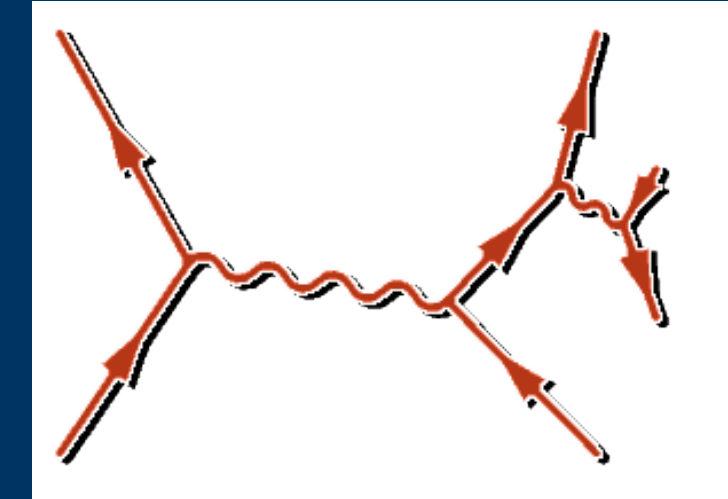
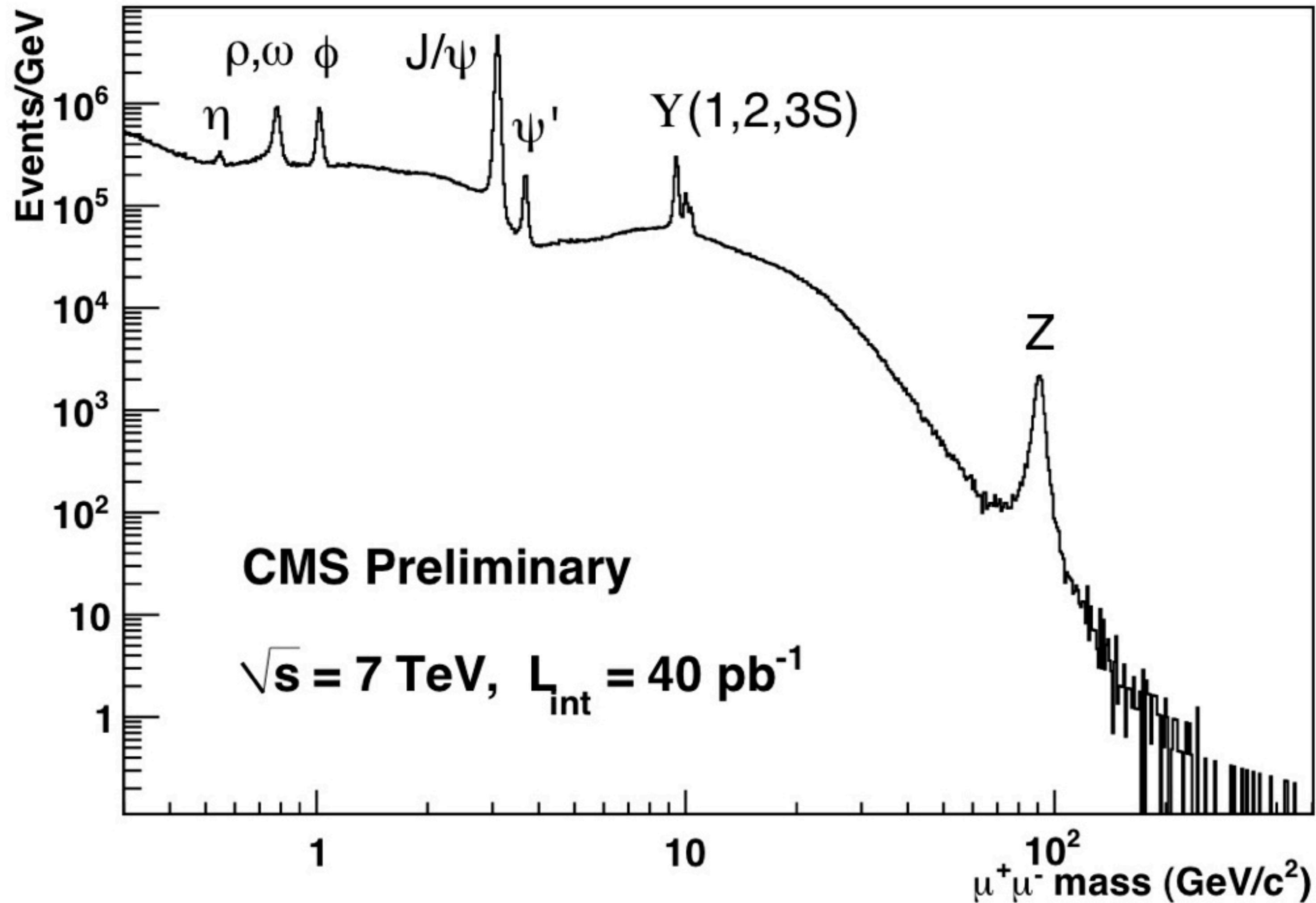
$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) \quad \text{and} \quad \eta = \frac{1}{2} \ln \left(\frac{1 + \cos \theta}{1 - \cos \theta} \right)$$

- Advantage: boost between the (subprocess) CM frame and LAB $y = y_{\text{CM}} + \frac{1}{2} \ln \left(\frac{x_1}{x_2} \right)$

LHC: observables



- Consider an s
- Invariant mass

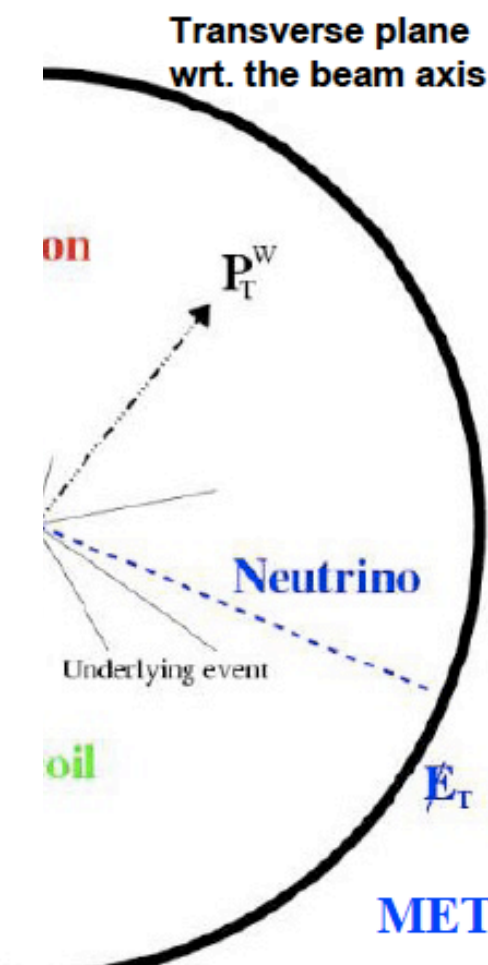
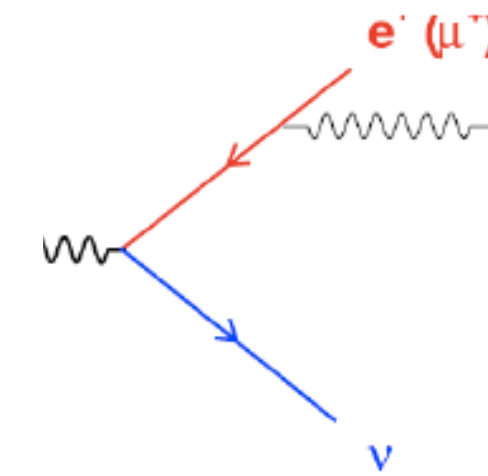
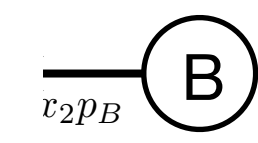
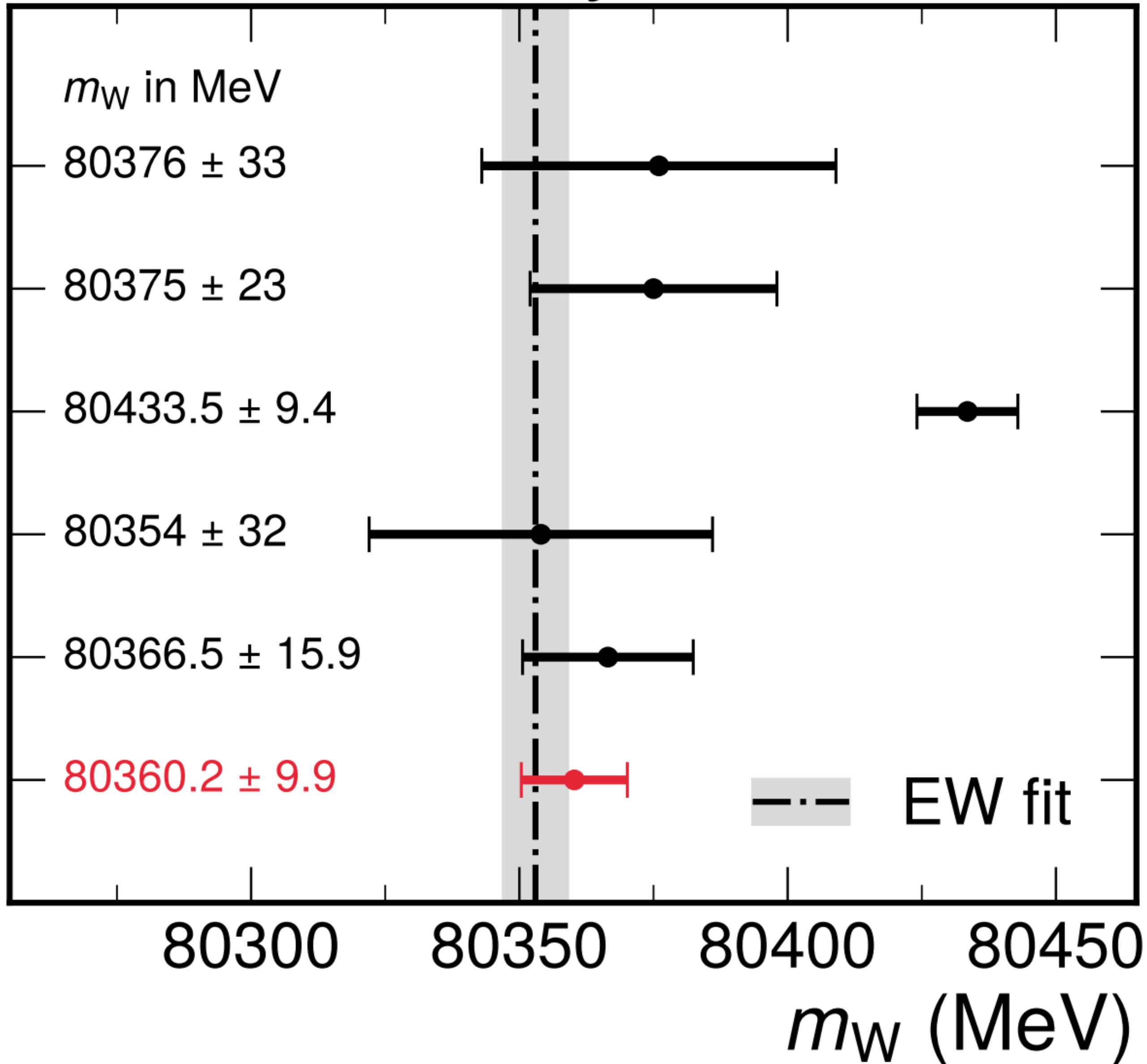


LHC:

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LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
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LHCb
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ATLAS
arxiv:2403.15085, subm. to EPJC
CMS
This Work

CMS Preliminary



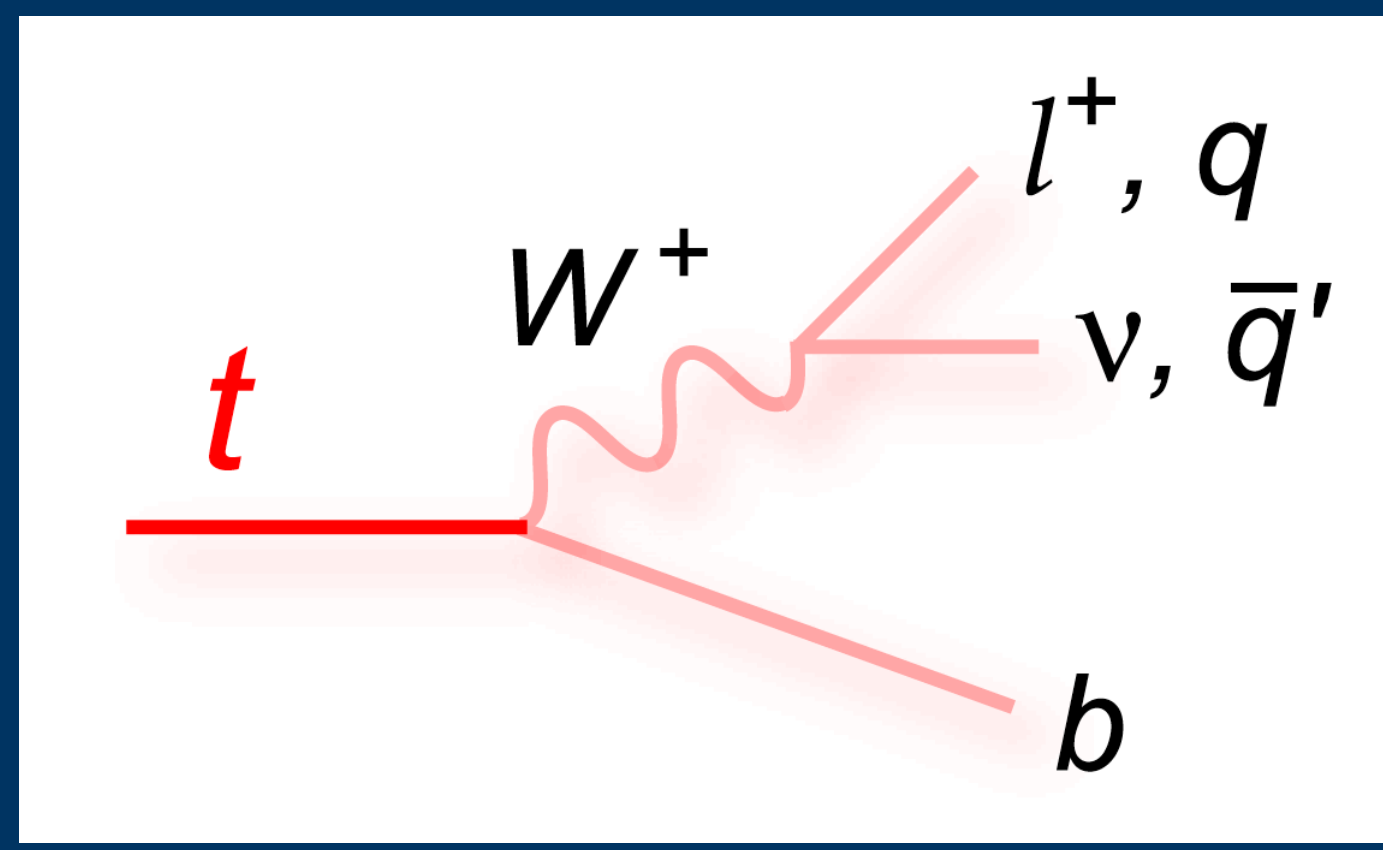
LHC: observables

- Top pairs are produced by

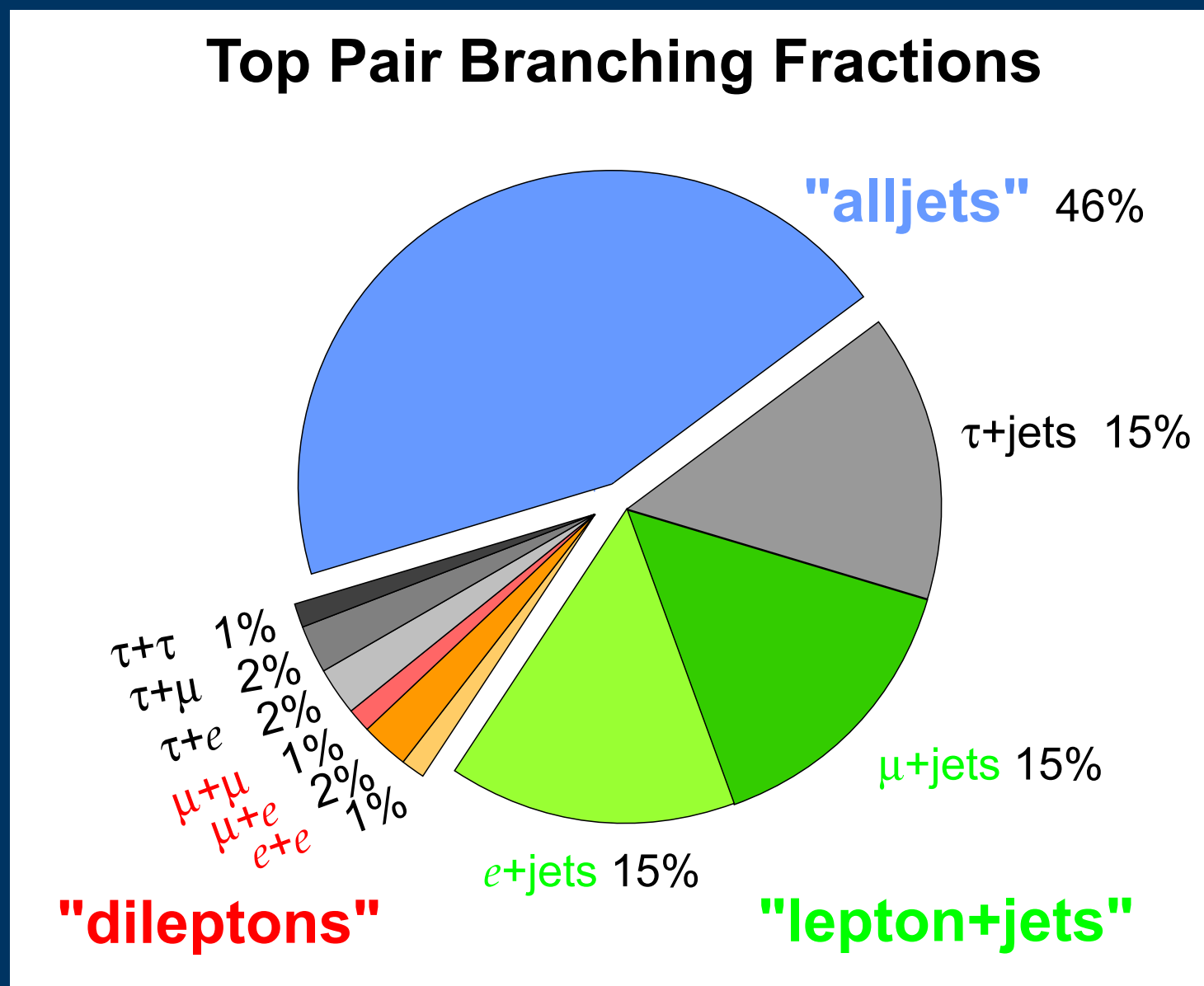
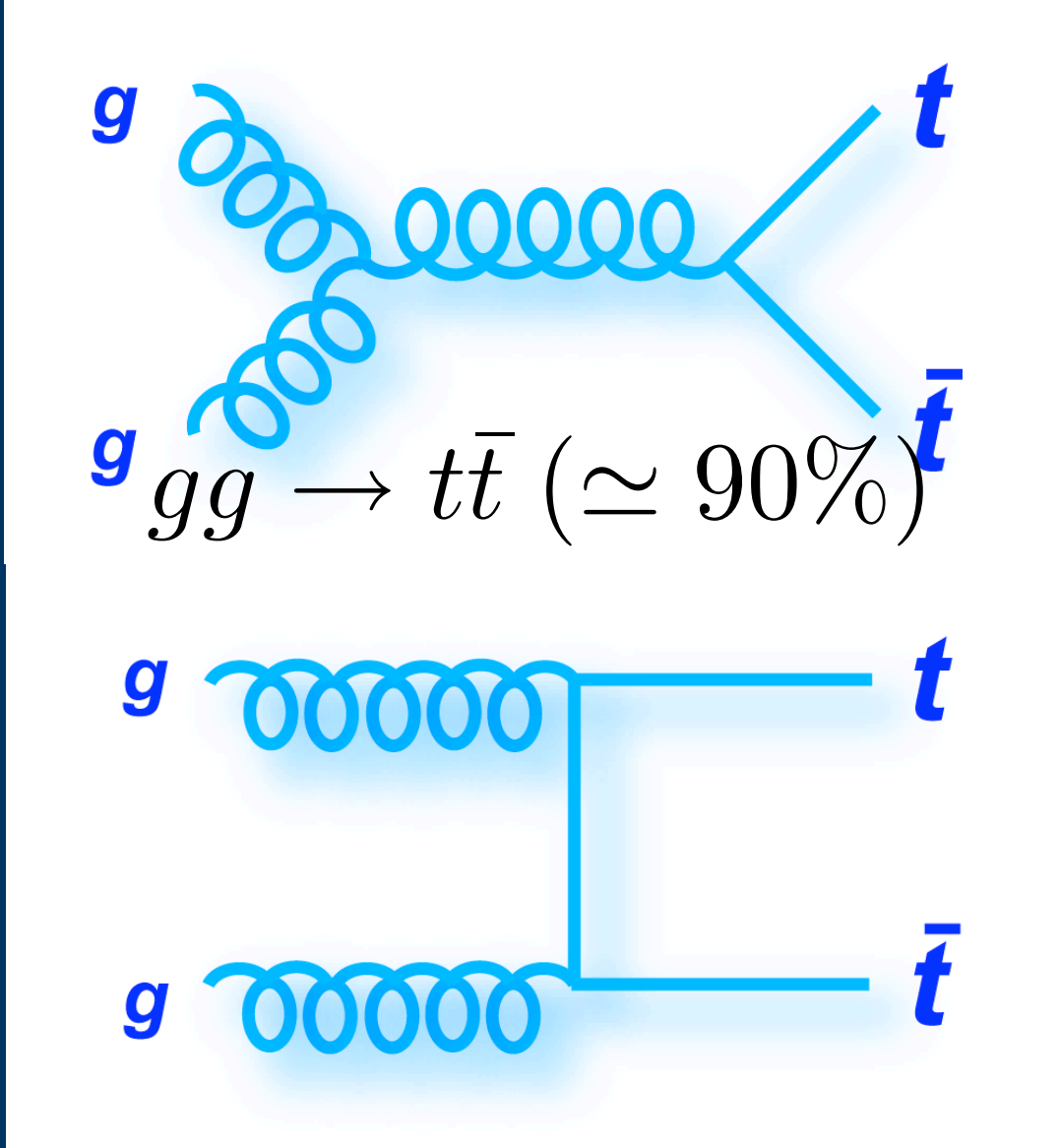
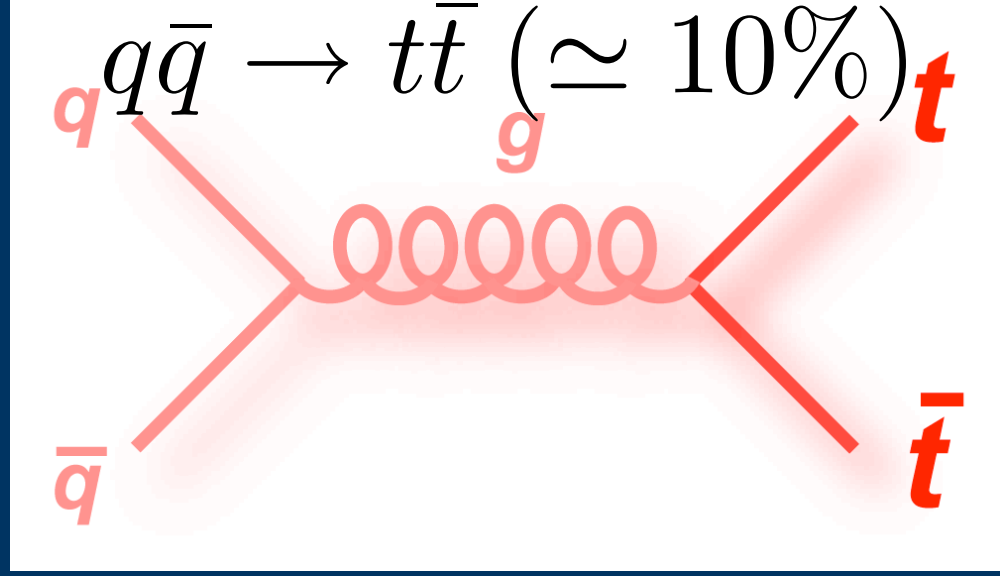
$\text{LHC } 13.6 \text{ TeV} \implies \sigma \simeq 240 \text{ pb}$

$\mathcal{L} \simeq 500 \text{ fb}^{-1} \implies 1.2 \times 10^8 \text{ } t\bar{t} \text{ pairs}$

- The dominant decay is $t \rightarrow W^+ b$

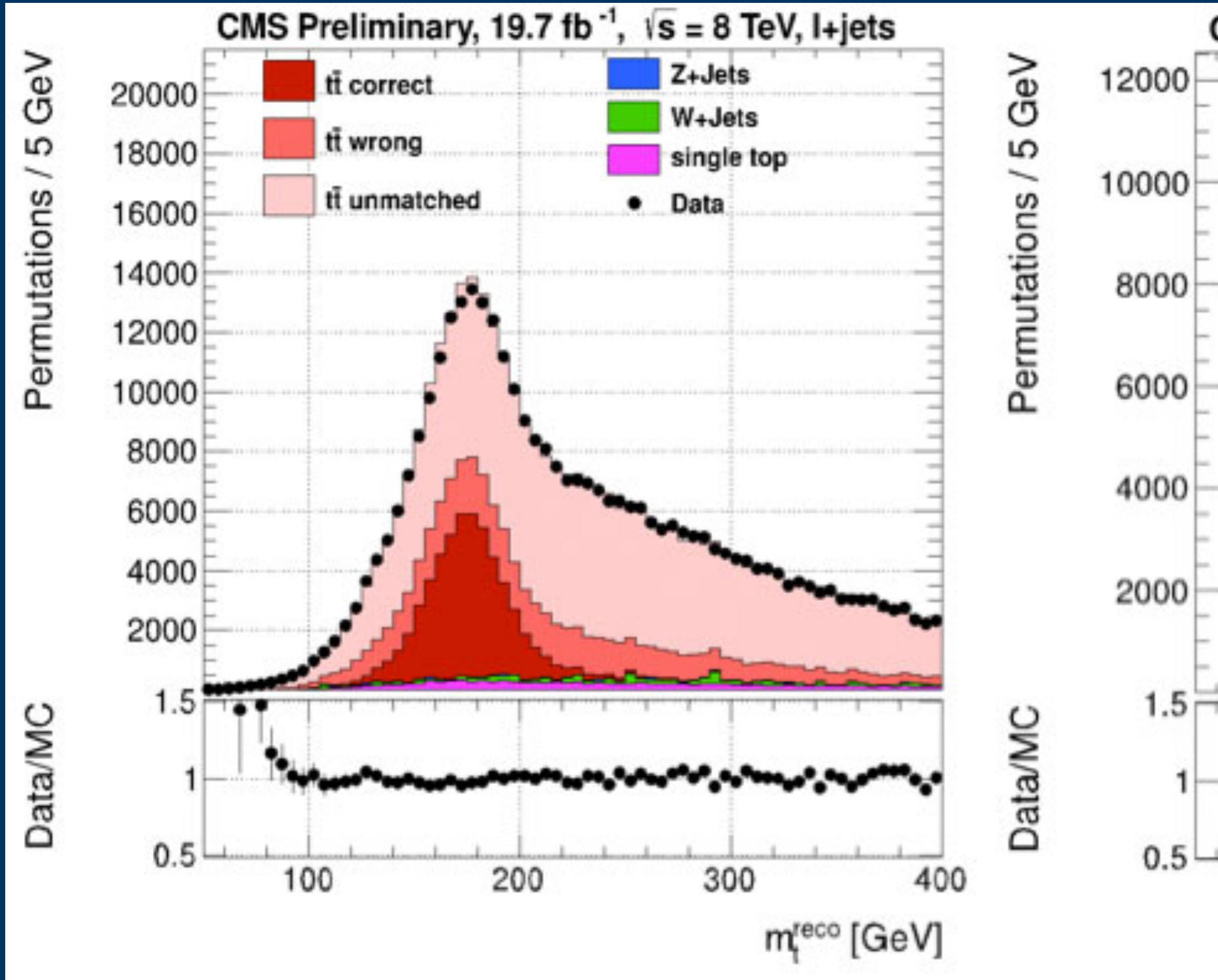


- We can study several properties of the top: mass, quantum numbers, decay W polarization, coupling Wtb , FCNC...



LHC: few SM measurements

- Top quark mass measurement: dilepton
- There are backgrounds to be mitigated



ATLAS+CMS

..... ATLAS+CMS combined
stat uncertainty
total uncertainty

ATLAS

dilepton 7 TeV
lepton+jets 7 TeV
all-jets 7 TeV
dilepton 8 TeV
lepton+jets 8 TeV
all-jets 8 TeV
combined

CMS

dilepton 7 TeV
lepton+jets 7 TeV
all-jets 7 TeV
dilepton 8 TeV
lepton+jets 8 TeV
all-jets 8 TeV
single top 8 TeV
J/ ψ 8 TeV
secondary vertex 8 TeV
combined

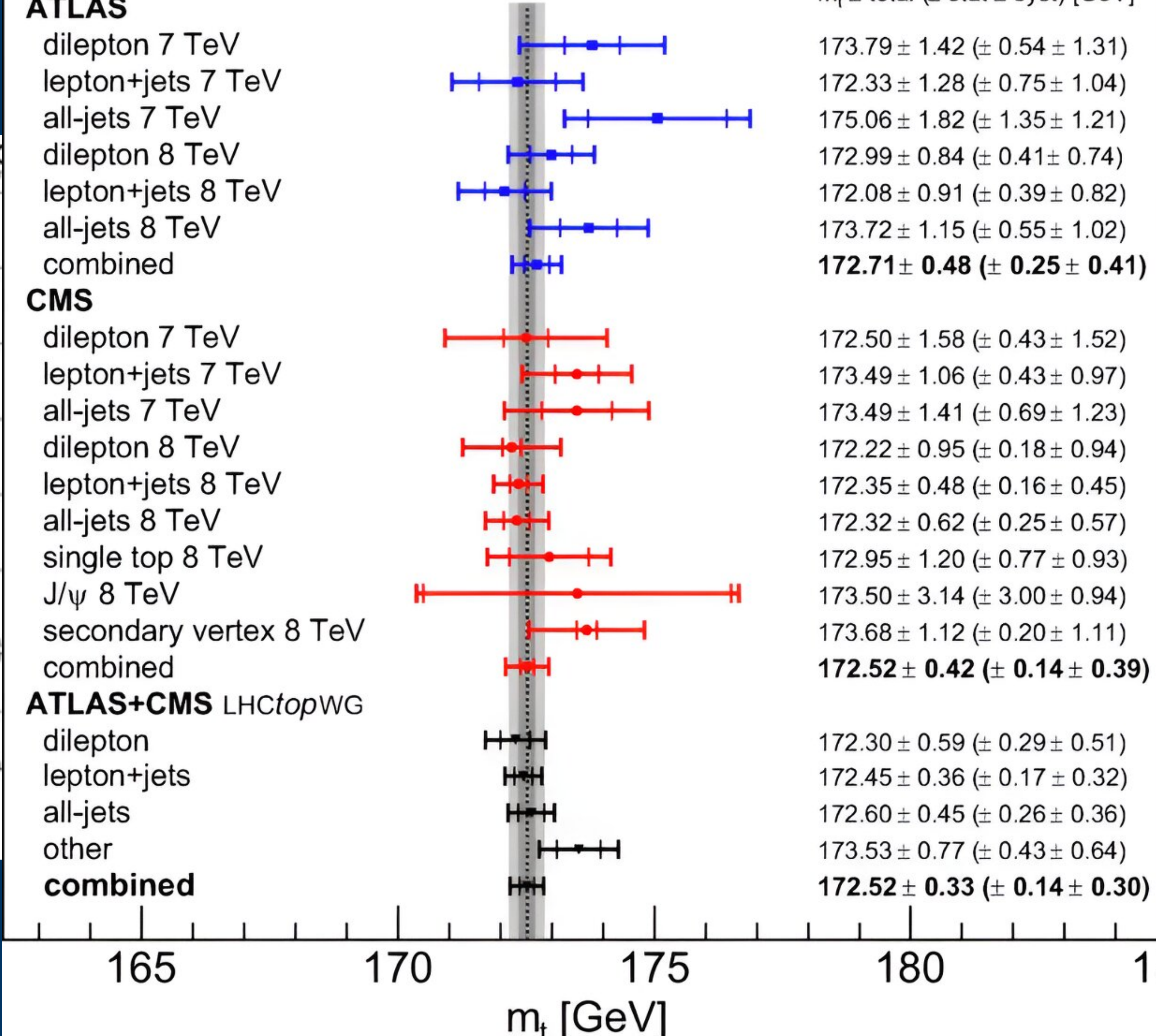
ATLAS+CMS LHCtopWG

dilepton
lepton+jets
all-jets
other
combined

$\sqrt{s} = 7,8$ TeV

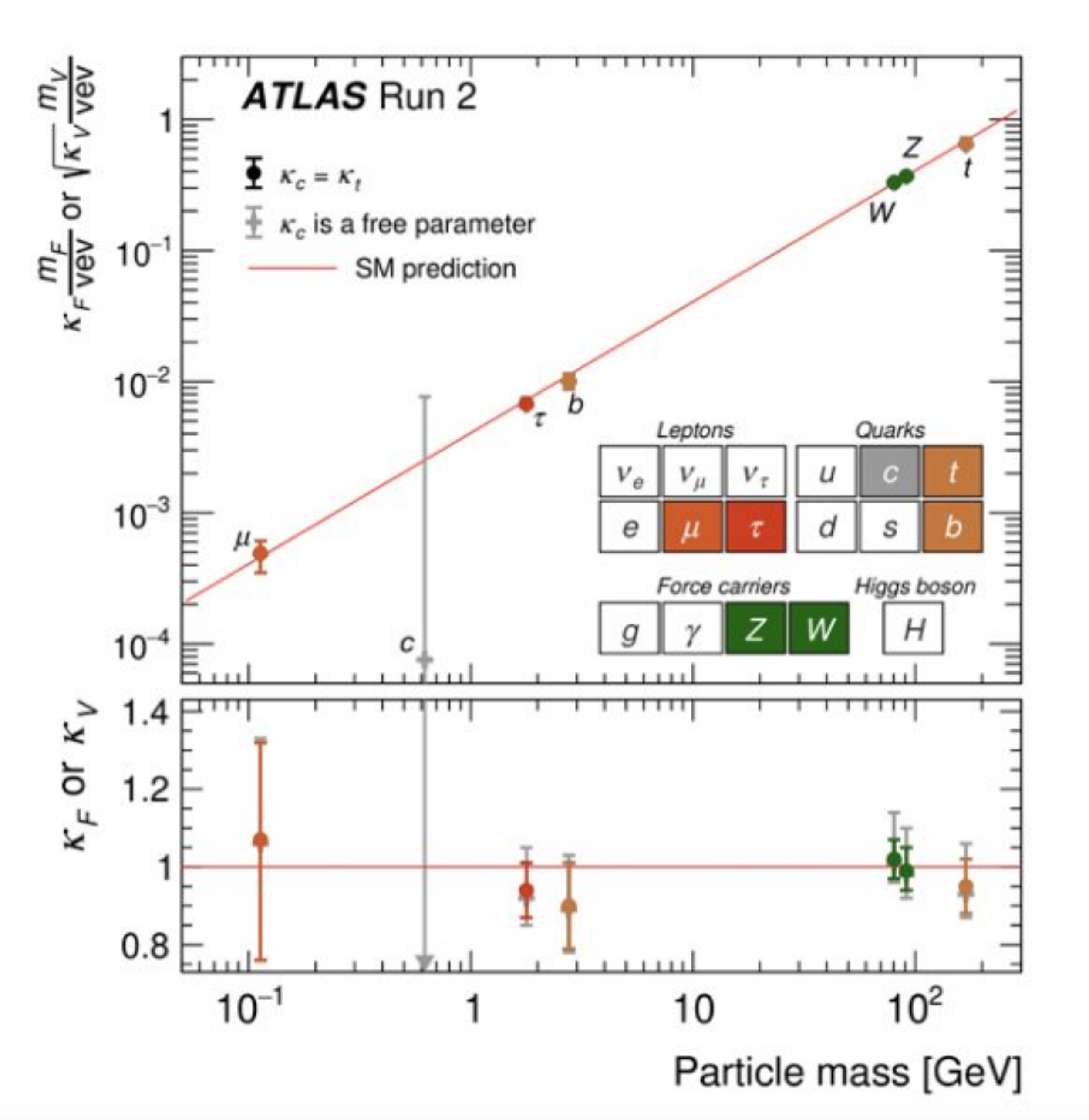
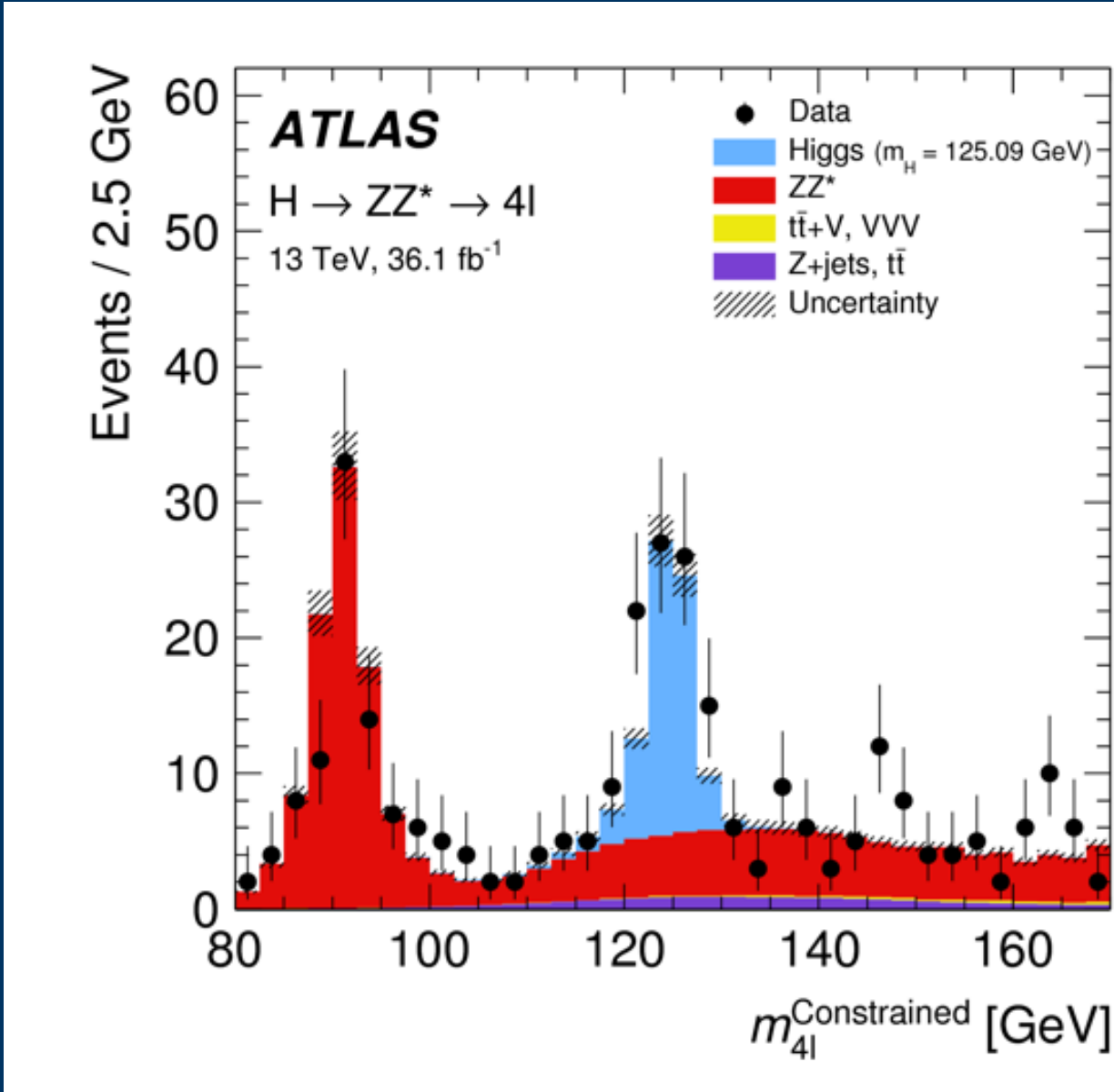
total
stat

$m_t \pm \text{total} (\pm \text{stat} \pm \text{syst})$ [GeV]

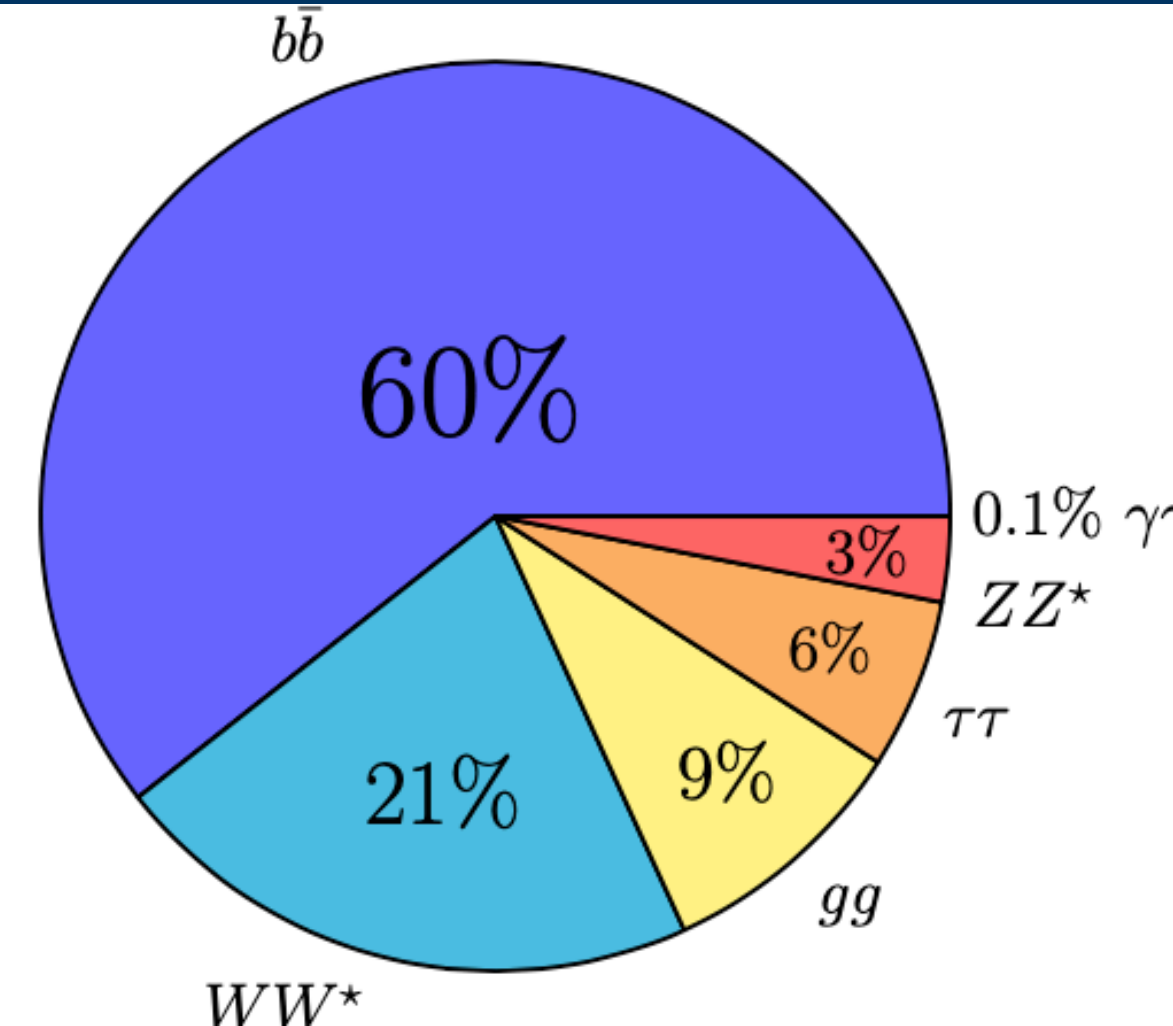
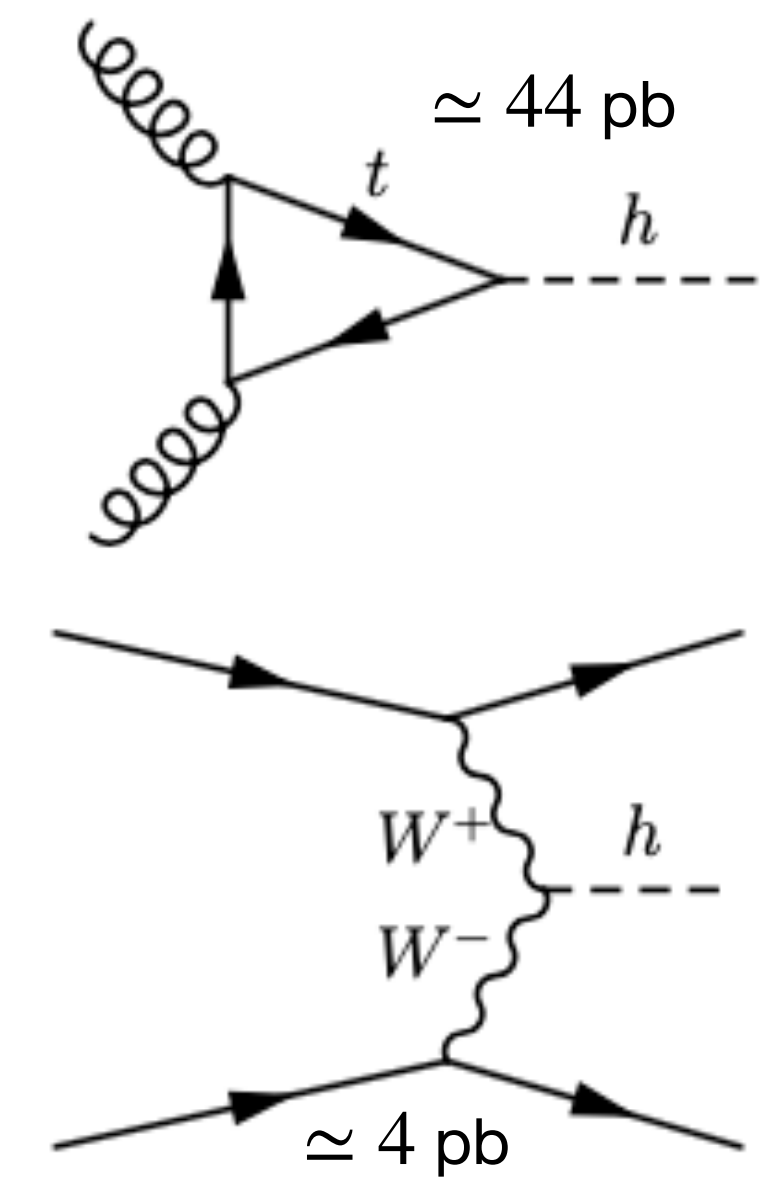


LHC: few SM measurements

- Higgs physics: SM Higgs
- Main decay modes: $b\bar{b}$,
- Many channels are observed



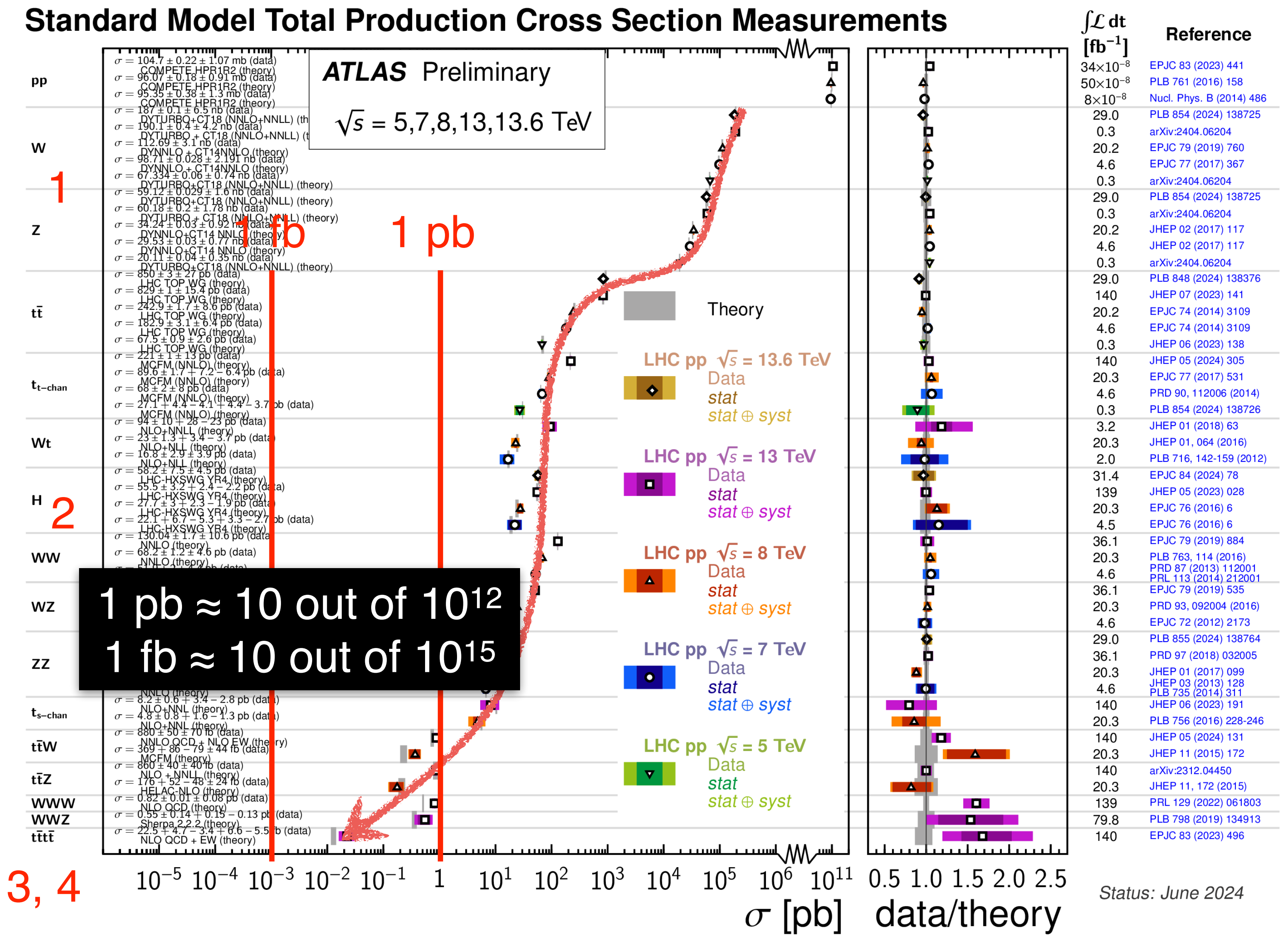
Production



LHC: SM measurements

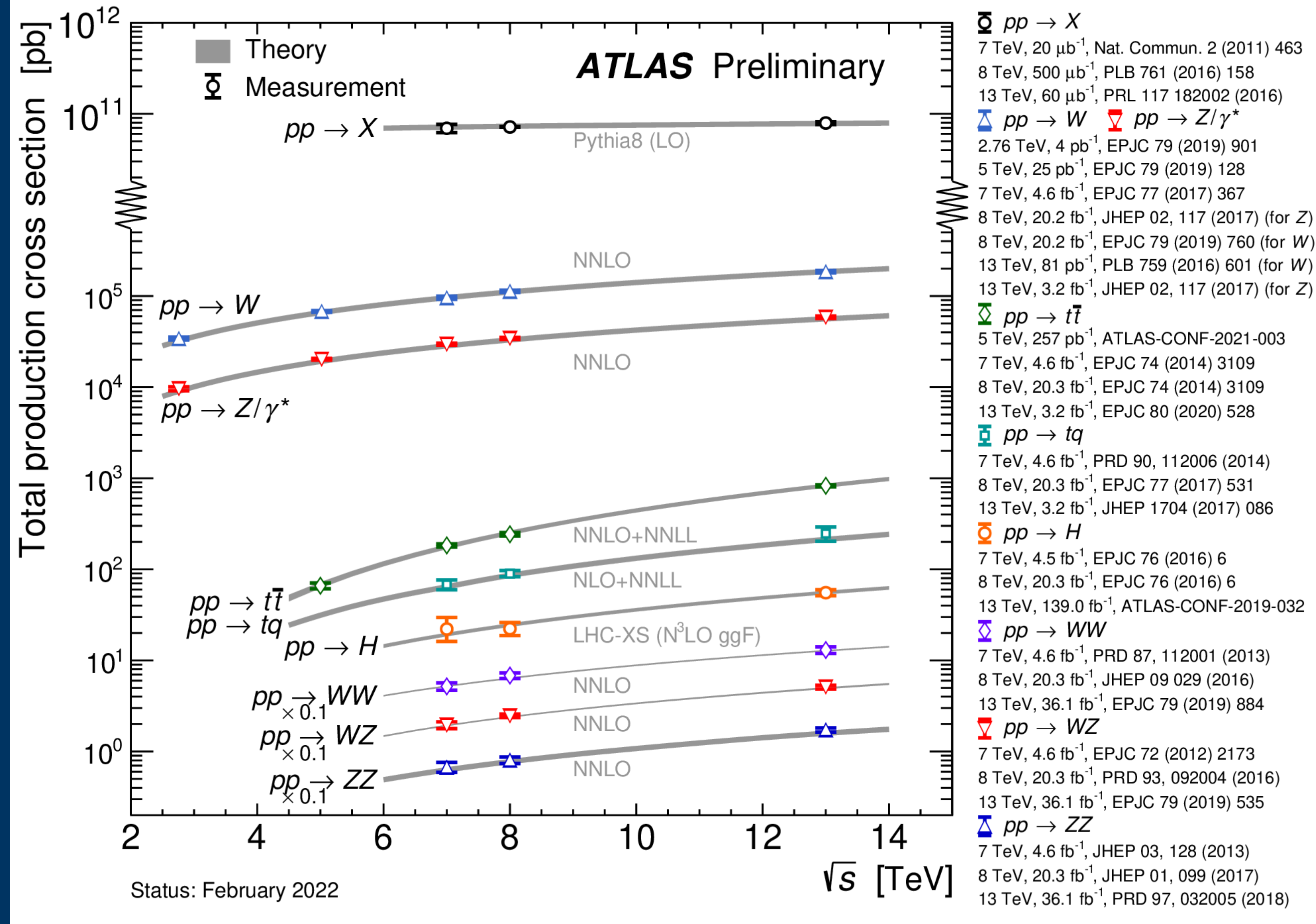
- Many SM processes have been studied
- σ varies but 10 orders of magnitude
- strong and weak processes
- In general, good agreement with SM

More multiplicity
More interesting vertices



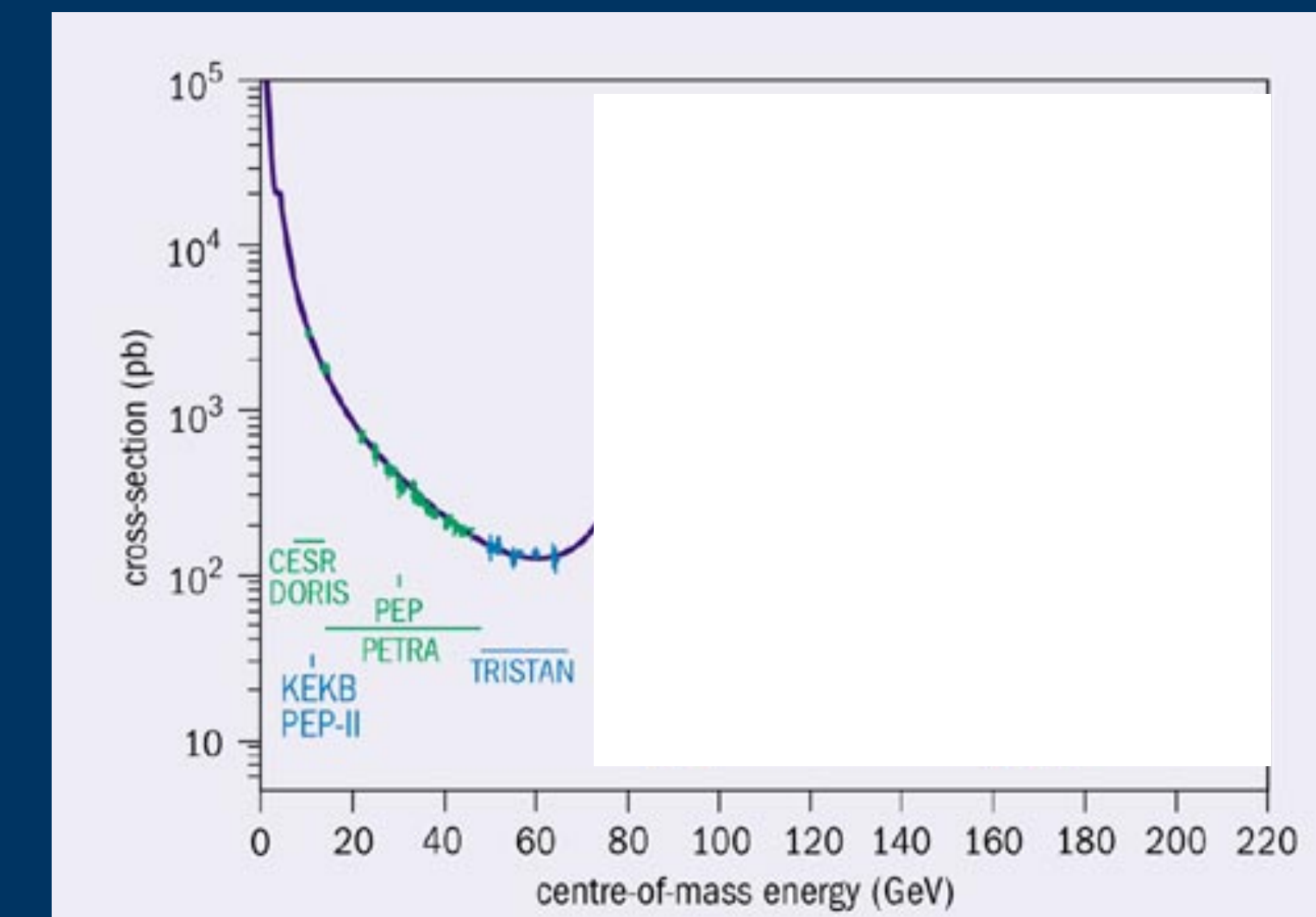
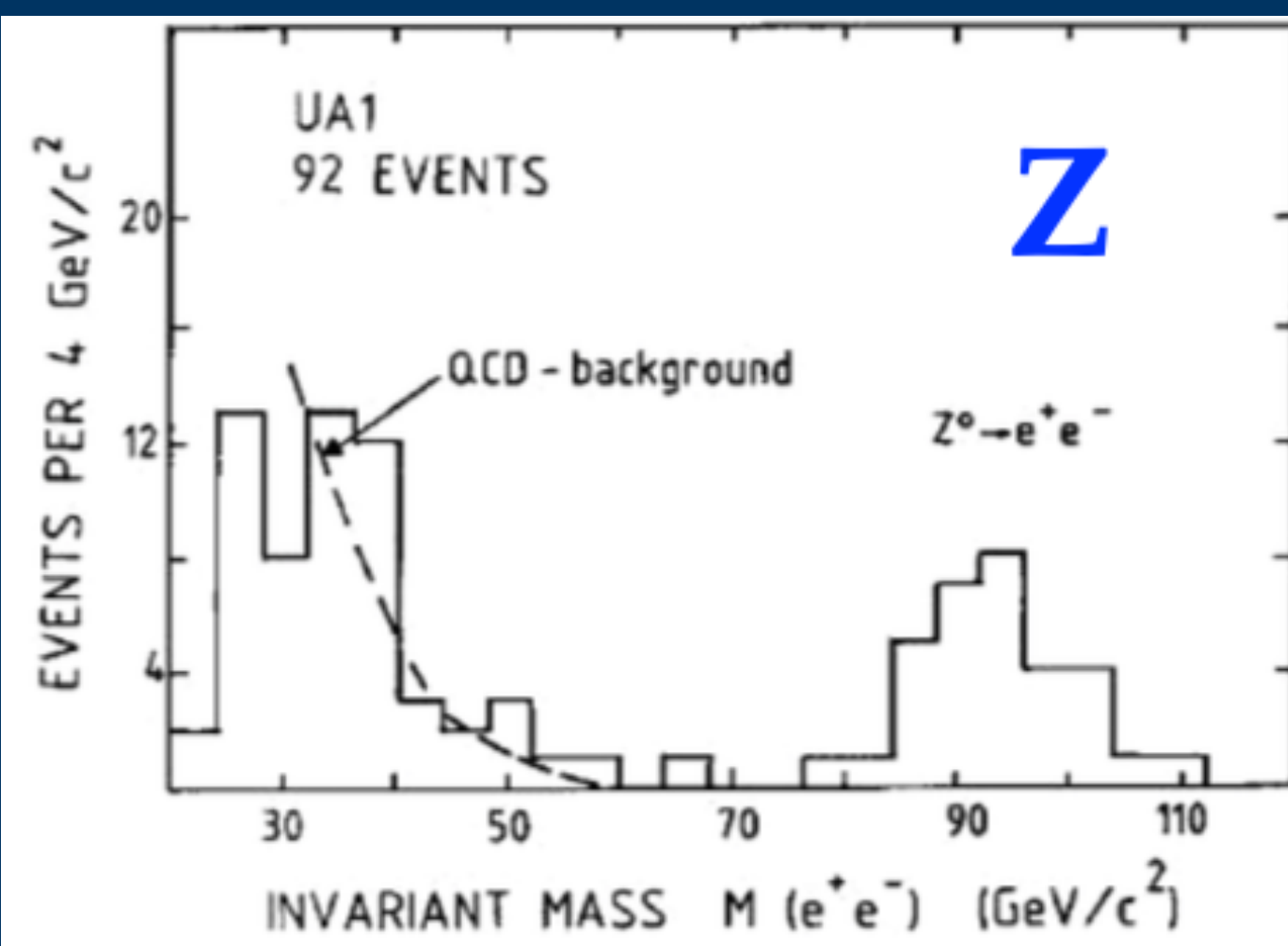
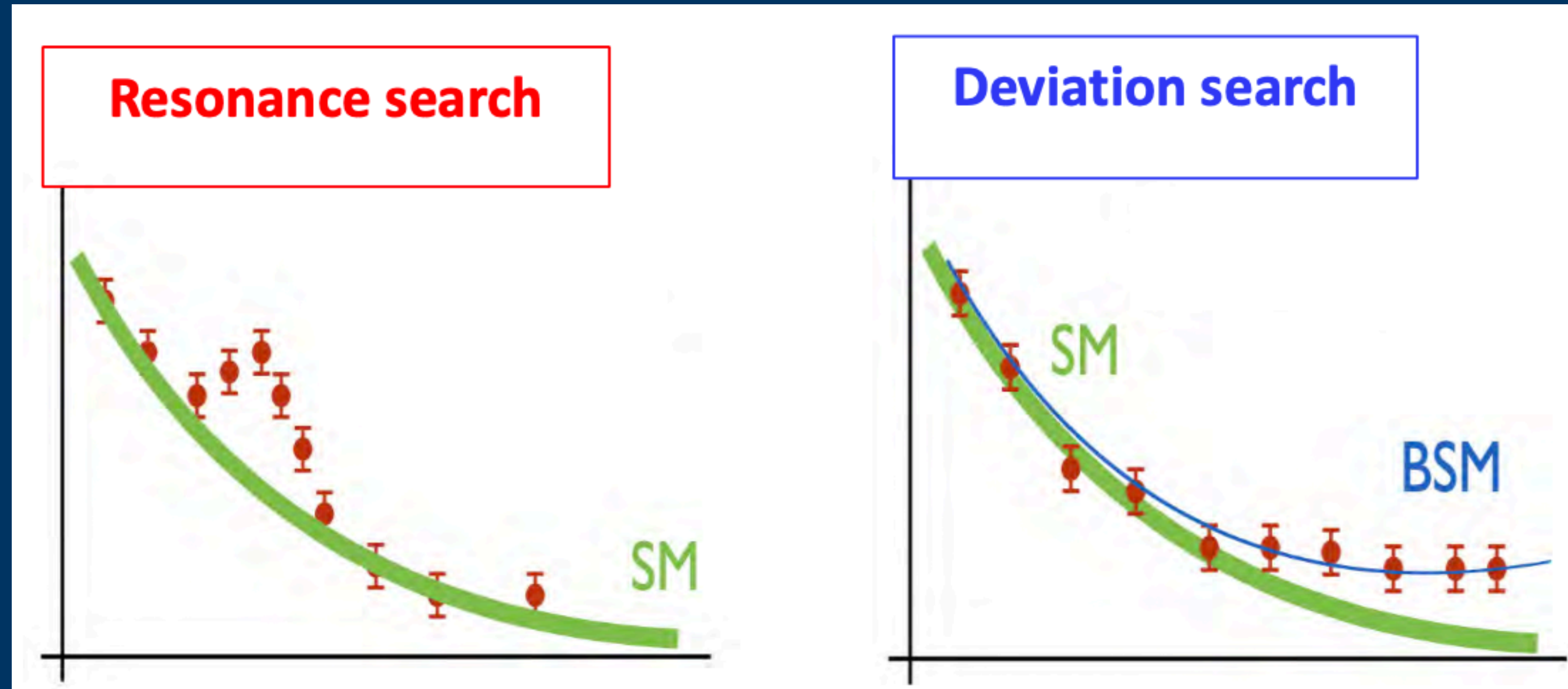
LHC: few SM measurements

- Many SM processes have been studied
- σ varies but 10 orders of magnitude
- strong and weak processes
- In general, good agreement with SM
- COM energy dependence is correct



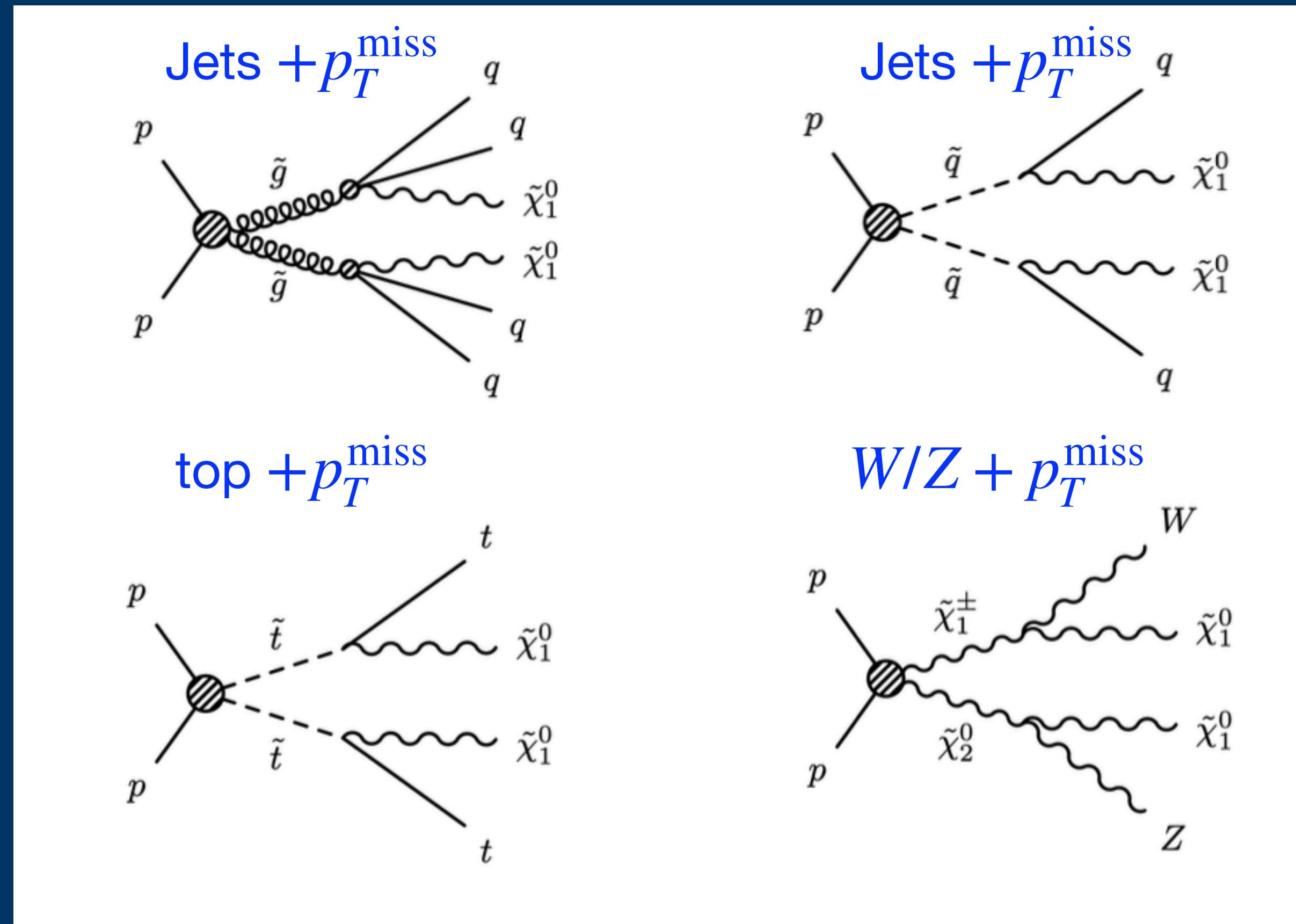
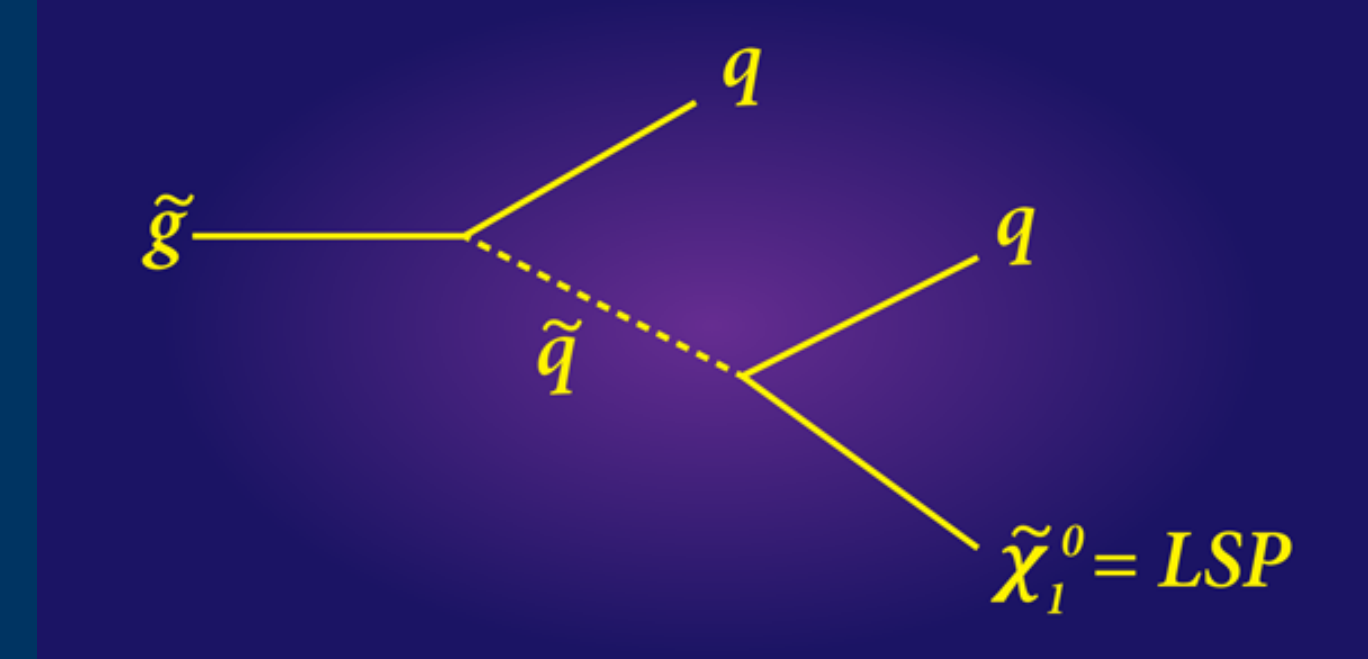
LHC: searches

- There are two possibility to look for signals: direct and indirect



Direct searches

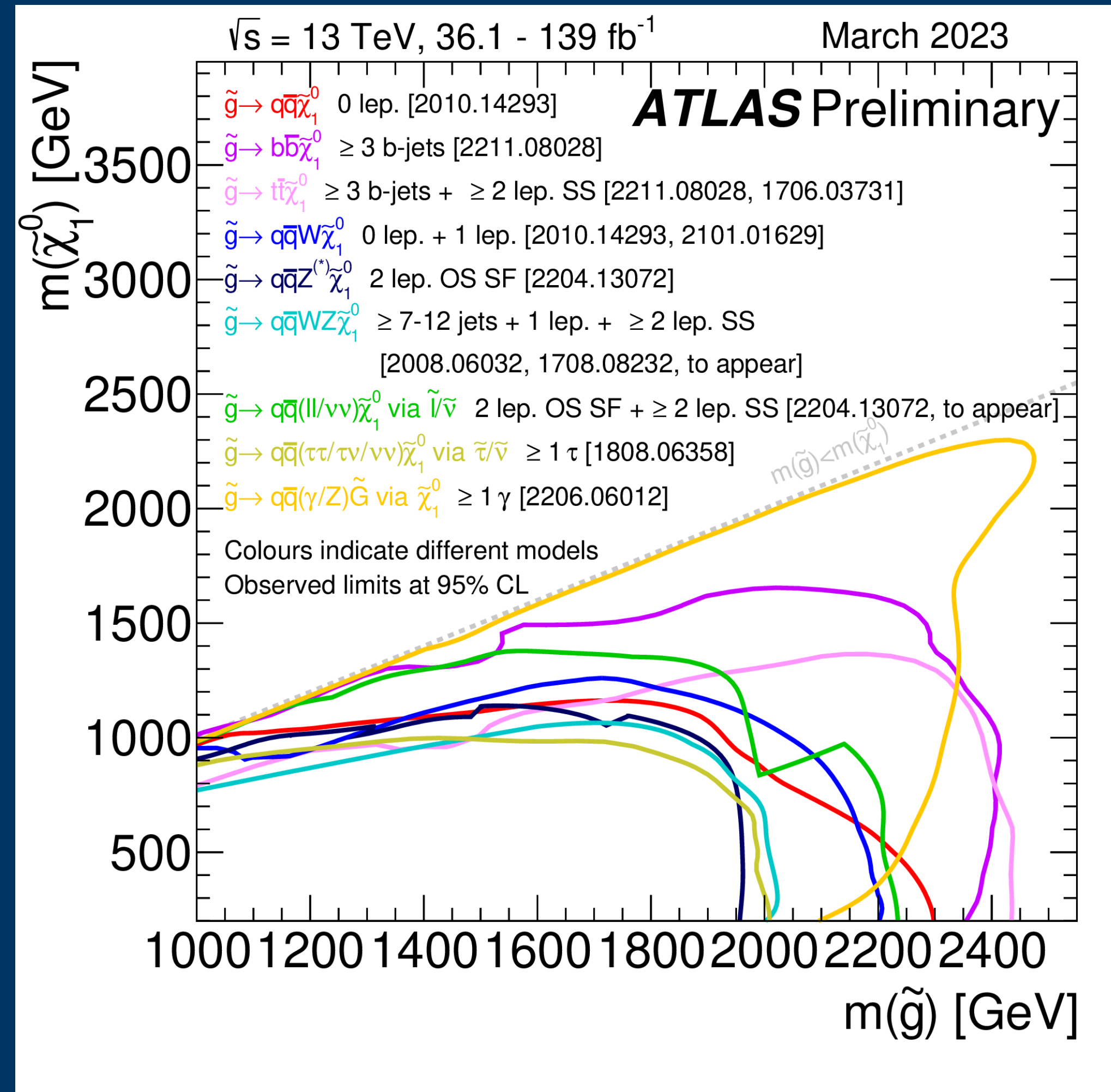
- Looking for new particles
- Signals depend on the model
- SUSY: many different signals. For instance, assuming R parity conservation



Nice feature: SUSY has a plethora of signals.

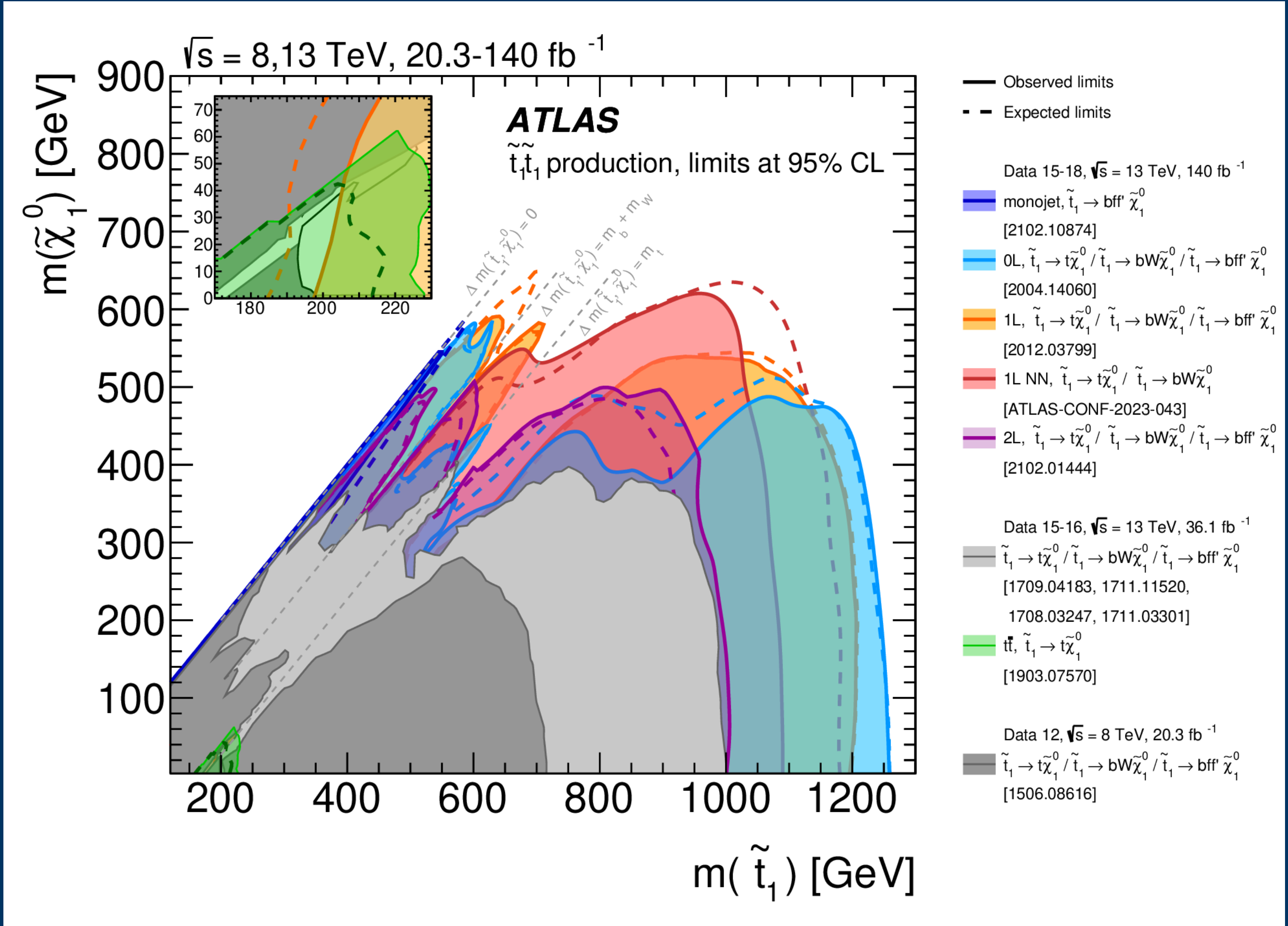
Direct searches

- SUSY searches haven't found any signal yet!



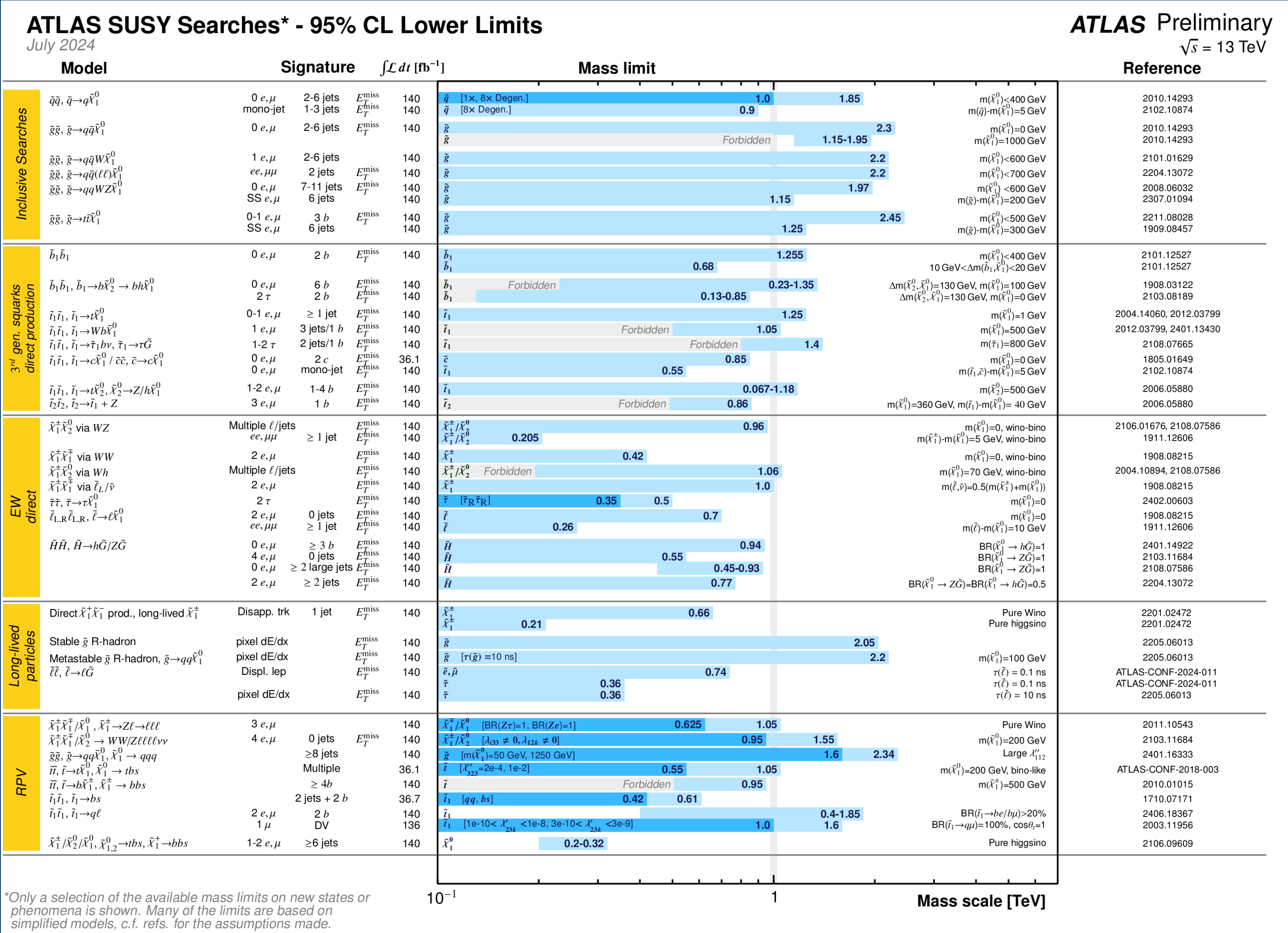
Direct searches

- SUSY searches haven't found any signal of top partners!



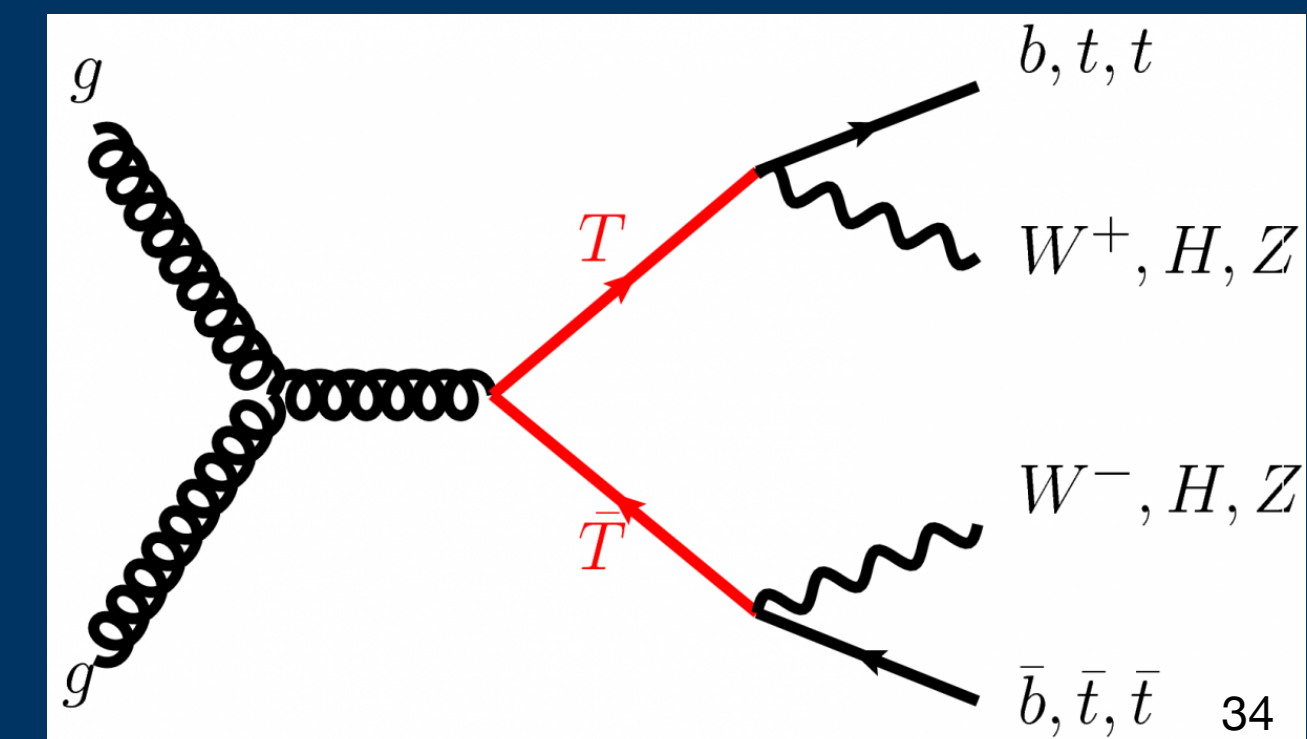
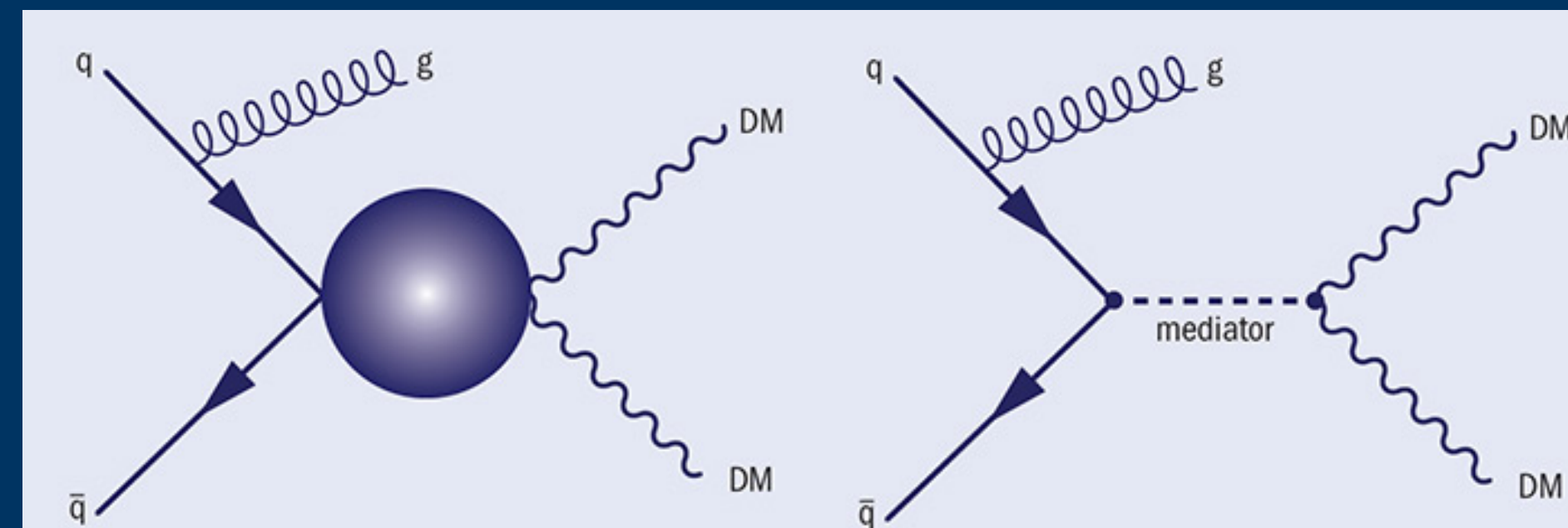
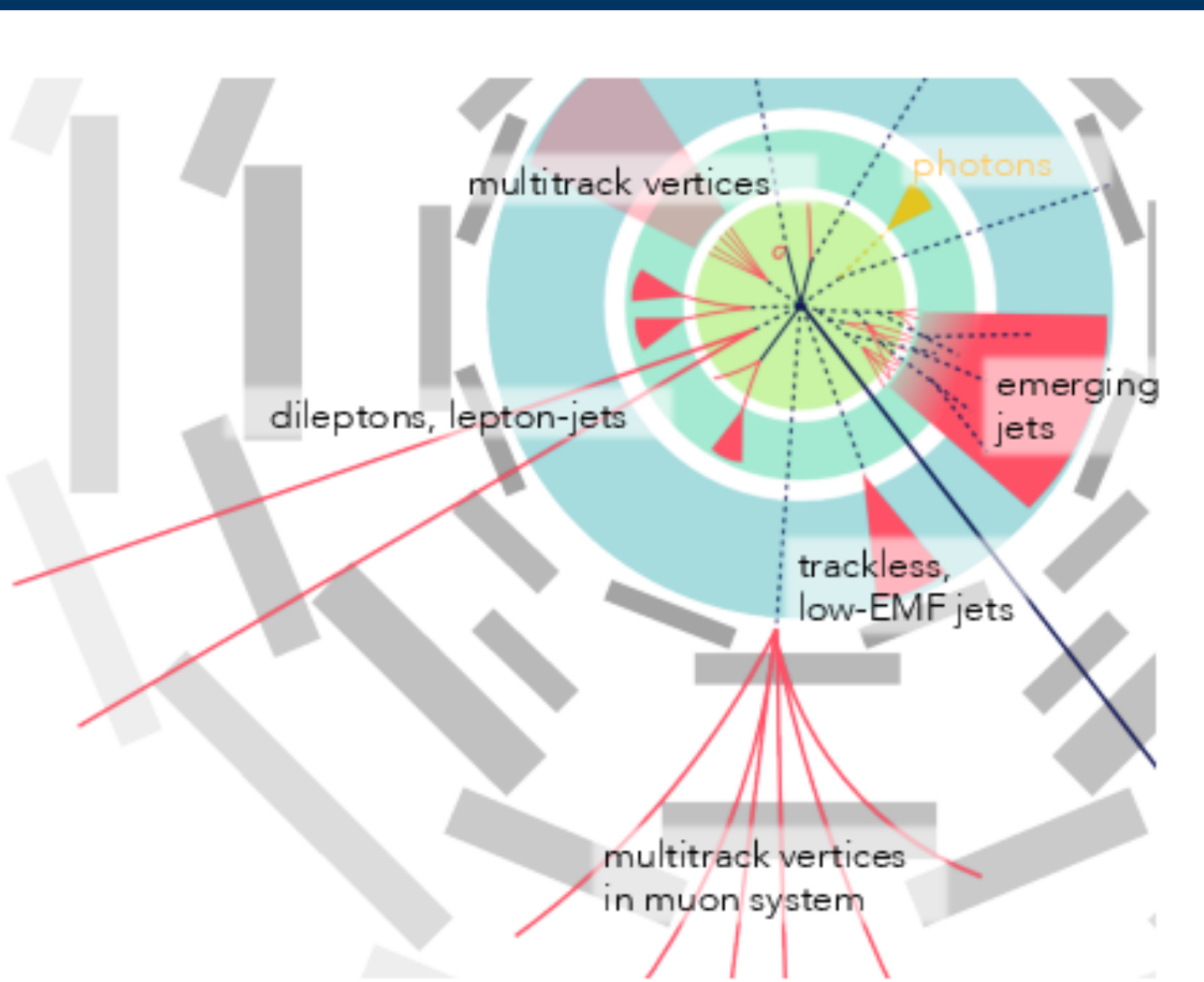
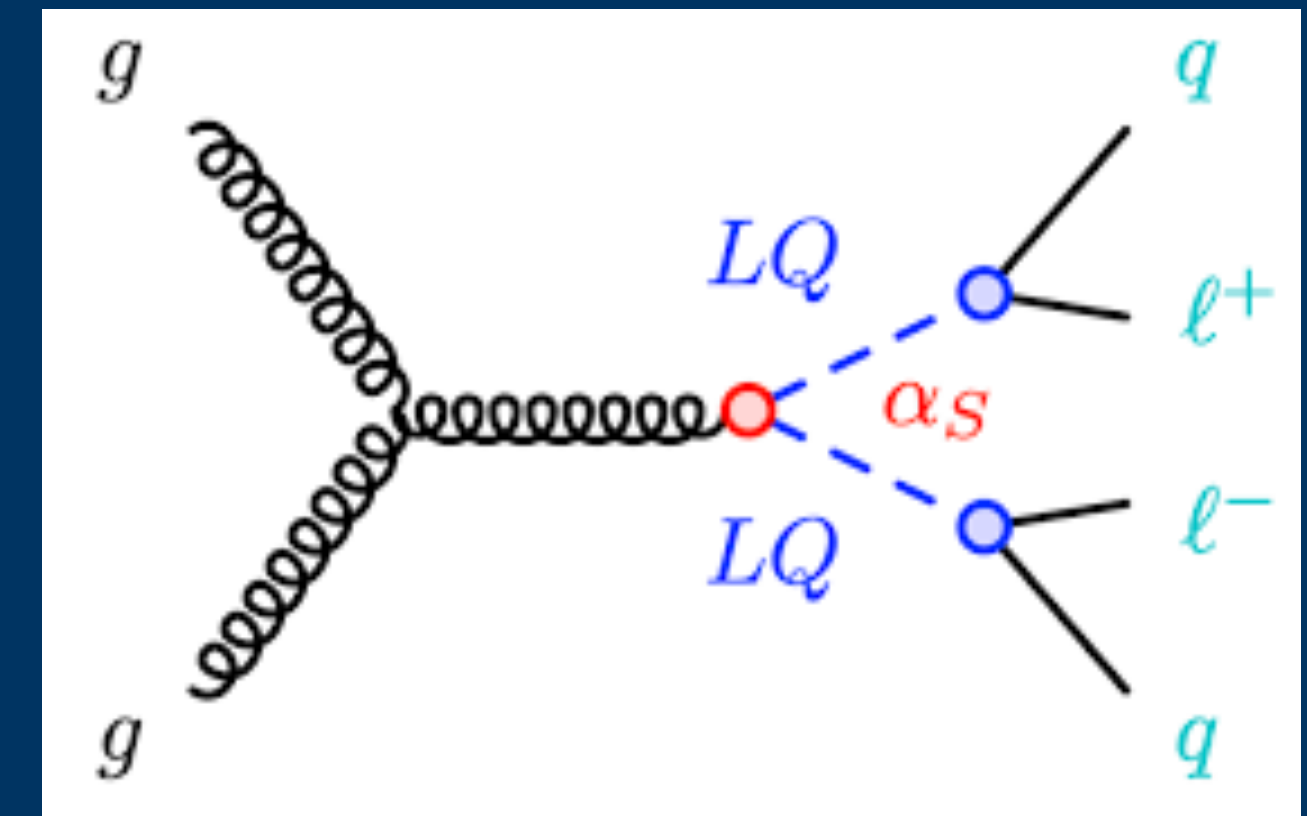
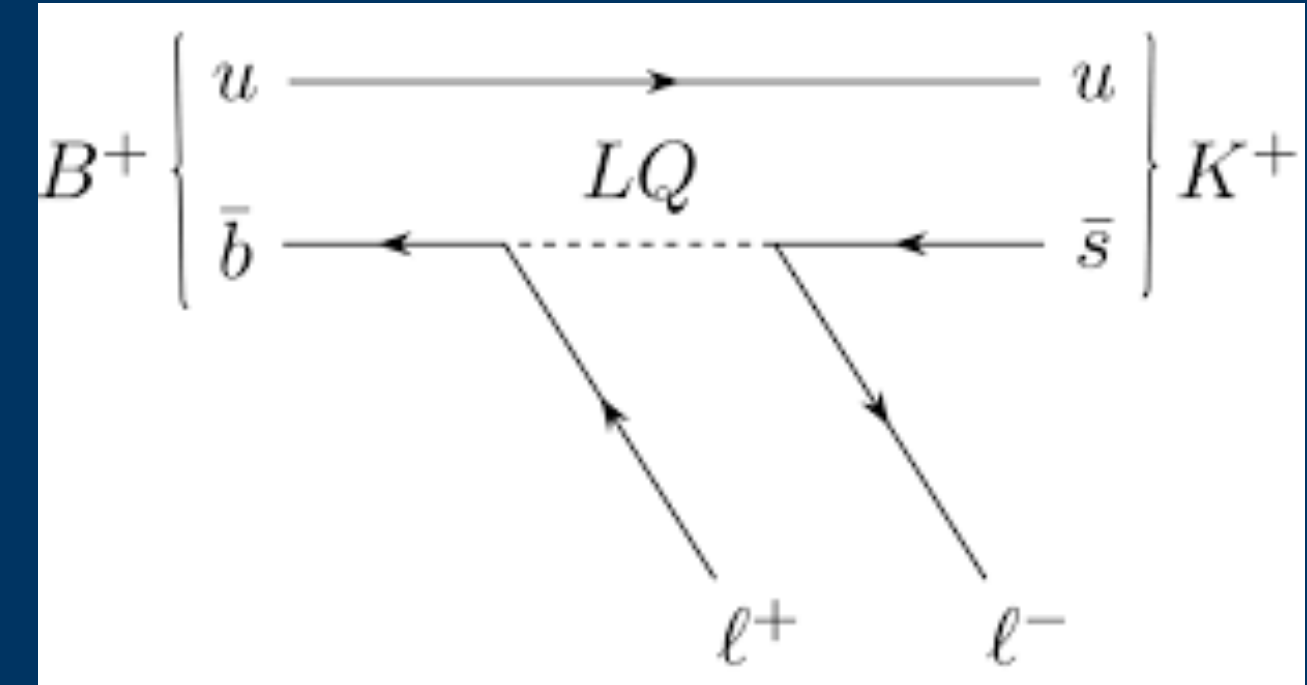
Direct searches

- SUSY searches haven’t found any signal yet!



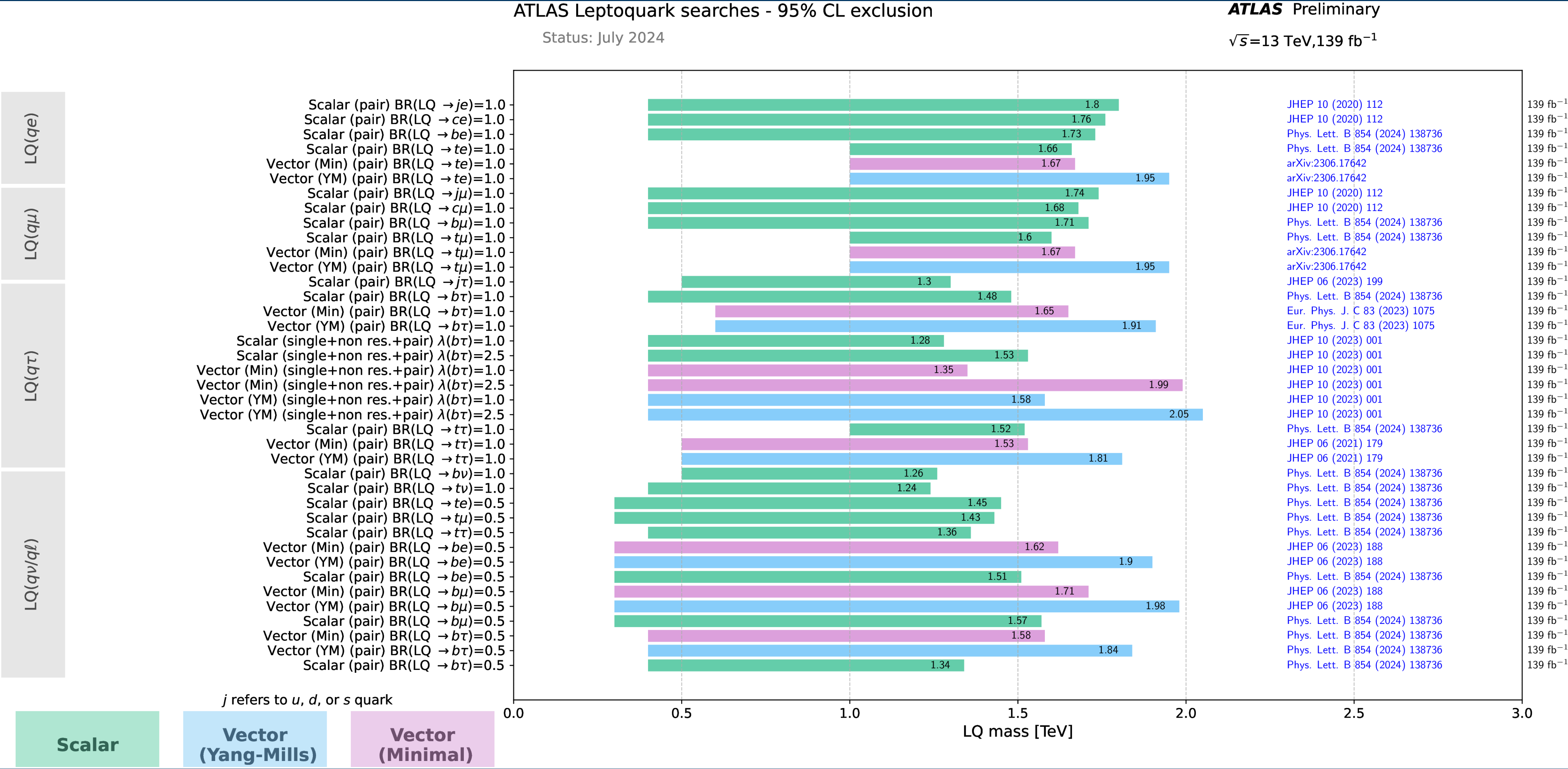
Direct searches

- Looking for new resonances/final states
- There are many possible final states
- Leptoquarks appear in many extensions of the SM
- The signal is a peak in lepton-jet invariant mass
- Dark matter: Mono-jet (Z, γ) plus missing p_T
- Long-lived particles give rise to displaced vertices
- Many final states are possible!



Direct searches

- Looking for new resonances



Direct searches

- Looking for new resonances

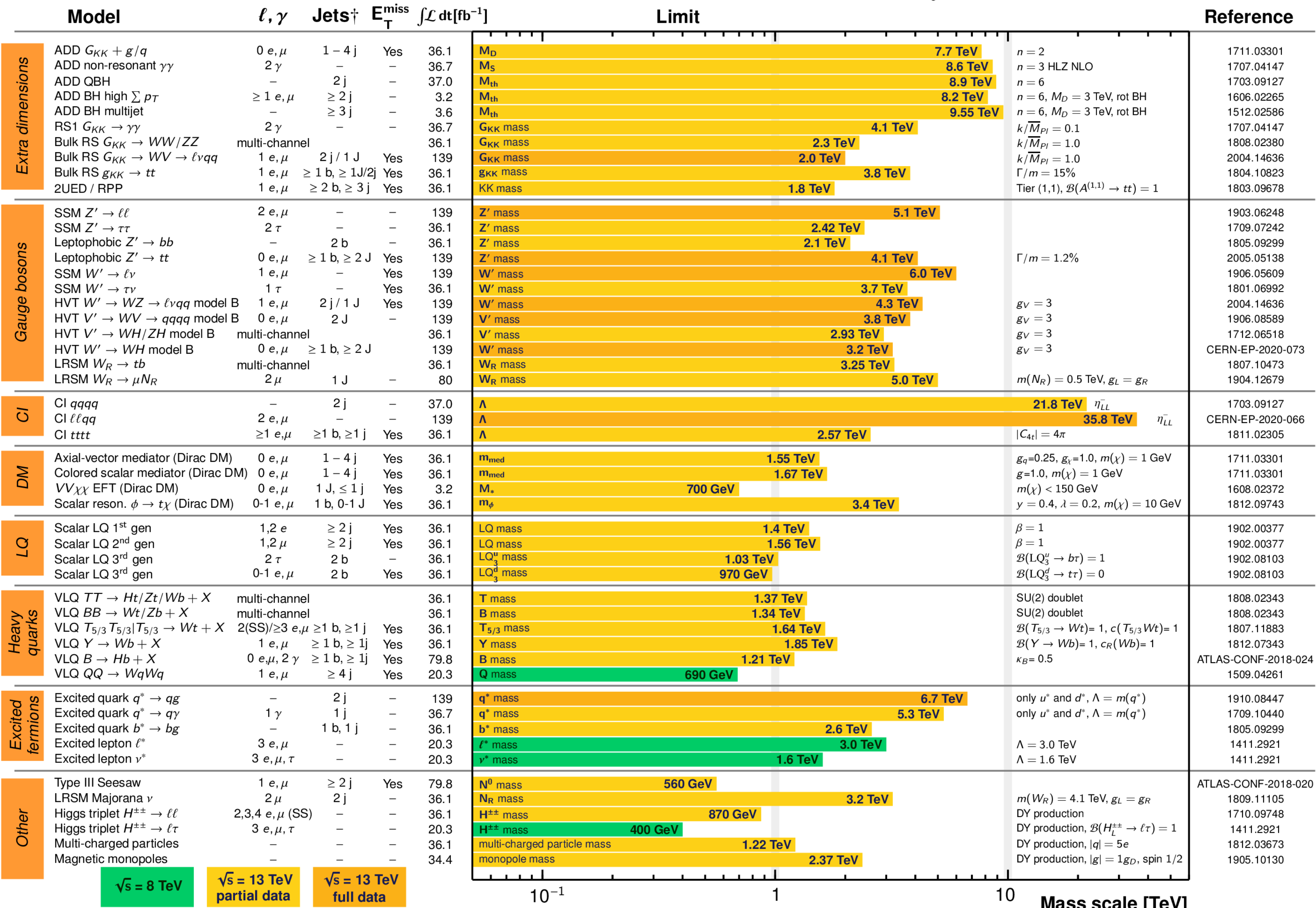
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

∫L dt = (3.2 – 139) fb⁻¹

√s = 8, 13 TeV



*Only a selection of the available mass limits on new states or phenomena is shown.

[†]Small-radius (large-radius) jets are denoted by the letter j (J).

Lack of conclusions: we have a lot of work ahead

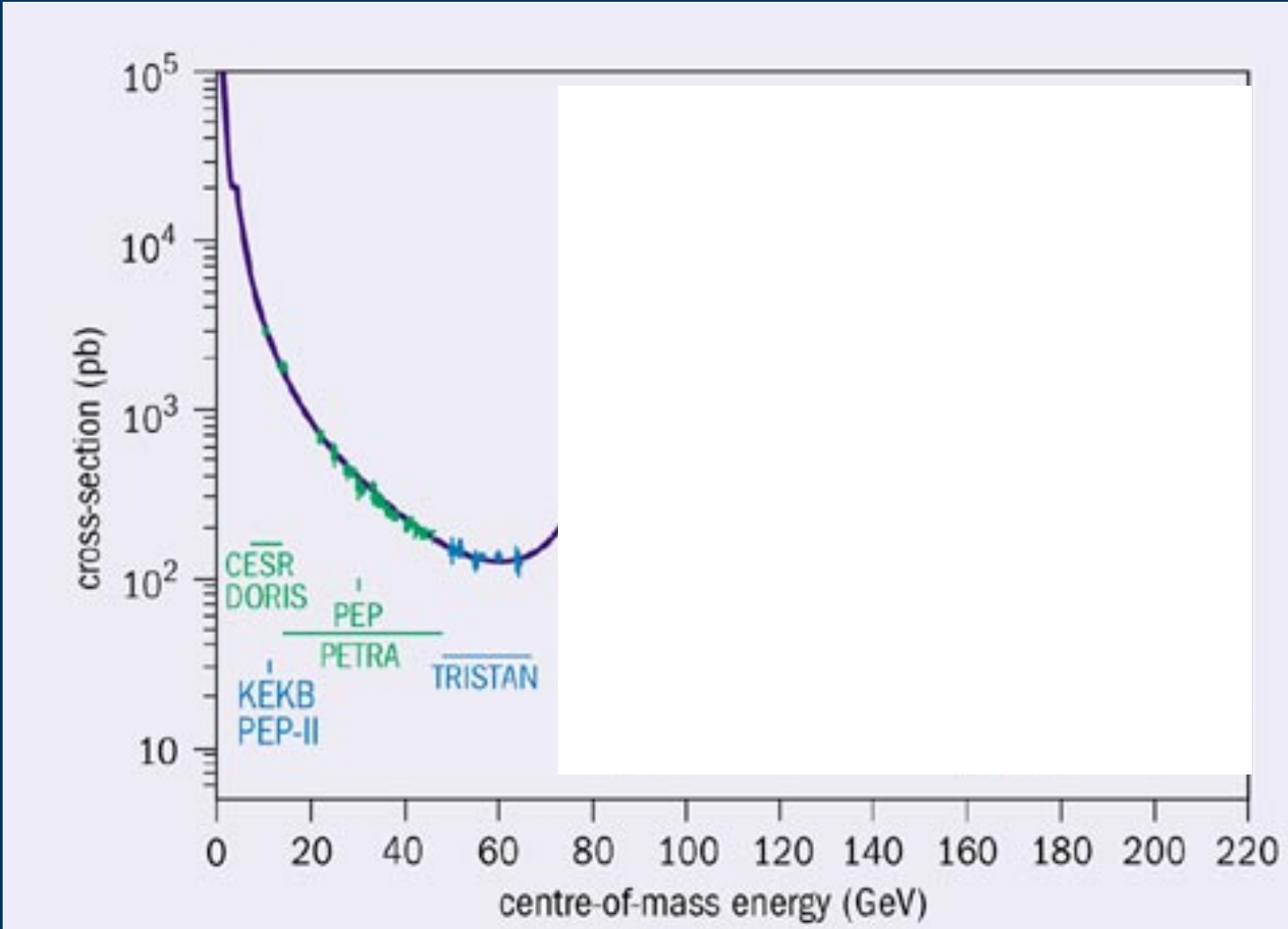
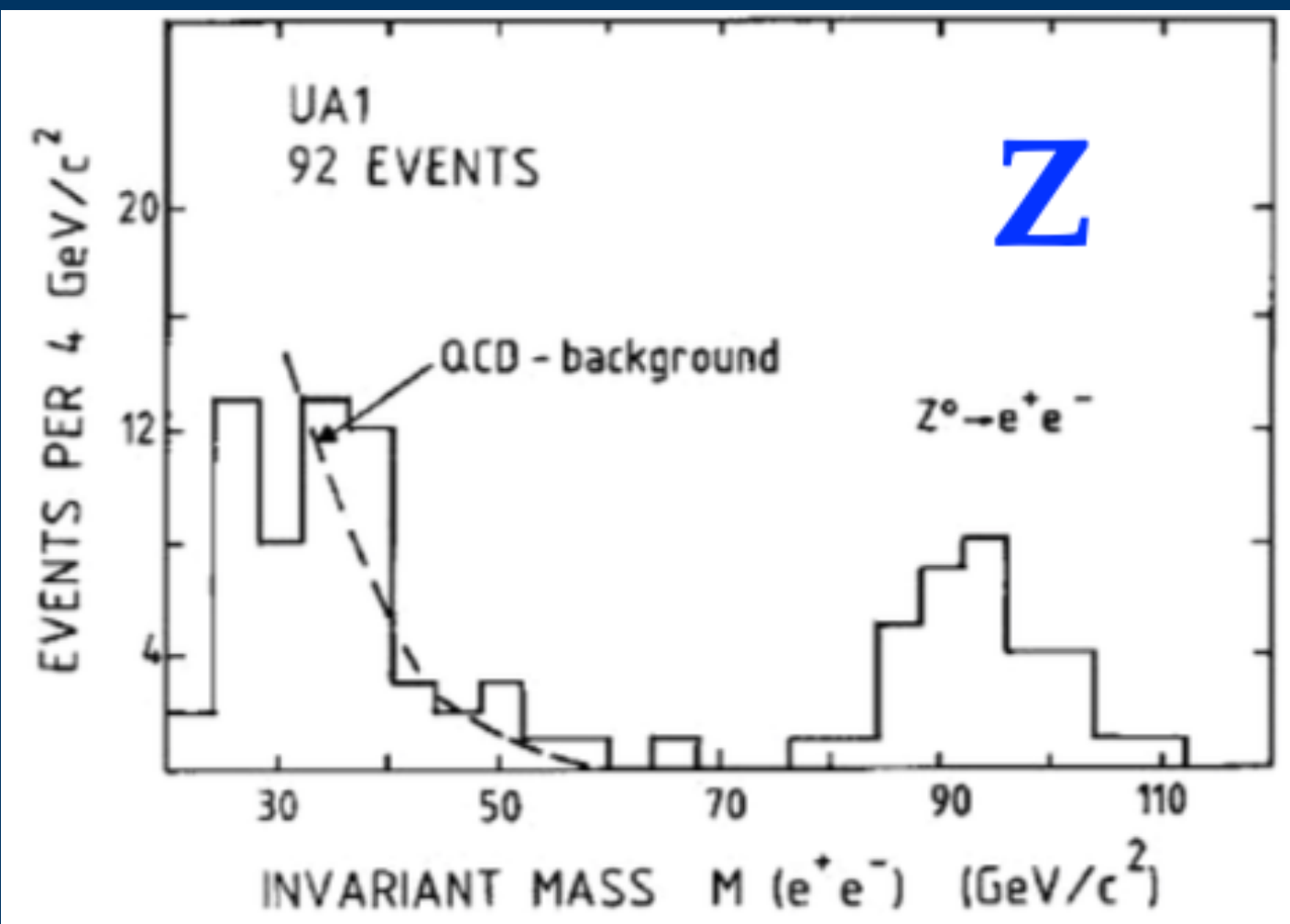
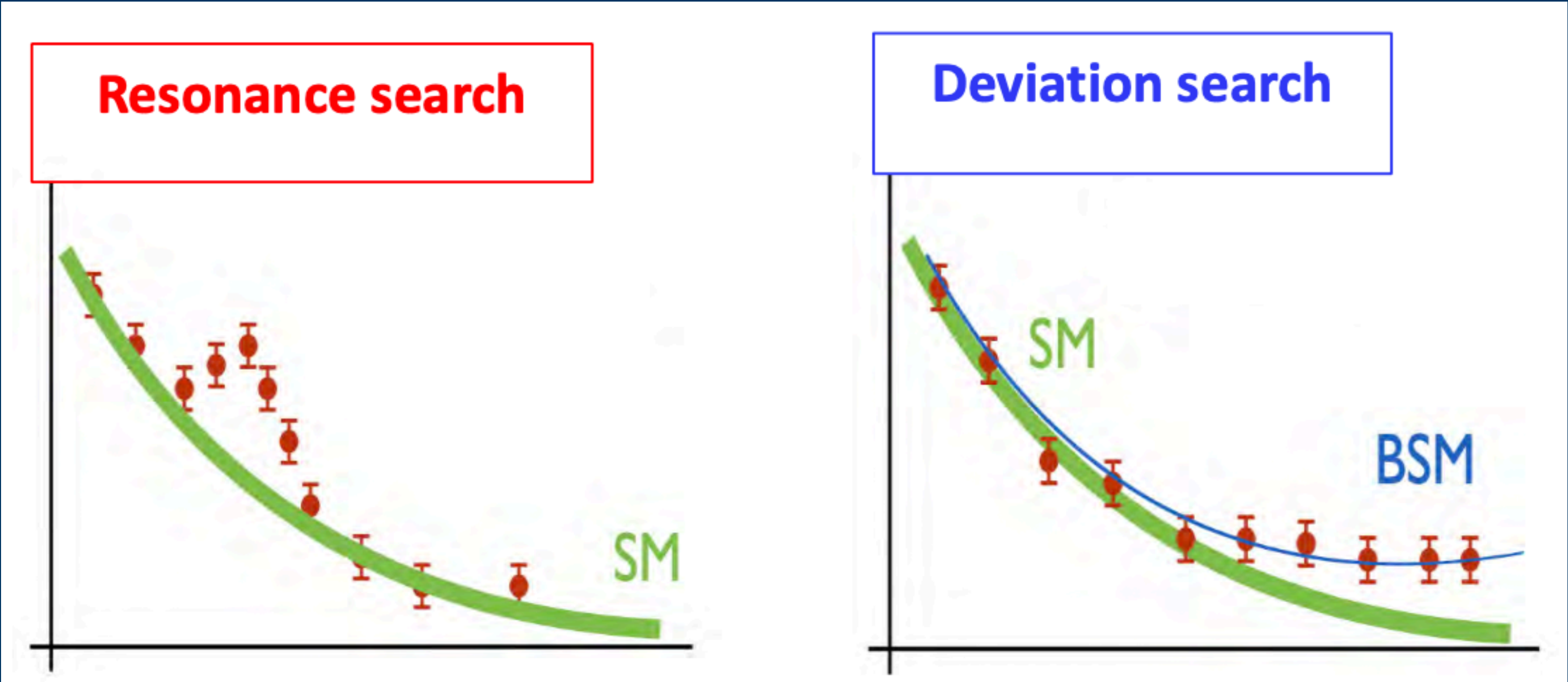
New physics searches at the LHC

Tilman Plehn

	missing energy (p.89)	cascade decays (p.91)	mono- jets/photon (p.15)	lepton resnce (p.109)	di-jet resnce (p.109)	top resnce (p.120)	WW/ZZ resnce (p.15)	W' resnce (p.93)	top partner (p.116)	charged tracks (p.123)	displ. vertex (p.123)	multi- photons (p.29)	spherical events (p.47,76)
SUSY (heavy grav.) (p.17,26)	✓ ✓	✓ ✓							✓				
SUSY (light grav.) (p.17,27)	✓	✓	✓						✓	✓	✓		
large extra dim (p.39)	✓ ✓		✓ ✓										✓
universal extra dim (p.47)	✓ ✓	✓ ✓		✓	✓	✓	✓	✓	✓				
technicolor (vanilla) (p.51)				✓	✓	✓	✓	✓ ✓					
topcolor/top seesaw (p.53,54)					✓	✓ ✓	✓						
little Higgs (w/o T) (p.55,58)				✓	✓	✓	✓	✓					
little Higgs (w T) (p.55,58)	✓ ✓	✓ ✓	✓	✓	✓	✓	✓	✓	✓				
warped extra dim (IR SM) (p.61,63)				✓	✓	✓	✓						
warped extra dim (bulk SM) (p.61,64)				✓	✓	✓ ✓	✓	✓					
'comp. Higgs (p.69,73)				✓	✓	✓ ✓	✓ ✓						
hidden valleys (p.75)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

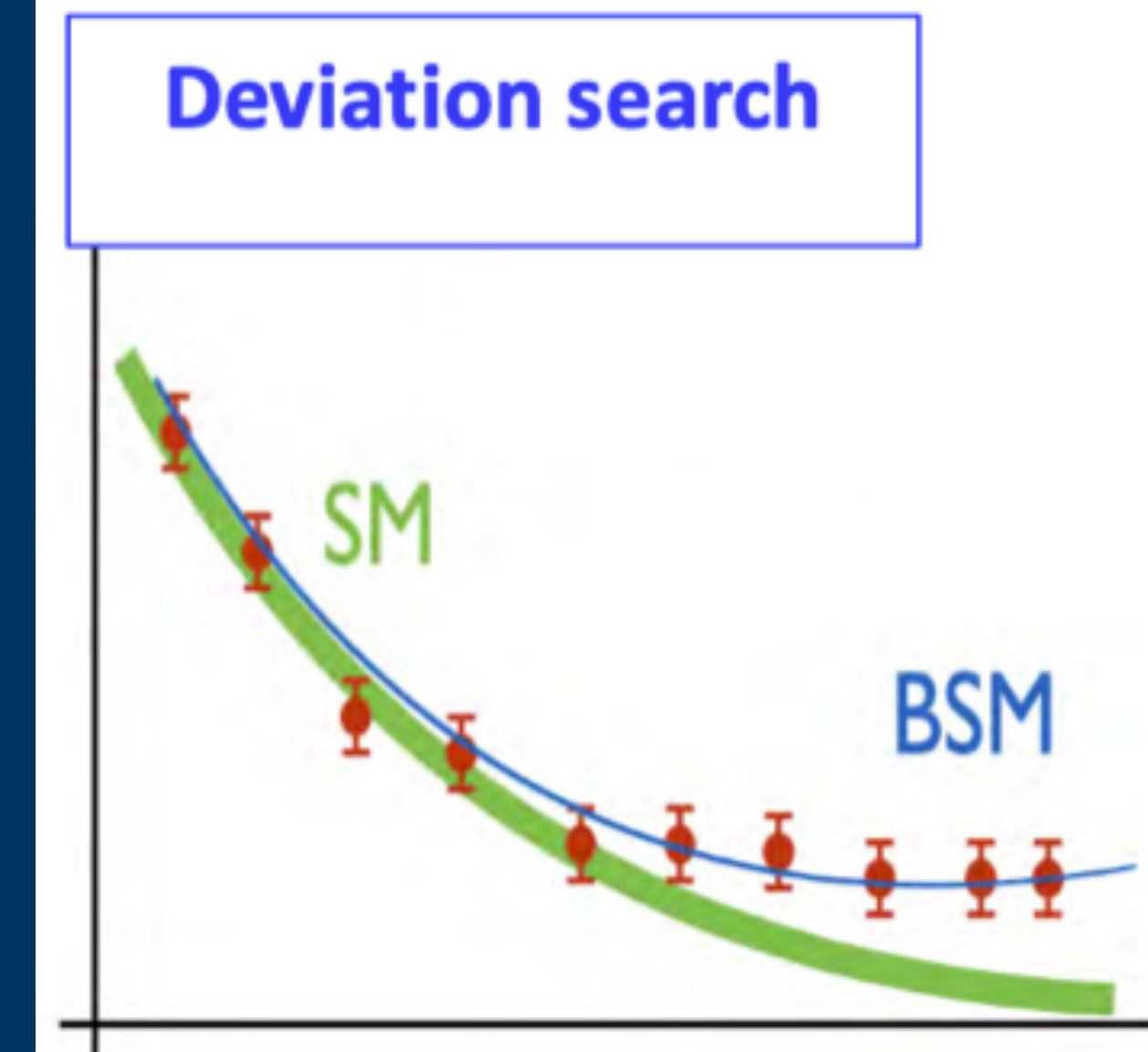
Searches

- There are two possibility to look for signals: direct and indirect



Indirect searches

- Total rates are in agreement with the SM predictions
- The high energy tail of the distribution might present deviation from the SM prediction
- This requires performing **precision measurements** at the LHC
- Hypothesis: there is a mass between the SM and BSM energy scales



UV Model

mass gap

EFT

- ▶ To look for footprints of the UV model we can use EFT
- ▶ Choice: the gauge symmetry is realized linearly as in the SM (**SMEFT**)

Indirect searches

- ▶ SMEFT is a consistent QFT

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{j \geq 5} \frac{f_{j,k}}{\Lambda^{j-4}} \mathcal{O}_j^{(k)}$$

- ▶ The truncation of the series is decided by the (th&exp) precisions

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \frac{1}{\Lambda^2} \mathcal{M}^{(6)} + \frac{1}{\Lambda^4} \mathcal{M}^{(8)} + \dots$$

$$\sigma \propto |\mathcal{M}_{\text{SM}}|^2 + \frac{1}{\Lambda^2} \mathcal{M}_{\text{SM}}^* \mathcal{M}^{(6)} + \frac{1}{\Lambda^4} \left[|\mathcal{M}^{(6)}|^2 + \mathcal{M}_{\text{SM}}^* \mathcal{M}^{(8)} \right]$$

- ▶ For the LHC: focus on dimension-six operators ("lowest" one)

Indirect searches

- Linear realization of the symmetry leads to correlations:

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \quad , \quad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \quad , \quad \mathcal{O}_B = (D_\mu \Phi)^\dagger B^{\mu\nu} D_\nu \Phi$$

$$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \quad , \quad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu (\Phi^\dagger \Phi) \partial_\mu (\Phi^\dagger \Phi)$$

	ZWW	γWW	$H\gamma\gamma$	HZZ	$HZ\gamma$	HWW
$\mathcal{O}_{WWW}$	X	X				
$\mathcal{O}_W$	X	X		X	X	X
$\mathcal{O}_B$	X	X		X	X	
$\mathcal{O}_{BW}$	X	X	X	X	X	X
$\mathcal{O}_{WW}$			X	X	X	X
$\mathcal{O}_{BB}$			X	X	X	
$\mathcal{O}_{\Phi,1}$	X			X		X
$\mathcal{O}_{\Phi,2}$				X		X



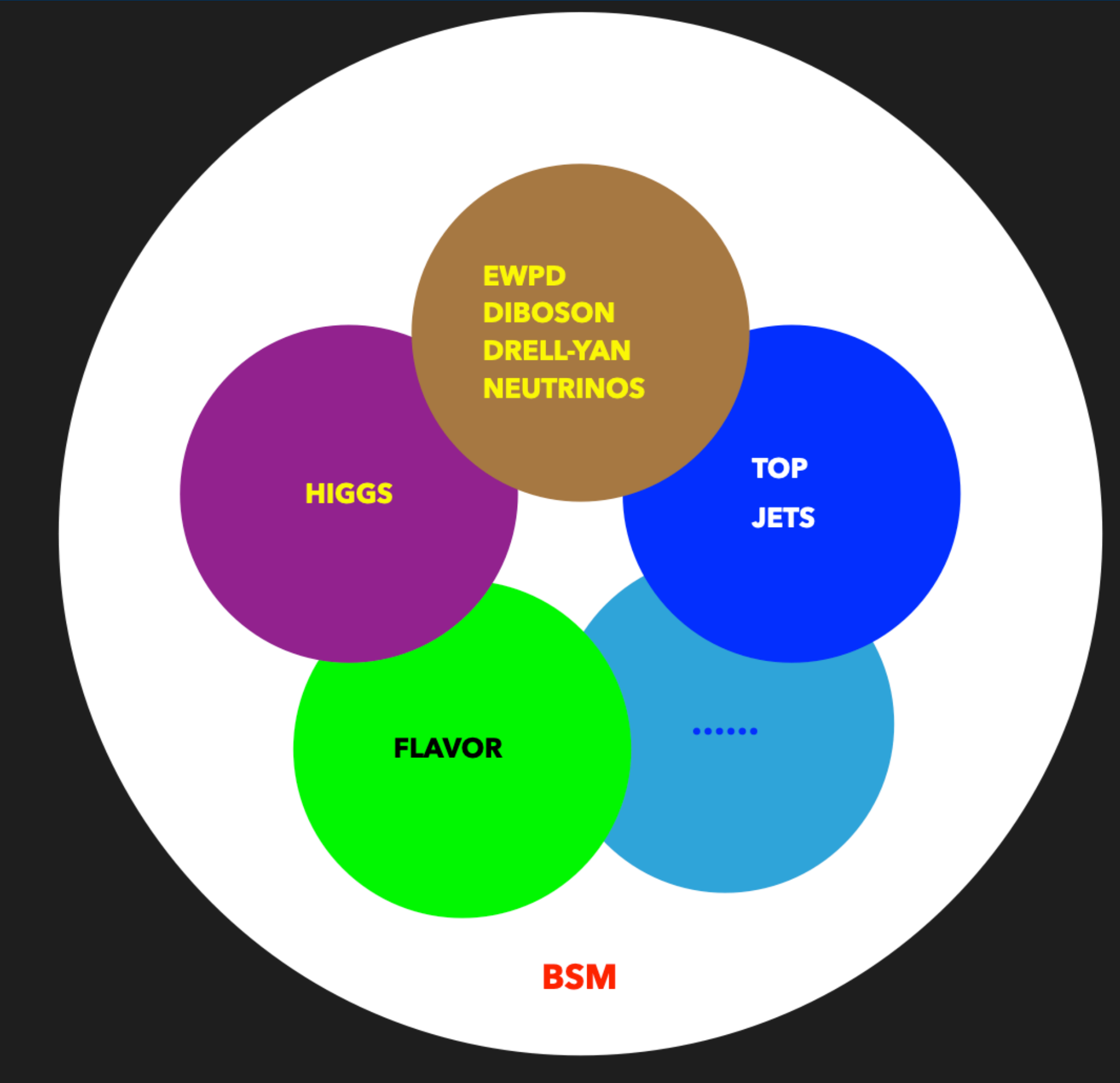
relacionados pela invariância de gauge

Indirect searches

- ▶ Taking flavor into account the number of operators might get out control!
- ▶ Without any flavor symmetry: 1350 (CP-even) and 1149 (CP-odd) = 2499
- ▶ Assuming $U(3)_L \times U(3)_\ell \times U(3)_Q \times U(3)_u \times U(3)_d$ there are 85
- ▶ Assuming $U(3)_L \times U(3)_\ell \times U(2)_Q \times U(2)_u \times U(2)_d$ there are 270
- ▶ Lesson 1: we need to introduce a hypothesis on the flavor symmetry
- ▶ Lesson 2: in any case, we need many datasets
- ▶ SMEFT has many parameters, so any measurement has blind directions
- ▶ Large number of Wilson coefficients and correlations between processes call for a global analysis

Indirect searches

- We also need many datasets

Dataset		hypothesis
EWPO		$SU(3)^5$
Diboson (TGC)		$SU(3)^5$
top		$U(2)_Q \times U(2)_u \times U(2)_d$
Higgs		$SU(3)^5$

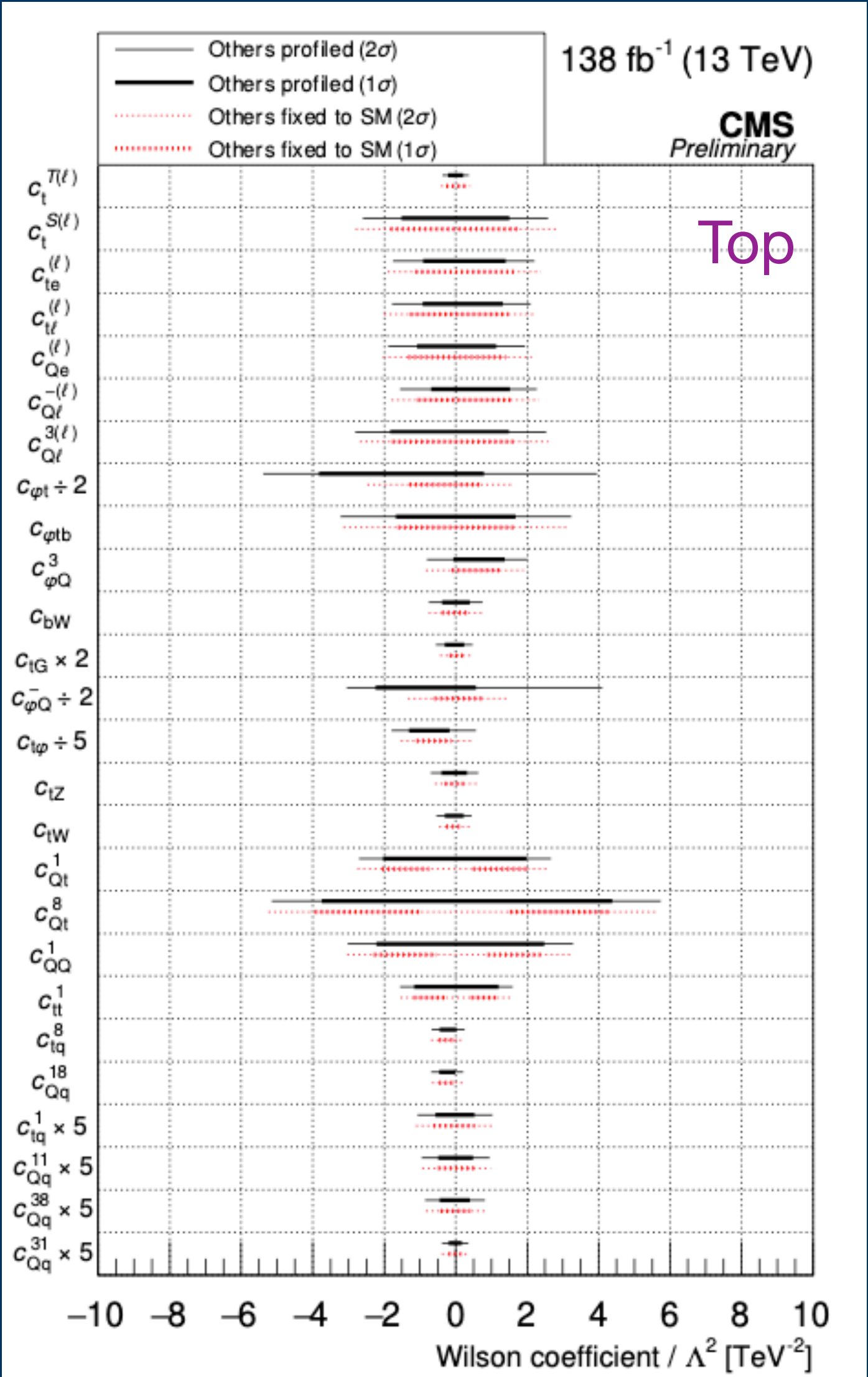
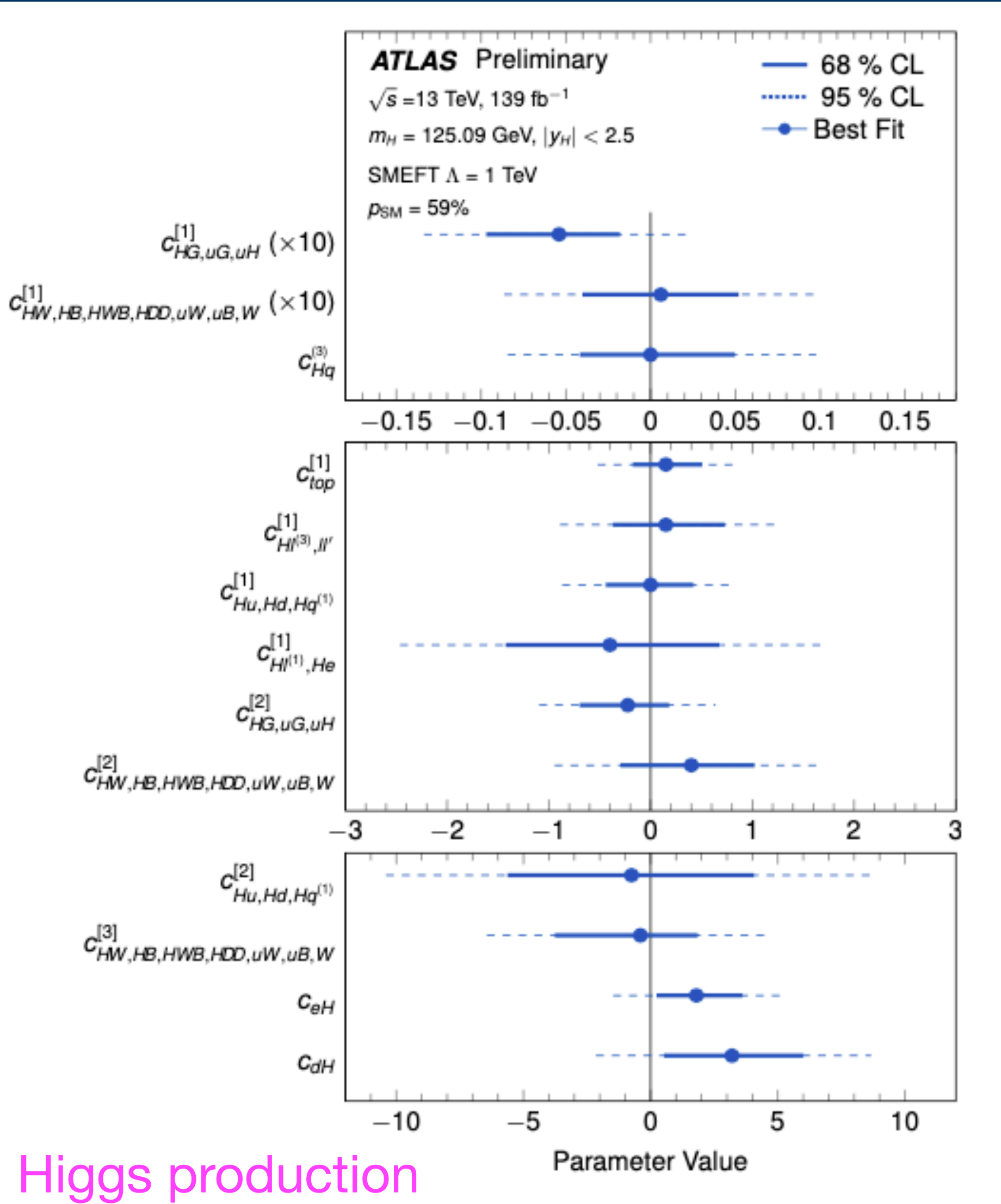
Indirect searches

- We need a basis of operators, e.g. the dimension-six Warsaw basis [arXiv:1008.4884](#)

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

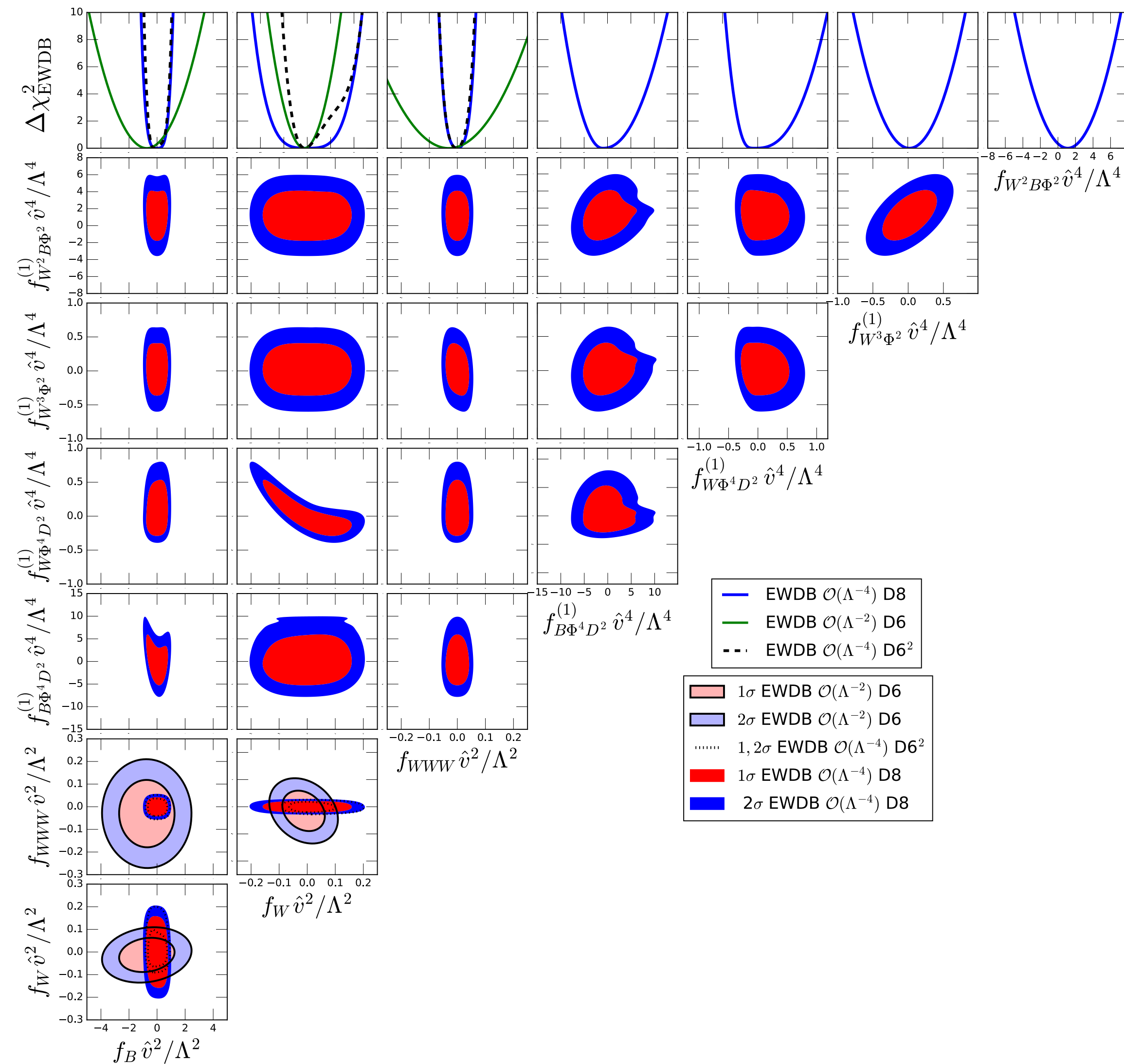
Indirect searches

- The experiments are already performing their analyses using SMEFT:



Indirect searches

- In some cases, e.g. W^+
- We can only estimate the
- $\sigma \propto |\mathcal{M}_{\text{SM}}|^2 + \frac{1}{\Lambda^2} \mathcal{M}_{\text{S}}^\star$
- Assuming universal phys

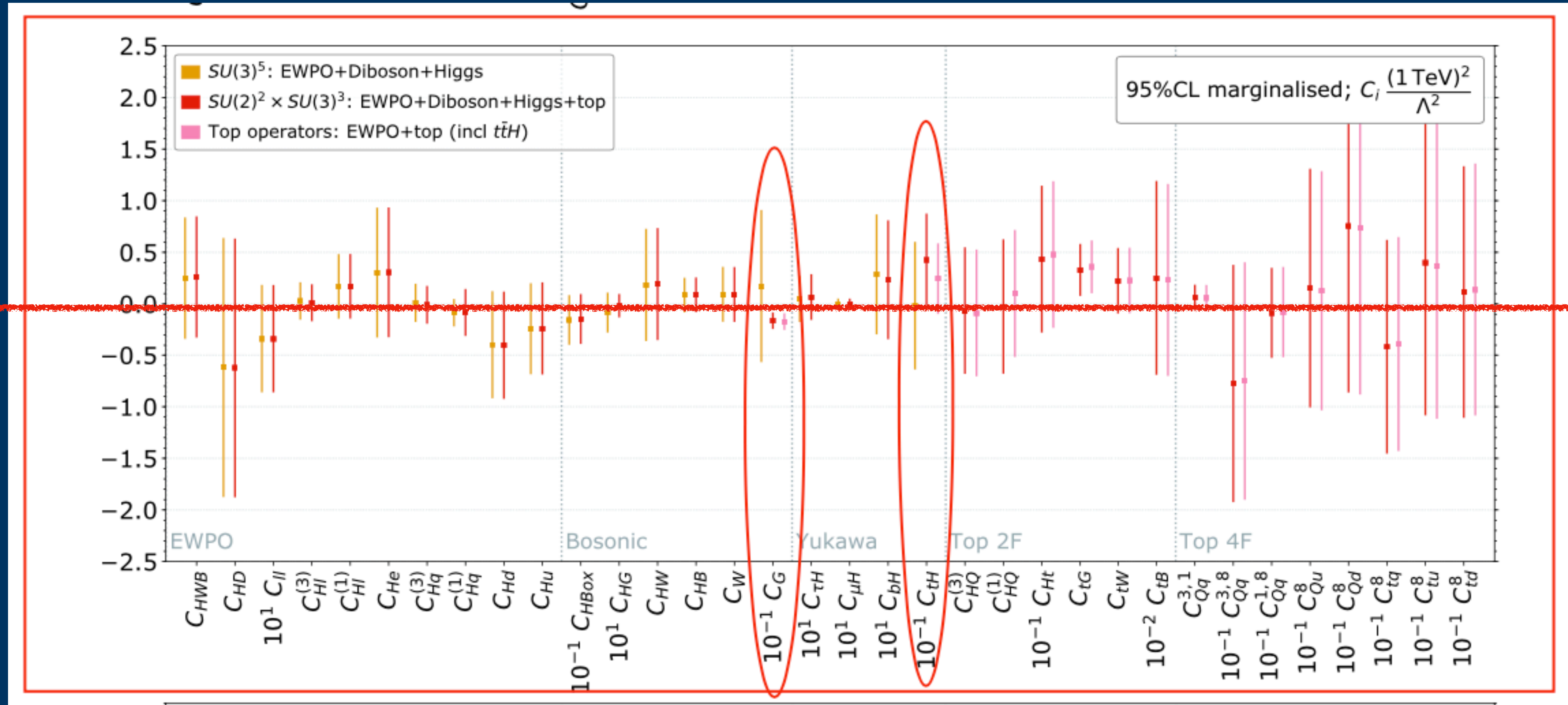


:2304.03305]

Indirect searches

- Theorists do global analyses : Linear fit by Ellis et al. 2012.02779

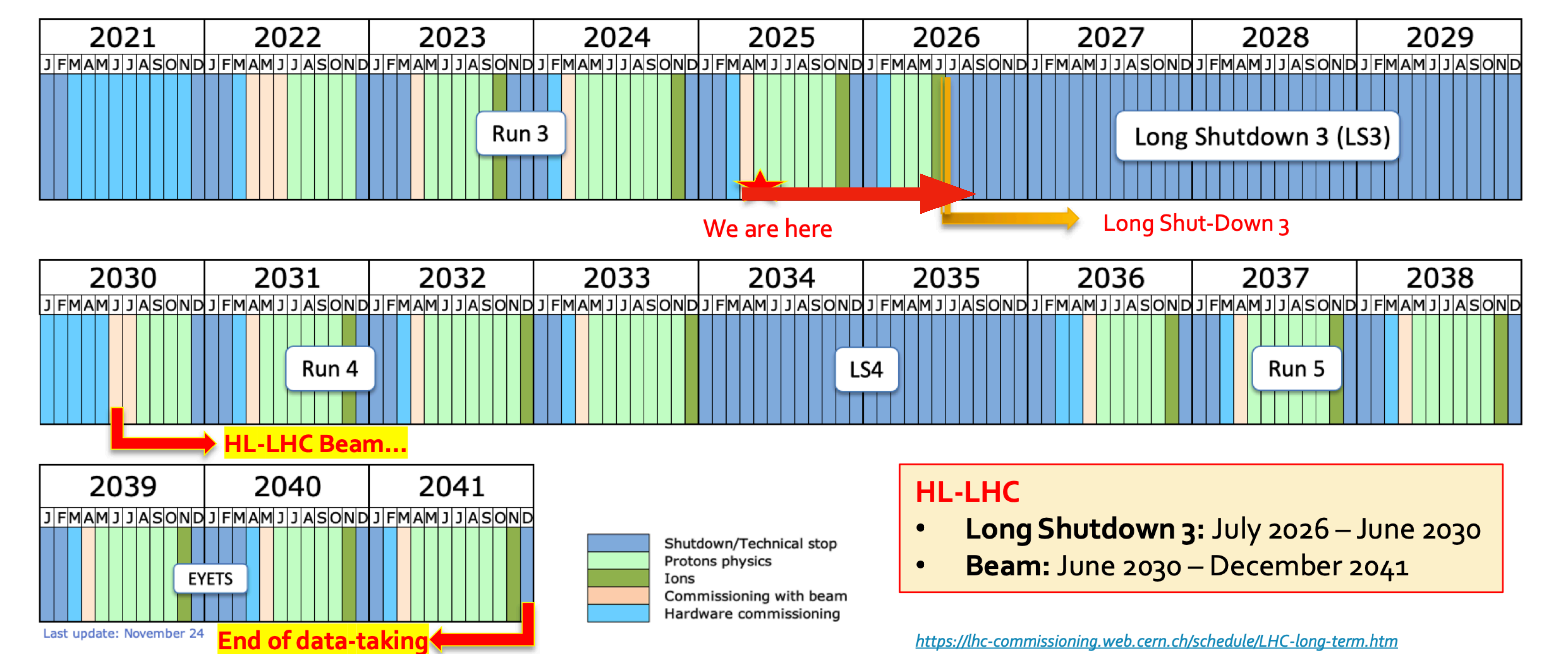
$$C \simeq \frac{g_{\star}^2}{\Lambda^2}$$



FINAL THOUGHTS

Final thoughts

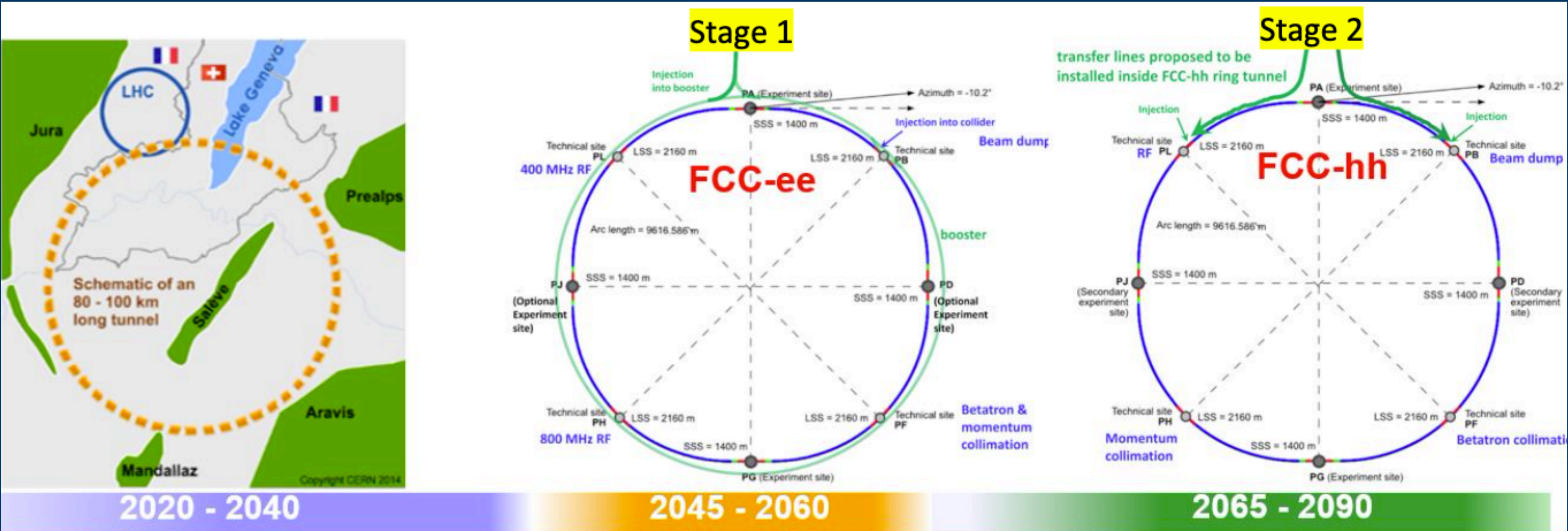
- The LHC will accumulate more data, so we can probe neutral top partners, etc
- The LHC is becoming a precision machine
- A great effort is on going from the experimental and theoretical communities



Final thoughts

- Future Circular Collider could follow the success story of LEP-LHC

for only 8-15



Final thoughts

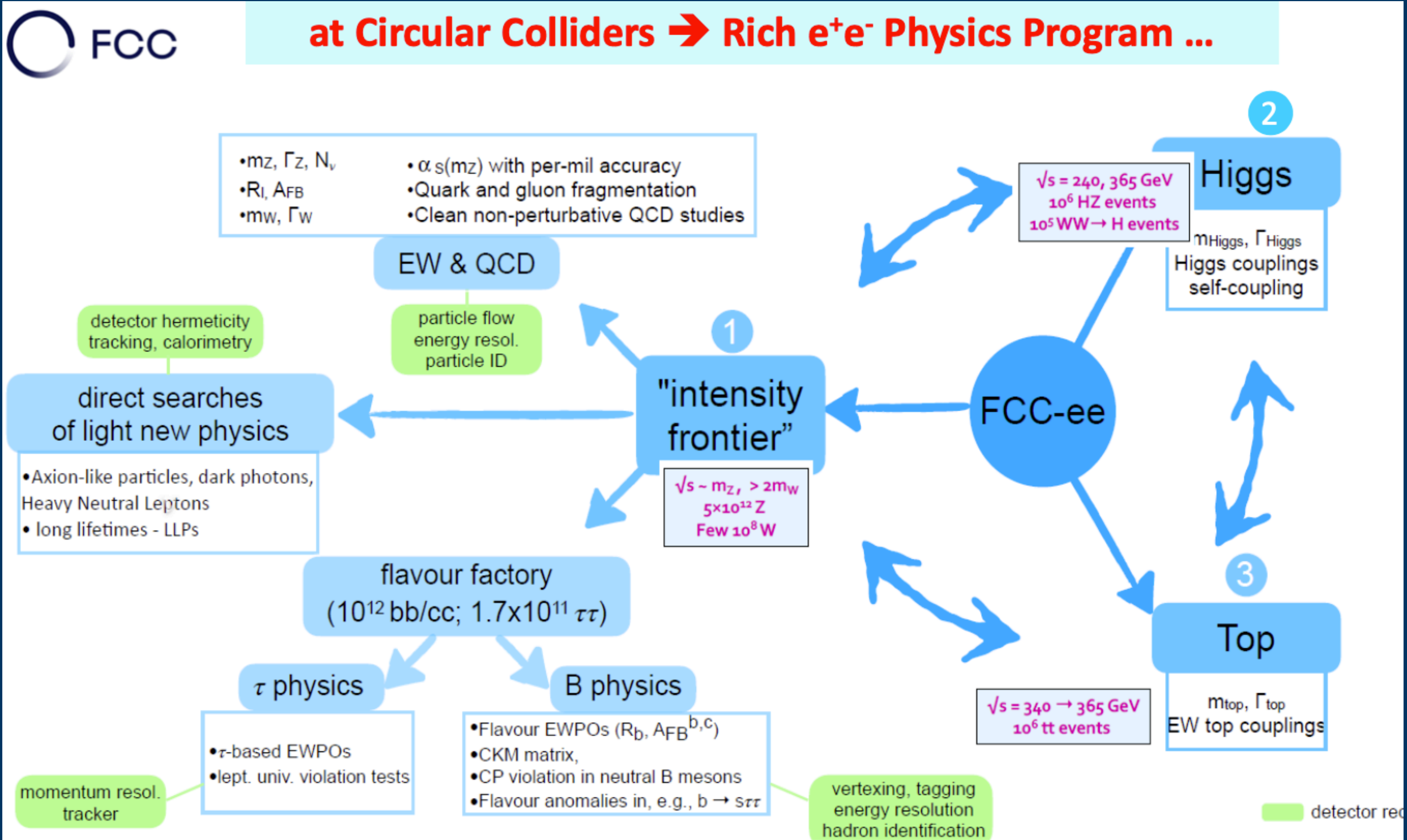
- These future machine will allow very precise measurements at least





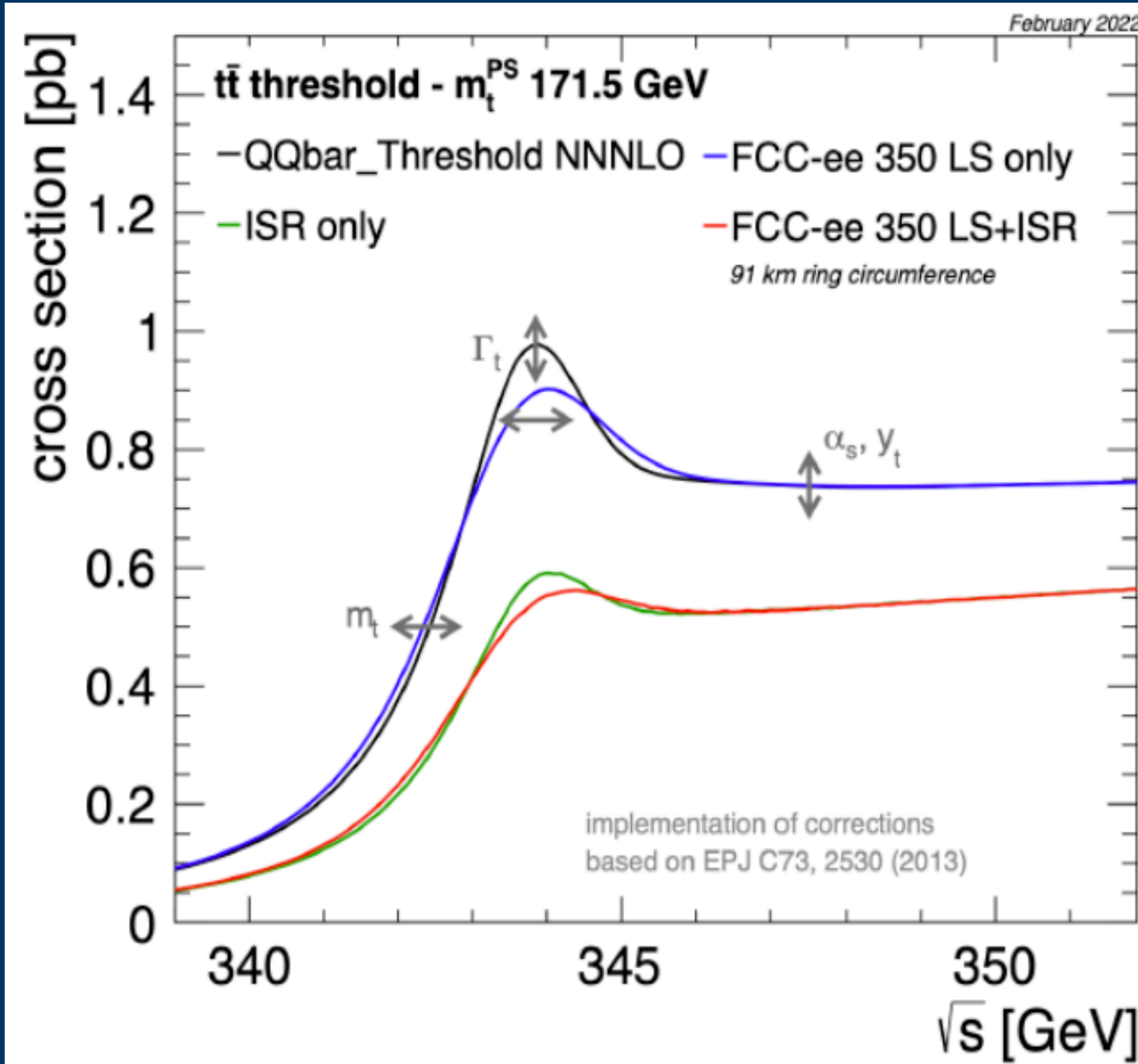
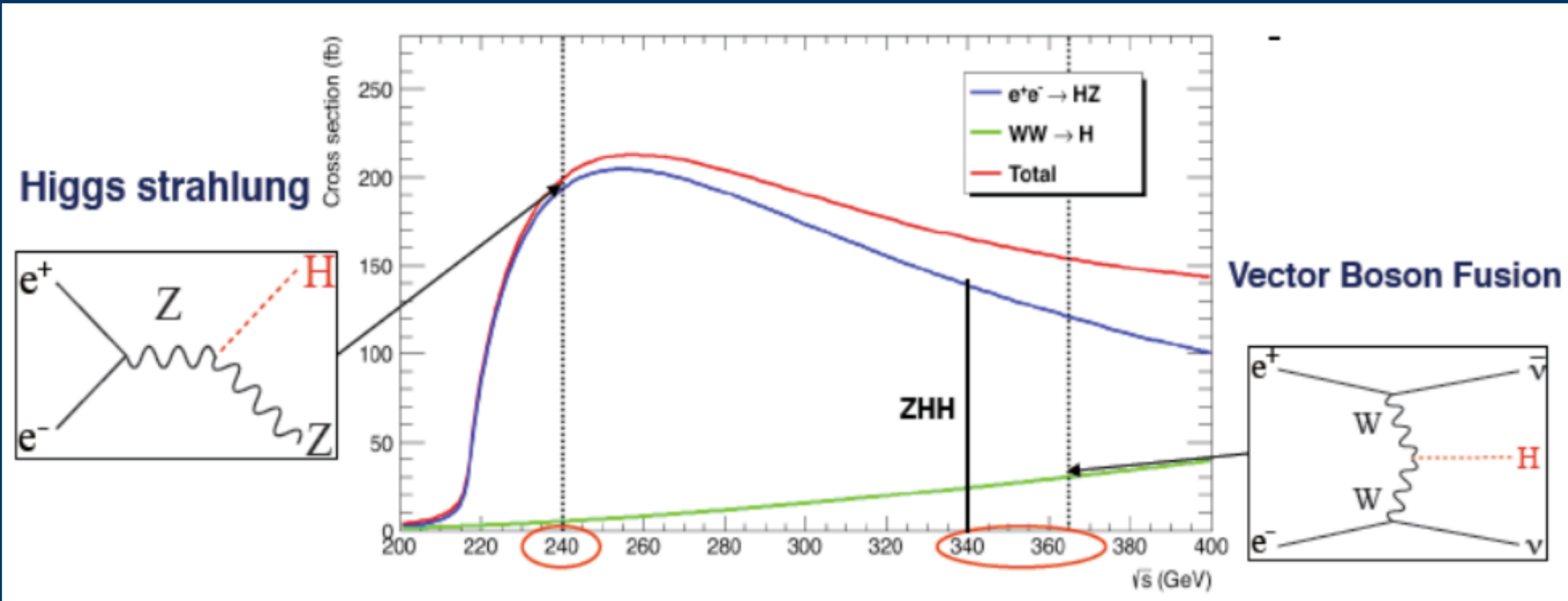
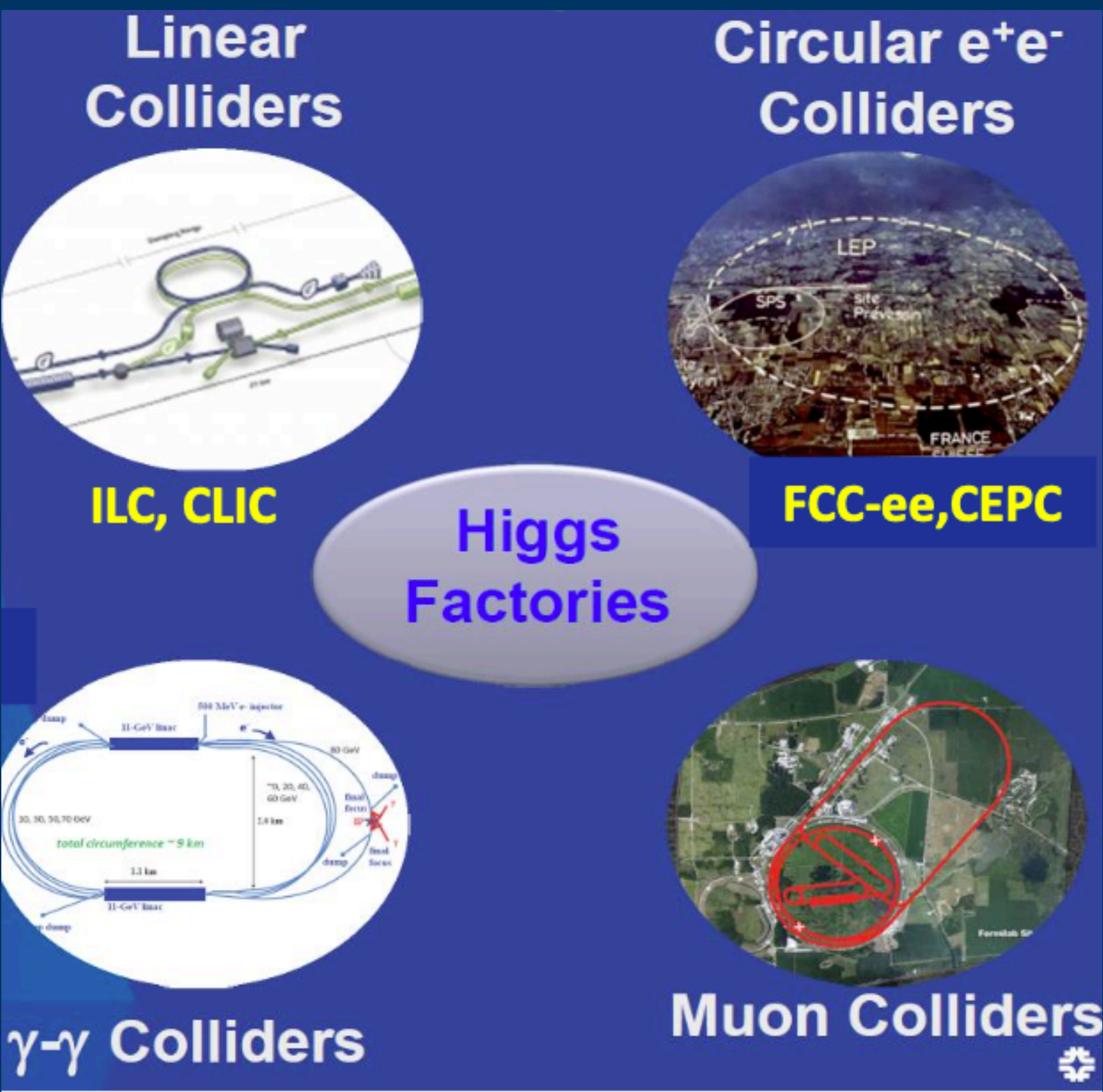
Final thoughts

- We need new toys!



Final thoughts

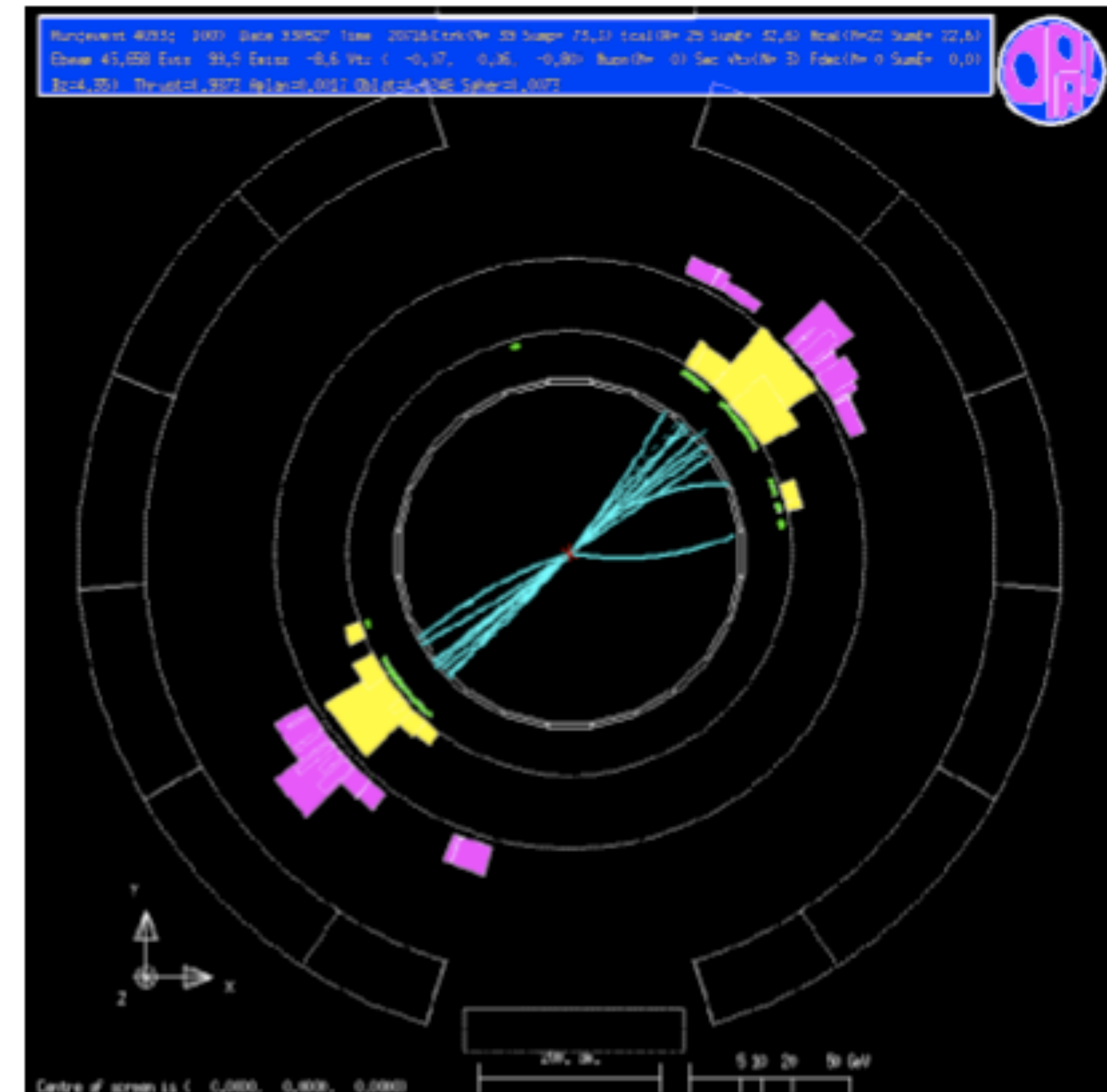
- We need new toys!



IV. Jets

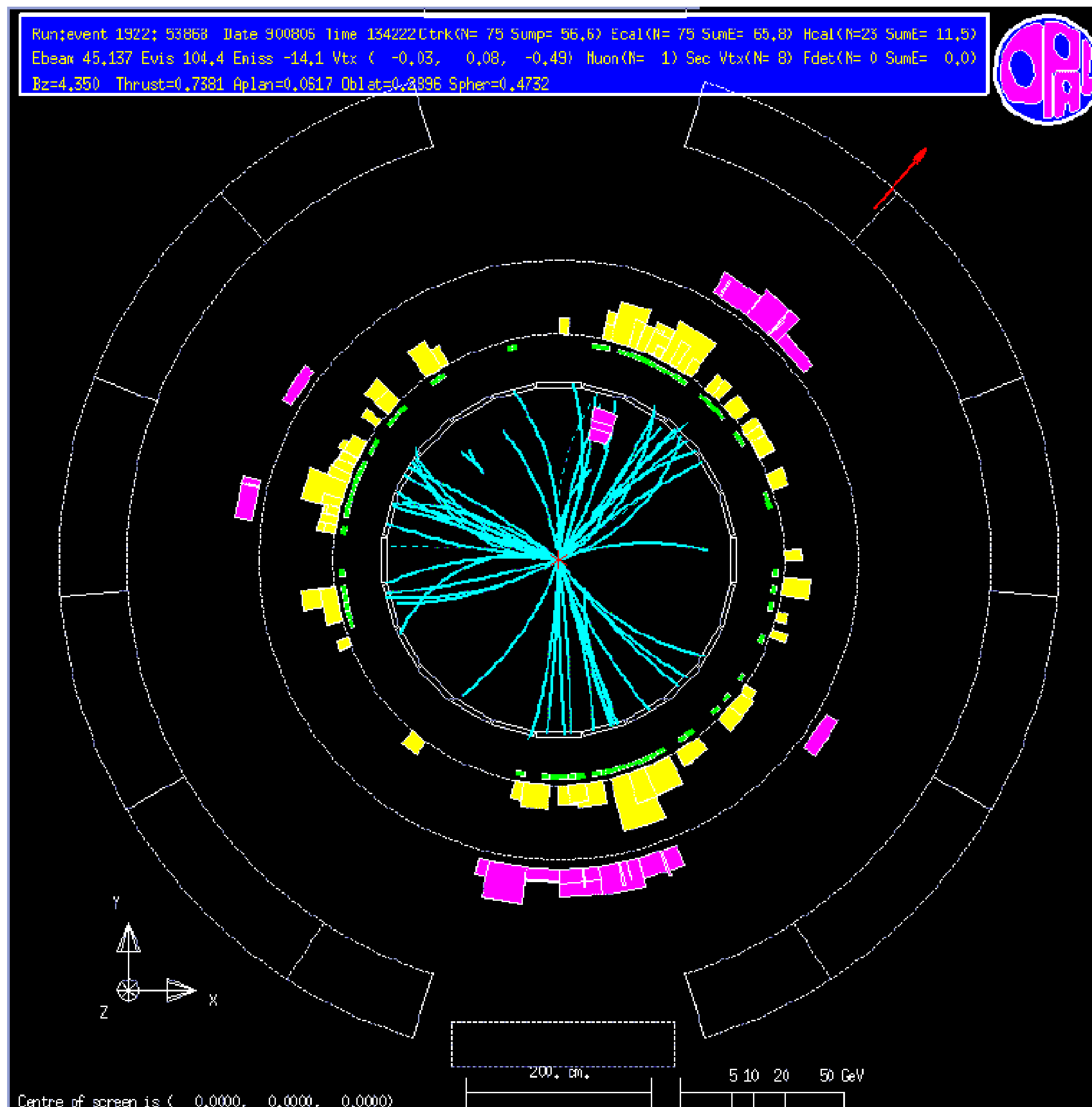
⇒ Can we obtain more information on the hadron production besides the total cross section?

⇒ We expect that soft process don't change completely the high energy features $\implies$ a spray of hadrons follows the direction of the original quarks and gluons.

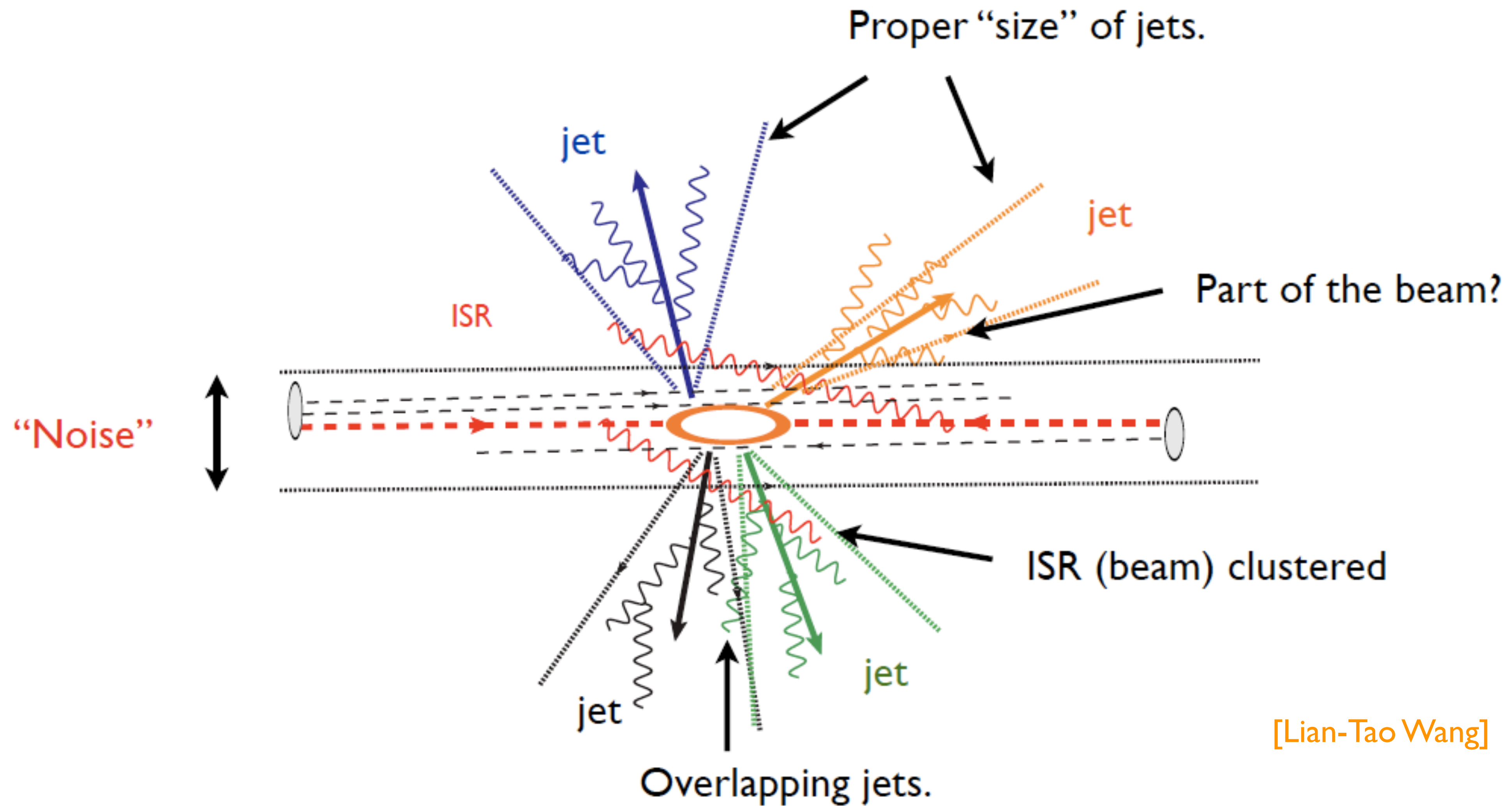


Three jet event:

- why not 4?
- Which particles belong to a jet?
- how to get $p_{parton} \simeq p_{jet}$?



Not an easy task:



[Lian-Tao Wang]

Criteria for a good jet recipe: [Snowmass]

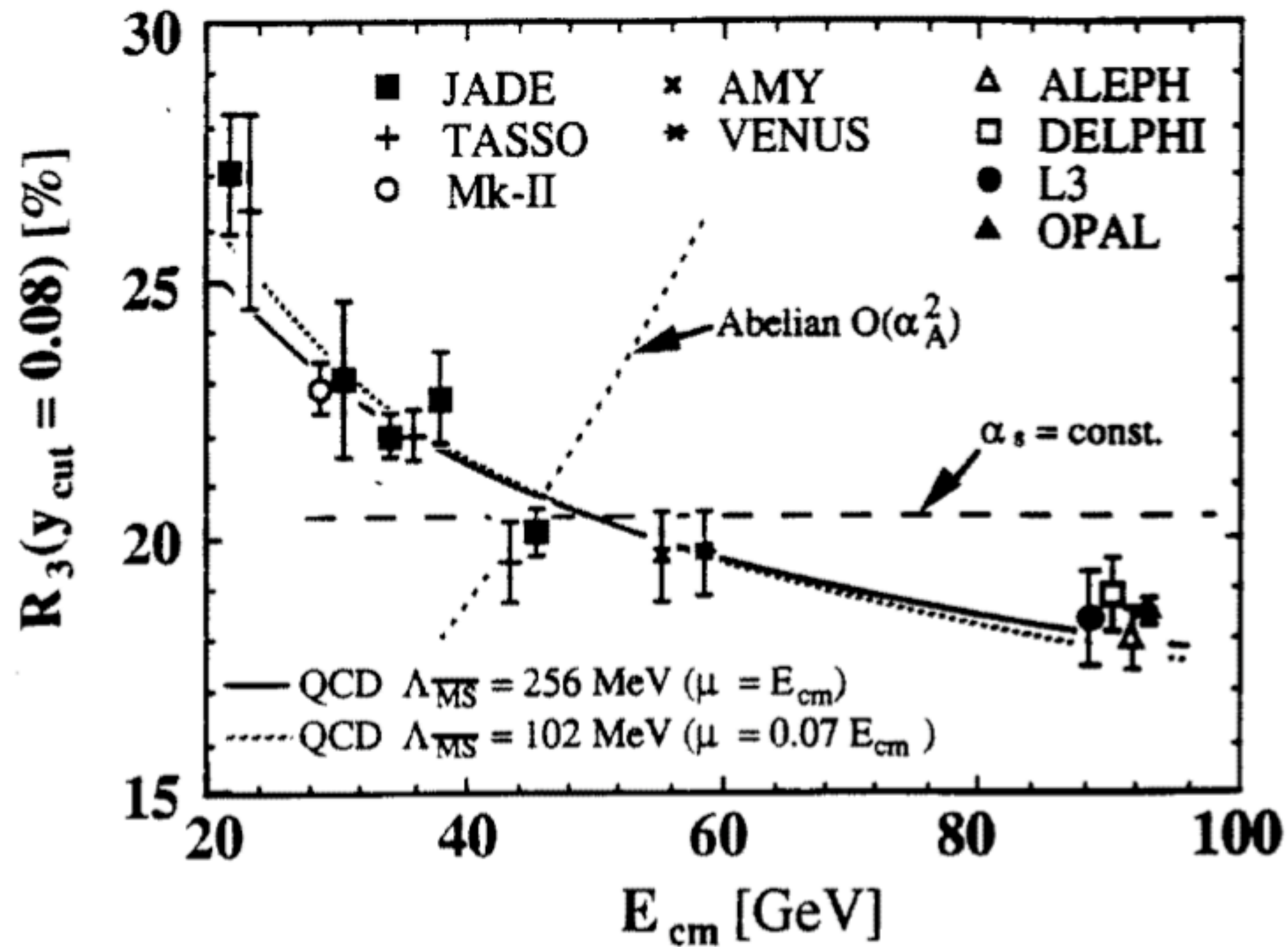
1. Simple to implement in an experimental analysis
2. Simple to implement in a theoretical calculation
3. Defined at any order of perturbation theory
4. Yields finite cross sections at any order of PT
5. Yields a cross section rather insensitive to hadronization

controls the number of jets

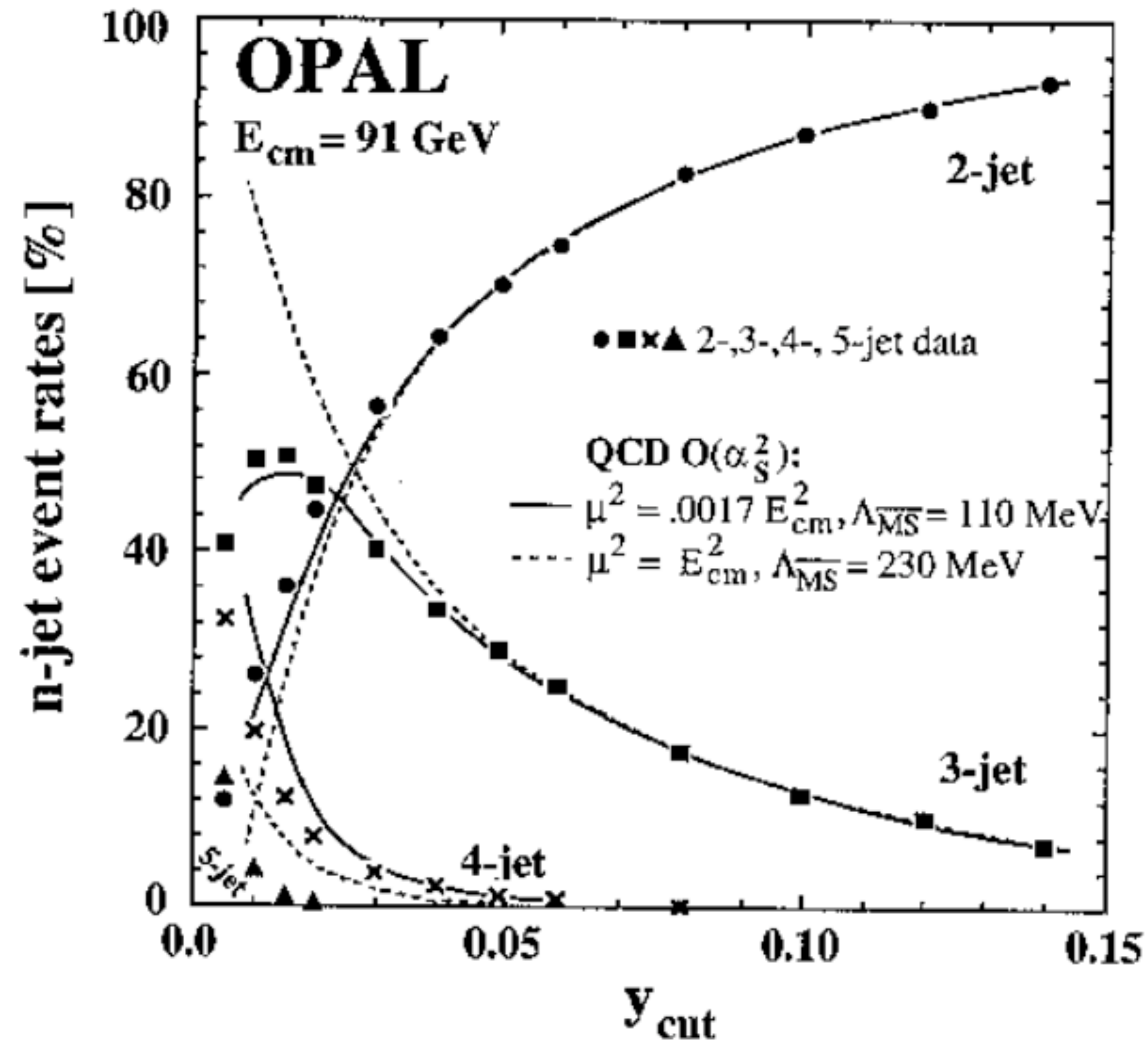
⇒ The JADE jet algorithm is the following: Consider n particles/partons and a cut y

- ✿ Identify the pair with minimal invariant mass $\bar{m}$. If $\bar{m}^2 < ys$ join the two particle into a single cluster.
- ✿ Apply the previous procedure to the $n - 1$ particles and clusters until we can not form new clusters.
- ✿ The number of particles/clusters at the end of the process is the number of jets.

⇒ This expression describes well the energy dependence of R_3



⇒ This expression also describes well the y dependence



A few jet algorithms

- Three popular jet algorithms are kT, anti-kT, and Cambridge/Aachen
- The distance and rule to join objects is

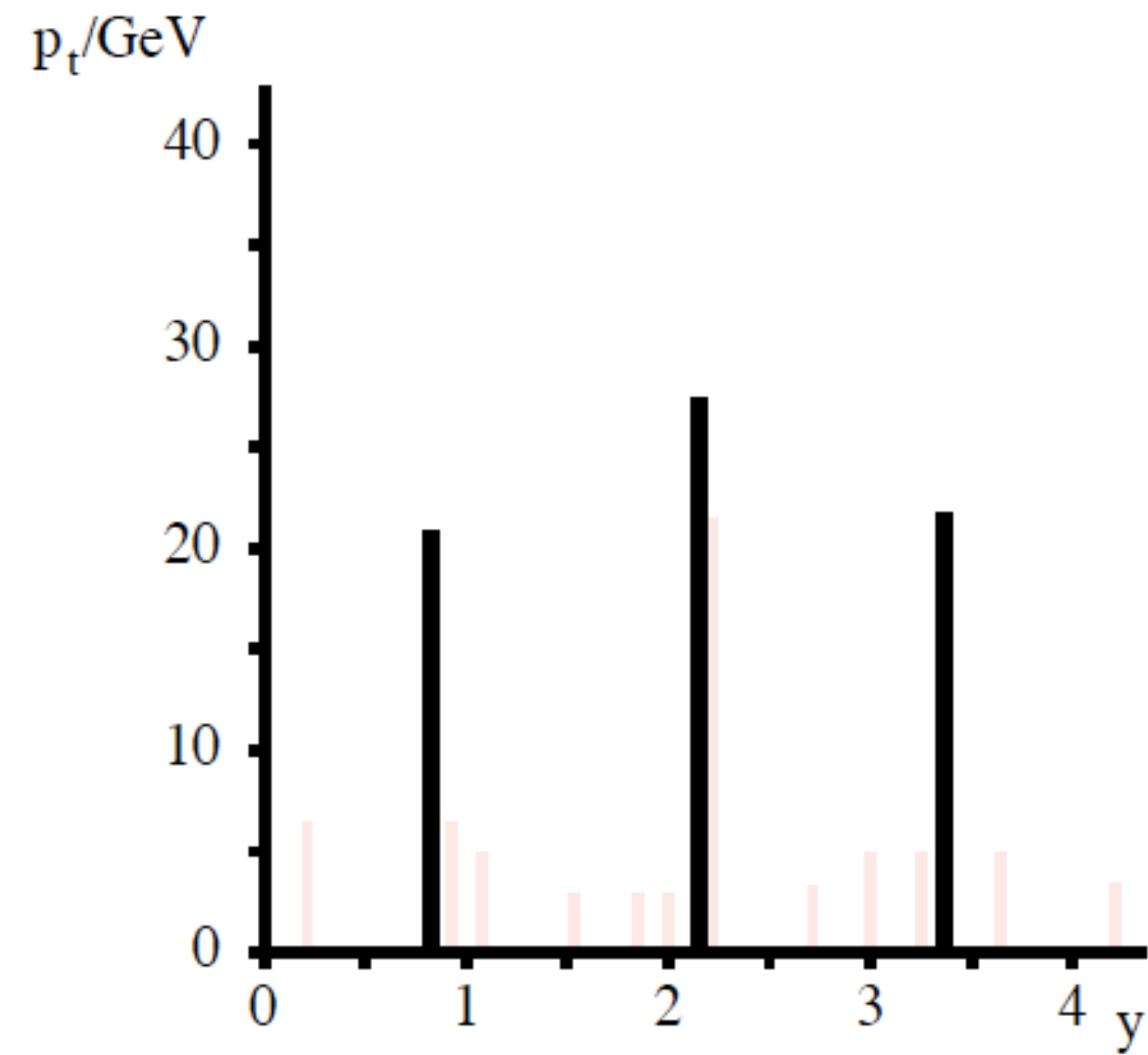
$$d_{ij} = \min[p_{Ti}^{2\alpha}, p_{Tj}^{2\alpha}] \left(\frac{\Delta R_{ij}}{R} \right)^2 \quad \text{and} \quad d_{iB} = p_{Ti}^{2\alpha}$$

with $\Delta R_{ij} = \sqrt{\Delta \eta_{ij}^2 + \Delta \varphi_{ij}^2}$

repeatedly combine objects until d_{iB} is the smaller distance.
Then call it a jet, remove from the list and start again

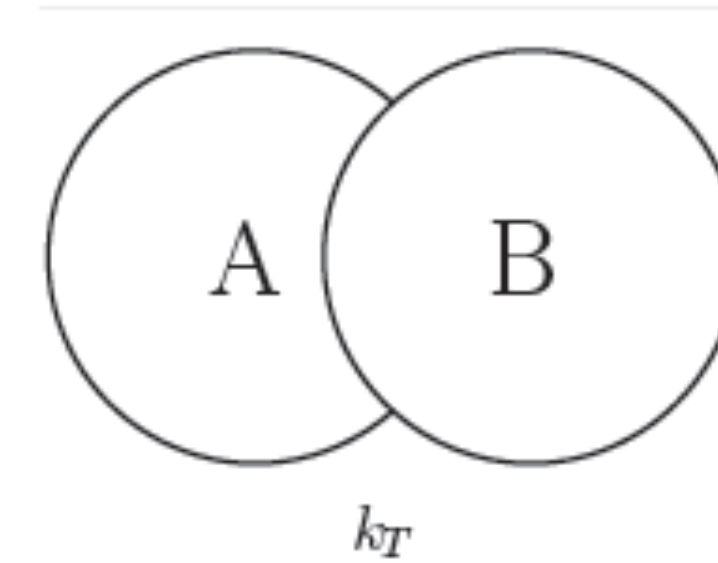
- The choices are: kT ($\alpha = 1$); anti-kT ($\alpha = -1$);
C/A ($\alpha = 0$)

- Example with C/A algorithm [borrow from G. Salam]

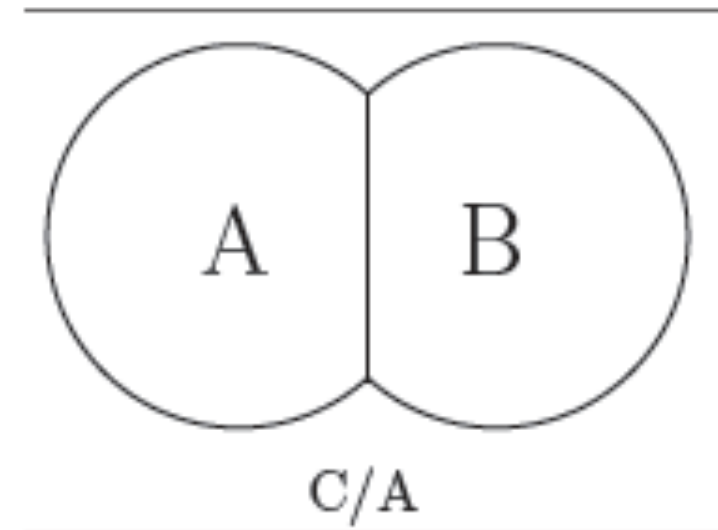


- The different algorithms lead to distinct jets shapes when they overlap

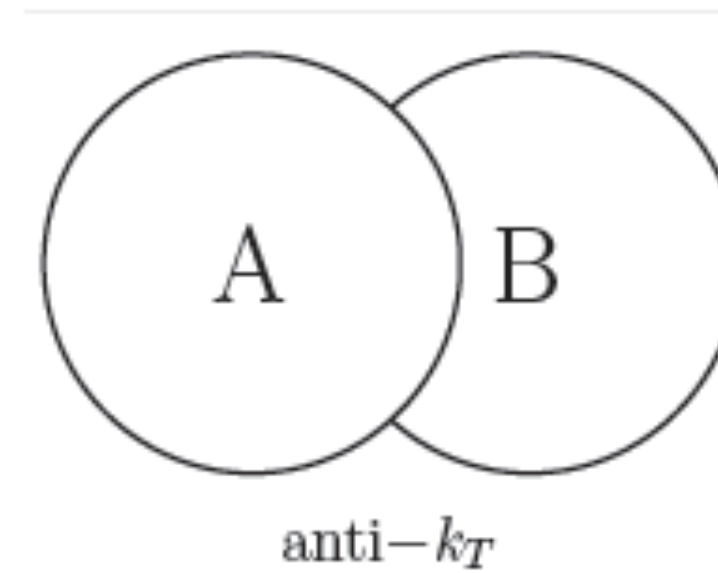
k_T (I) starts around softer objects



C/A (0) cares only about distances



anti- k_T (-I) clusters around hard objects



$$d_{ij} = \min[p_{Ti}^{2\alpha}, p_{Tj}^{2\alpha}] \left(\frac{\Delta R_{ij}}{R} \right)^2 \quad \text{and} \quad d_{iB} = p_{Ti}^{2\alpha}$$

$$p_T^A > p_T^B$$

