THE PRECISION FRONTIER LANDSCAPE

Germán Rodrigo

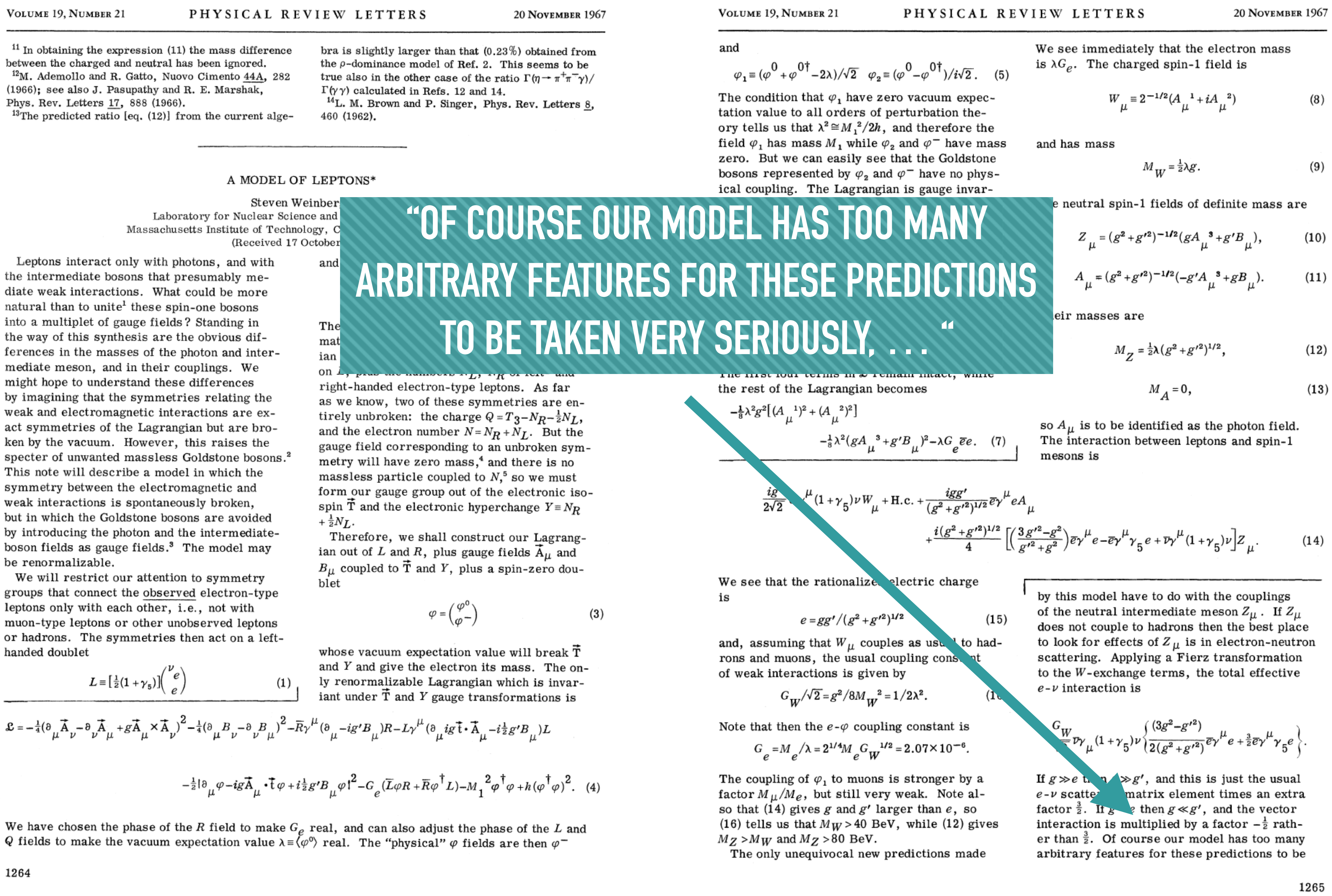
IFIC INSTITUT DE FÍSICA CORPUSCULAR
EXCELENCIA SEVERO OCHOA
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
VNIVERSITAT DE VALÈNCIA

24th International Symposium on
PArticles, **S**trings & **COS**mology

June 4-8, 2018, Cleveland, USA

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
particleface

WHY IS THE SM SO SUCCESSFUL 50 YEARS LATER?



[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

[12] M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).

[13] The predicted ratio [eq. (12)] from the current algebra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta\to\pi^+\pi^-\gamma)/\Gamma(\gamma\gamma)$ calculated in Refs. 12 and 14.

[14] L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

A MODEL OF LEPTONS*

Steven Weinber
Laboratory for Nuclear Science and
Massachusetts Institute of Technology, C
(Received 17 October

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

We will restrict our attention to symmetry groups that connect the observed electron-type leptons only with each other, i.e., not with muon-type leptons or other unobserved leptons or hadrons. The symmetries then act on a left-handed doublet

$$L\equiv[\tfrac{1}{2}(1+\gamma_5)]\binom{\nu_e}{e} \qquad (1)$$

and

The
mat
ian
on

right-handed electron-type leptons. As far as we know, two of these symmetries are entirely unbroken: the charge $Q=T_3-N_R-\frac{1}{2}N_L$, and the electron number $N=N_R+N_L$. But the gauge field corresponding to an unbroken symmetry will have zero mass,[4] and there is no massless particle coupled to N,[5] so we must form our gauge group out of the electronic isospin $\vec{T}$ and the electronic hyperchange $Y\equiv N_R+\frac{1}{2}N_L$.

Therefore, we shall construct our Lagrangian out of L and R, plus gauge fields $\vec{A}_\mu$ and B_μ coupled to $\vec{T}$ and Y, plus a spin-zero doublet

$$\varphi=\binom{\varphi^0}{\varphi^-} \qquad (3)$$

whose vacuum expectation value will break $\vec{T}$ and Y and give the electron its mass. The only renormalizable Lagrangian which is invariant under $\vec{T}$ and Y gauge transformations is

$$\mathfrak{L}=-\tfrac{1}{4}(\partial_\mu\vec{A}_\nu-\partial_\nu\vec{A}_\mu+g\vec{A}_\mu\times\vec{A}_\nu)^2-\tfrac{1}{4}(\partial_\mu B_\nu-\partial_\nu B_\mu)^2-\bar{R}\gamma^\mu(\partial_\mu-ig'B_\mu)R-L\gamma^\mu(\partial_\mu ig\vec{t}\cdot\vec{A}_\mu-i\tfrac{1}{2}g'B_\mu)L$$

$$-\tfrac{1}{2}|\partial_\mu\varphi-ig\vec{A}_\mu\cdot\vec{t}\varphi+i\tfrac{1}{2}g'B_\mu\varphi|^2-G_e(\bar{L}\varphi R+\bar{R}\varphi^\dagger L)-M_1{}^2\varphi^\dagger\varphi+h(\varphi^\dagger\varphi)^2. \qquad (4)$$

We have chosen the phase of the R field to make G_e real, and can also adjust the phase of the L and Q fields to make the vacuum expectation value $\lambda\equiv\langle\varphi^0\rangle$ real. The "physical" φ fields are then φ^-

---

and

$$\varphi_1\equiv(\varphi^0+\varphi^{0\dagger}-2\lambda)/\sqrt{2}\quad\varphi_2\equiv(\varphi^0-\varphi^{0\dagger})/i\sqrt{2}. \qquad (5)$$

The condition that φ_1 have zero vacuum expectation value to all orders of perturbation theory tells us that $\lambda^2\cong M_1{}^2/2h$, and therefore the field φ_1 has mass M_1 while φ_2 and φ^- have mass zero. But we can easily see that the Goldstone bosons represented by φ_2 and φ^- have no physical coupling. The Lagrangian is gauge invar-

the rest of the Lagrangian becomes

$$-\tfrac{1}{8}\lambda^2g^2[(A_\mu{}^1)^2+(A_\mu{}^2)^2]$$
$$-\tfrac{1}{8}\lambda^2(gA_\mu{}^3+g'B_\mu)^2-\lambda G_e\bar{e}e. \qquad (7)$$

We see immediately that the electron mass is λG_e. The charged spin-1 field is

$$W_\mu\equiv2^{-1/2}(A_\mu{}^1+iA_\mu{}^2) \qquad (8)$$

and has mass

$$M_W=\tfrac{1}{2}\lambda g. \qquad (9)$$

e neutral spin-1 fields of definite mass are

$$Z_\mu=(g^2+g'^2)^{-1/2}(gA_\mu{}^3+g'B_\mu), \qquad (10)$$

$$A_\mu=(g^2+g'^2)^{-1/2}(-g'A_\mu{}^3+gB_\mu). \qquad (11)$$

eir masses are

$$M_Z=\tfrac{1}{2}\lambda(g^2+g'^2)^{1/2}, \qquad (12)$$

$$M_A=0, \qquad (13)$$

so A_μ is to be identified as the photon field. The interaction between leptons and spin-1 mesons is

$$\frac{ig}{2\sqrt{2}}\quad{}^\mu(1+\gamma_5)\nu W_\mu+\text{H.c.}+\frac{igg'}{(g^2+g'^2)^{1/2}}\bar{e}\gamma^\mu eA_\mu$$
$$+\frac{i(g^2+g'^2)^{1/2}}{4}\Big[\Big(\frac{3g'^2-g^2}{g'^2+g^2}\Big)\bar{e}\gamma^\mu e-\bar{e}\gamma^\mu\gamma_5e+\bar{\nu}\gamma^\mu(1+\gamma_5)\nu\Big]Z_\mu. \qquad (14)$$

We see that the rationalize electric charge is

$$e=gg'/(g^2+g'^2)^{1/2} \qquad (15)$$

and, assuming that W_μ couples as usu to hadrons and muons, the usual coupling cons nt of weak interactions is given by

$$G_W/\sqrt{2}=g^2/8M_W{}^2=1/2\lambda^2. \qquad (1$$

Note that then the e-φ coupling constant is

$$G_e=M_e/\lambda=2^{1/4}M_eG_W{}^{1/2}=2.07\times10^{-6}.$$

The coupling of φ_1 to muons is stronger by a factor M_μ/M_e, but still very weak. Note also that (14) gives g and g' larger than e, so (16) tells us that $M_W>40$ BeV, while (12) gives $M_Z>M_W$ and $M_Z>80$ BeV.

The only unequivocal new predictions made by this model have to do with the couplings of the neutral intermediate meson Z_μ. If Z_μ does not couple to hadrons then the best place to look for effects of Z_μ is in electron-neutron scattering. Applying a Fierz transformation to the W-exchange terms, the total effective e-ν interaction is

$$G_W\;\bar{\nu}\gamma_\mu(1+\gamma_5)\nu\Big\{\frac{(3g^2-g'^2)}{2(g^2+g'^2)}\bar{e}\gamma^\mu e+\tfrac{3}{2}\bar{e}\gamma^\mu\gamma_5e\Big\}.$$

If $g\gg e$ t n $\gg g'$, and this is just the usual e-ν scatte matrix element times an extra factor $\frac{3}{2}$. If then $g\ll g'$, and the vector interaction is multiplied by a factor $-\frac{1}{2}$ rather than $\frac{3}{2}$. Of course our model has too many arbitrary features for these predictions to be

> "OF COURSE OUR MODEL HAS TOO MANY ARBITRARY FEATURES FOR THESE PREDICTIONS TO BE TAKEN VERY SERIOUSLY, . . . "

WHY IS THE SM SO SUCCESSFUL 50 YEARS LATER?

- Based in the simplest gauge symmetries: SU(3)xSU(2)xU(1)
- Also the **flavour sector very symmetric (GIM)**
- The “natural” theory at “low” energies (below the TeVs)
- We should expect that it will break at high energies: **departure scale undetermined**
- The solution is not necessarily more symmetry (**SUSY***), rather **less symmetry** at high energies?

* J. Bernabeu: “Excess of symmetry leads to more parameters, if all the terms are symmetric by themselves.”

WHERE TO EXPECT A BSM SIGNAL?

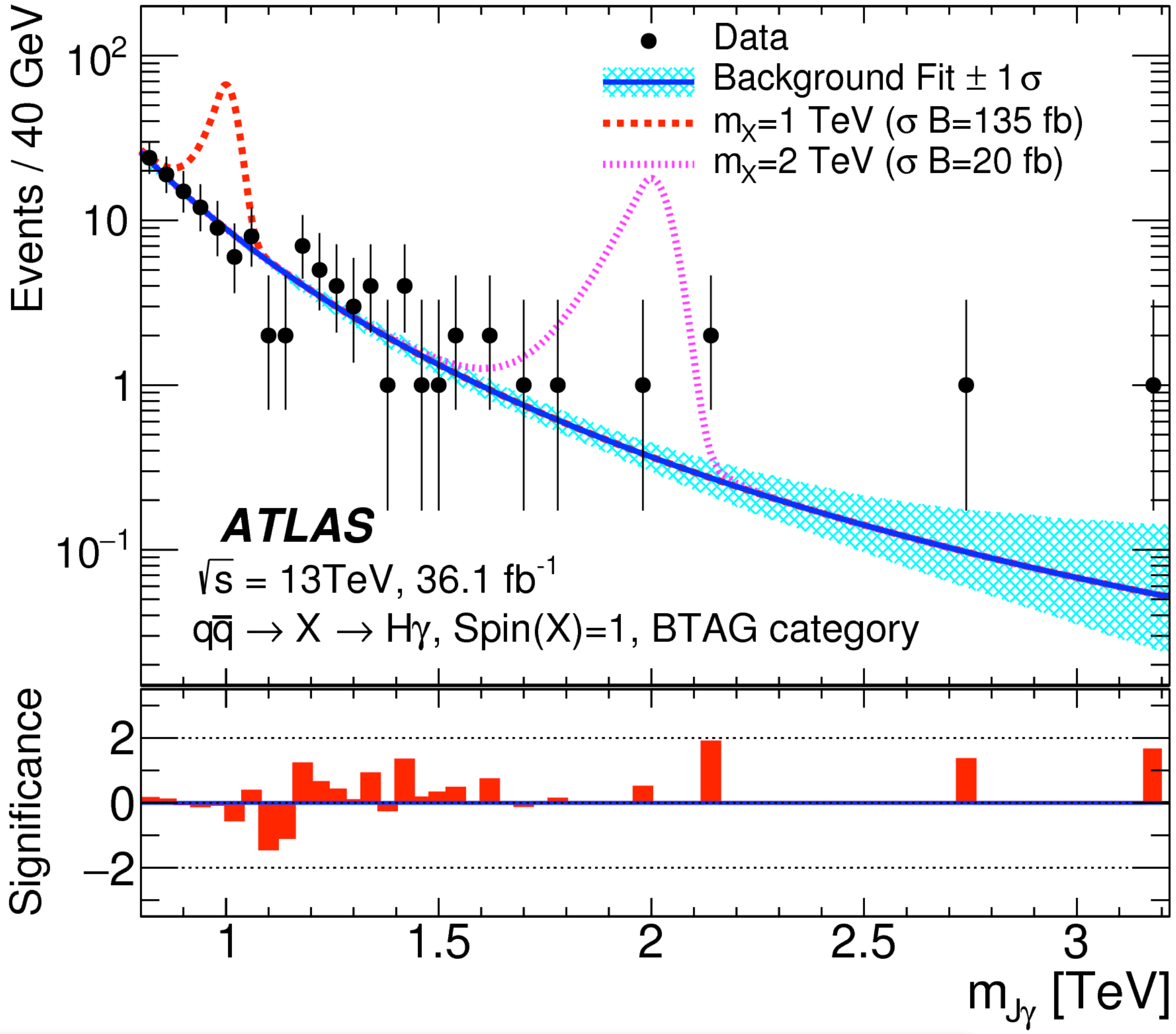
- LHC results suggest that **new physics** will appear as a gentle deviation from the SM predictions / rare events suppressed in the SM

- The quest for precision is at the forefront for new discoveries

- Very unlikely to be visible in inclusive observables or total decay rates of known particles: the bulk of the contributions at “low energies”, the characteristic hard scale is “low energy”

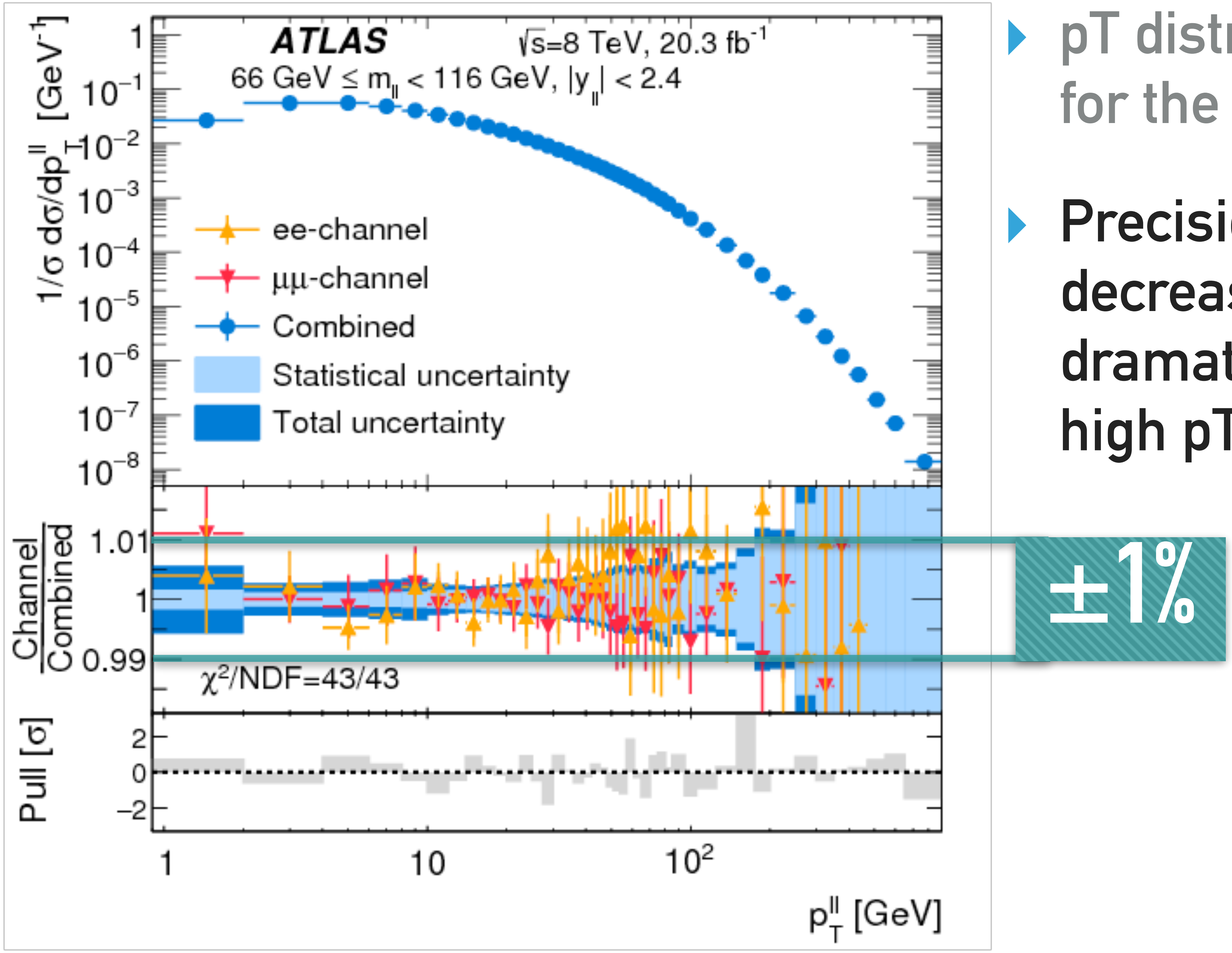
WHERE TO EXPECT A BSM SIGNAL?

- Higher chances at the **tail of differential distributions (not necessarily a clear bump)**
  - high pT
  - high invariant mass
  - boosted objects
- “**high energy**” characteristic hard scale



- lower statistics
- more sensitive to theory / higher theoretical uncertainties due to missing higher orders
- fake BSM by missing higher order corrections

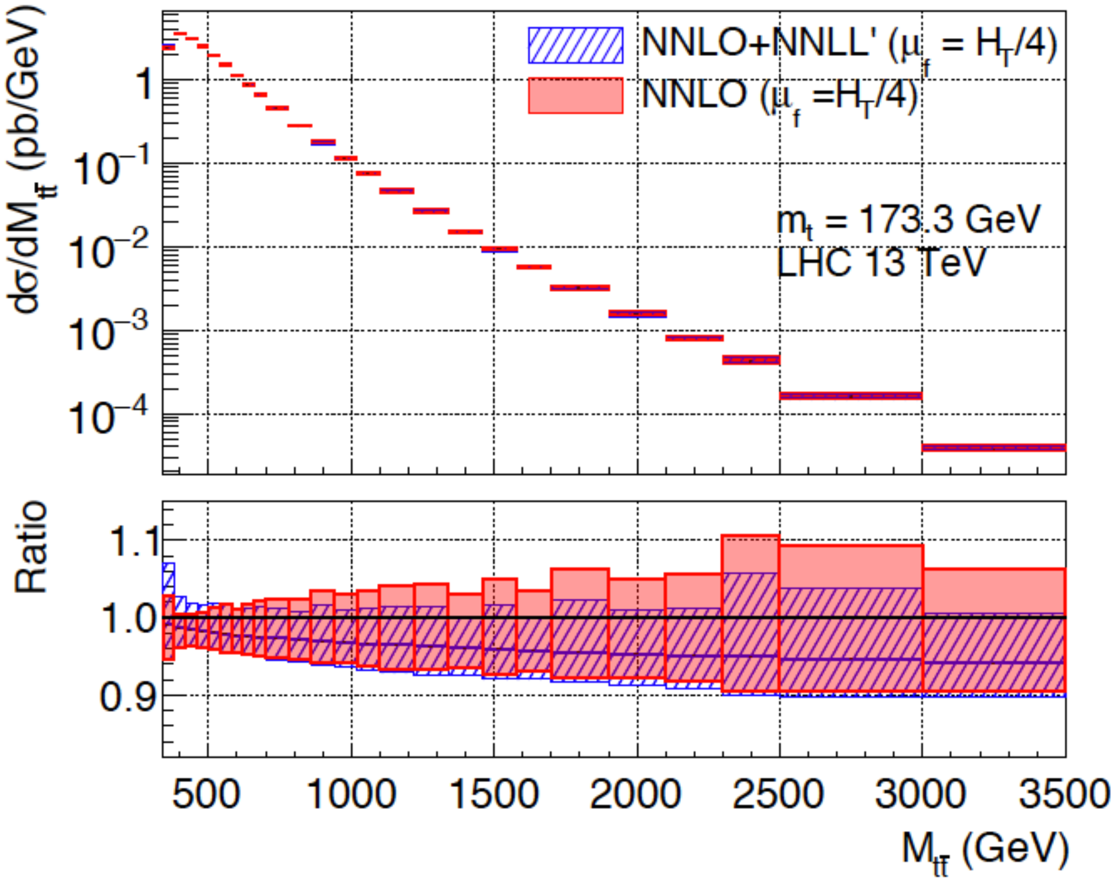
ONE OF THE MOST PRECISE MEASUREMENTS

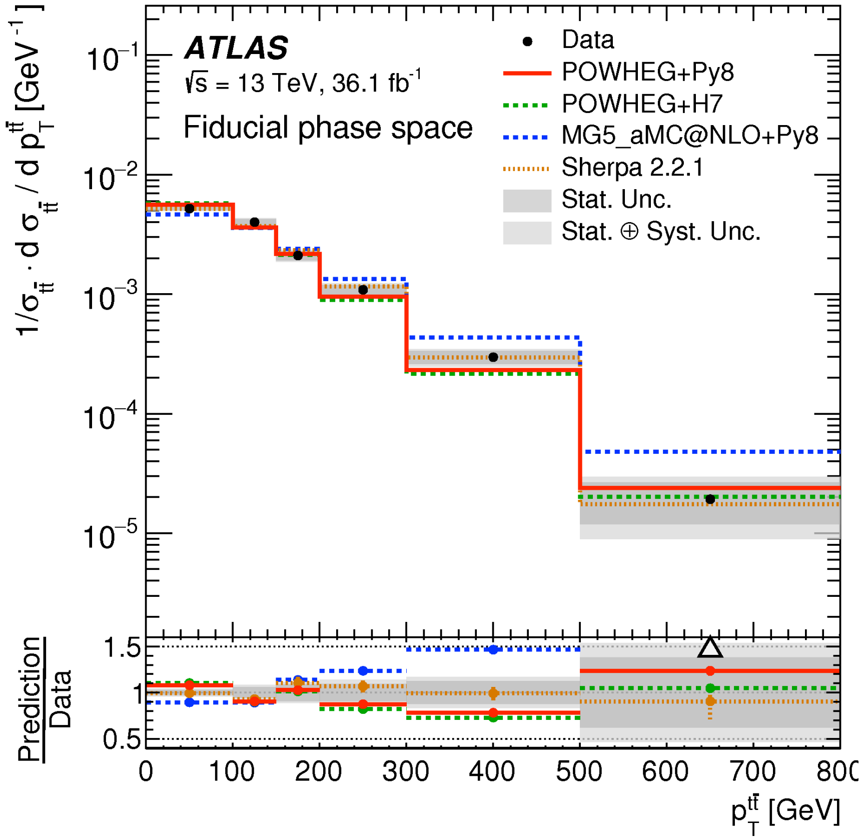


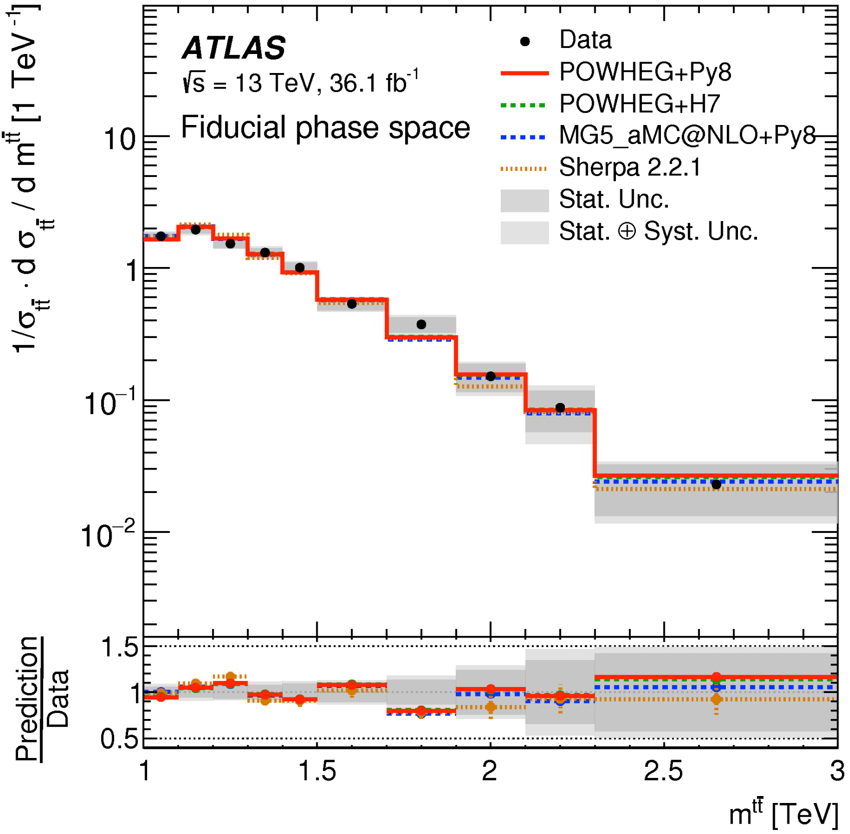
- pT distribution for the Z boson
- **Precision decreases dramatically at high pT**

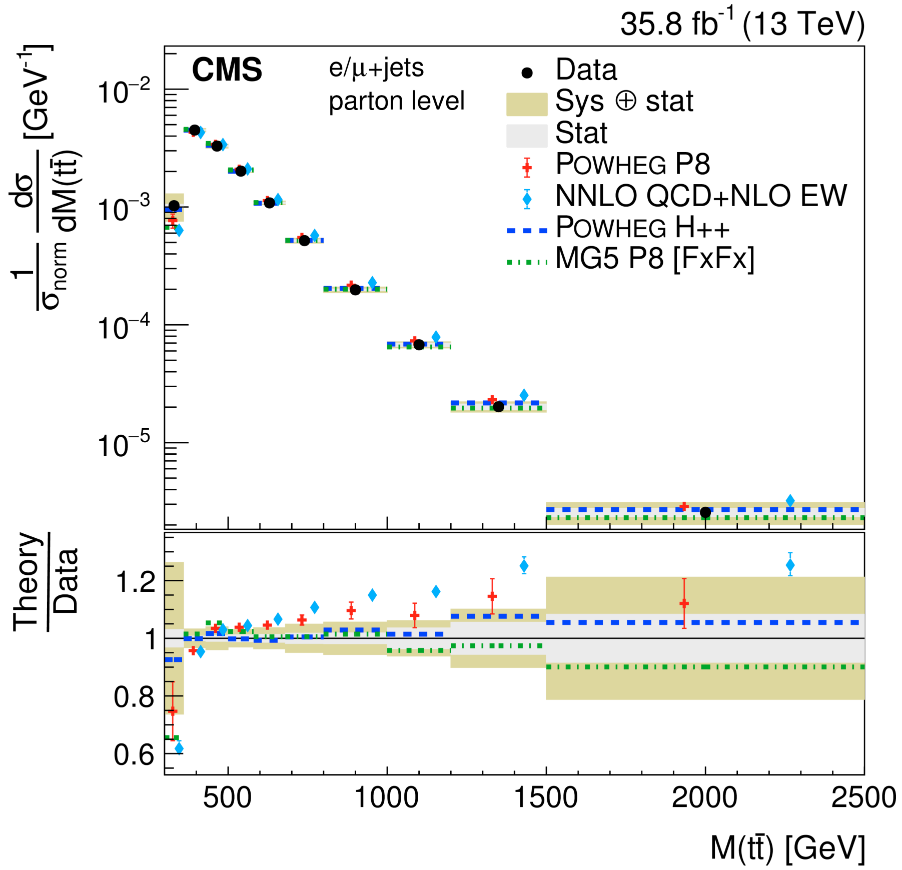
10%, 20%, 50% IS THE MOST COMMON UNCERTAINTY FOR HADRONIC COLLISIONS

Czakon et al., arXiv:1803.07623



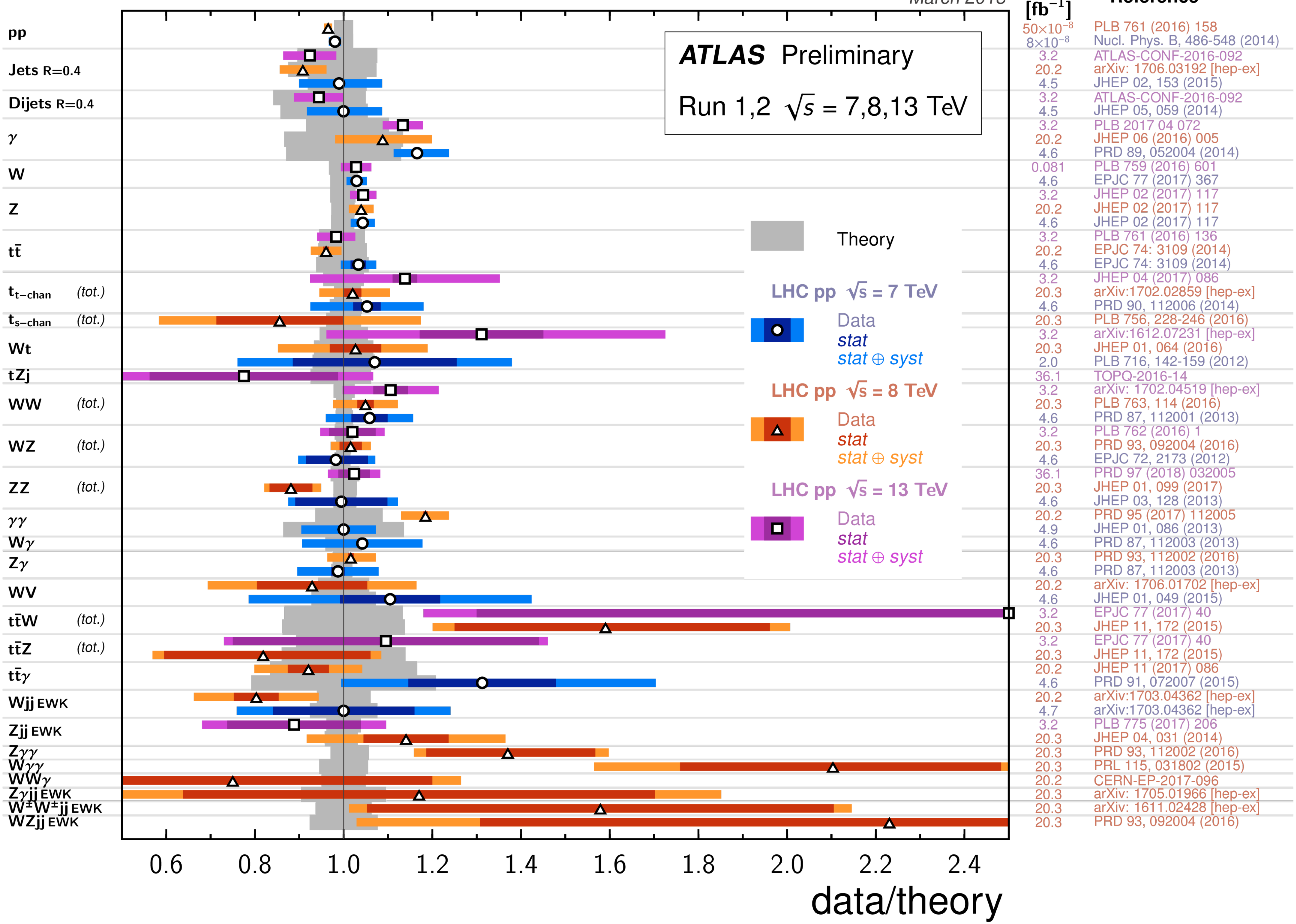






Standard Model Production Cross Section Measurements

Status: March 2018



PRECISION IS ABOUT MULTI-LOOP FEYNMAN DIAGRAMS

- Complexity grows with the number of scales (loops, legs, masses)
- That´s why most recent developments try to circumvent the use of (loop) Feynman diagrams: e.g. **Generalized Unitarity, recursion relations**

BUT NOT ONLY

- subtraction of IR singularities
- all orders resummation of large logs
- proton is not elementary (collinear factorization, PDF …)

EXCELENCIA
SEVERO
OCHOA

STUNNING PROGRESS IN THEORETICAL CALCULATIONS IN THE PAST YEARS

- NLO revolution (2010-2011) leading to automation in event generators
  - first serious order because protons are not elementary
  - thanks to a better understanding of the mathematical beauty of scattering amplitudes
- Many 2➔2 processes at NNLO (since 2015), current frontier is 2➔3

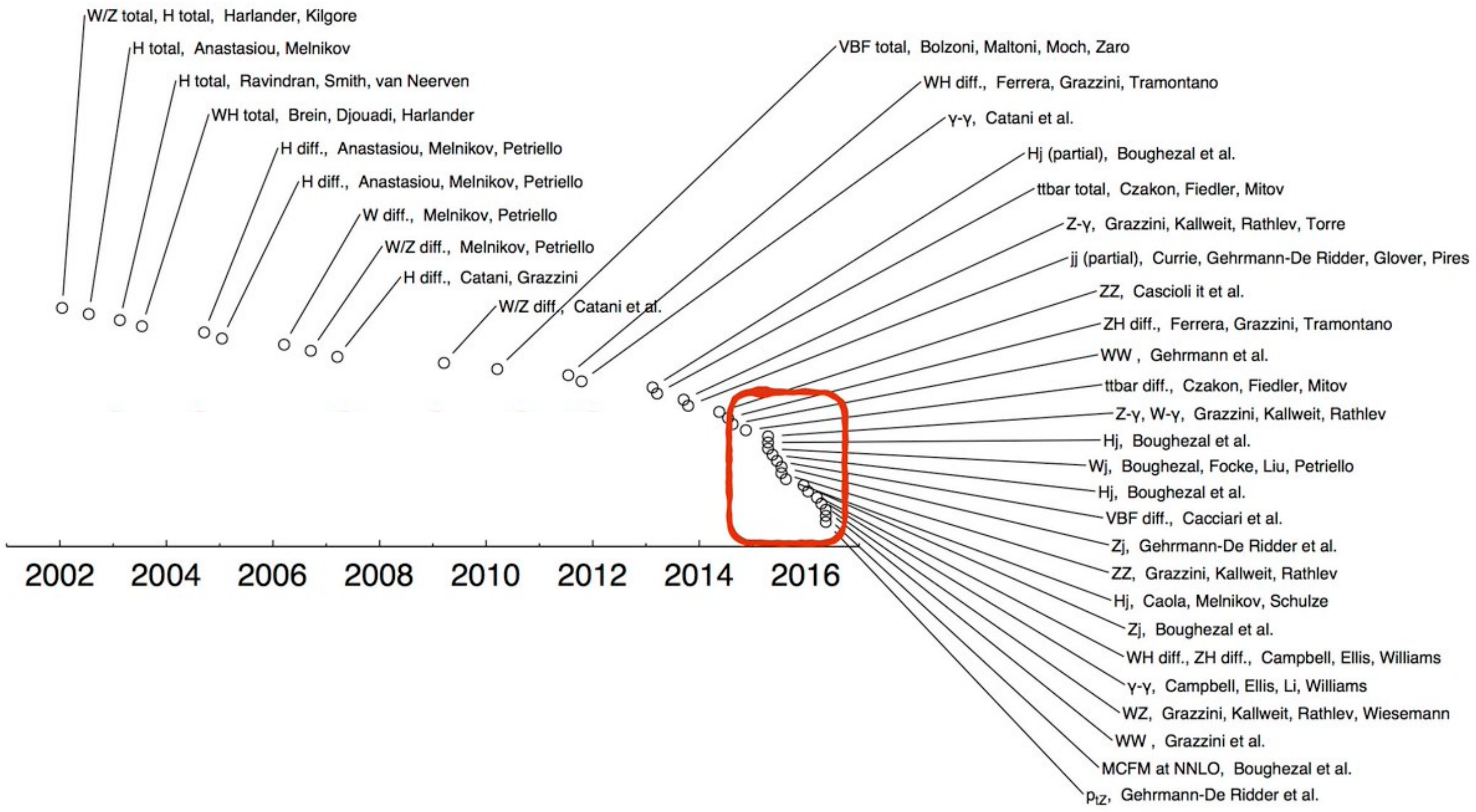
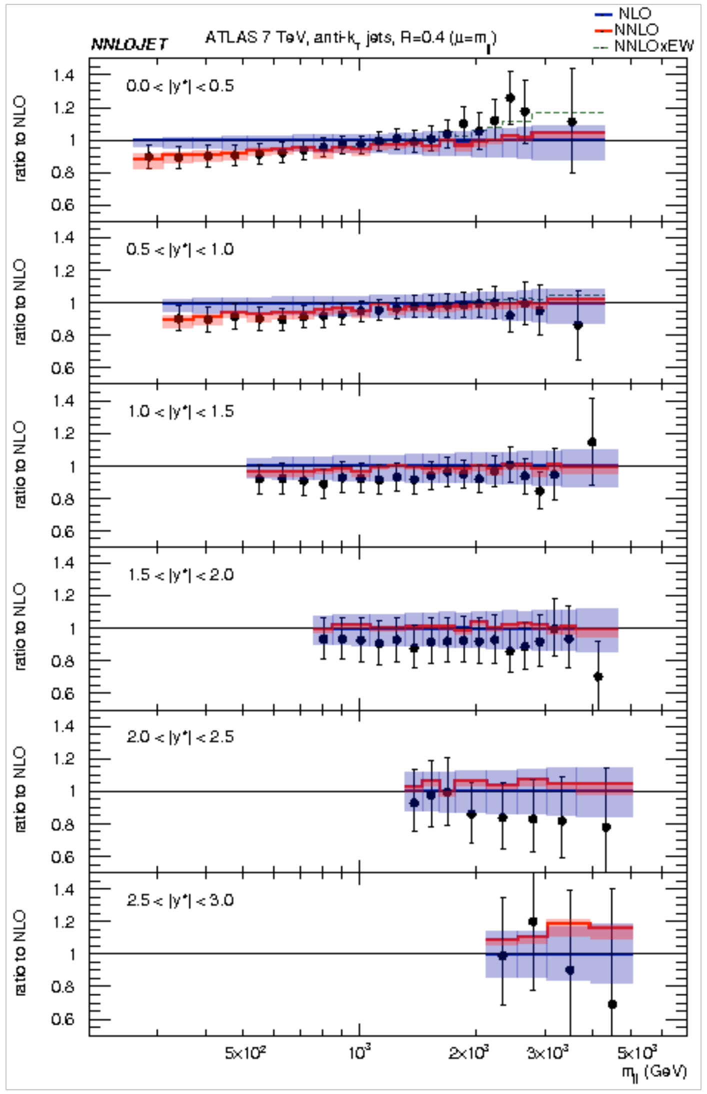


Figure by G.P. Salam

STUNNING PROGRESS IN THEORETICAL CALCULATIONS IN THE PAST YEARS

- NLO revolution (2010-2011) leading to automation in event generators
  - first serious order because protons are not elementary
  - thanks to a better understanding of the mathematical beauty of scattering amplitudes
- Many 2➔2 processes at NNLO (since 2015), current frontier is 2➔3

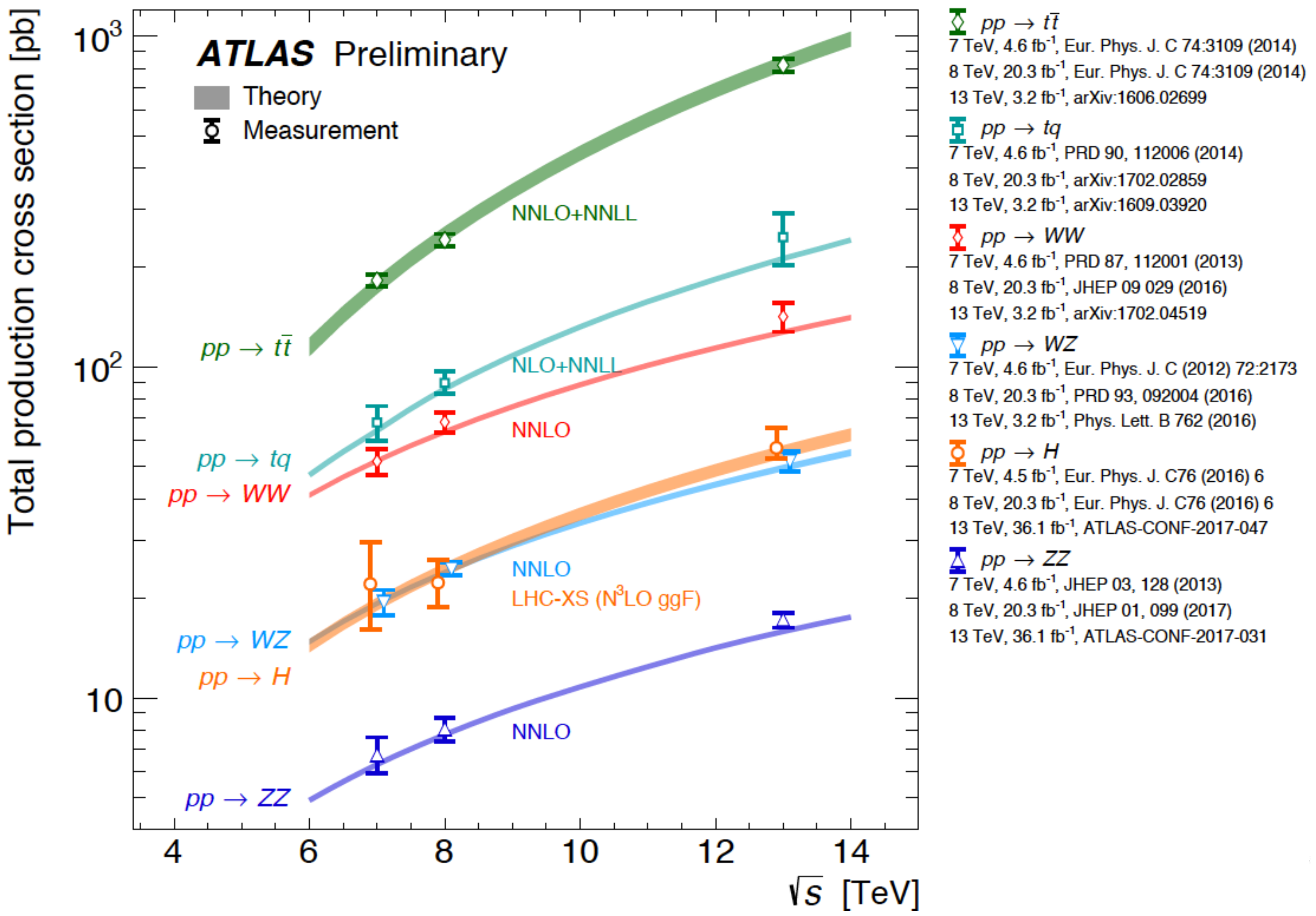
e.g. dijet production
data prefer NNLO



STUNNING PROGRESS IN THEORETICAL CALCULATIONS IN THE PAST YEARS

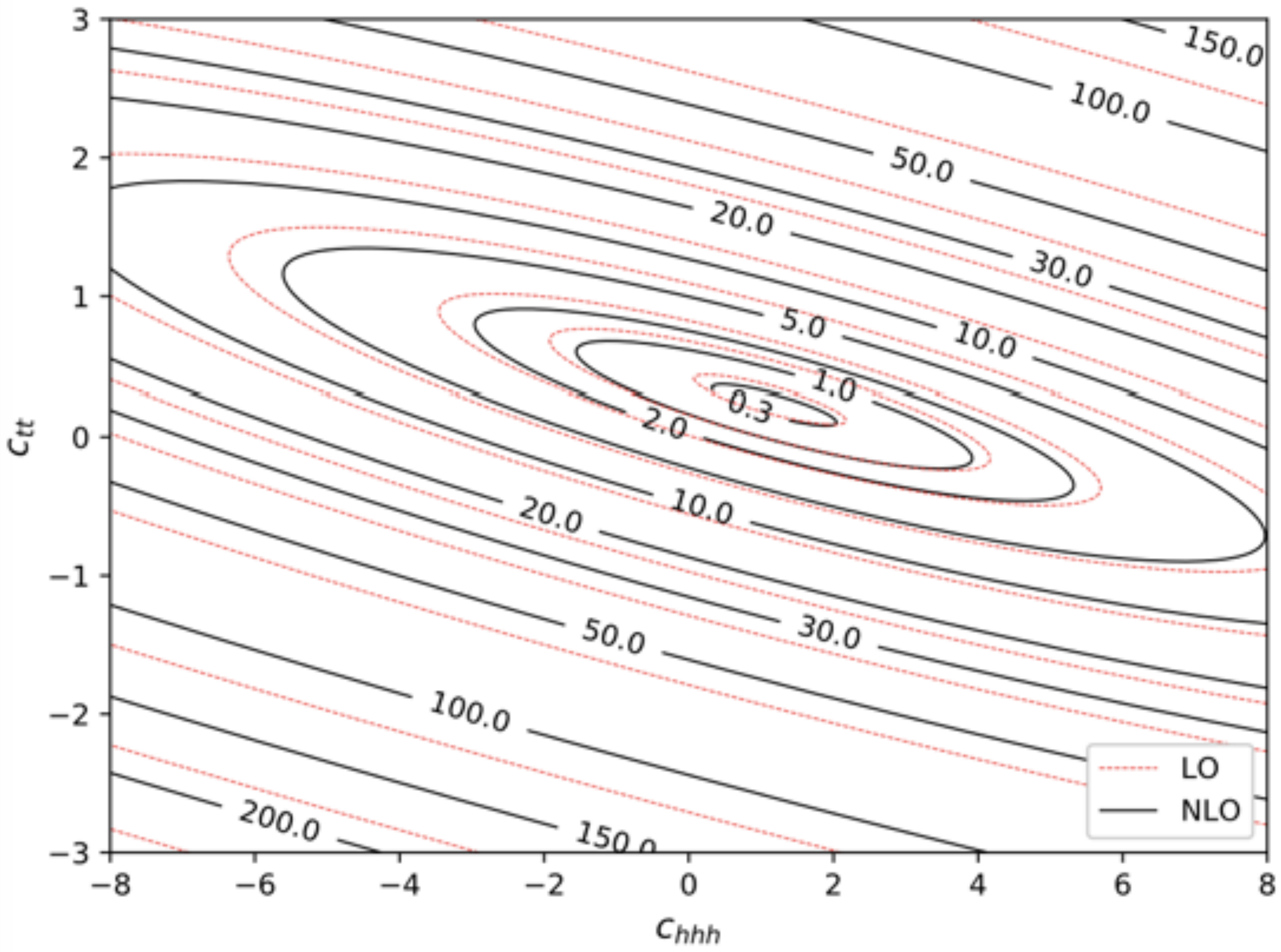
- NLO revolution (2010-2011) leading to automation in event generators
  - first serious order because protons are not elementary
  - thanks to a better understanding of the mathematical beauty of scattering amplitudes
- Many 2➔2 processes at NNLO (since 2015), current frontier is 2➔3
- N3LO ggH (2➔1): 5% th+3% (PDF-α_S) [Anastasiou et al. (Dulat´s talk)][see also talk by T. Neumann]

- NNLL resummations
- NLO + PS
- First attempts towards NNLO+PS
- EW cannot anymore be ignored
- Power corrections
- Finite width effects of unstable particles
- better PDF, strong coupling



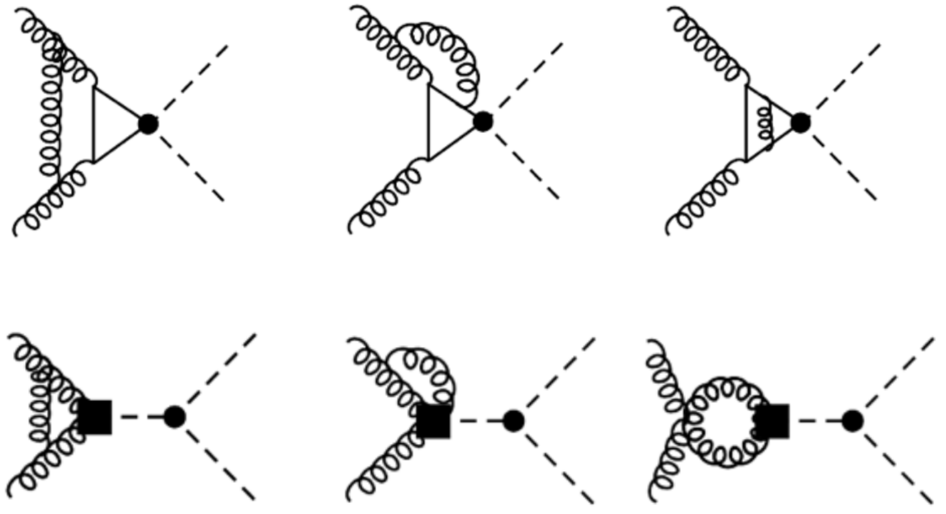
HIGHER ORDERS IN BSM SEARCHES

G. Heinrich, Loops and Legs in QFT, May 2018

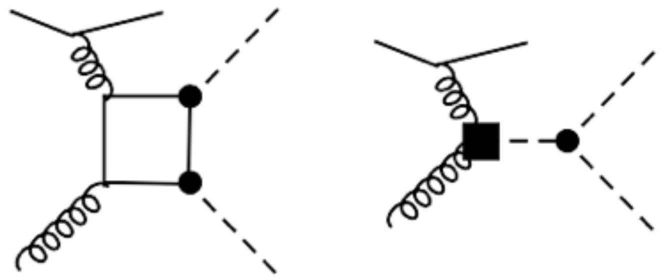


HH@NLO QCD within non-linear EFT framework

- because protons are not elementary QCD corrections may modify substantially BSM predictions
- typically granting less room for BSM



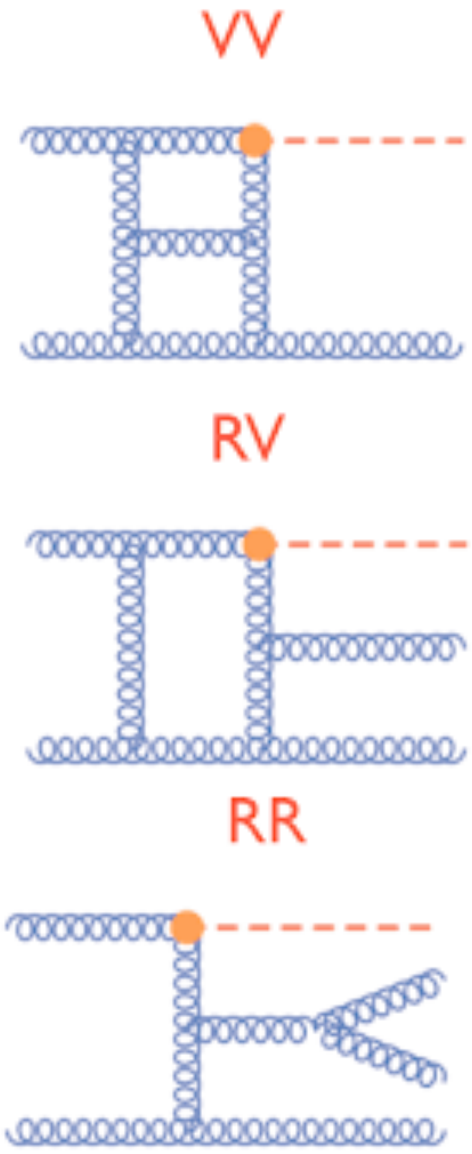
gg+qg



see also talk by I. Lewis

SUBTRACTION OF IR SINGULARITIES

- Subtraction of IR singularities at NLO is solved: efficient algorithms applicable to any process for which matrix elements are known
- At NNLO several working algorithms, successfully applied to "simple" processes with up to four legs. Heavy computational costs



- Antennae Subtraction [Gehrmann et al.]
- Stripper [Czacon et al.]
- Nested Soft-Collinear Subtraction [Caola et al.]
- Colourful Subtraction [Del Duca et al.]
- N-Jettiness [Boughezal, Petriello et al., Gaunt et al.]
- qT Substraction [Catani, Grazzini et al.]
- Projection to Born [Bonciani et al.]
- Geometric Substraction [Herzog]
- Unsubtration [Driencourt-Mangin, Hernández-Pinto, Sborlini, GR]

QFT NOT OPTIMAL

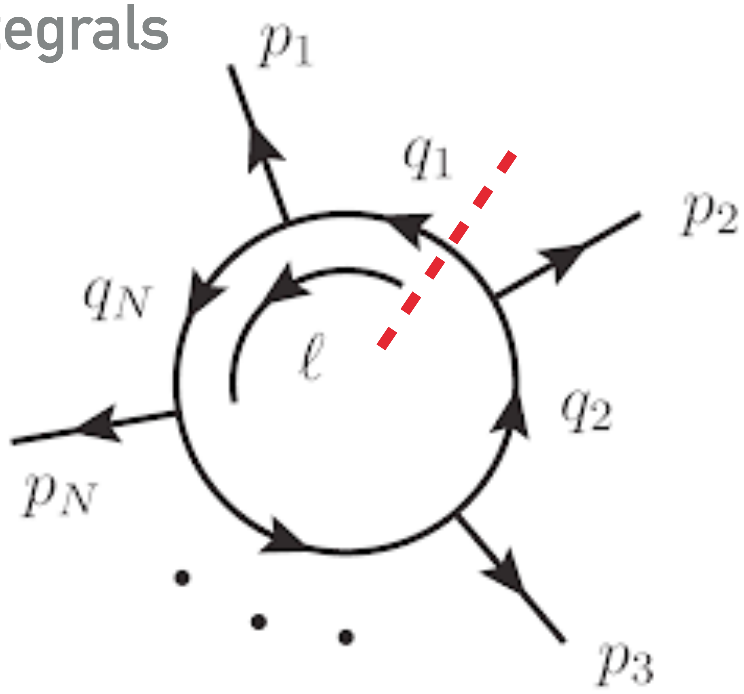
- SM extrapolated to infinite energy in loop corrections >> MPlank
- Quantum state with N partons not = quantum state with zero energy emission of extra partons
- partons can be emitted in exactly the same direction (not enough space)

modify the number of space-time dimensions to $d=4-2e$

THE LOOP-TREE DUALITY THEOREM (LTD)

One-loop integrals and scattering amplitudes in any relativistic, local and unitary QFT represented as a linear combination of N single-cut phase-space integrals (at higher orders: number of cuts equal to the number of loops)

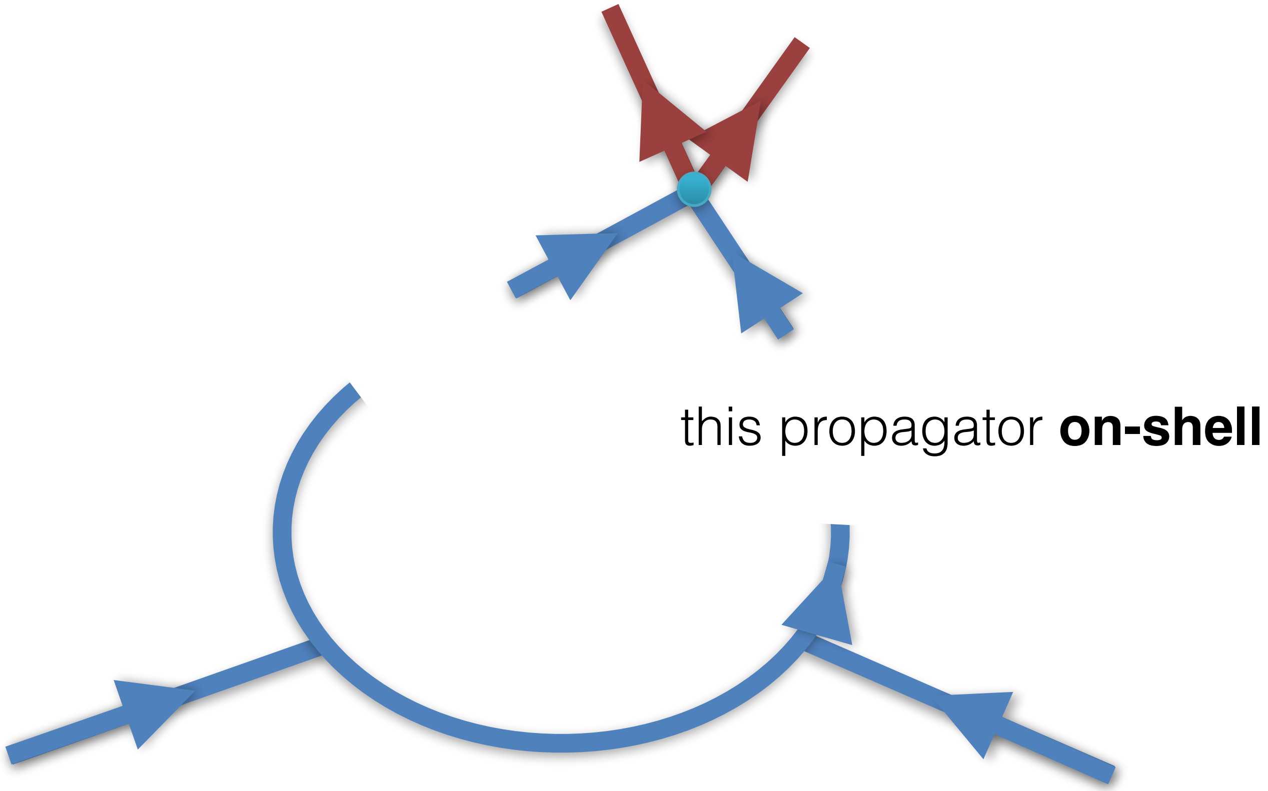
$$\boxed{\int_\ell \prod G_F(q_i) = -\sum \int_\ell \tilde{\delta}(q_i) \prod_{j\neq i} G_D(q_i;q_j)}$$



- $\tilde{\delta}(q_i) = i\,2\pi\,\theta(q_{i,0})\,\delta(q_i^2 - m_i^2)$ sets internal line on-shell, positive energy mode
- $G_D(q_i;q_j) = \dfrac{1}{q_j^2 - m_j^2 - \boxed{i0\,\eta\,k_{ji}}}$ dual propagator, $k_{ji} = q_j - q_i$
- LTD realised by modifying the customary +i0 prescription of the Feynman propagators (only the sign matters), it compensates for the absence of multiple-cut contributions that appear in the Feynman Tree Theorem
- best choice $\eta^\mu = (1,\mathbf{0})$: energy component integrated out, remaining integration in Euclidean space

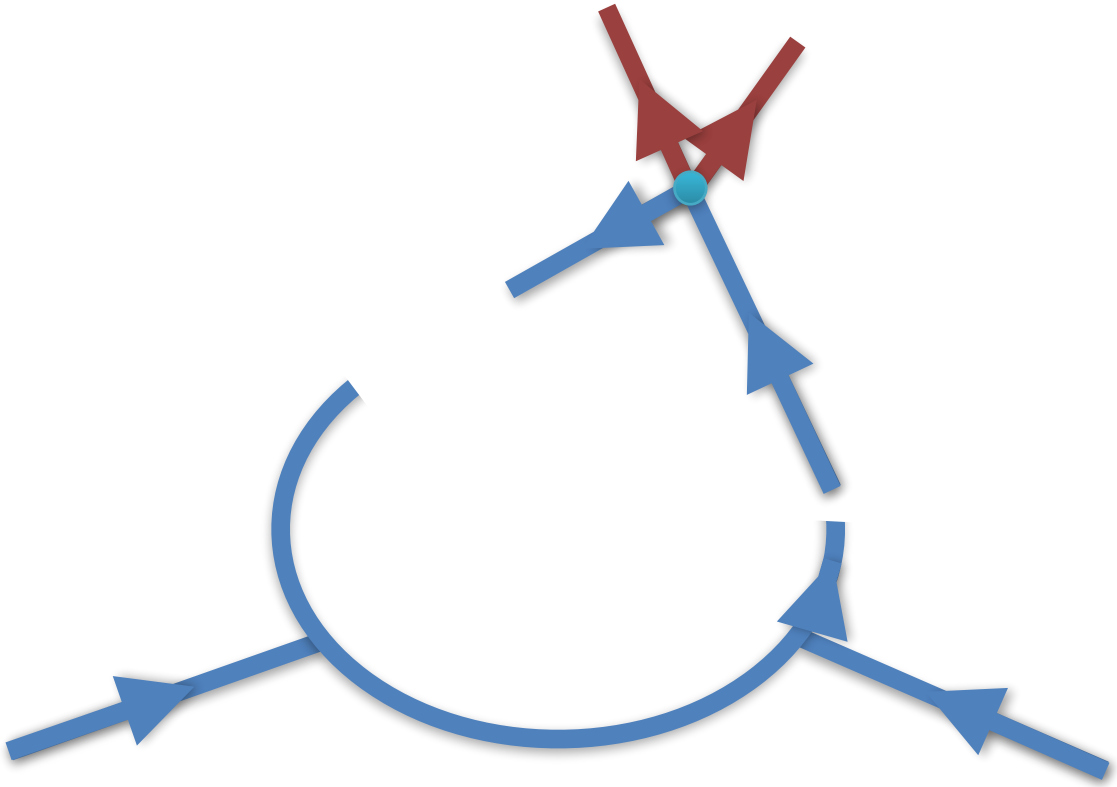
SINGULARITIES IN THE LTD FRAMEWORK

energy of the **on-shell** propagator smaller than the energy of the emitted particles



- **Threshold** singularities occur when a second propagator gets on-shell: consistent with **Cutkosky**
- It becomes **collinear (soft)** when a single massless particle is emitted

energy of the **on-shell** propagator larger than the energy of the emitted particles



- Virtual particle emitted and absorbed
- Potential **singularities cancel** in the sum of all the single-cut contributions
- Expected to be **suppressed.** If it is not sufficiently suppressed, we **renormalise**
- **The bulk of the physics** is in the **"low" energy** region of the loop momentum

Sborlini, Driencourt-Mangin, Hernández-Pinto, GR, JHEP **1608,** 160

IR UNSUBTRACTION (FDU): MULTI-LEG

- The dual representation of the renormalised (UV subtracted locally) loop cross-section: one single integral in the loop three-momentum

$$\int_N d\sigma_{\rm V}^{(1,{\rm R})} = \int_N \int_{\vec{\ell}_1} 2\,{\rm Re}\,\langle \mathcal{M}_N^{(0)} | \left(\sum_i \mathcal{M}_N^{(1)}(\tilde{\delta}(q_i)) \right) - \mathcal{M}_{\rm UV}^{(1)}(\tilde{\delta}(q_{\rm UV})) \rangle$$

- A partition of the real phase-space

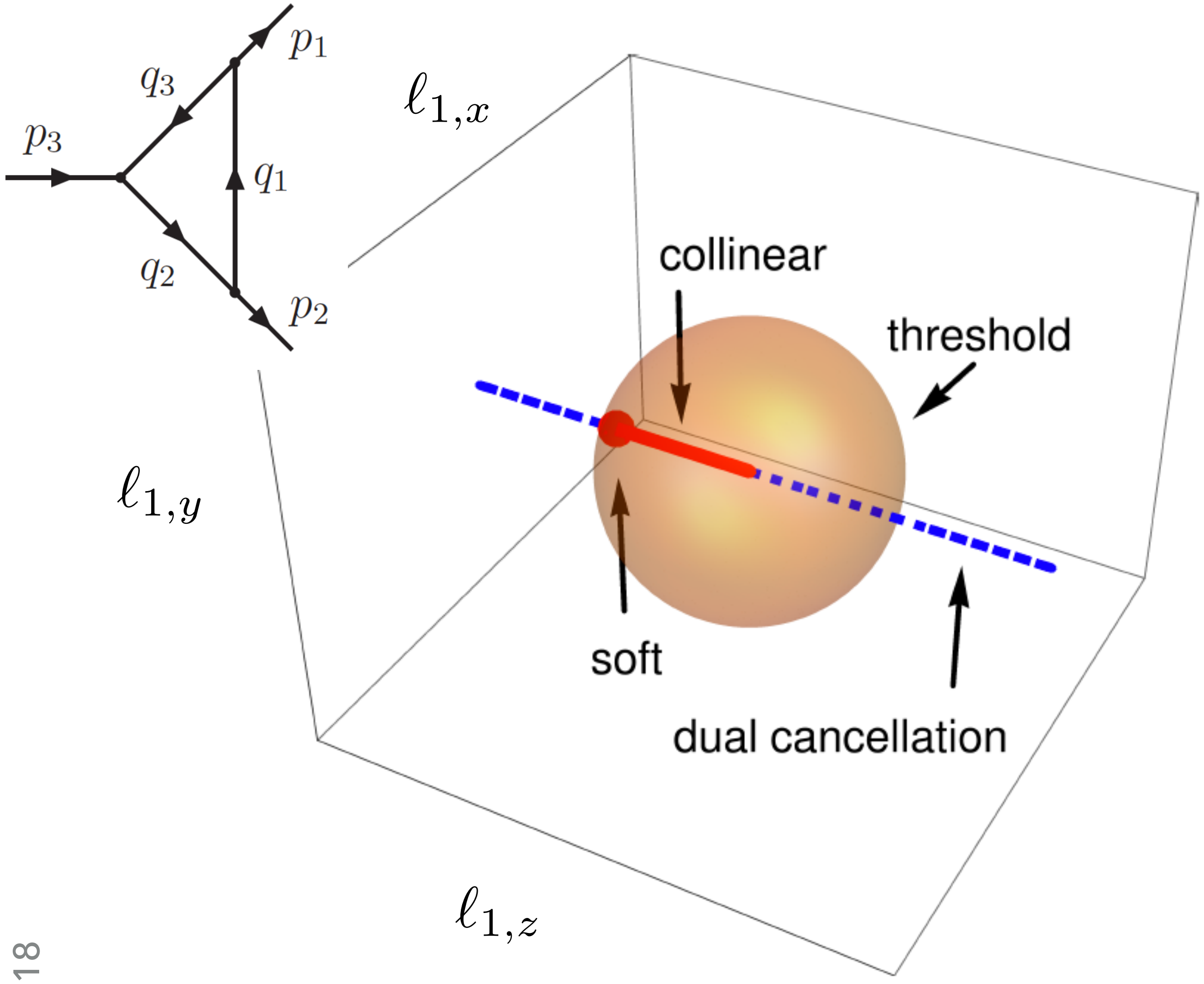
$$\sum_i \mathcal{R}_i(\{p'_j\}_{N+1}) = 1$$

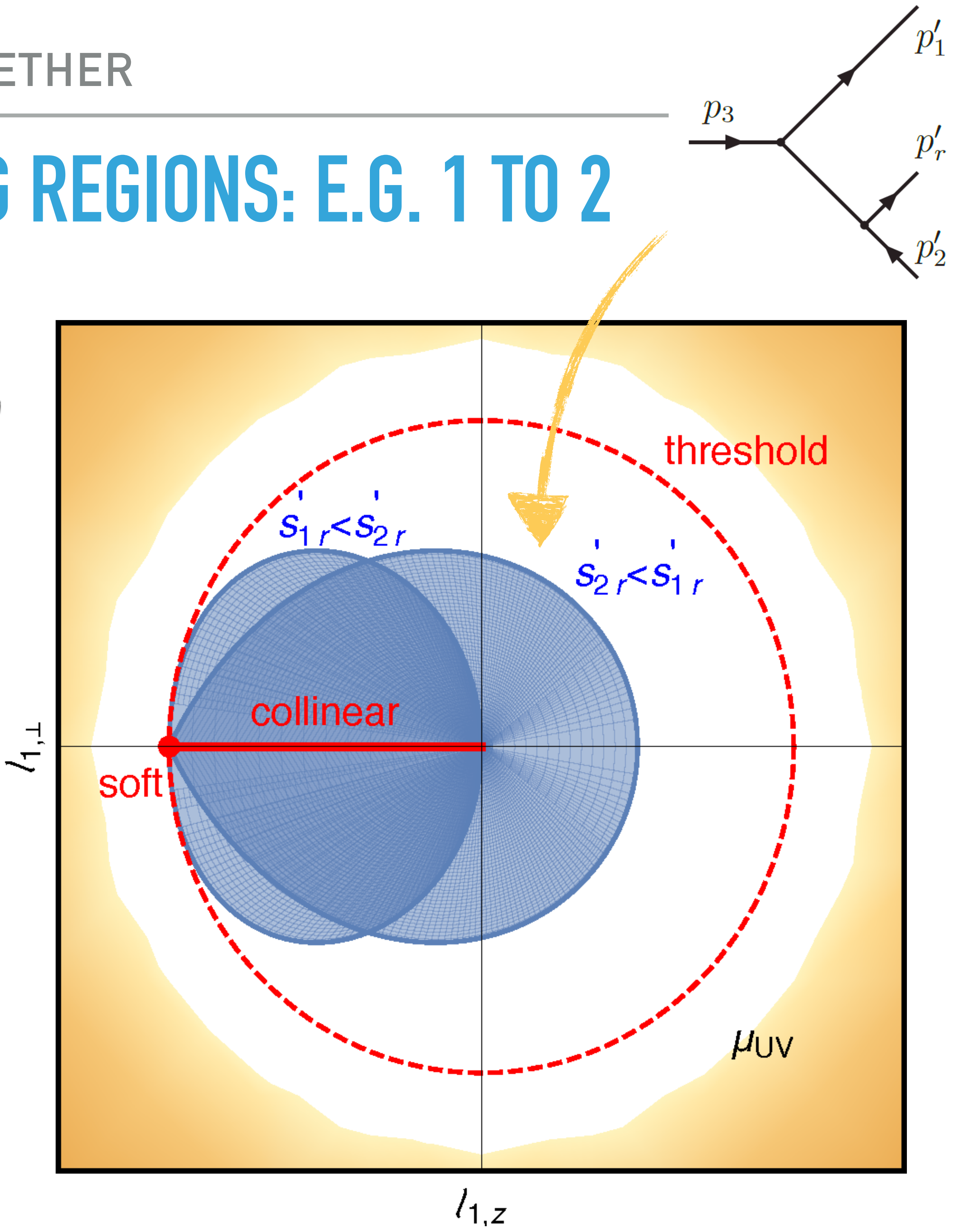
- The real contribution mapped to the Born kinematics + loop three-momentum (inspired by the factorization properties of QCD to built the mapping)

$$\int_{N+1} d\sigma_{\rm R}^{(1)} = \int_N \int_{\vec{\ell}_1} \sum_i \mathcal{J}_i(q_i)\, \mathcal{R}_i(\{p'_j\})\, |\mathcal{M}_{N+1}^{(0)}(\{p'_j\})|^2 \Big|_{\{p'_j\}_{N+1} \to (q_i, \{p_k\}_N)}$$

- At NNLO: the RV and RR contributions mapped to the Born kinematics + the two independent loop three-momenta

IR SINGULARITIES AND MAPPING REGIONS: E.G. 1 TO 2





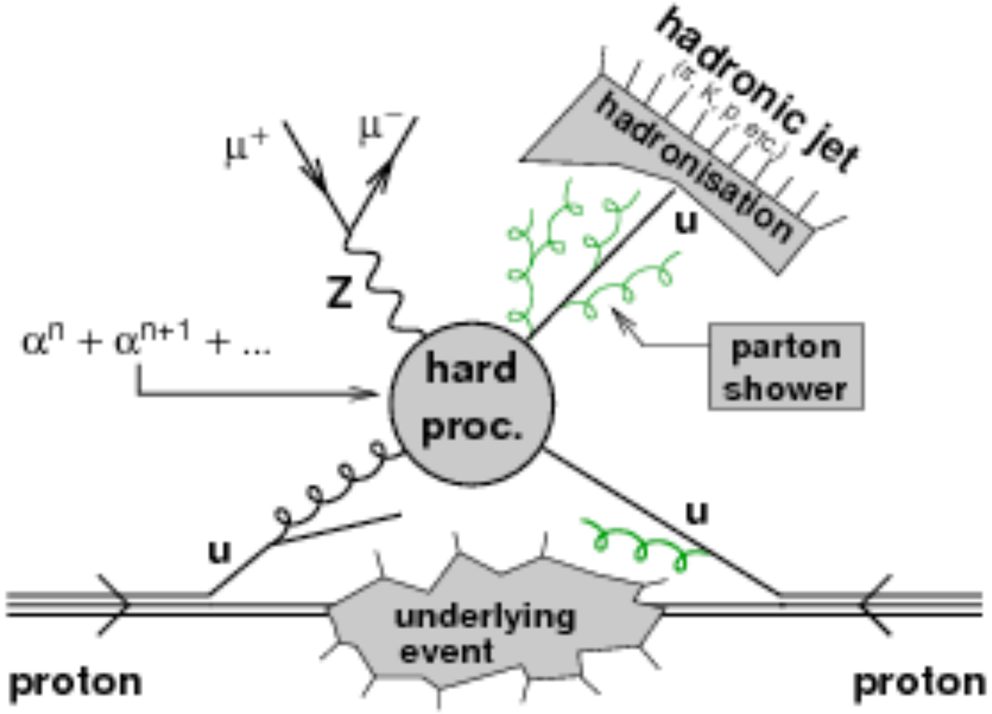
- there is partial cancellation of singularities among single-cut dual contributions
- physics is in a region of the loop three-momentum which is of the size of the hard scale

- integrand cancellation of IR singularities: works in d=4 space-time dimensions

COLLINEAR FACTORIZATION AT HIGHER-ORDERS

- Theory predictions in hadron collisions are based on factorization
- long vs short distance physics: PDF+pQCD+hadronization (up to power corrections)

$\sim M_{\rm had}$ $Q \gg M_{\rm had}$ $\mathcal{O}(M_{\rm had}/Q)^n$



source:
Butterworth et al. 2012

- Implicitly assumed, but not yet proven
- Breaking of collinear factorization starting from N3LO [Catani, Florian, GR / Forshaw, Seymour, Siodmok 2012]
- Uncanceled soft divergences from two colliding massive quarks starting from NNLO [Catani et. al 2002] because Block-Nordsieck not valid for non-Abelian
- Protons are not SU(2) symmetric: EW corrections violate Block-Nordsieck [Ciafaloni et al. 2001], potentially relevant at HE-HLC/FCC

HL-LHC PROSPECTS

$100\ \mathrm{fb}^{-1}$ today

$3000\ \mathrm{fb}^{-1}$ by 2037

- statistical errors in the range 1% - 2%

LHC PHYSICS AT % PRECISION ?

% PHYSICS AT THE LHC IS A GREAT CHALLENGE

CONCLUSIONS

- LHC data is challenging our expectations to find BSM
- The quest for precision is at the forefront for new discoveries
- It requires to challenge our current understanding of QFT in many different aspects
- % physics still far away (2037?), but promising landscape given the recent successful developments in the field