QCD
Taller de Altas Energías - TAE 2019

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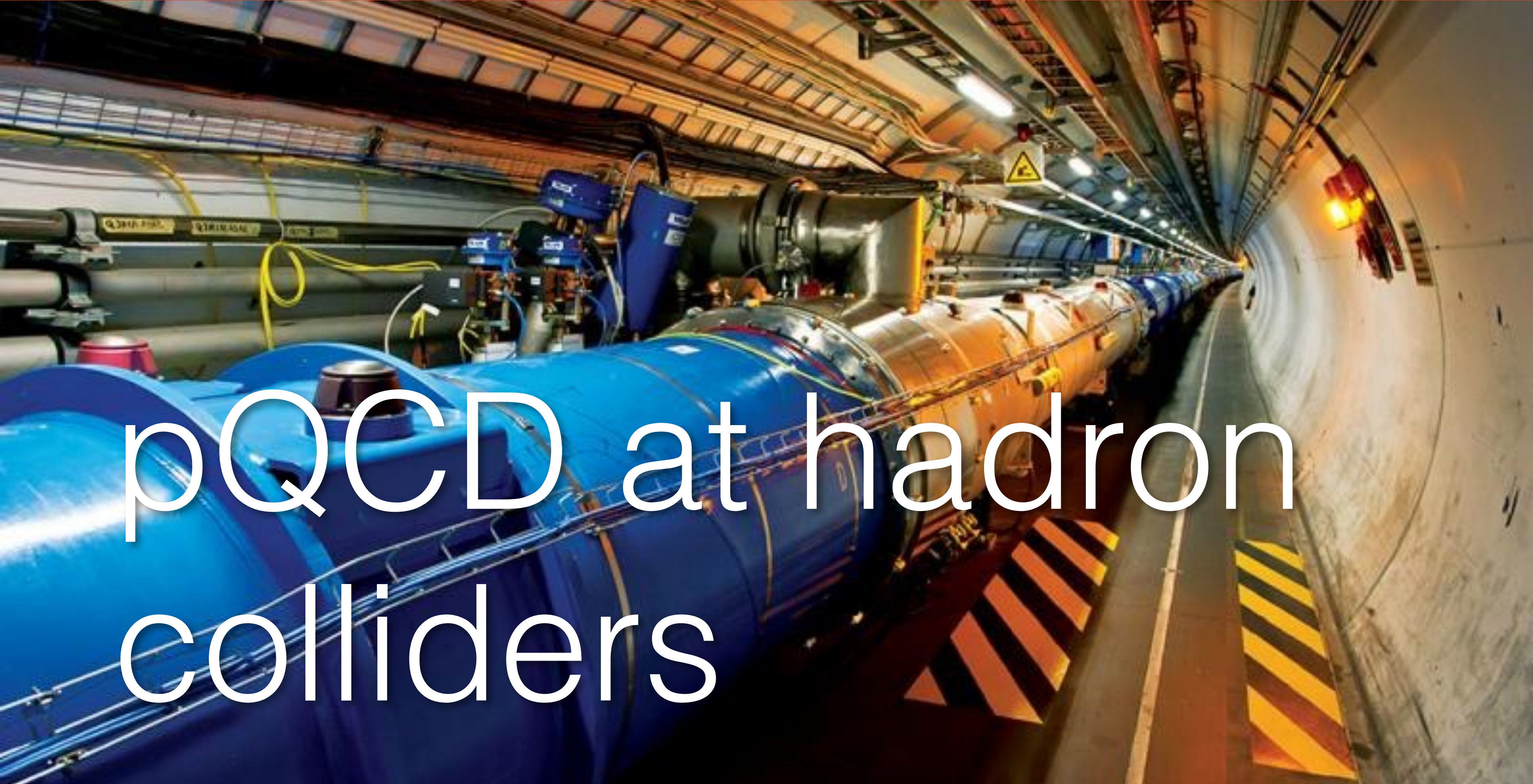
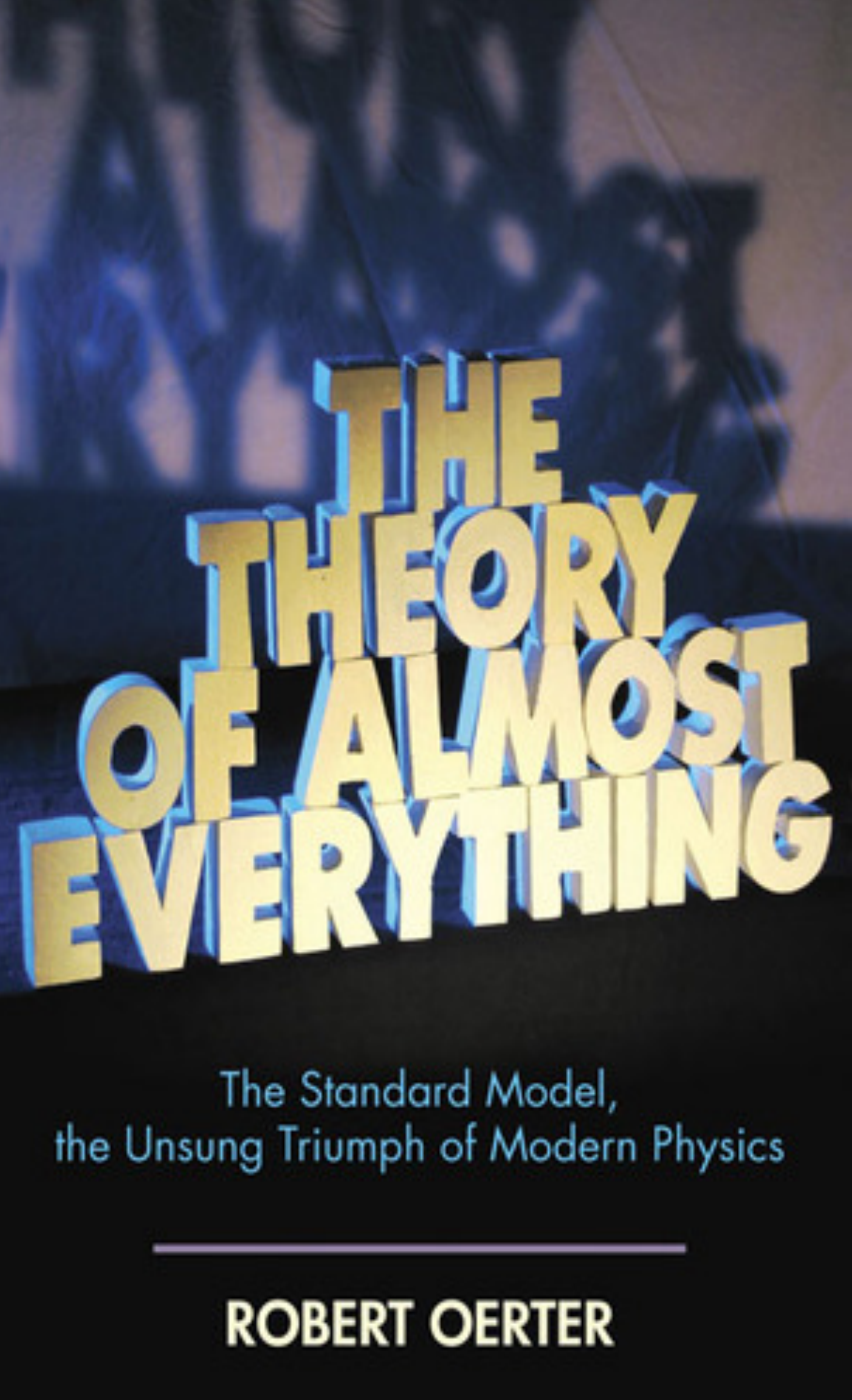
Lecture 3: pQCD at hadron colliders

particleface
COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

pQCD at hadron colliders





NO CLEAR BSM SIGNAL AT THE LHC SO FAR

- SM 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 | no theory guidance**

EXCELENCIA SEVERO OCHOA

WHERE TO EXPECT A BSM SIGNAL?

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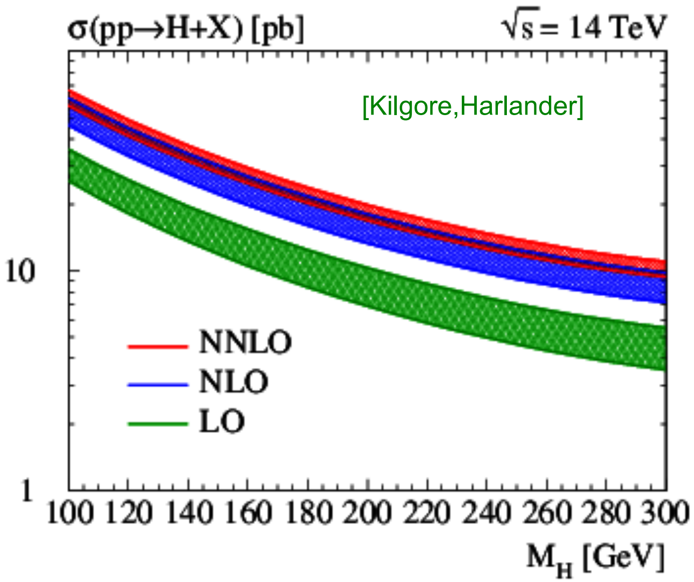
- Higher chances at the tail of differential distributions (not necessarily a clear bump) **"high energy"** characteristic hard scale: more sensitive to **quantum corrections** / missing quantum corrections can fake BSM

Perturbative view at hadron-hadron colliders



higher orders improve systematically the precision of the theoretical predictions (estimated by **varying the renormalization / factorization scales**) for background and signal. Uncertainty bands are **expected to narrow and overlap** from one order to the next one

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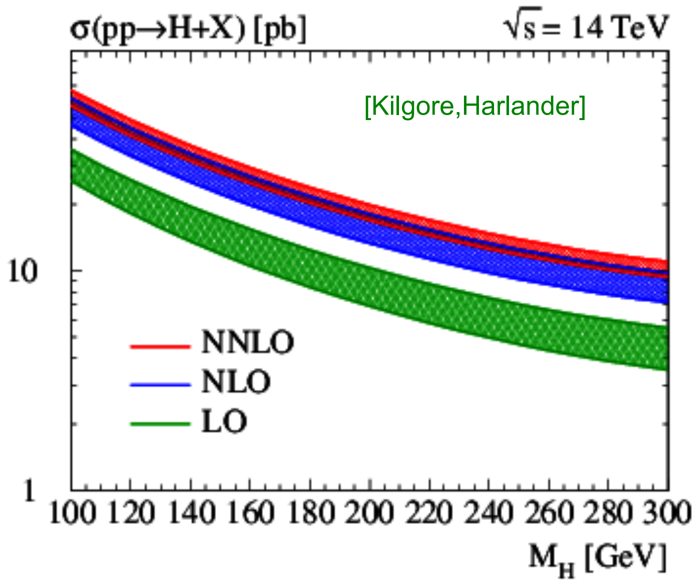

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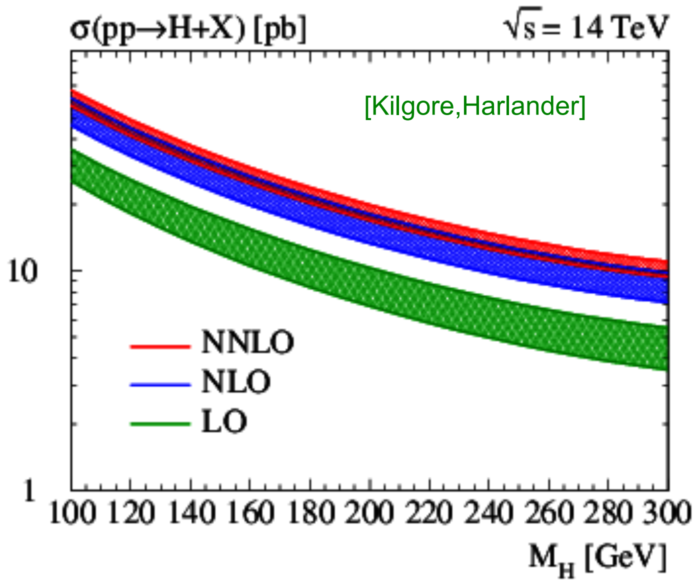

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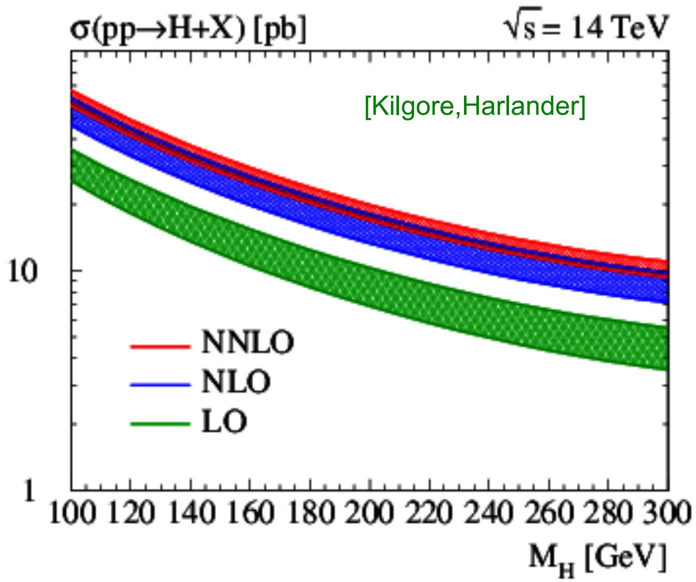

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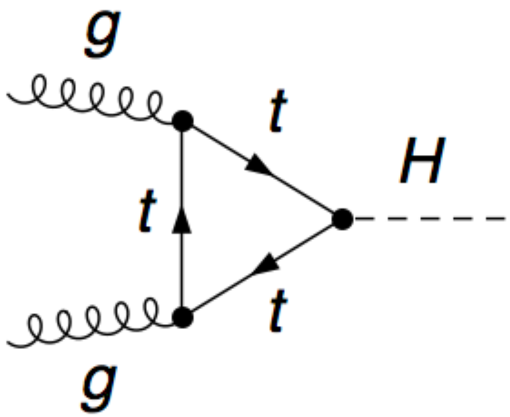
- NNLO: first **serious estimate** of the theoretical uncertainty

New channels open from LO to NLO



Higgs boson production is one loop at **LO**

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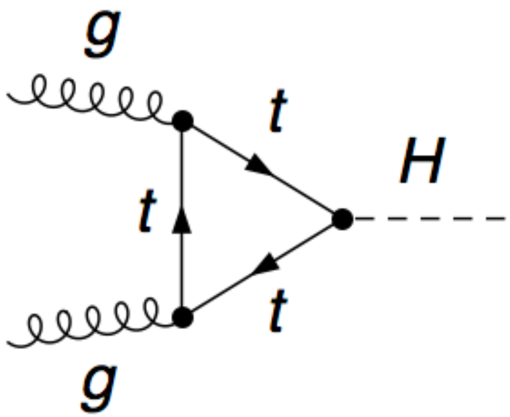

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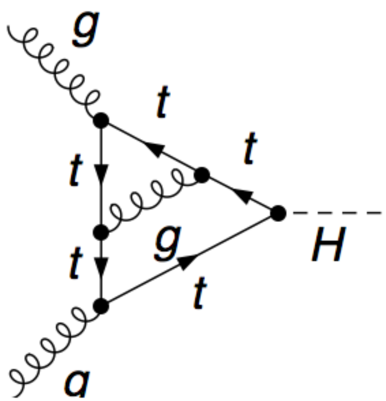

QCD correction to the **LO**

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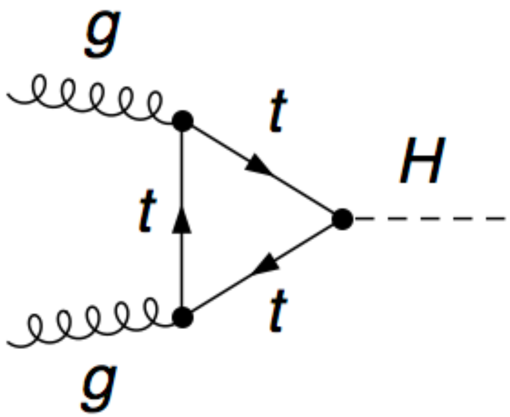

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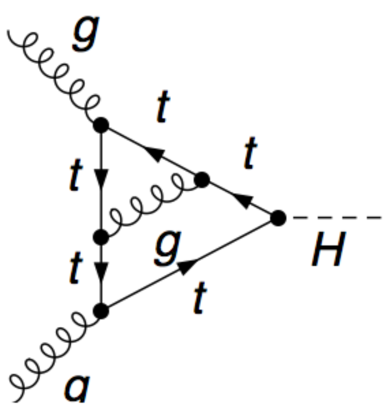

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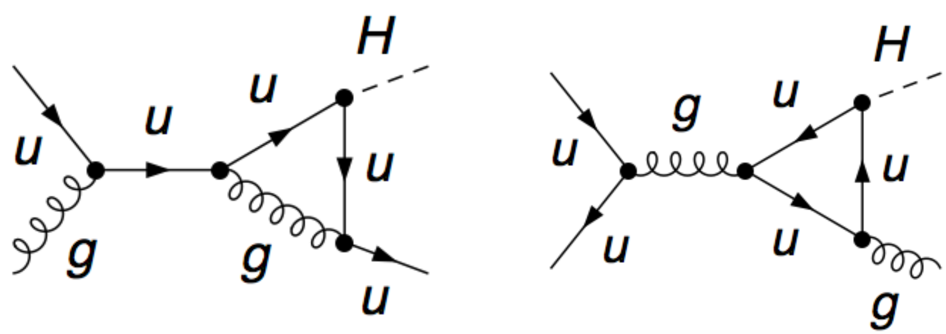

New channels at **NLO**
$qg(\bar{q}g)$ and $q\bar{q}$

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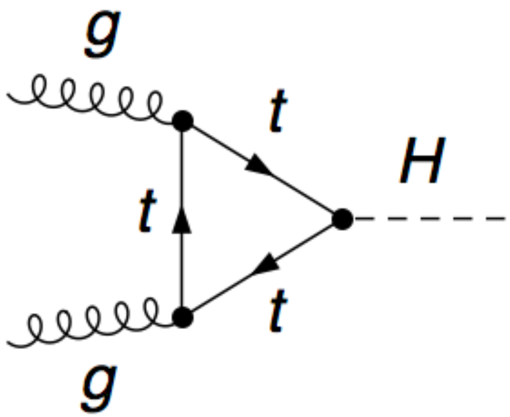

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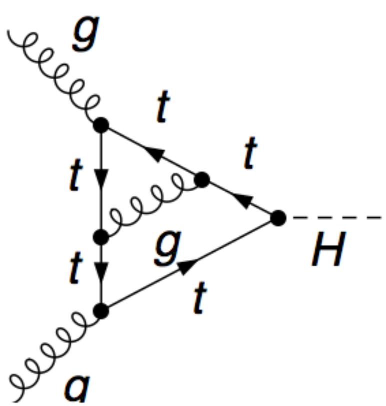

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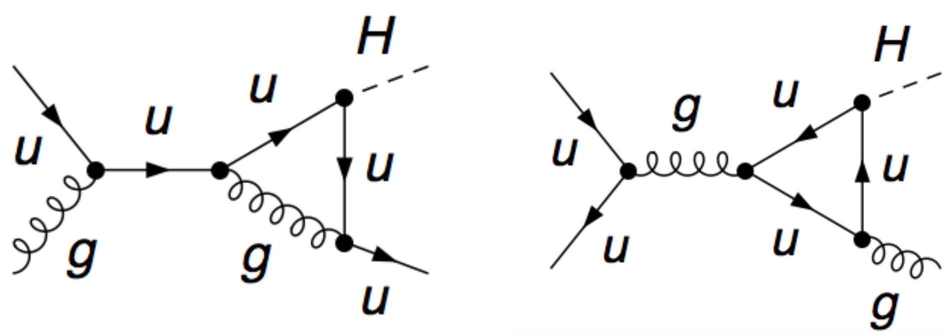

New channels at **NLO**
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Only **NNLO** is a correction to all the channels that appear at the NLO

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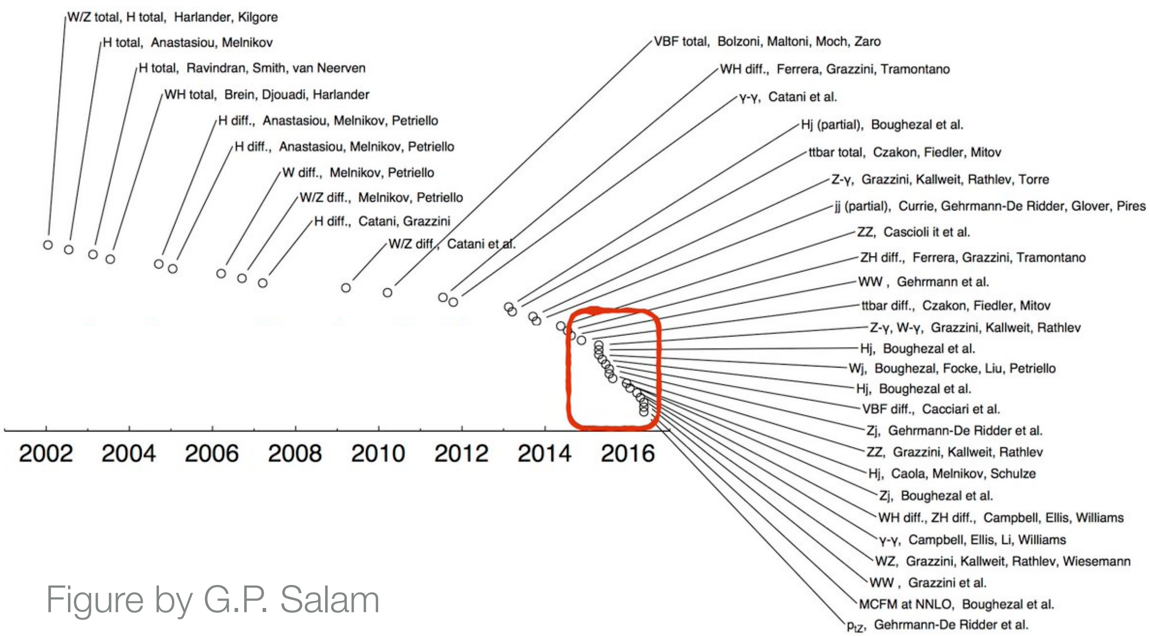

Figure by G.P. Salam

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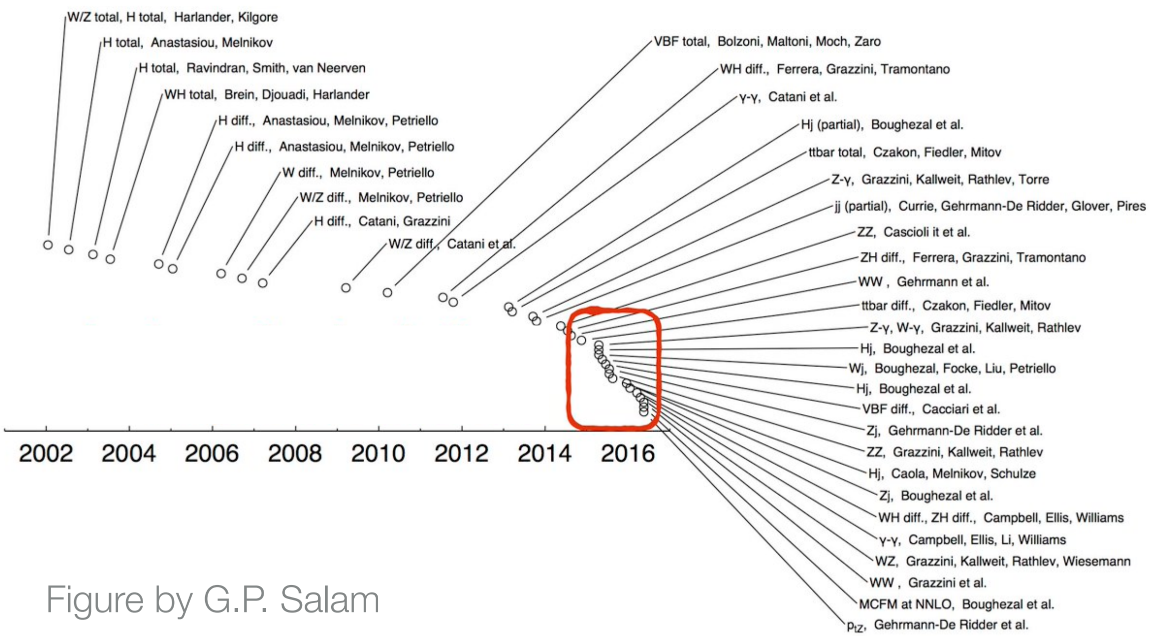

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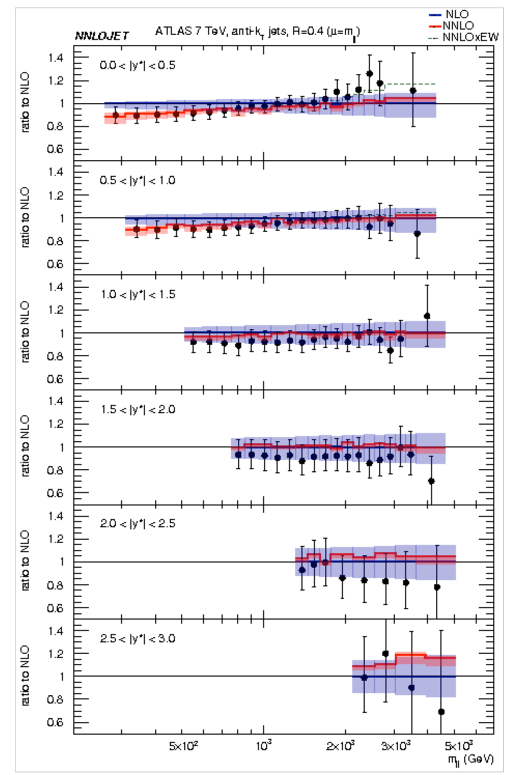
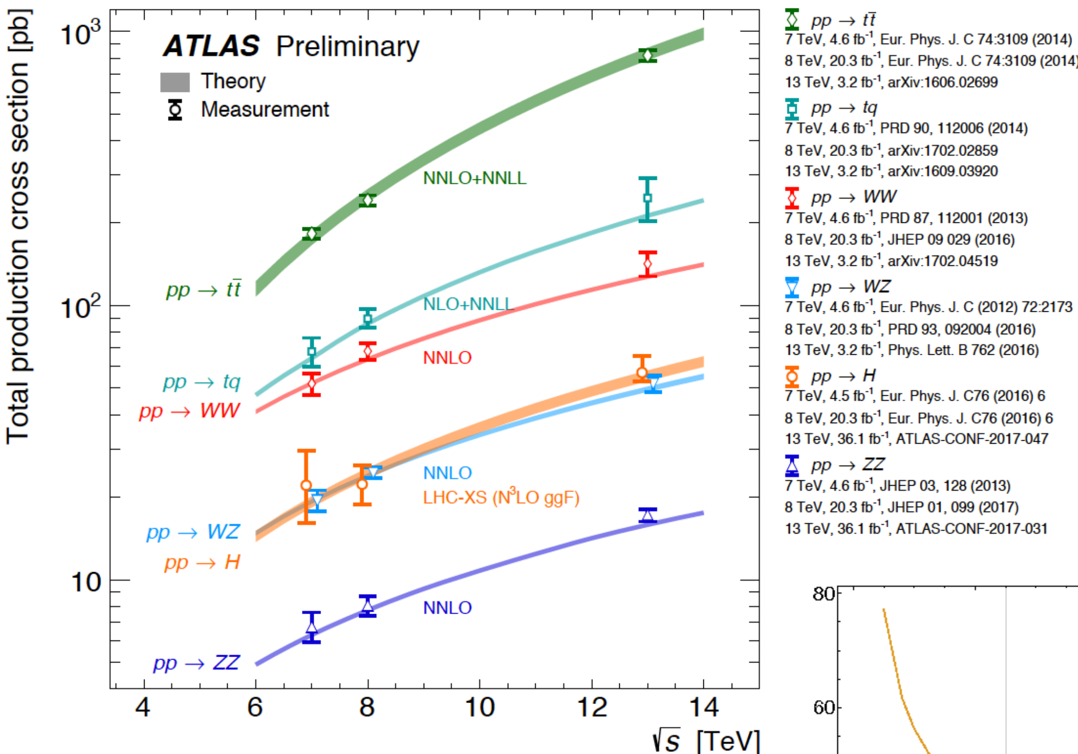
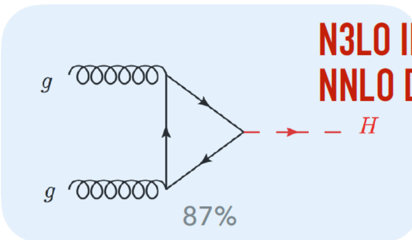


e.g. dijet production
data prefer NNLO

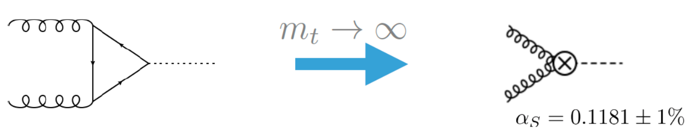
STUNNING PROGRESS IN THEORETICAL CALCULATIONS IN THE PAST YEARS

- **N3LO** ggH (2➔1): 5% th+3% (PDF- α_S) [Anastasiou et al., 2016]



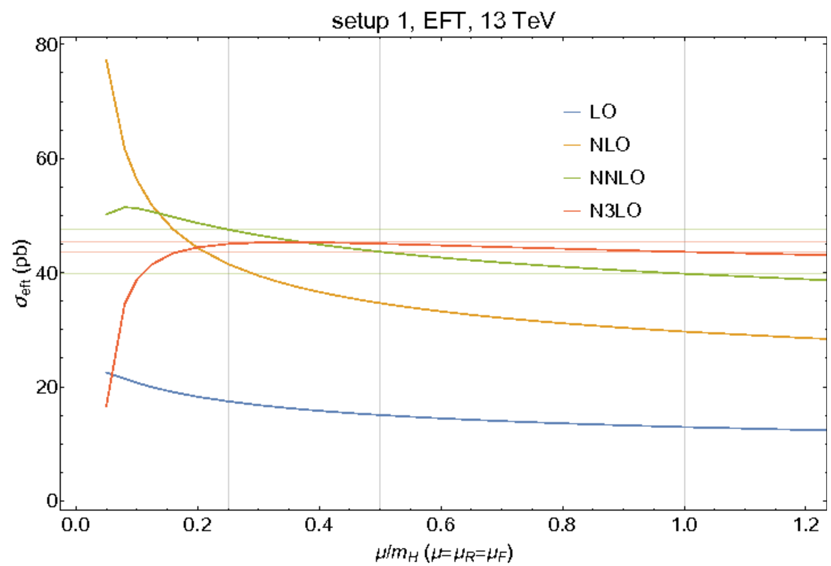


N3LO INCLUSIVE
NNLO DIFFERENTIAL

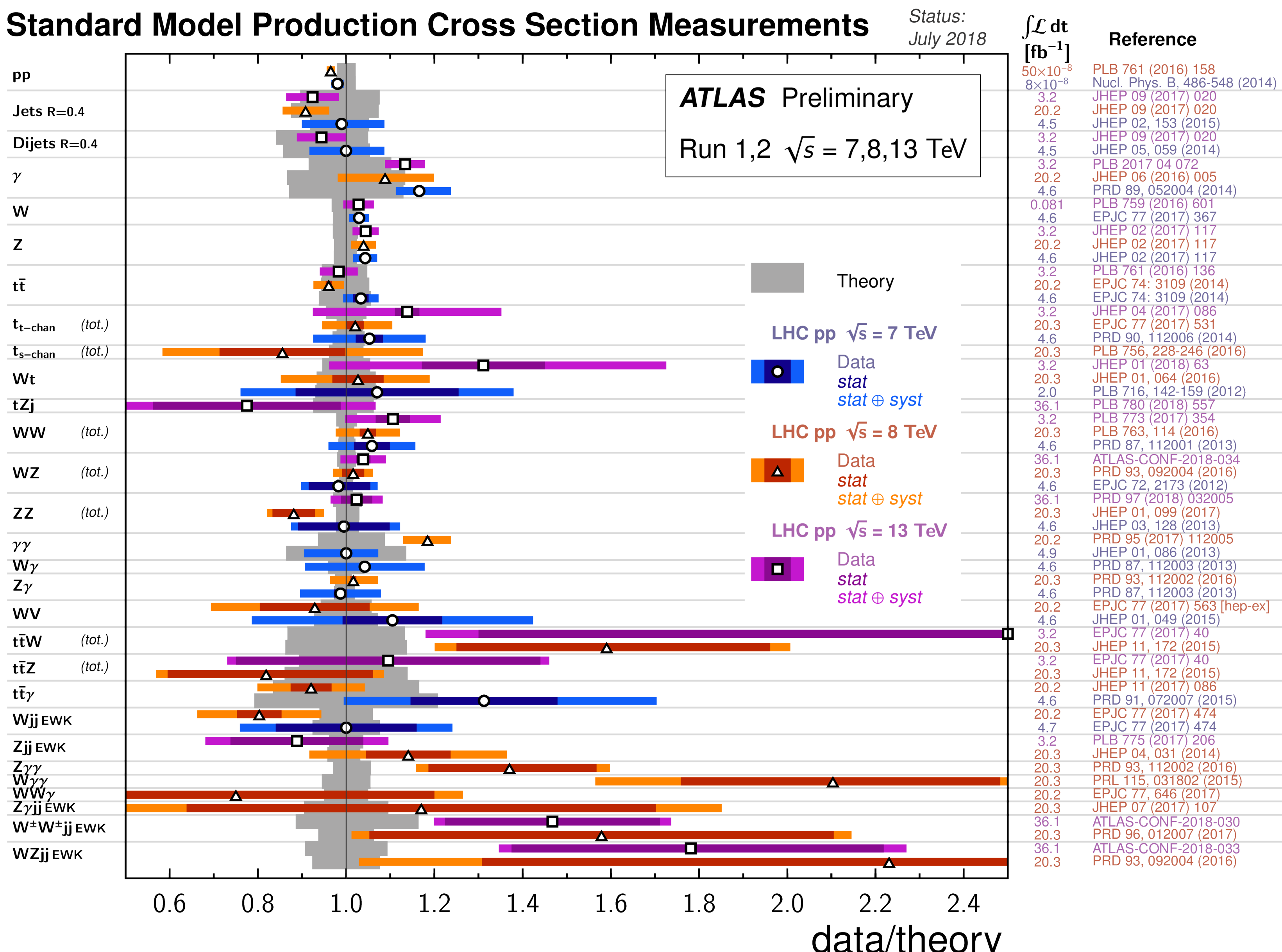


$$\hat{\sigma} = \alpha_s^2 \sigma^{\rm LO} + \alpha_s^3 \sigma^{\rm NLO} + \alpha_s^4 \sigma^{\rm NNLO} + \alpha_s^5 \sigma^{\rm N3LO}$$
✓ ✓ ✓ ✓

[Dulat at PASCOS2018]



DATA/THEORY I INCLUSIVE OBSERVABLES 5-20% THEORETICAL ACCURACY



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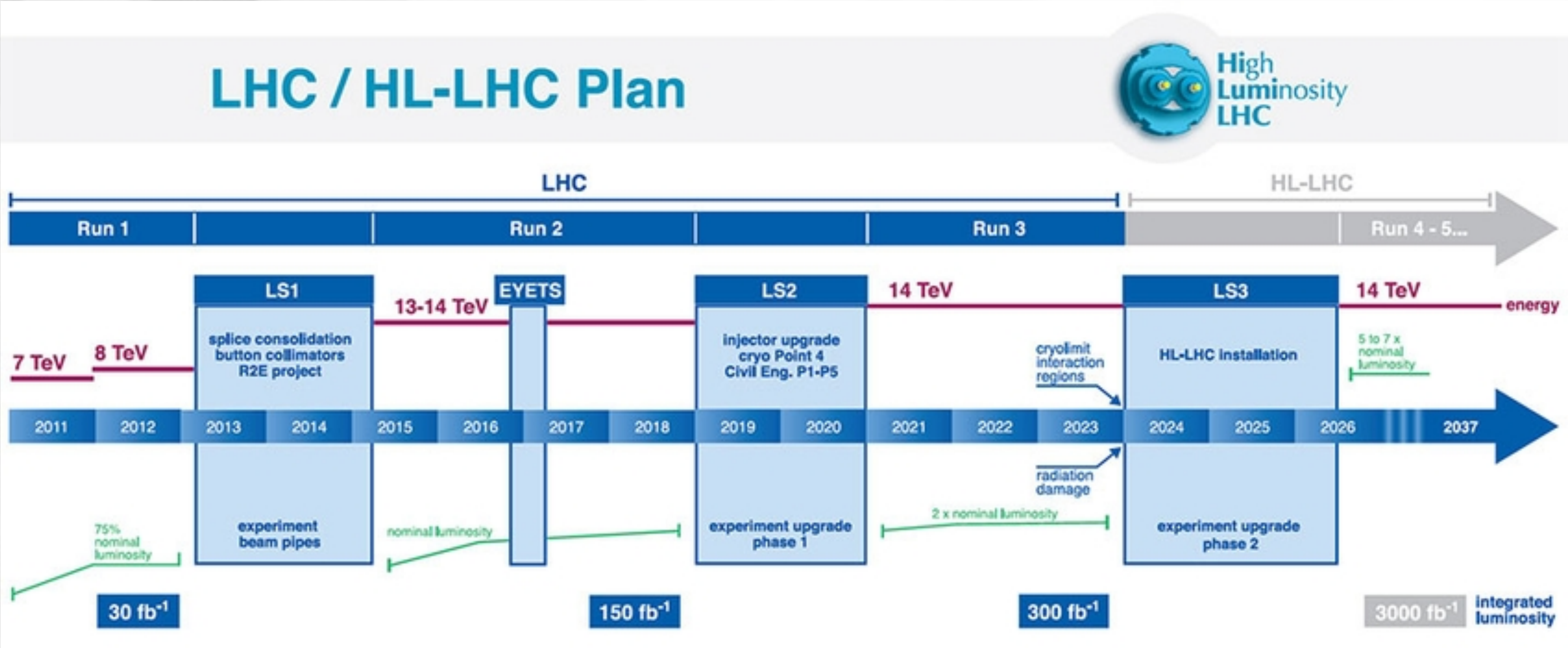
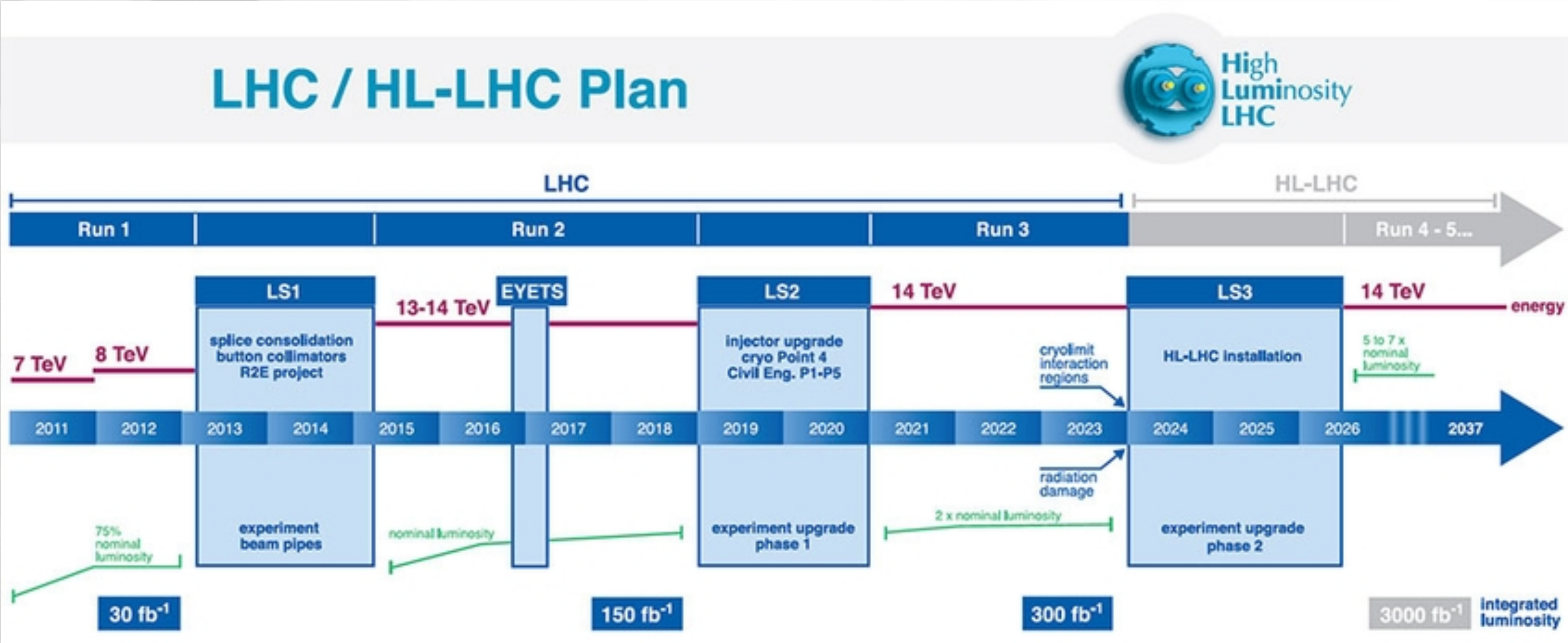


- **150 fb^{-1}** today (only ~ 1/3 analysed)
- **300 fb^{-1}** by 2023
- **3000 fb^{-1}** by 2037



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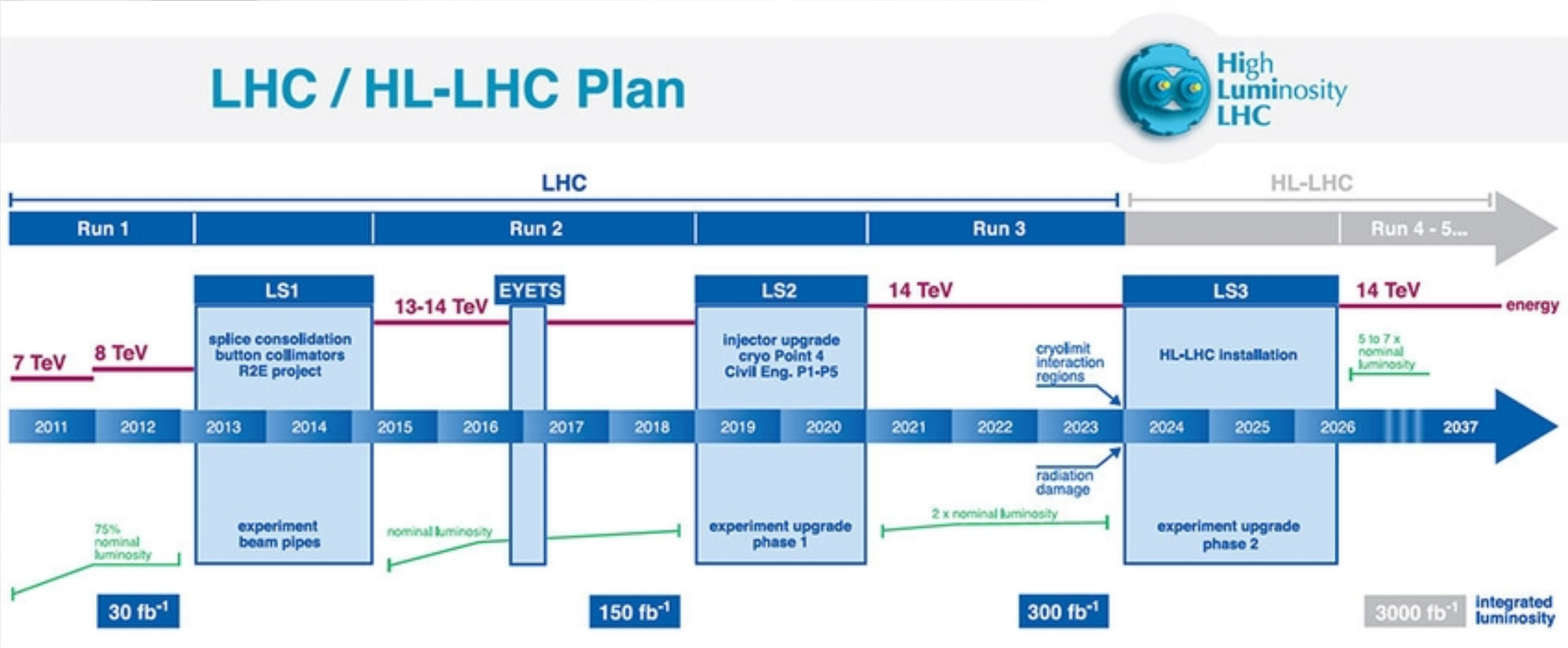

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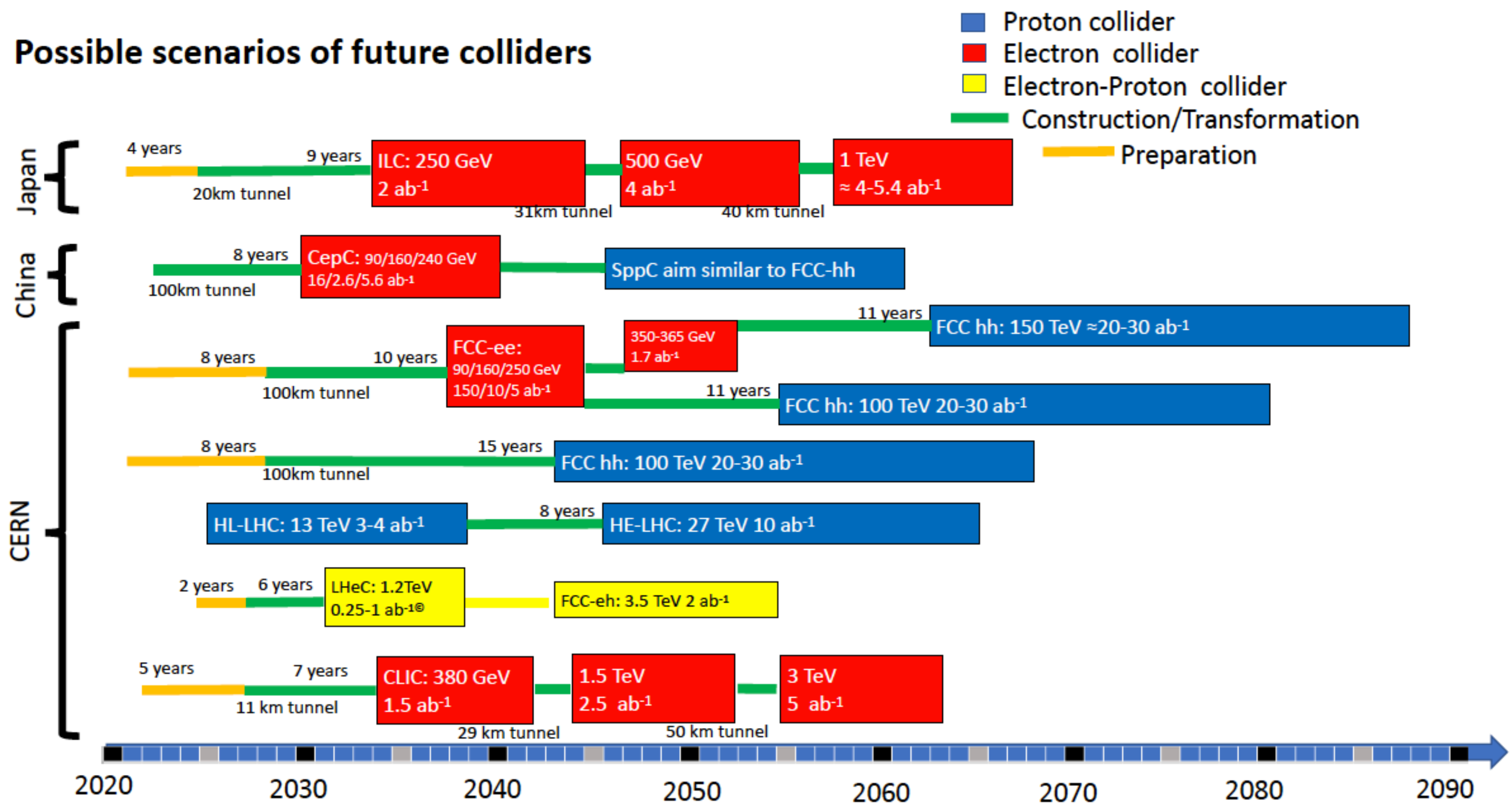
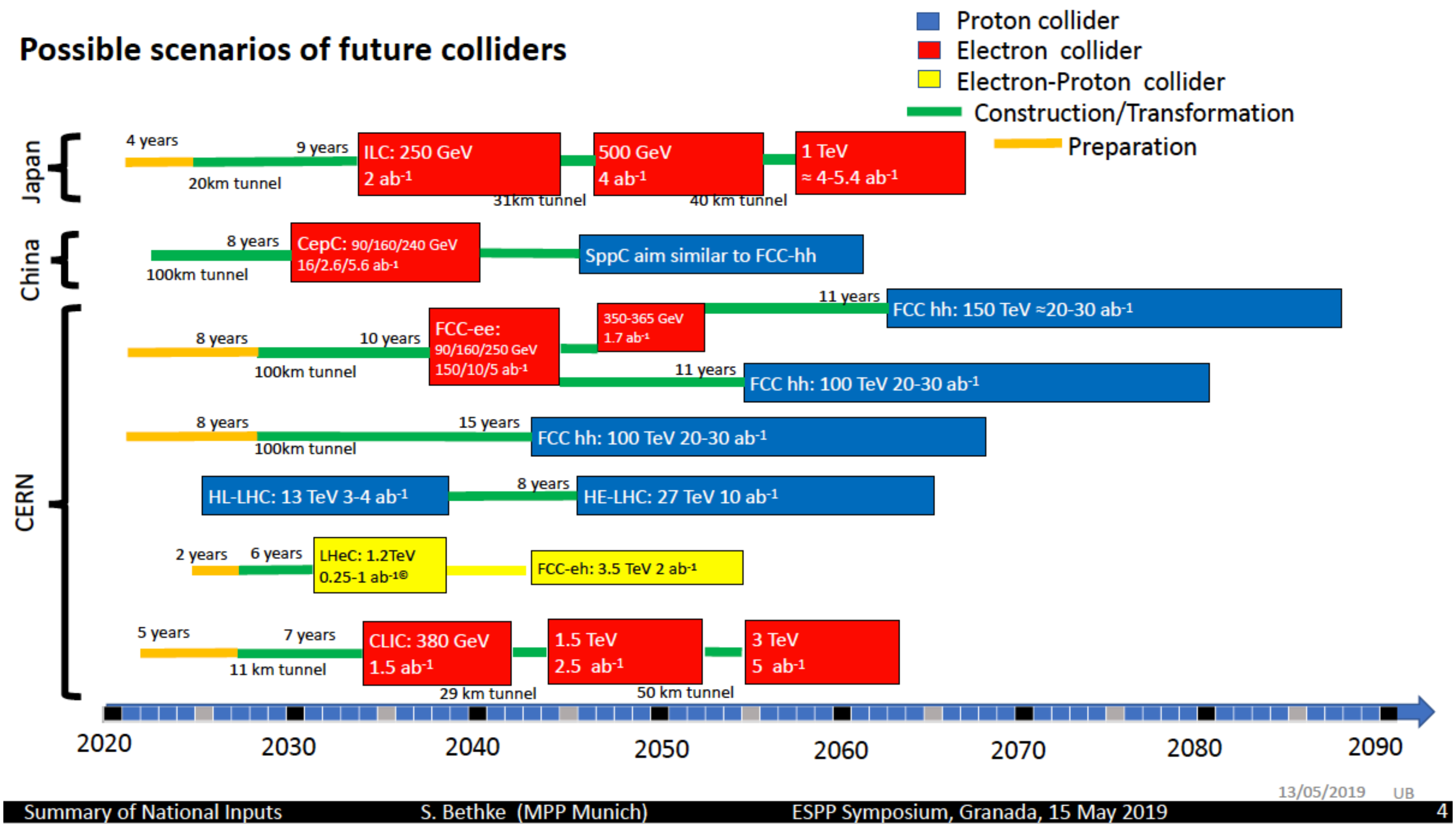
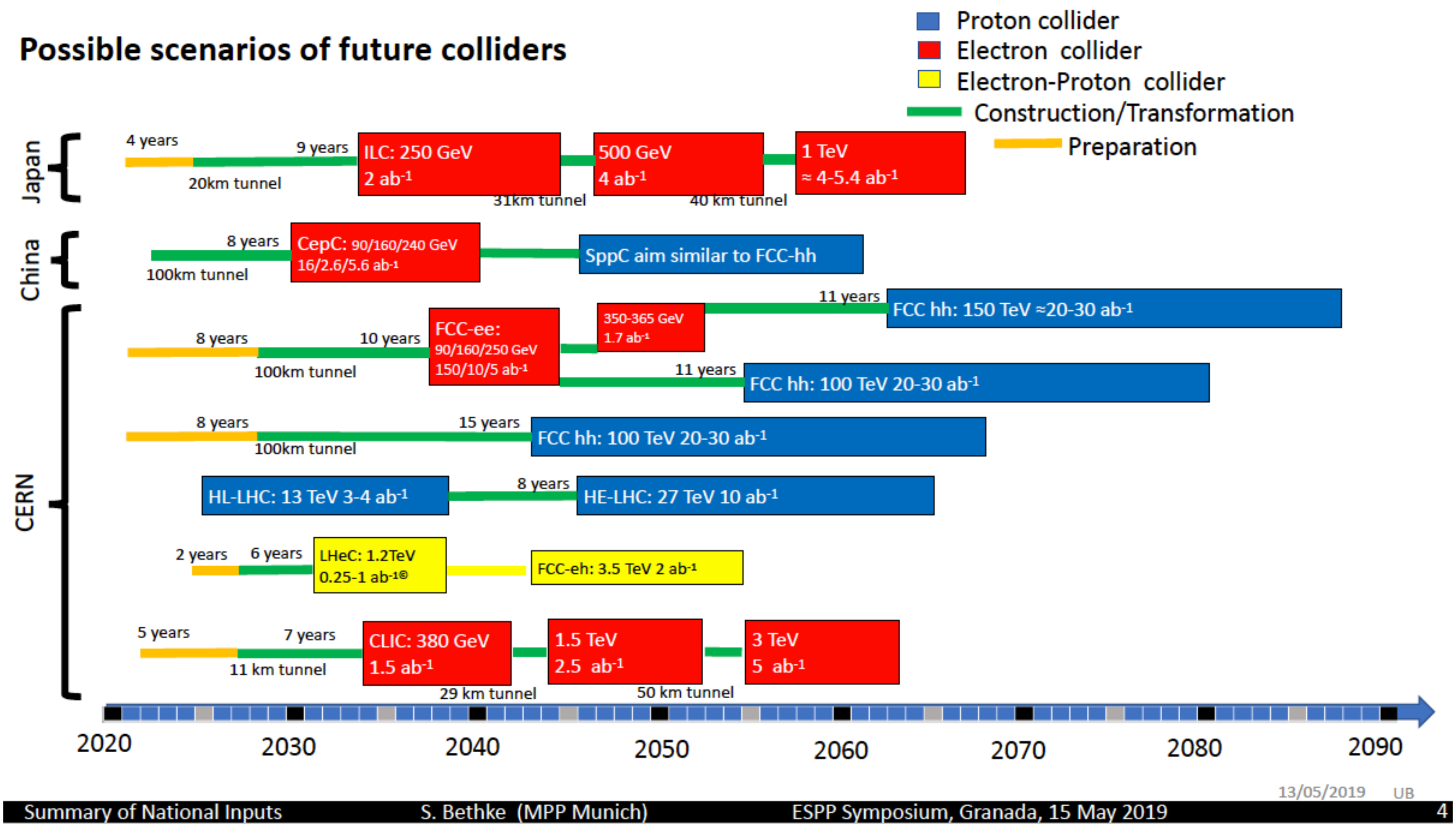
LHC PHYSICS AT % PRECISION ?

Possible scenarios of future colliders





- all options aimed at **attobarn^{-1} physics**



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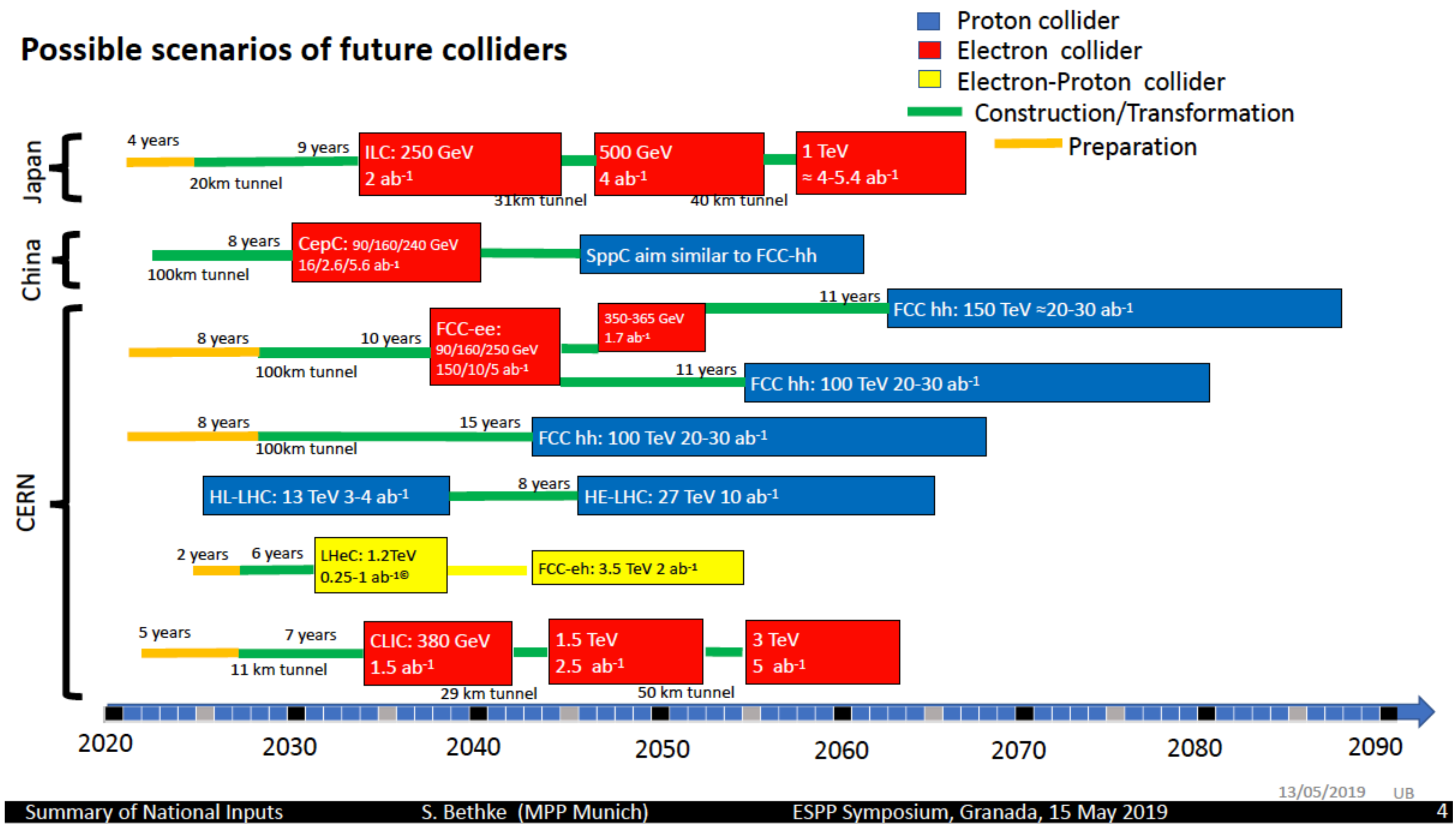
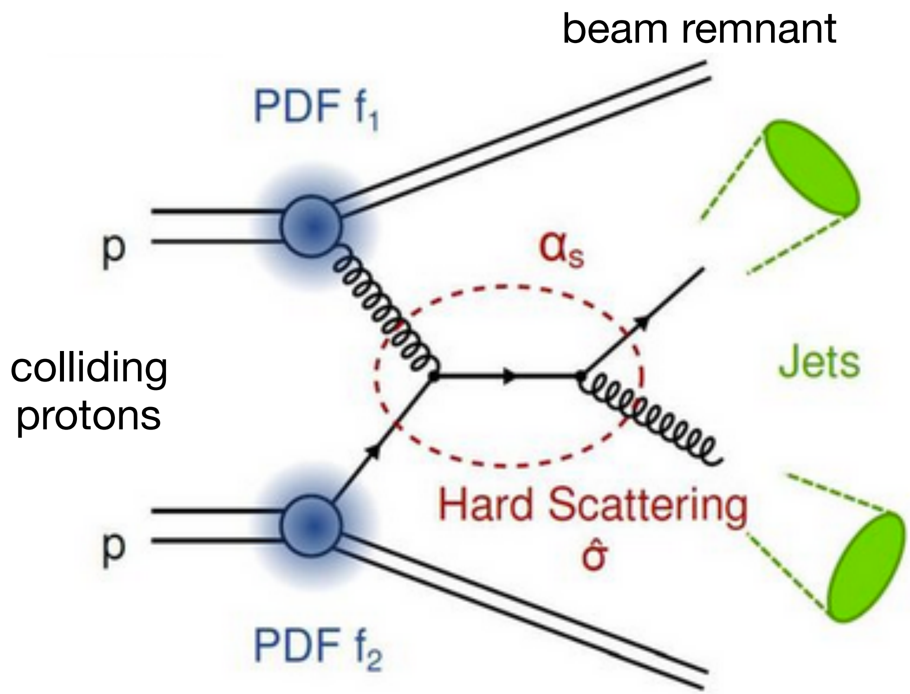
- requires to go **far beyond NNLO for theory**



- all options aimed at **attobarn^{-1} physics**
- requires to go **far beyond NNLO for theory**
- Even conservative estimates **not reachable with current techniques**

Factorisation in hadronic collisions



- Factorise physics into **long distance** (hadronic $\sim M_{\text{had}}$) and **short distance** (partonic $Q \gg M_{\text{had}}$)
- factorisation violation is power suppressed $\sim \mathcal{O}(M_{\text{had}}/Q)^q$

Parton densities PDF

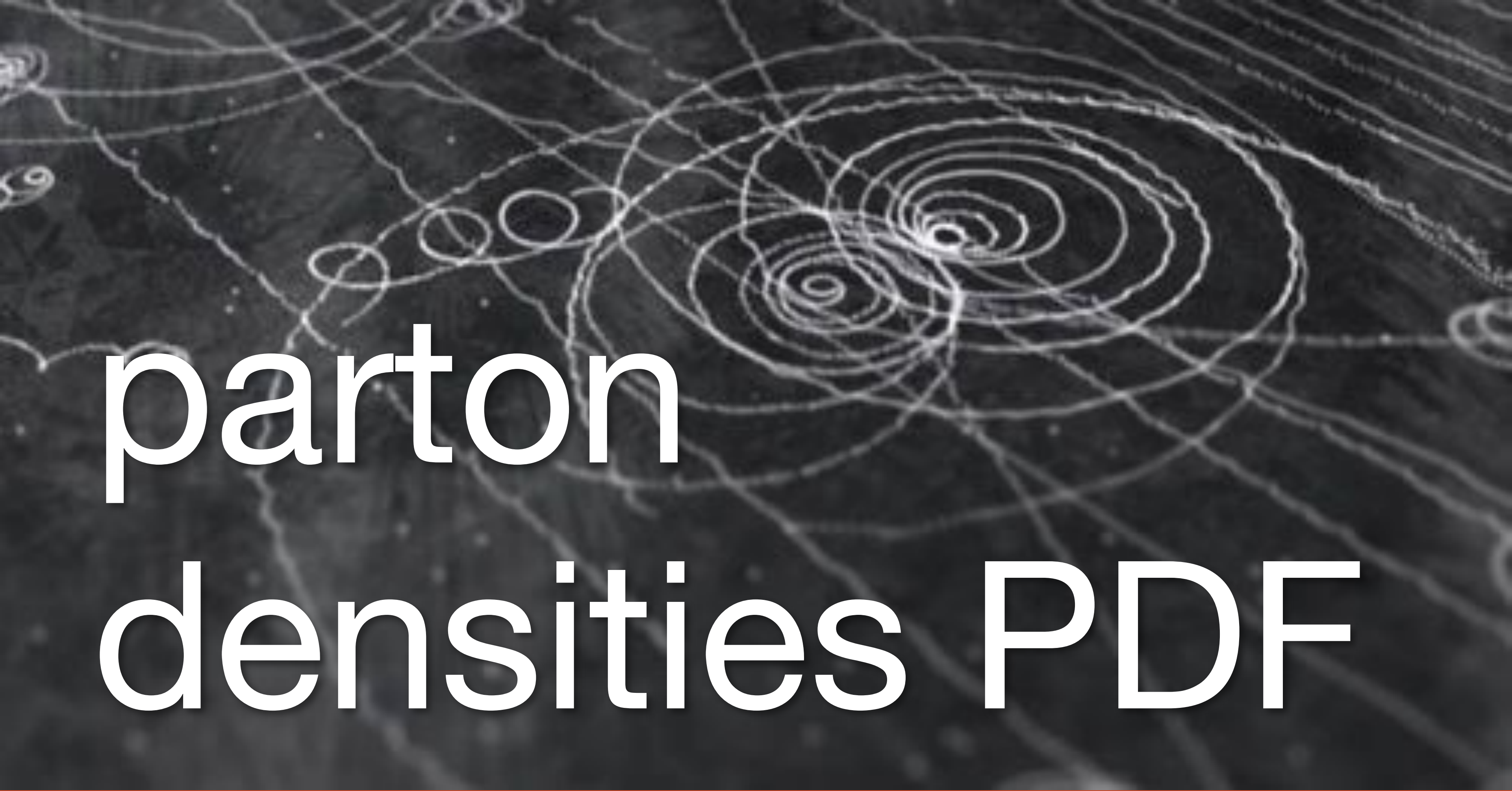
Hard scattering cross-section

$$\sigma = \sum_{a,b} \int dx_1\, dx_2\, f_a(x_1, \mu_F) f_b(x_2, \mu_F)\, \hat{\sigma}_{ab}(x_1 p_A, x_2 p_B; \mu_F, \mu_R) + \mathcal{O}\left(\frac{1}{Q}\right)$$

Factorization and renormalization scales

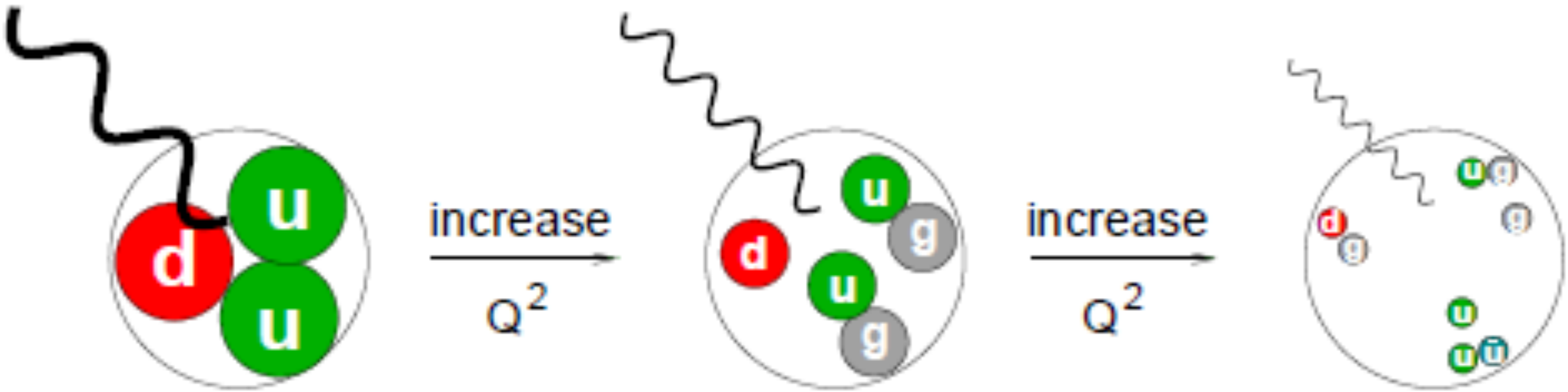
Higher twist

Partonic cms energy $\hat{s} = x_1\, x_2\, s$



parton densities PDF

Looking inside the proton



non-perturbative
input

scale evolution
determined by
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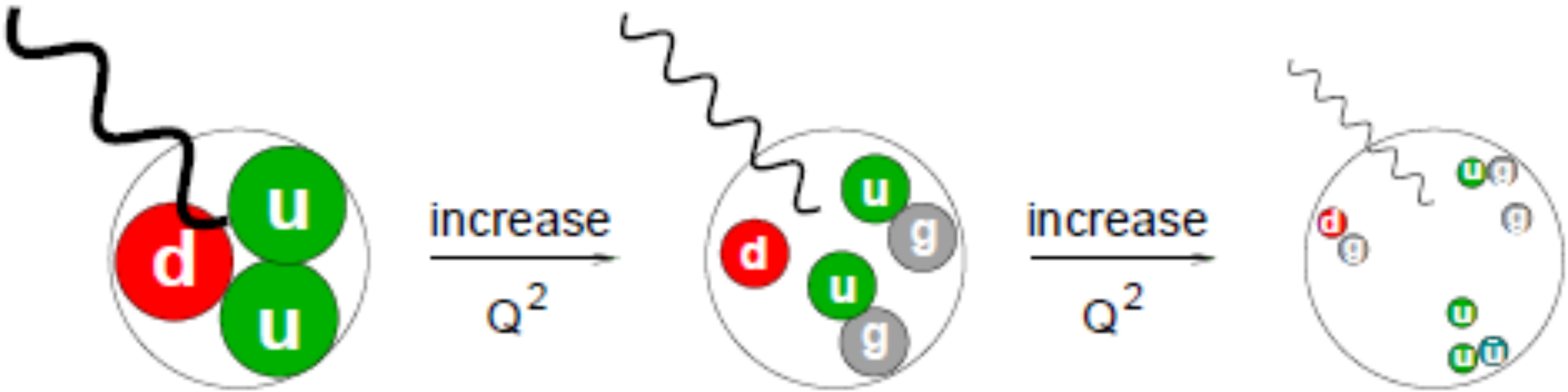
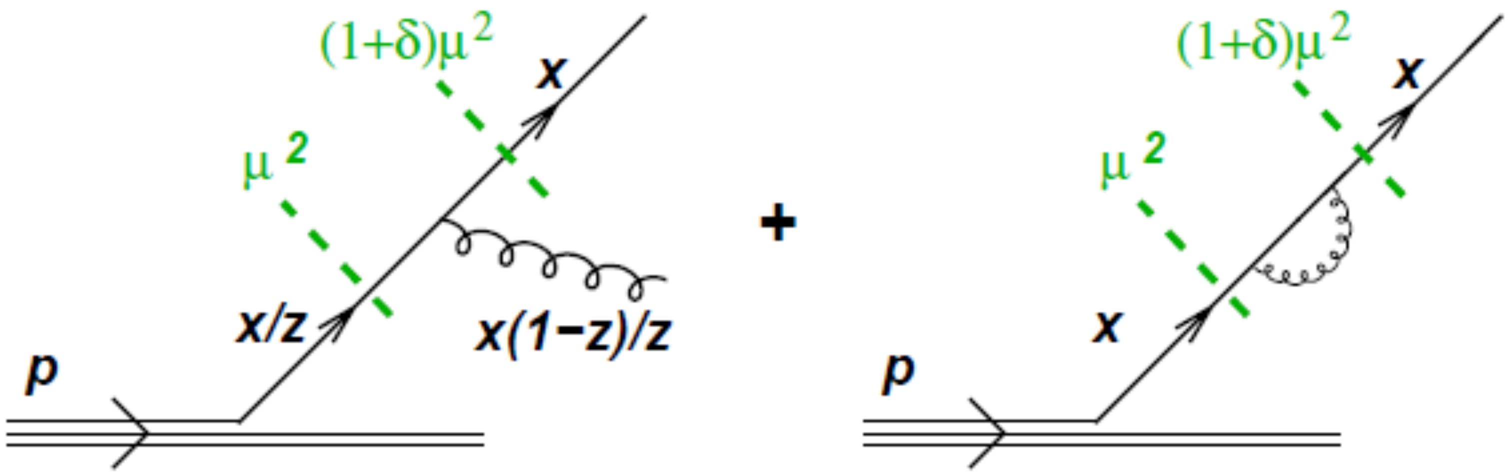


non-perturbative input

scale evolution determined by pQCD

Parton density (PDF): "*probability*" to find a parton of a given flavour carrying a longitudinal momentum fraction $x \in [0,1]$ of the momentum of the proton

DGLAP evolution [Dokshitzer 1977–Gribov–Lipatov 1972–Altarelli–Parisi 1977]



$$\frac{\partial\, q(x,\mu^2)}{\partial \log \mu^2} = \frac{\alpha_S}{2\pi} \int_x^1 \frac{dz}{z}\, P_{q\to qg}(z)\, q(x/z,\mu^2)$$

DGLAP flavour structure

The proton contains both quarks and gluons: DGLAP is a matrix in flavour space

$$\frac{\partial}{\partial \log \mu^2} \begin{pmatrix} q \\ g \end{pmatrix} = \begin{pmatrix} P_{q\to qg} & P_{g\to q\bar{q}} \\ P_{q\to gq} & P_{g\to gg} \end{pmatrix} \otimes \begin{pmatrix} q \\ g \end{pmatrix}$$

spanning over all flavours and anti-flavours

$$P_{q\to qg} = C_F \left(\frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z) \right)$$

$$P_{q\to gq} = C_F \, \frac{1+(1-z)}{z}$$

$$P_{g\to q\bar{q}} = T_R \left[z^2 + (1-z)^2 \right]$$

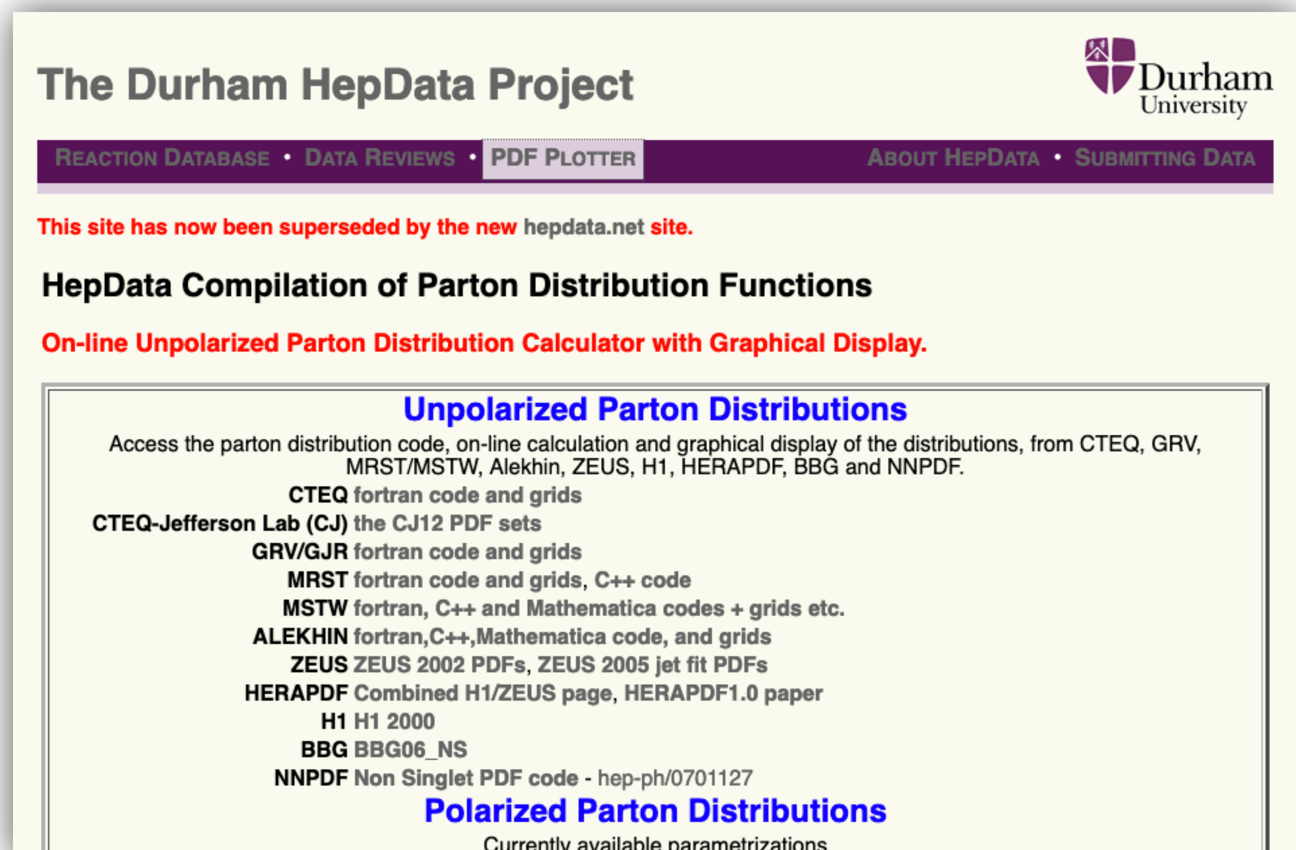
$$P_{g\to gg} = 2C_A \left[\frac{z}{(1-z)_+} + \frac{1-z}{z} + z(1-z) \right] + b_0\, \delta(1-z)$$

with the plus-prescription
$z = 1$ is soft: only soft configurations
matches virtual with real corrections

$$\int_0^1 dz \, \frac{f(z)}{(1-z)_+} = \int_0^1 dz \, \frac{f(z)-f(1)}{1-z}$$

Parton densities

- Non-perturbative input determined from global fits to collider data, scale evolution from pQCD (NNLO)
- Vast choice: e.g. http://hepdata.cedar.ac.uk/pdfs



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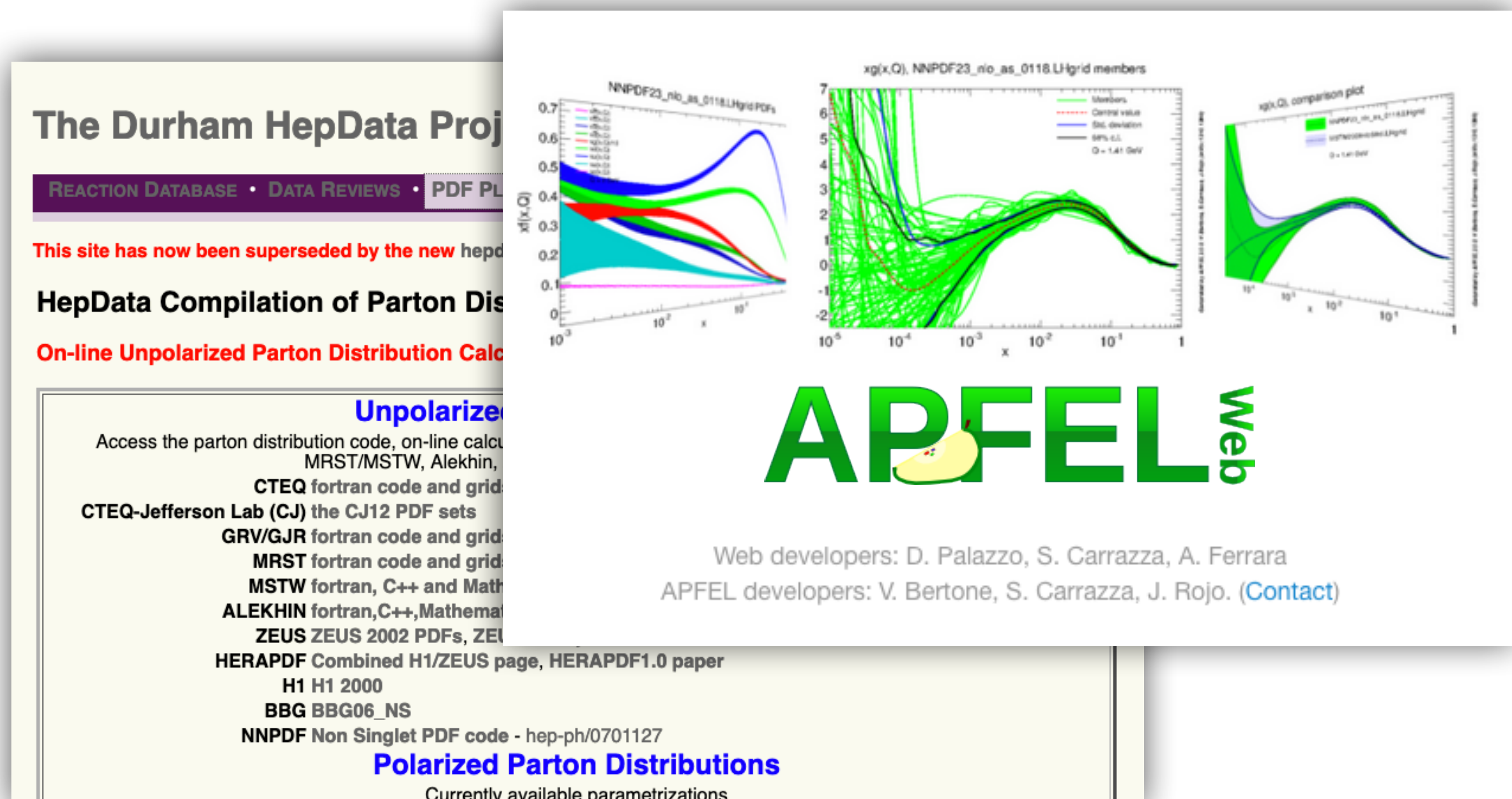


PDFs strategy in a nutshell

- Make an **ansatz** for the functional form of the PDFs at some fixed low scale value ($Q_0 \sim 1\ \mathrm{GeV}$): e.g. in MRST/MSTW

$$x\, u_V = A_u\, x^{\eta_1} (1-x)^{\eta_2} (1 + \epsilon_u \sqrt{x} + \gamma_u x) \qquad u_V = u - \bar{u}$$

$$x\, d_V = A_d\, x^{\eta_3} (1-x)^{\eta_4} (1 + \epsilon_d \sqrt{x} + \gamma_d x) \qquad d_V = d - \bar{d}$$

$$x\, g = A_g\, x^{-\lambda_g} (1-x)^{\eta_g} (1 + \epsilon_g \sqrt{x} + \gamma_g x)$$

- Note: **NNPDF** use neural networks and does not need such explicit functional form

- Collect data at various (x, Q^2) from different experiments (e.g. DIS), use DGLAP equations to evolve down to Q_0 and fit parameters, including α_S

- Ensure sum rules: (Gottfried, momentum, …).

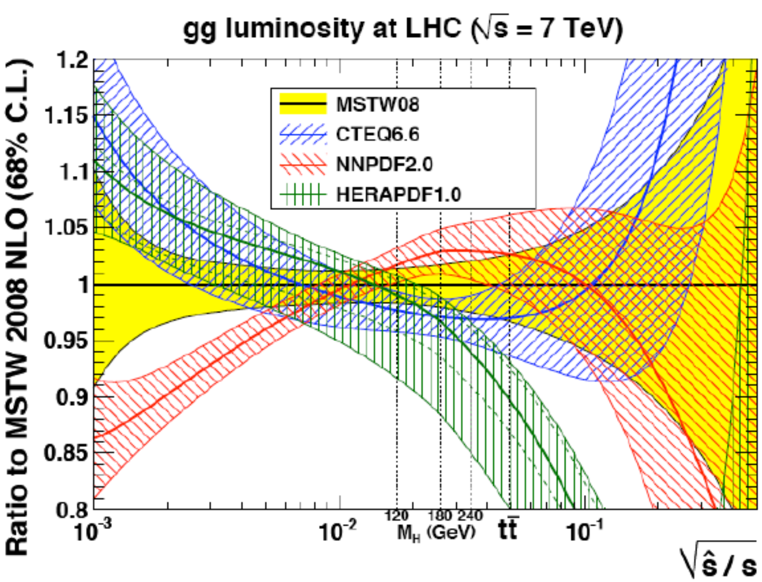
$$\int dx\, x \sum_i f_i(x, Q^2) = 1$$

Parton densities

- Differences are due to different:

Data sets in fits, parameterization of starting distributions, order of pQCD evolution, power law contributions, nuclear target corrections, resummation corrections (ln 1/x, …), treatment of heavy quarks, strong coupling, choice of factorization and renormalization scales.

- at least 5-10% uncertainty in theoretical predictions



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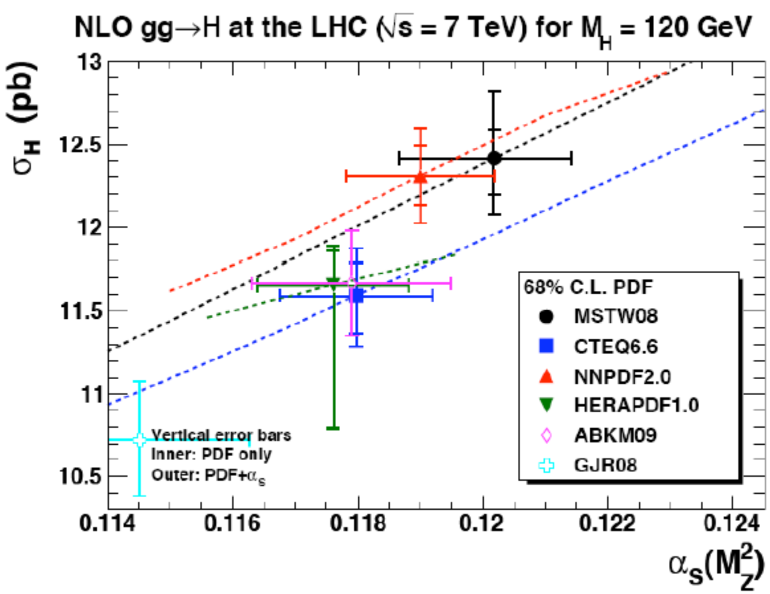
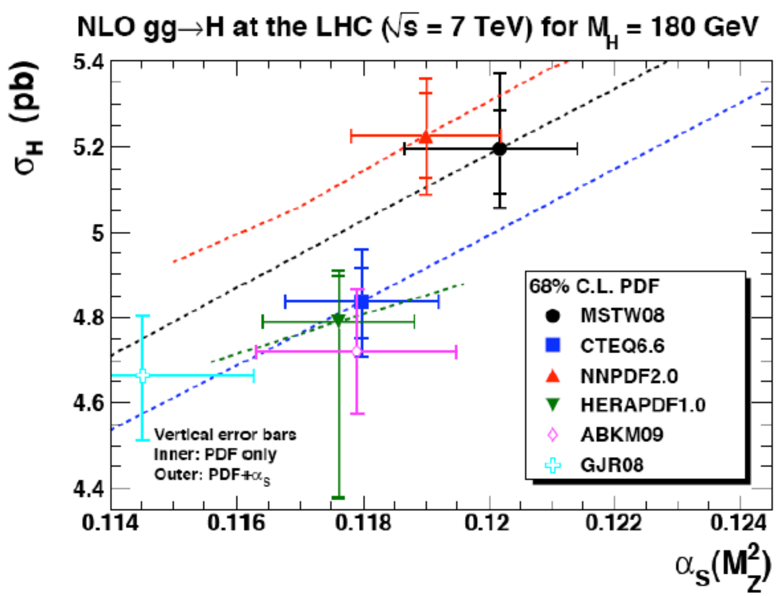




Online PDF plotting and calculation

xf(x,Q2) *v* **x**

Using the form below you can calculate, in real time, values of *xf(x,Q^2)* for any of the PDFs from the different groups. You can also generate and compare plots of *xf(x,Q^2) v x* at any *Q^2* for up to 4 different parton types or PDF sets.

Select:	Parton	Group	Set
☑	up	MSTW-nnlo	MSTW2008nnlo
☑	down	MSTW-nnlo	MSTW2008nnlo
☑	strange	MSTW-nnlo	MSTW2008nnlo
☑	gluon	MSTW-nnlo	MSTW2008nnlo

Xmin = 0.01 Xmax = 0.8 Xinc = 0.01

Q2 = 1 GeV**2

x axis: ○ lin ◉ log

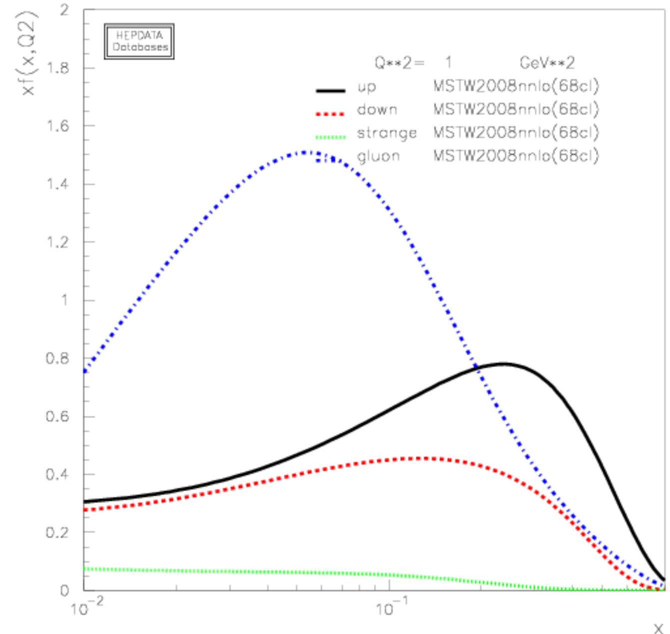
y axis: ◉ lin ○ log, ymin= 0.0 ymax = 2.0

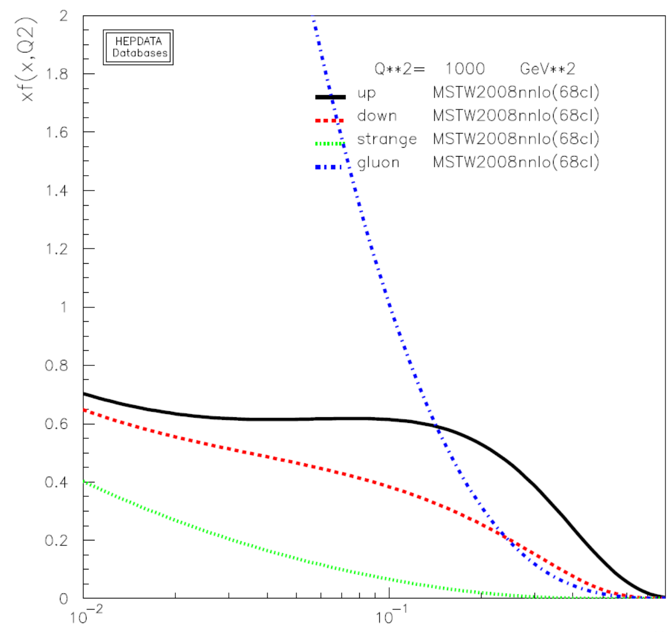
Output as: ○ numbers or ◉ plot (line width = 10) as ratio ☐

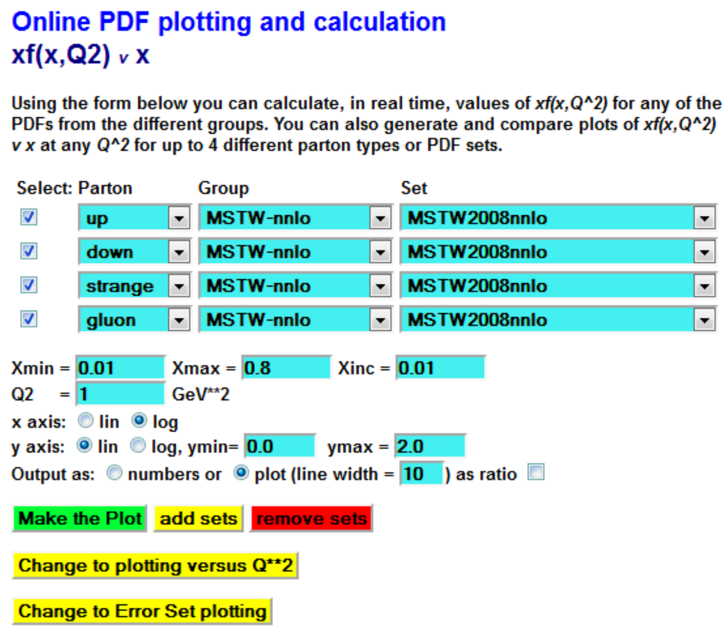
Make the Plot | add sets | remove sets

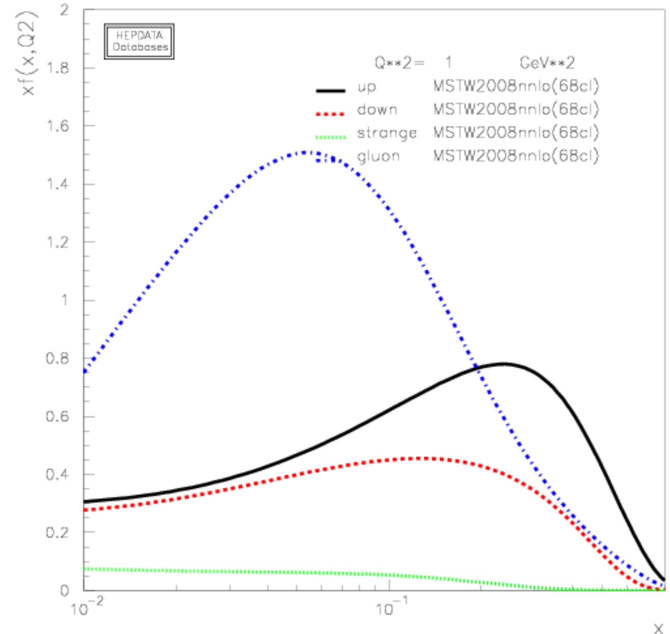
Change to plotting versus Q**2

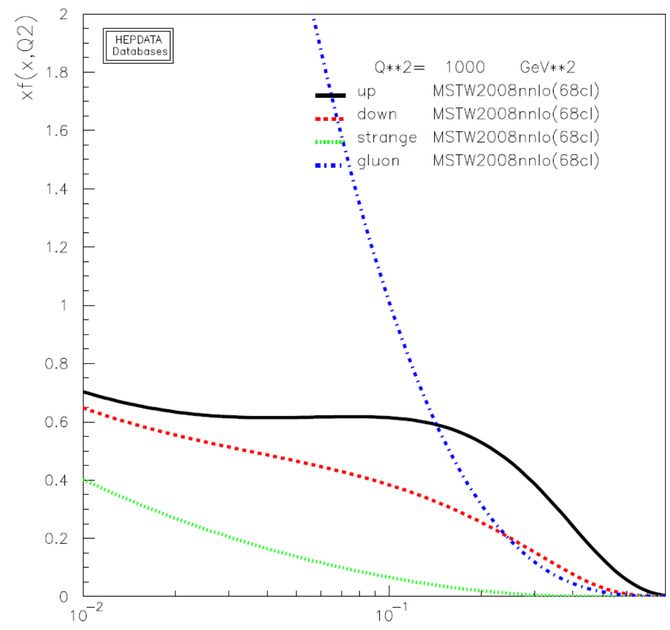
Change to Error Set plotting



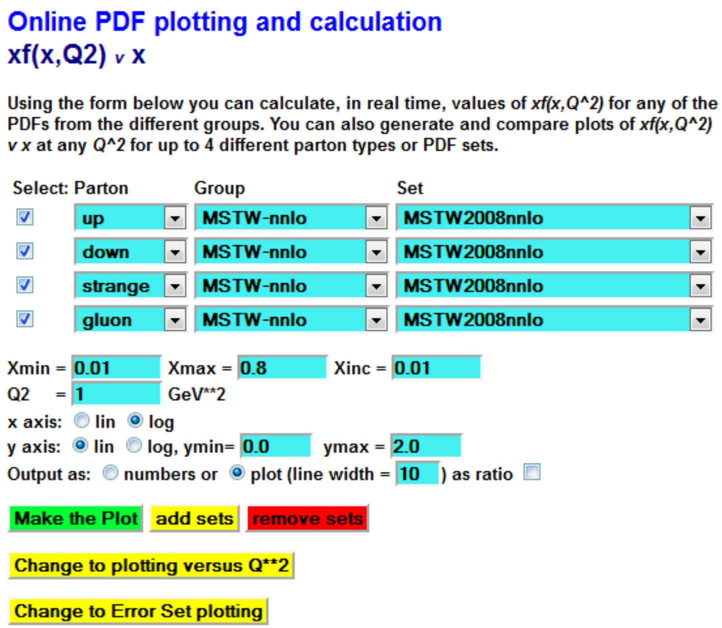


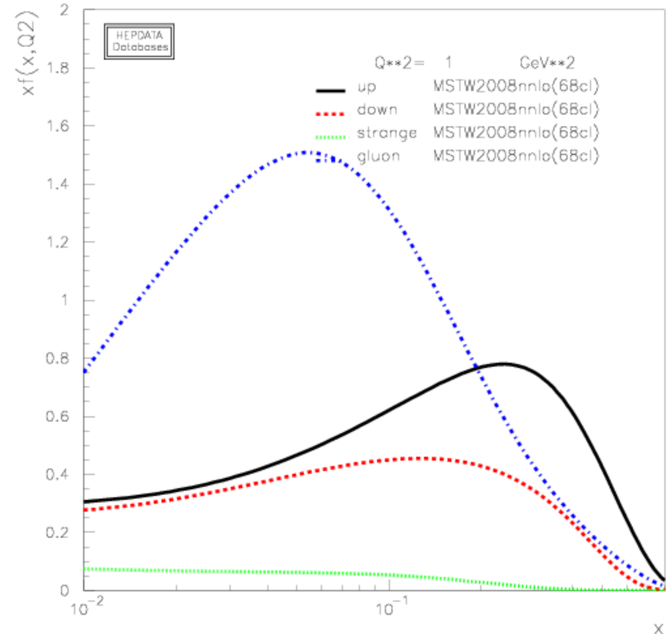


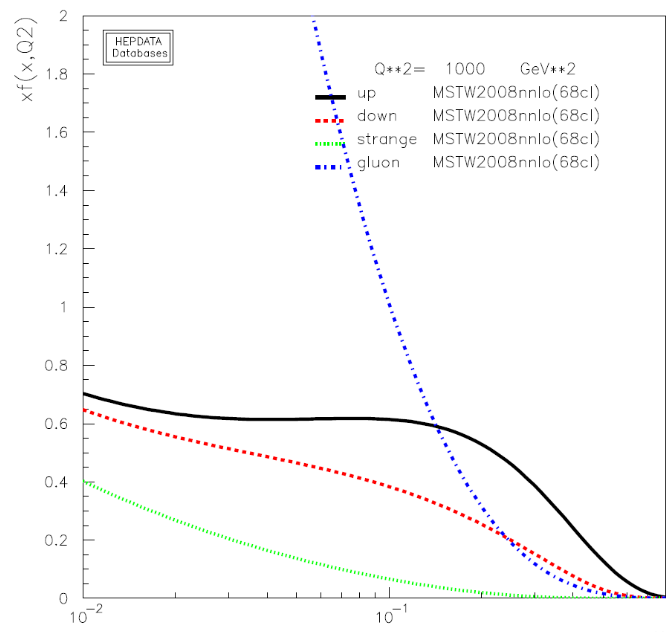




- Maximum of up and down at x=1/3: three quarks sharing the proton momentum







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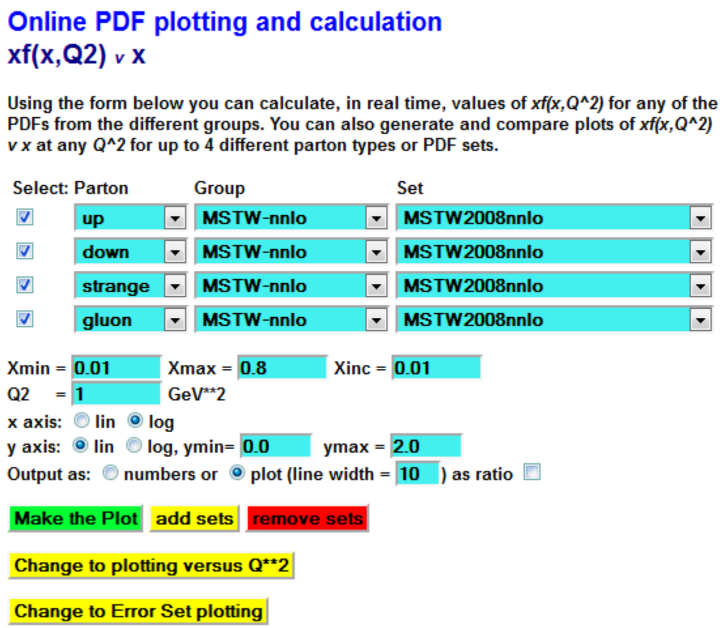

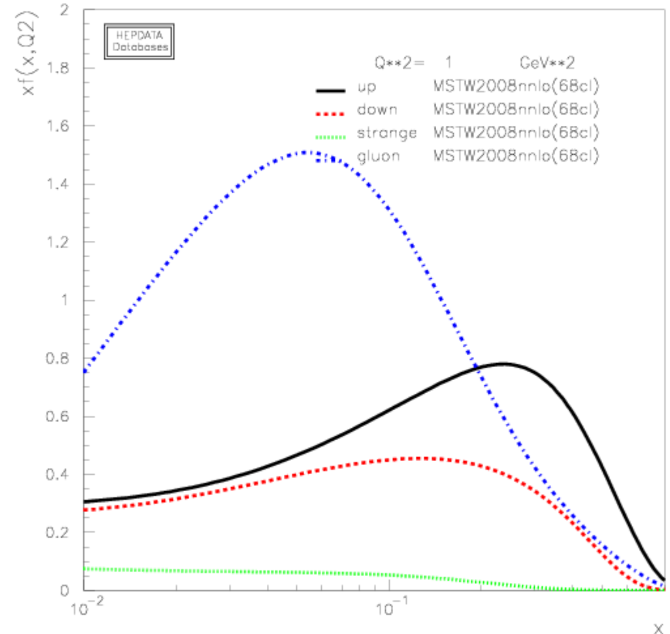

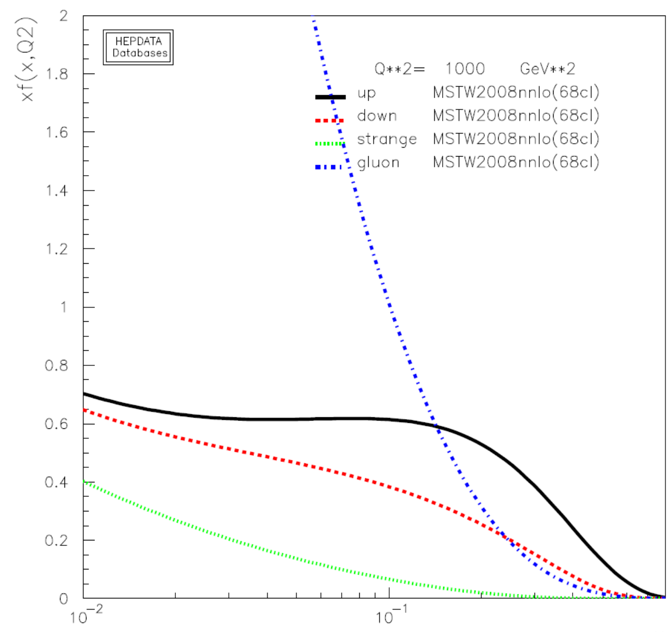

- Maximum of up and down at x=1/3: three quarks sharing the proton momentum
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- gluon density evolves faster: colour charge $C_A = 3$ versus quark colour charge $C_F = 4/3$

Jets

What´s a jet

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- a bunch of energetic and collimated particles

What´s a jet

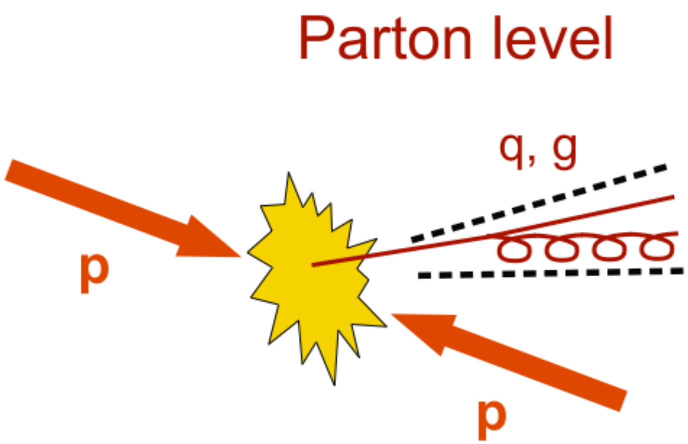
- a bunch of energetic and collimated particles
- 60% of LHC papers use jets [Salam, Soyez]

Why and how do we see jets?

Gluon emission

$$\int \alpha_S \frac{dE}{E} \frac{d\theta}{\theta} \gg 1$$

higher probability at small angle (collinear) and small energy (soft)



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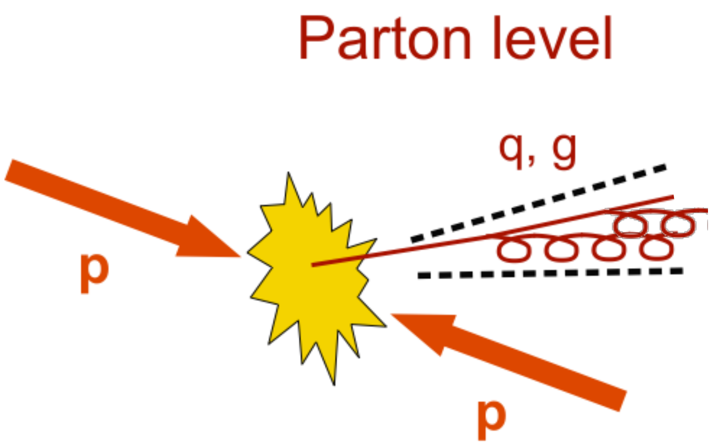

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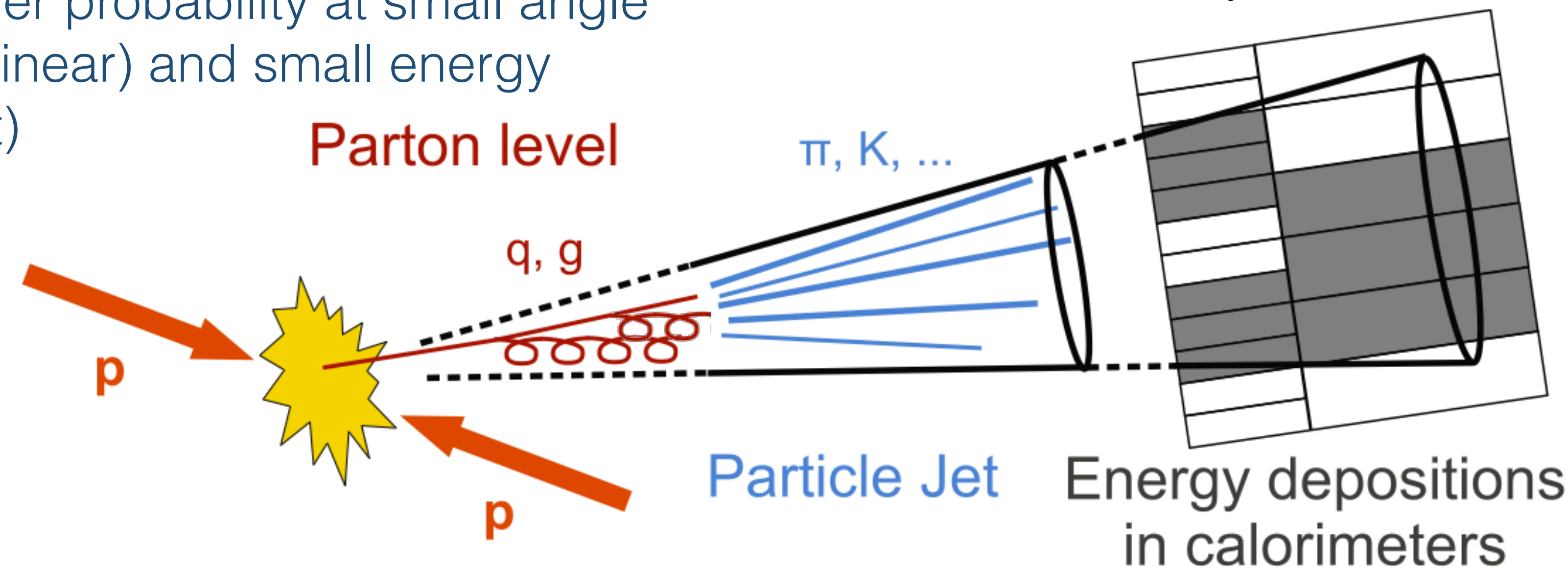

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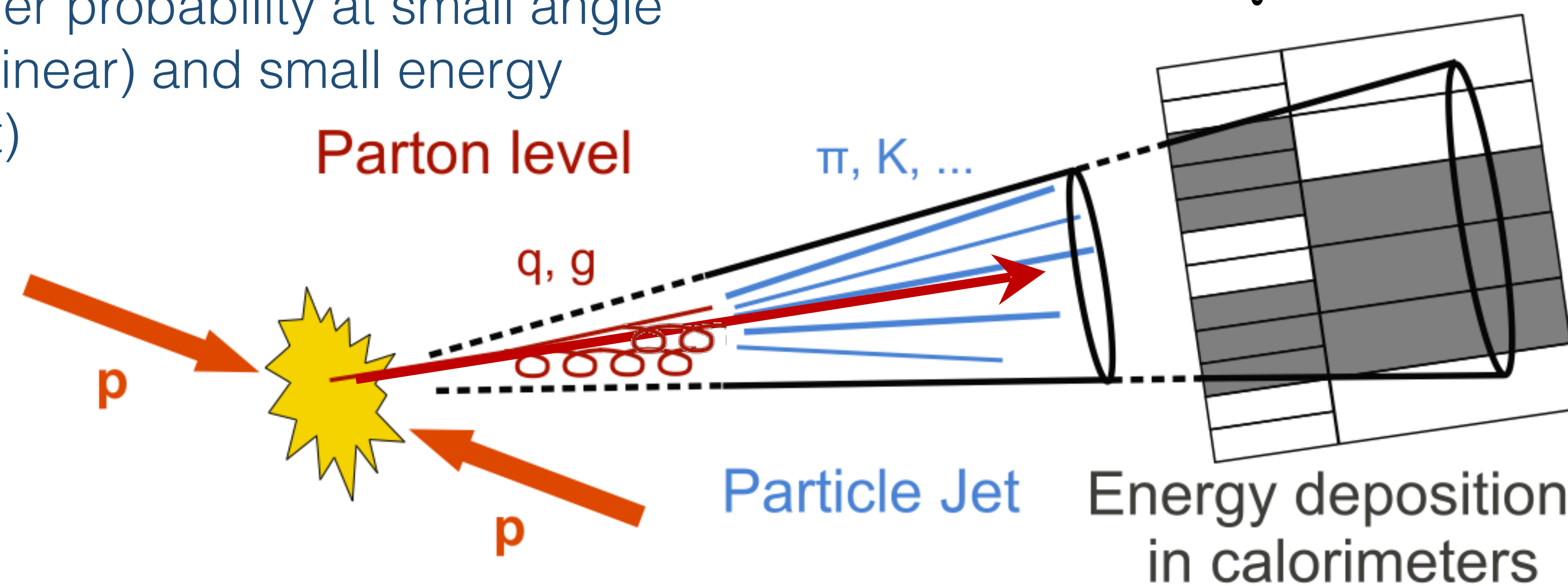

$\{j_k\}$ jet definition $\longleftarrow$ $\{p_i\}$

jets

final-state 4-momenta

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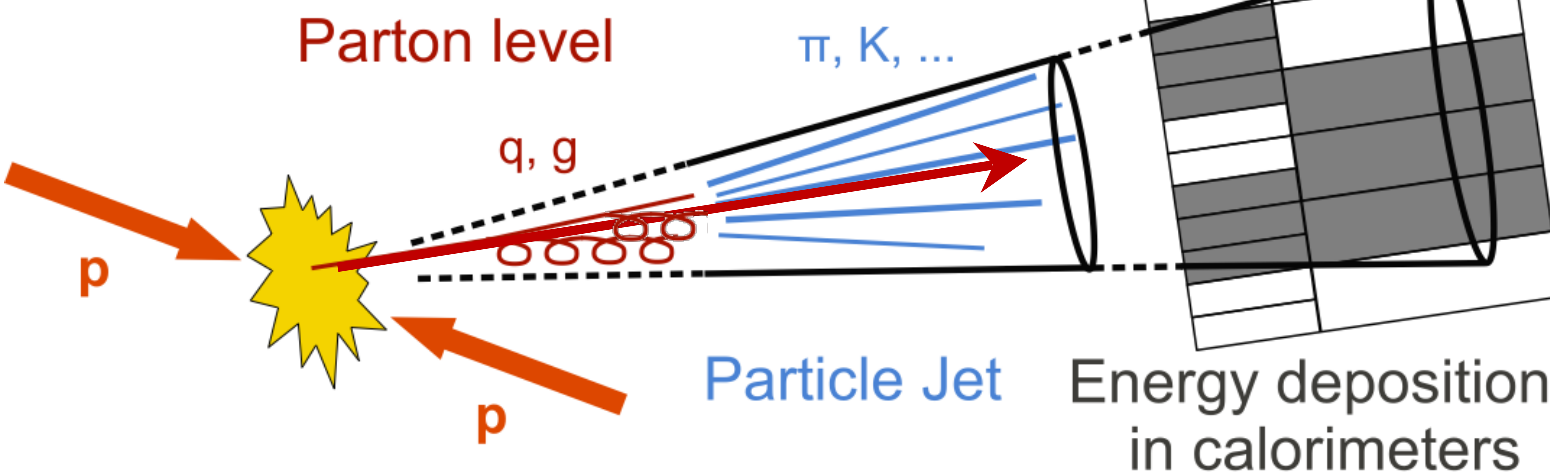


hard partons $\xleftarrow{\text{interpretation}}$ $\{j_k\}$ jets $\xleftarrow{\text{jet definition}}$ $\{p_i\}$ final-state 4-momenta

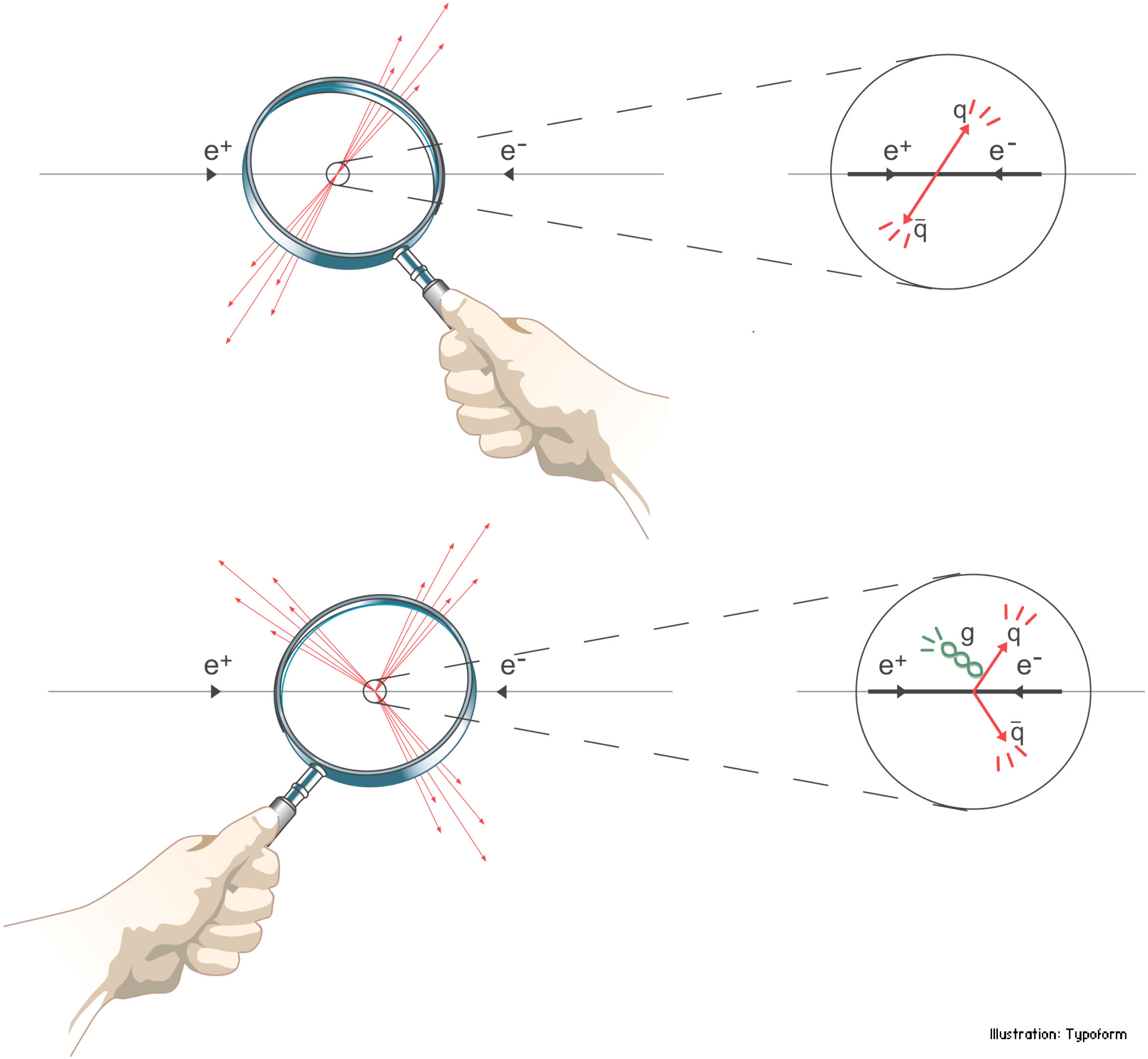
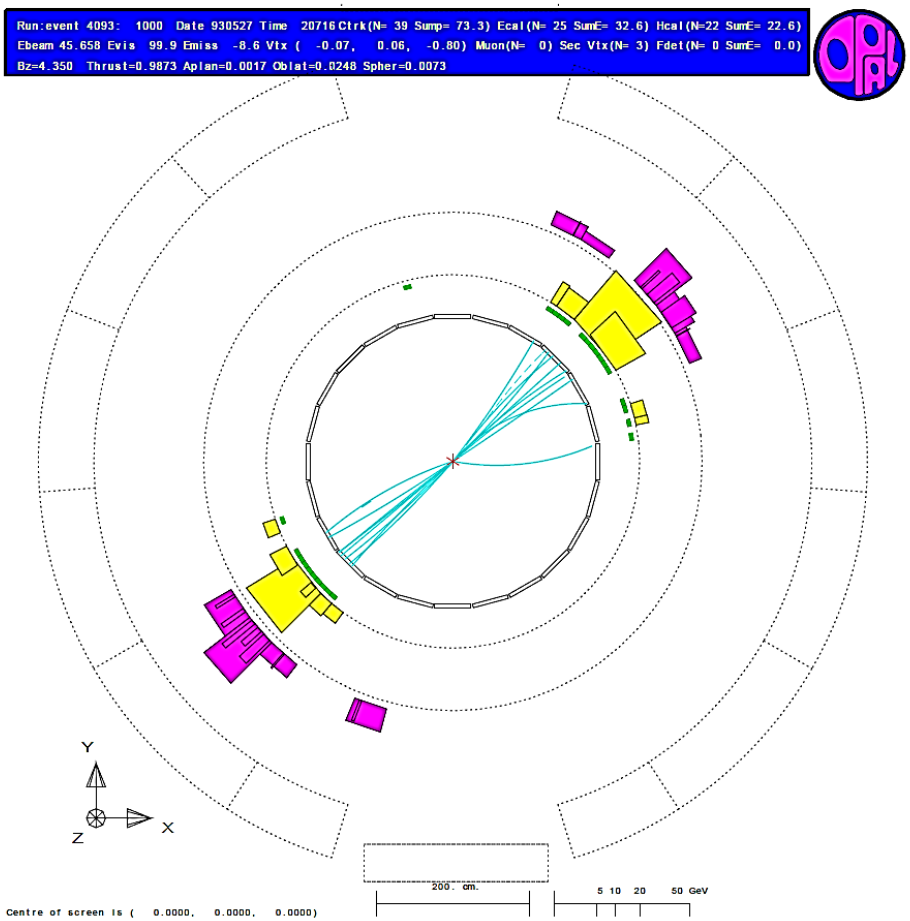
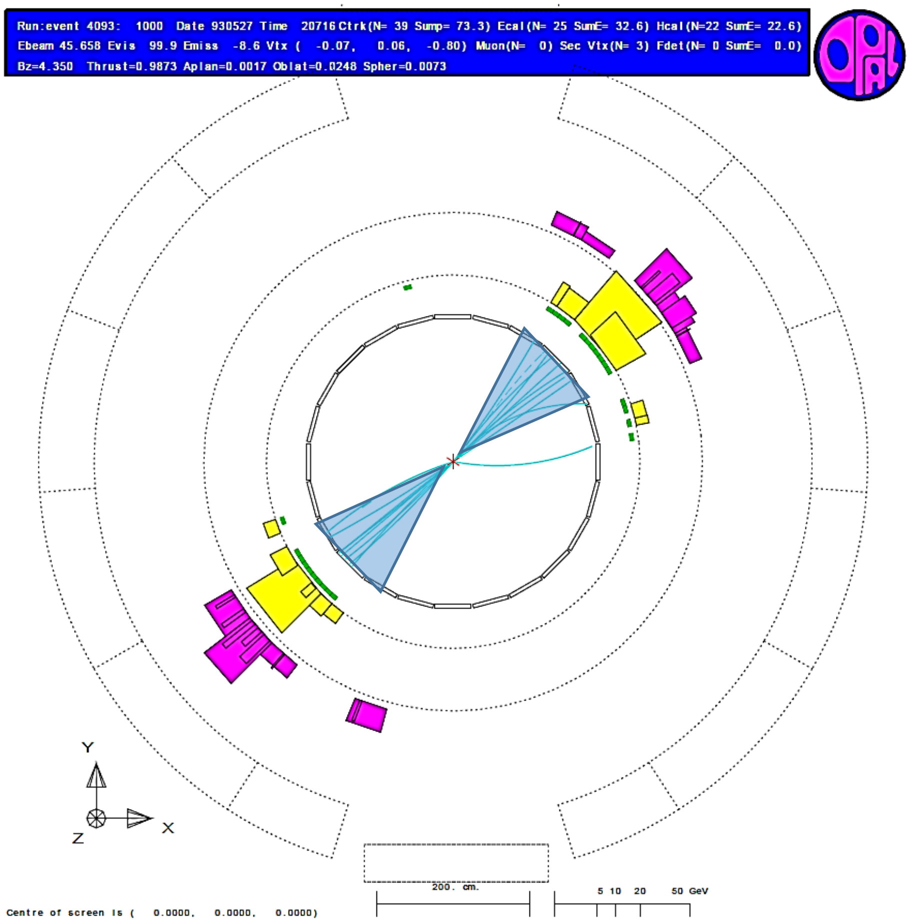
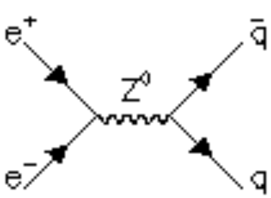


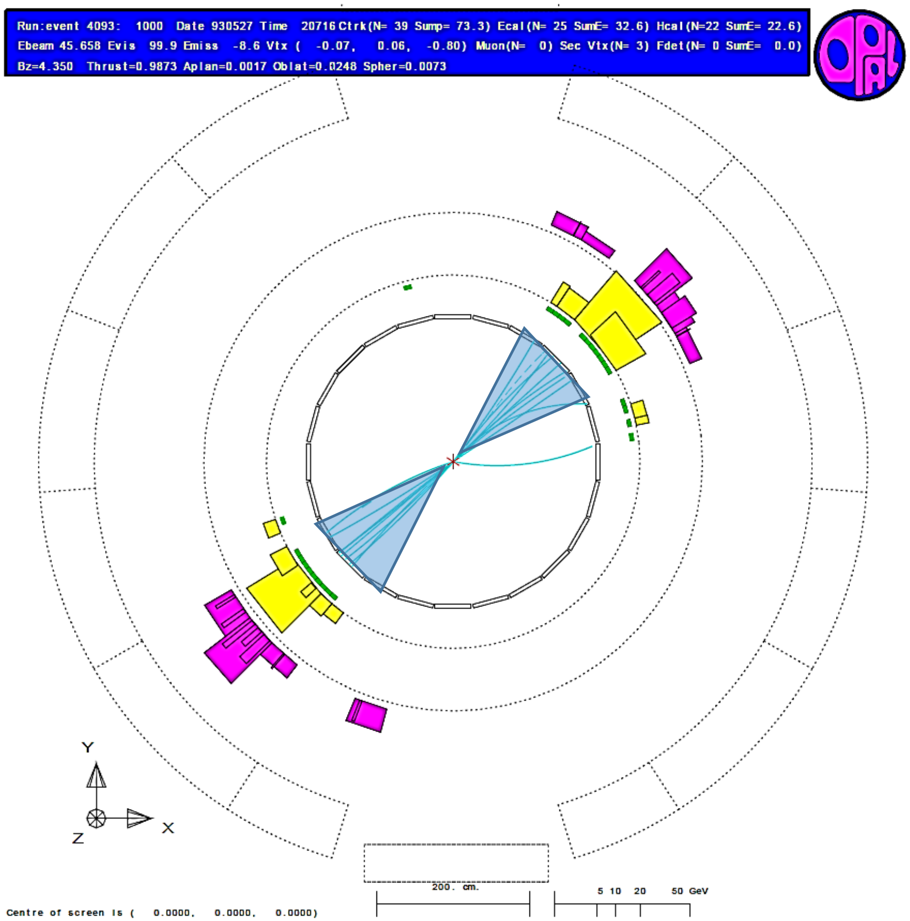
Illustration: Typoform

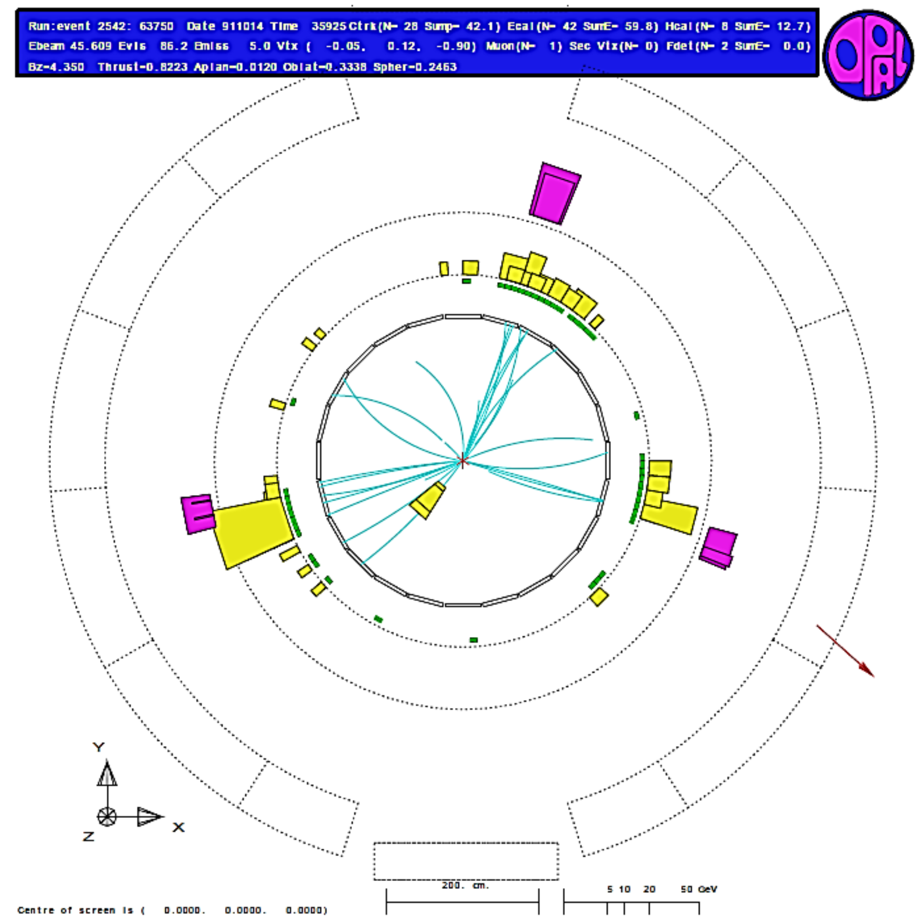

Run:event 4093: 1000 Date 930527 Time 20716 Ctrk(N= 39 Sump= 73.3) Ecal(N= 25 SumE= 32.6) Hcal(N=22 SumE= 22.6)
Ebeam 45.658 Evis 99.9 Emiss -8.6 Vtx (-0.07, 0.06, -0.80) Muon(N= 0) Sec Vtx(N= 3) Fdet(N= 0 SumE= 0.0)
Bz=4.350 Thrust=0.9873 Aplan=0.0017 Oblat=0.0248 Spher=0.0073
Y
X
Z
200. cm.
5 10 20 50 GeV
Centre of screen is (0.0000, 0.0000, 0.0000)

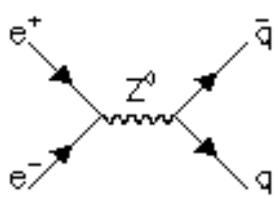




- Clearly
a two-jet event







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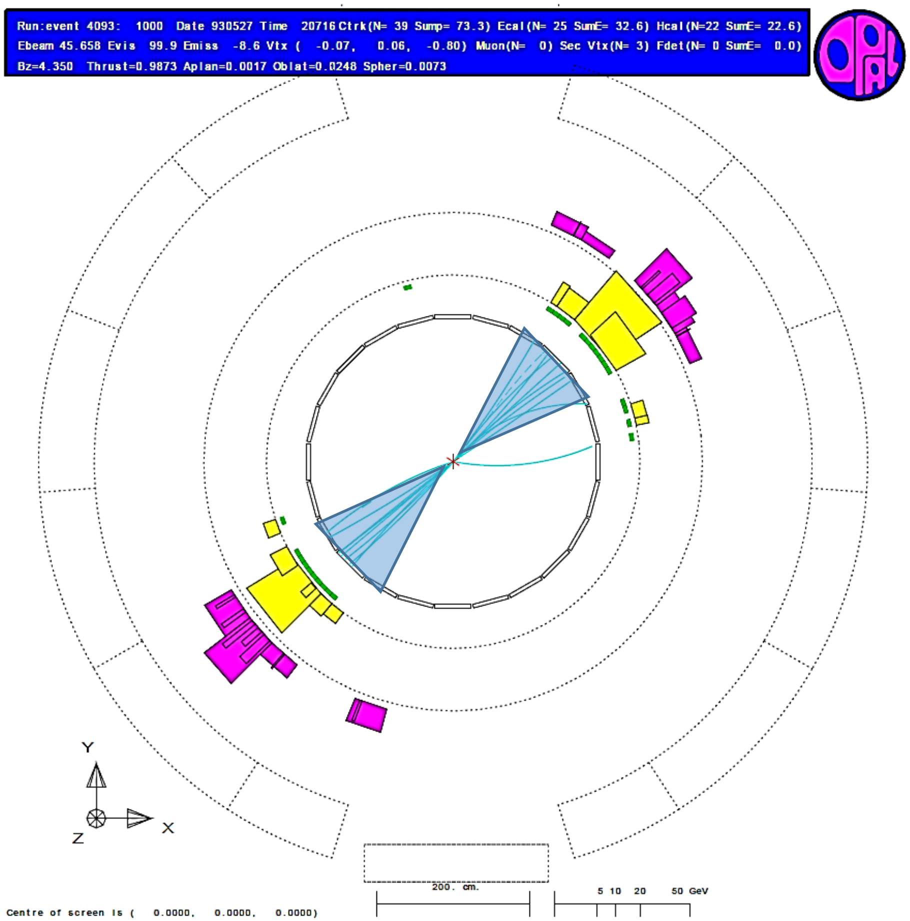

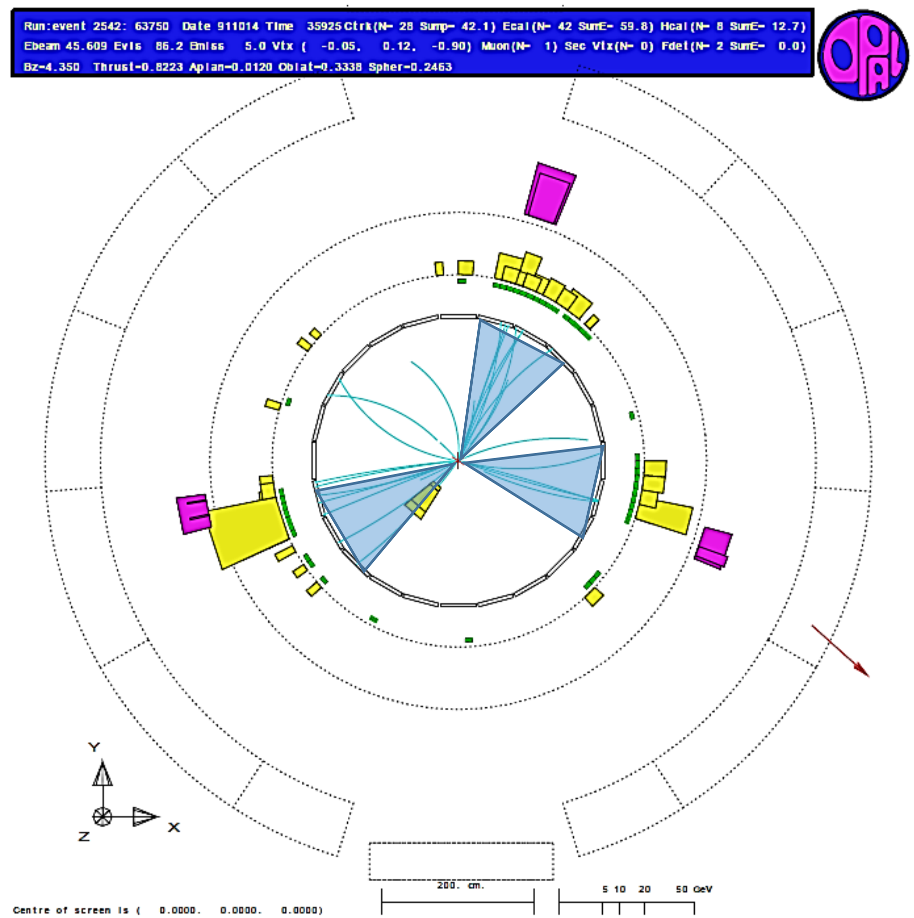

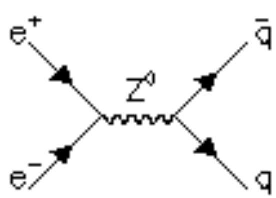

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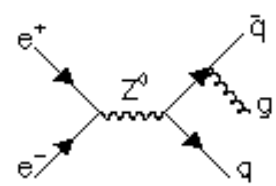

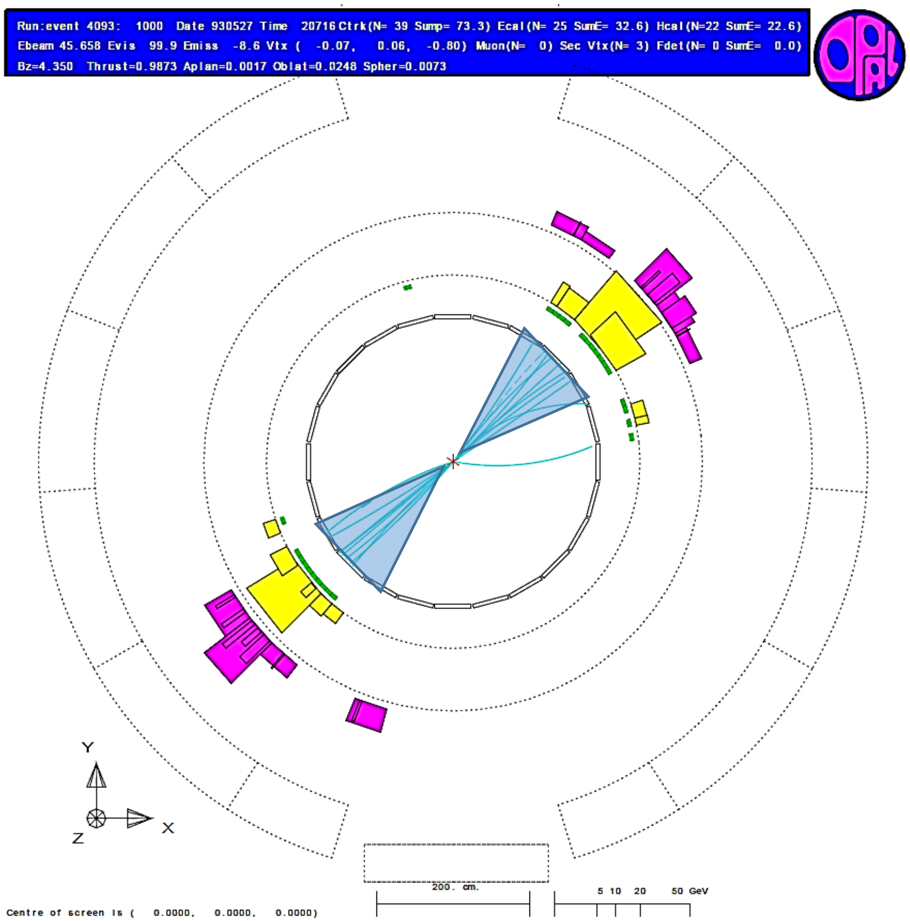

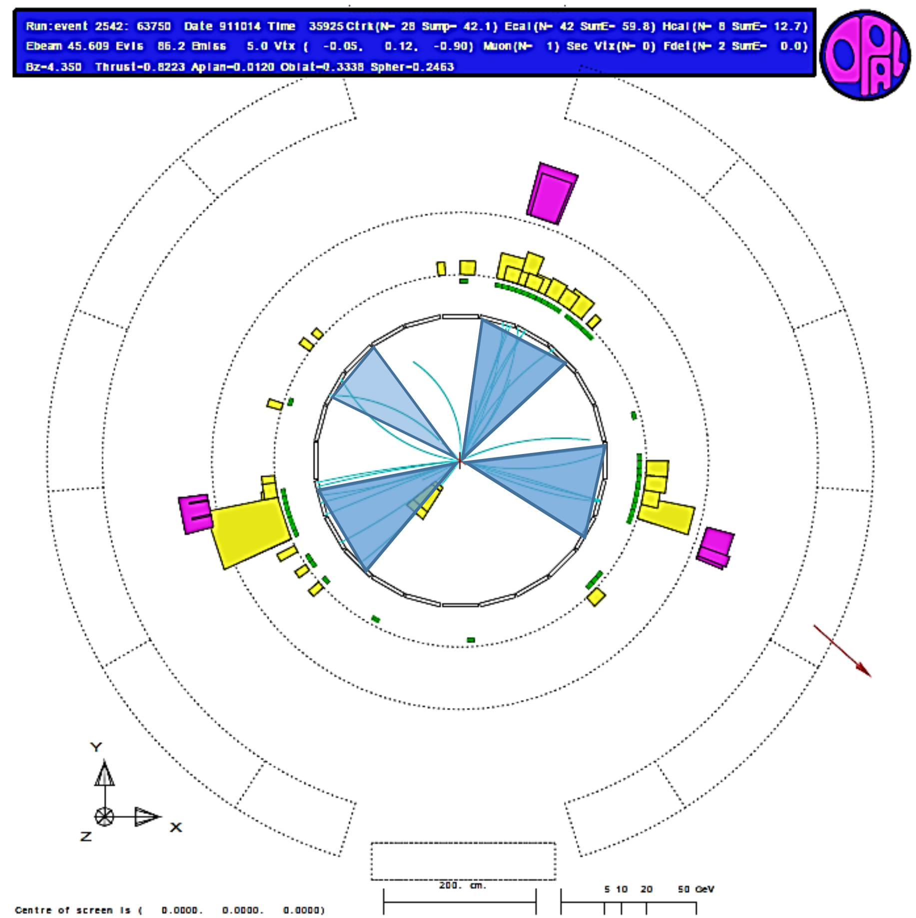

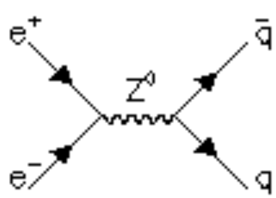

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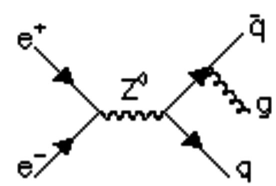

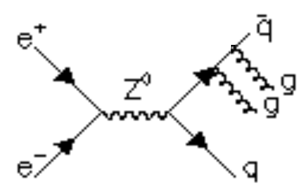

- Three- or four-jet event ?
- Depends on the jet resolution parameter

The k_T algorithm at hadron colliders

[Catani, Dokshitzer, Seymour, Webber, 93]
[Ellis, Soper, 93]

- Define distance among particles: e.g. $d_{ij} = (p_i + p_j)^2$

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- Two parameters R and minimal transverse momentum $p_{Ti} > p_{T,\min}$

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$$y = \frac{1}{2}\log\frac{E + p_z}{E - p_z} \quad \neq \quad \eta = -\log(\tan(\theta/2)) \quad \text{for massive particles}$$

The anti-k_T algorithm

[Cacciari, Salam, Soyez 08]

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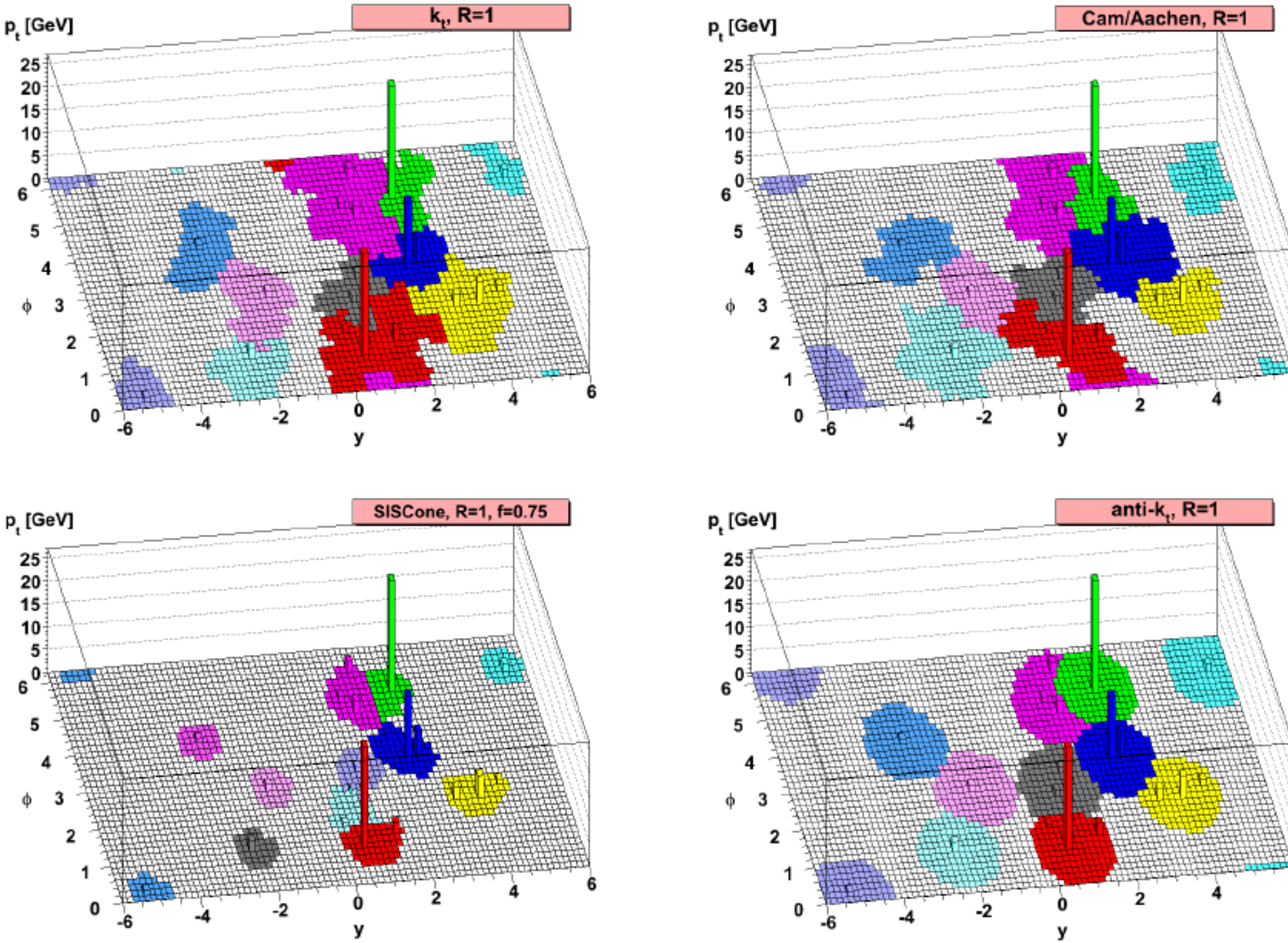
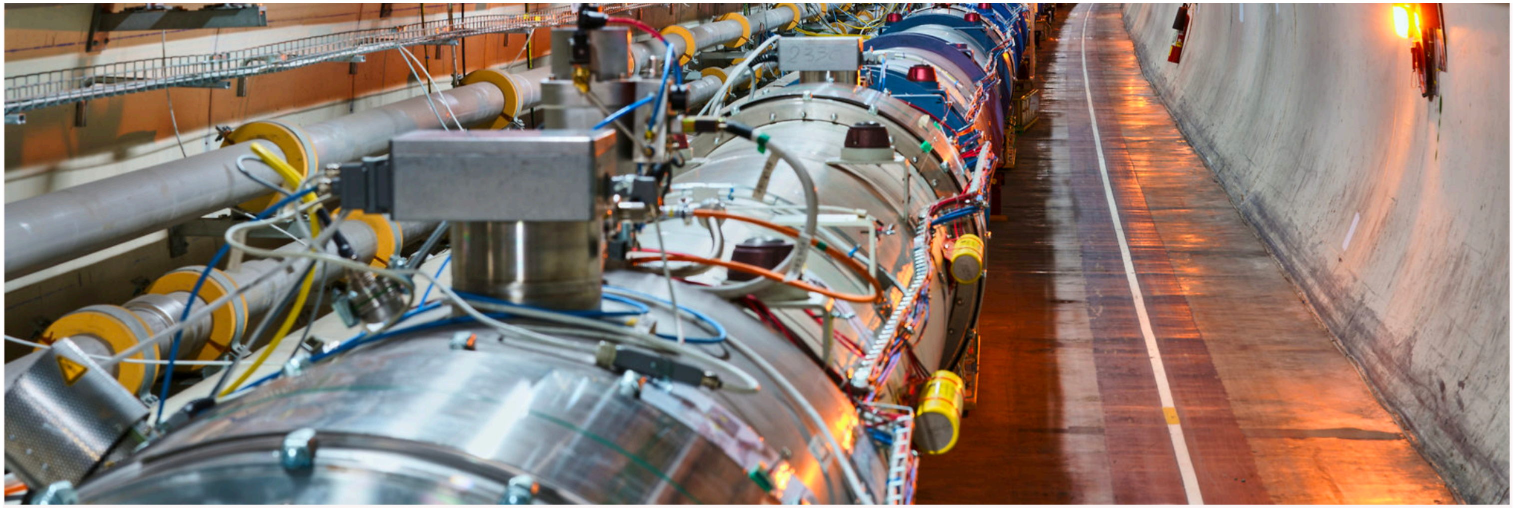


“ Precise measurements of known particles and interactions are just as important as finding new particles symmetry topics



Maximilien Brice and Julien Marius Ordan, CERN

The unseen progress of the LHC

05/02/19 | By Sarah Charley

It's not always about what you discover.

"This work naturally pushes our search methods towards making more detailed and higher precision measurements that will help us constrain possible deviations by new physics," Willocq says.

Exploring through precision

The universe is full of fields, and what we think of as particles are just excitations of those fields, like waves in an ocean. An electron, for example, is just an excitation of an electron field. Resonances and wave crests break up out of the fields and thus we reproduce very rare processes study to search for new physics. The key to observe these very rare processes is a particle accelerator for electrons and anti-electrons in a new 100 km tunnel.

http://codeoftheuniverse.web.cern.ch/