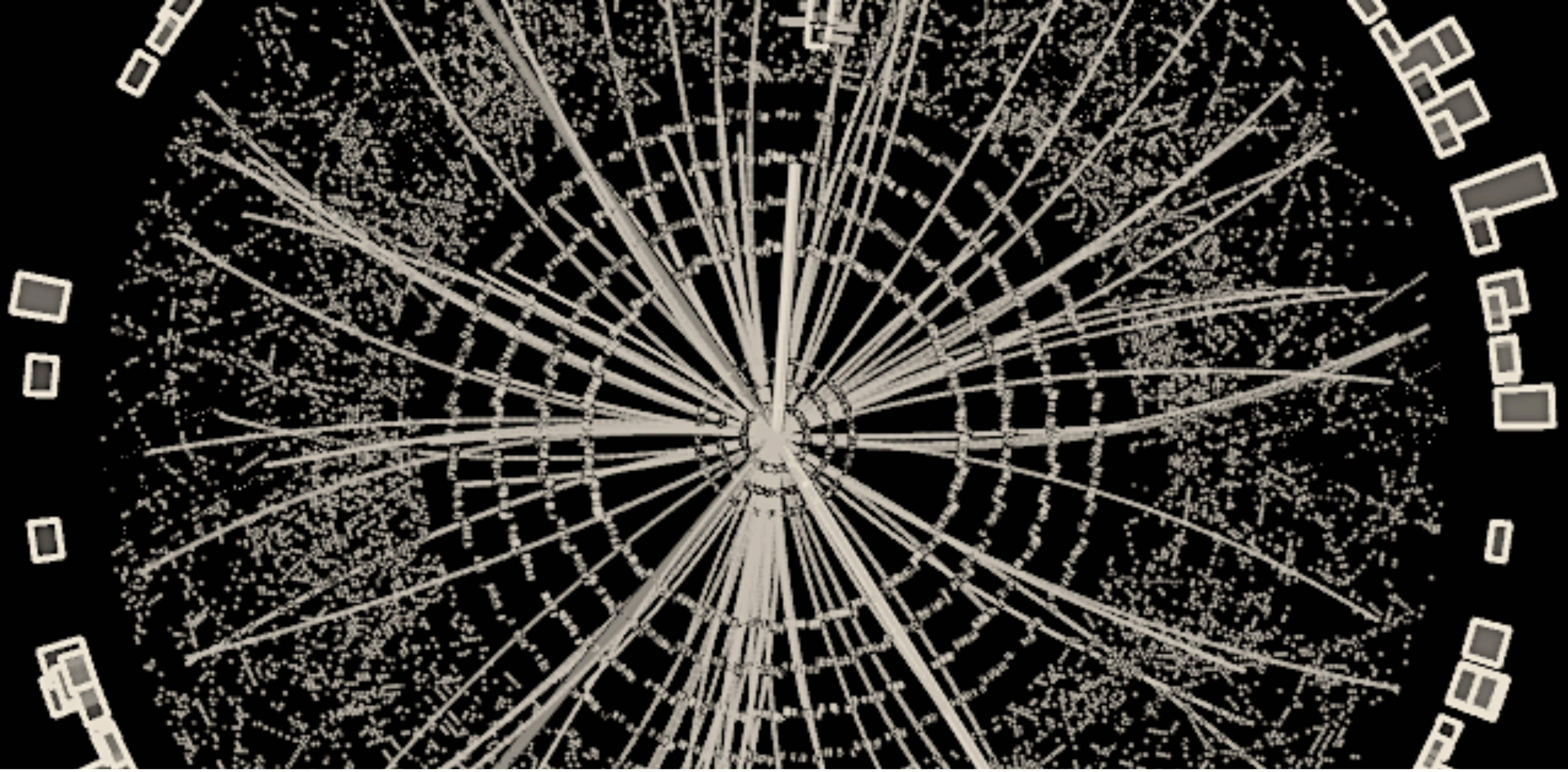


PHYSICS AT COLLIDERS I

Laura Jeanty
University of Oregon

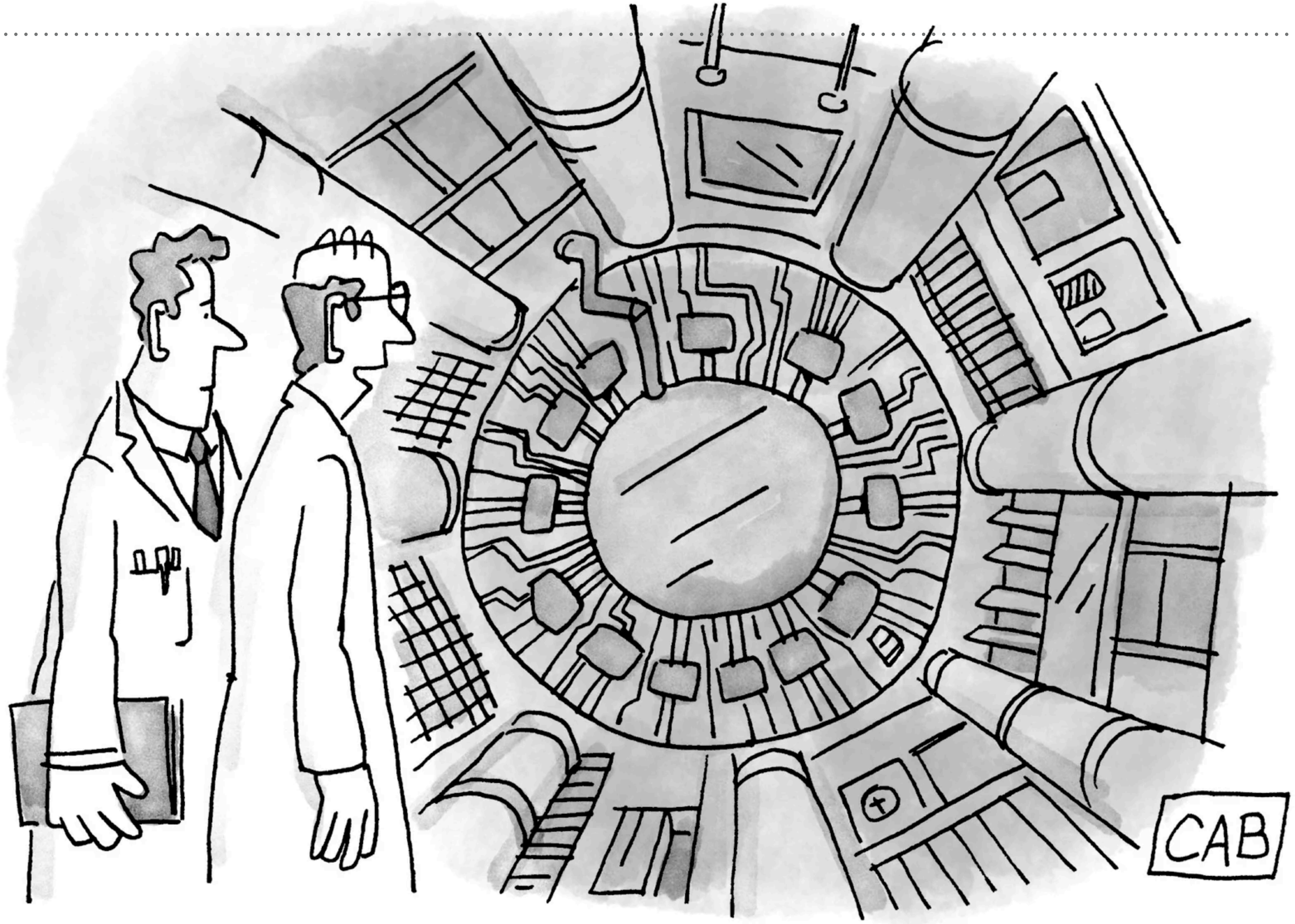
TRISEP Summer School, July 2022

OUTLINE

- **Lecture I**
  - Collider overview
  - Cross-sections in principle and in practice
  - QCD, W/Z, and precision electroweak physics

- **Lecture II**
  - Top and Flavour Physics
  - The Higgs Boson
  - Searches for new physics

WHY COLLIDERS



"Once you have a collider, every problem starts to look like a particle."

the New Yorker

WHY COLLIDERS: EXPLORING THE TEV SCALE TO ANSWER OPEN QUESTIONS

Big Questions

Evolution of early Universe

Matter Antimatter Asymmetry

Nature of Dark Matter

Origin of Neutrino Mass

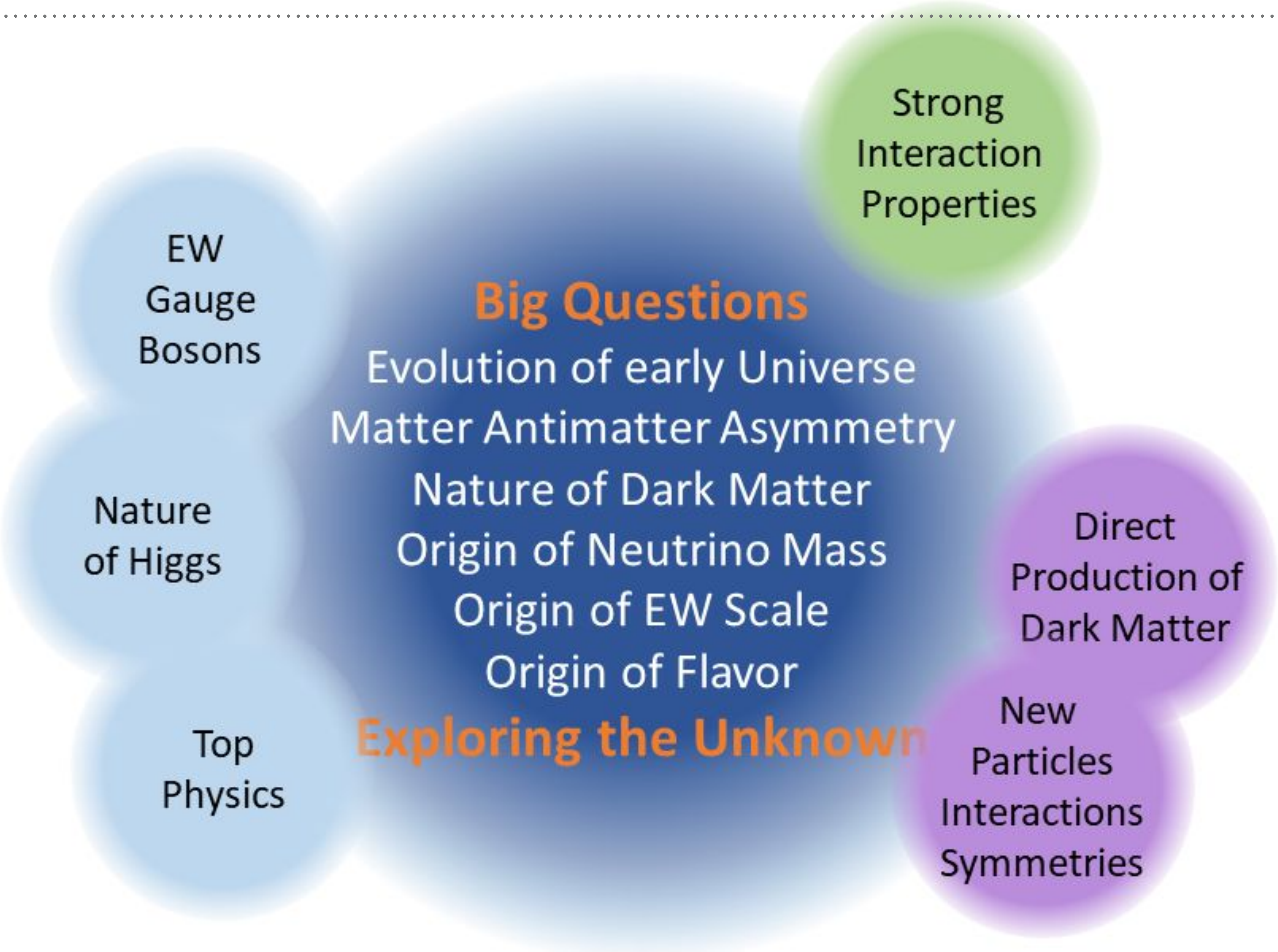
Origin of EW Scale

Origin of Flavor

Exploring the Unknown

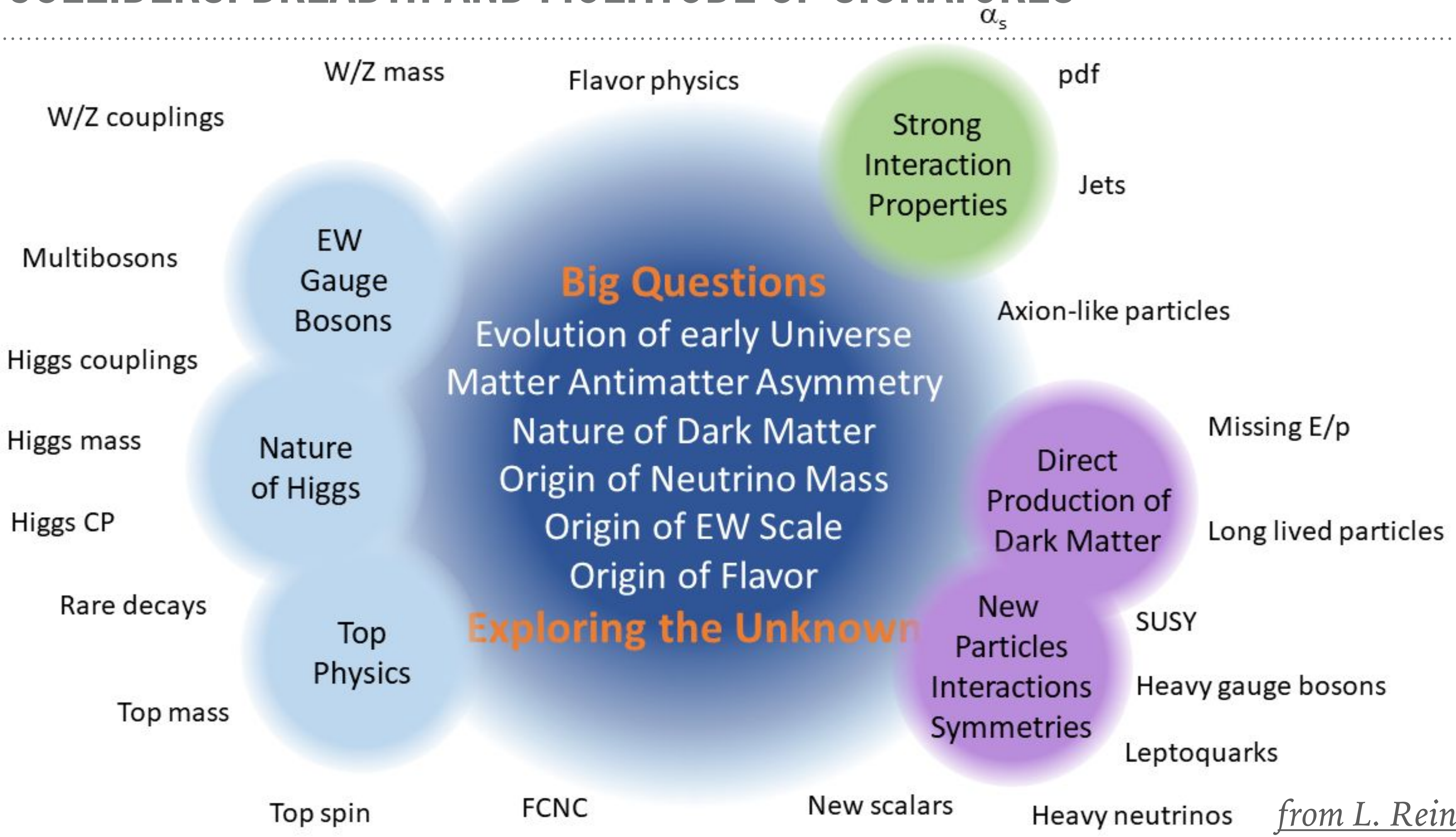
from L. Reina

WHY COLLIDERS: USING SM PROBES AND SEARCHING FOR BSM



from L. Reina

WHY COLLIDERS: BREADTH AND MULTITUDE OF SIGNATURES



from L. Reina

WHY COLLIDERS

- Probe structure of matter and fundamental constituents
  - Special resolution limited by wavelength of probe
  - $\lambda = h/p$
- Search for new particles and interactions
  - Indirect measurements can point to new physics
  - $E = mc^2$
  - Need high energy to observe new physics

Rutherford experiment
$p \sim 10$ keV, $\lambda \sim 10^{-10}$ m

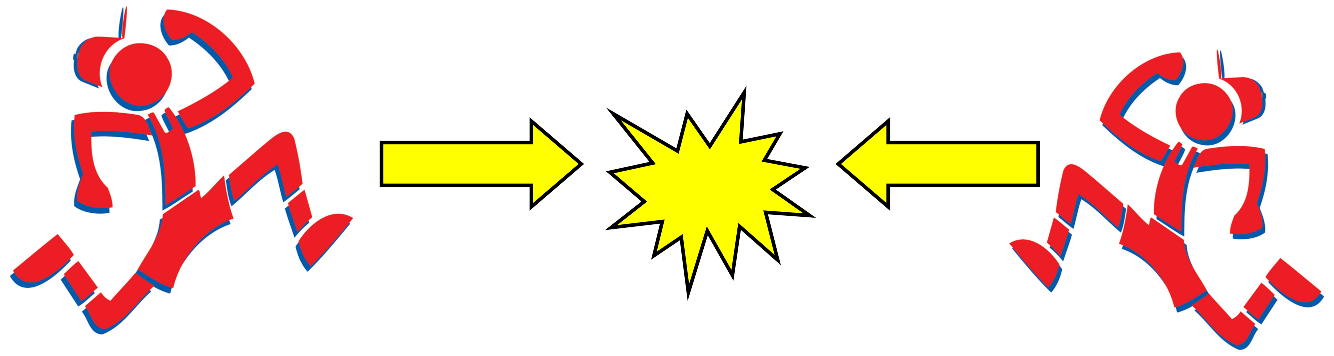
Discovery of quarks
$p \sim 10$ GeV, $\lambda \sim 10^{-16}$ m

LHC
$p \sim 10$ TeV, $\lambda \sim 10^{-19}$ m

LEPTON AND HADRON COLLIDERS

- **Lepton colliders**
  - electron — positron (so far)
  - All beam energy used to make new particles
  - Can tune center-of-mass energy
  - Energy limited by synchrotron radiation
  - Precision measurements

Lepton Collider
(collision of two point-like particles)



Synchrotron Radiation
Energy loss per turn

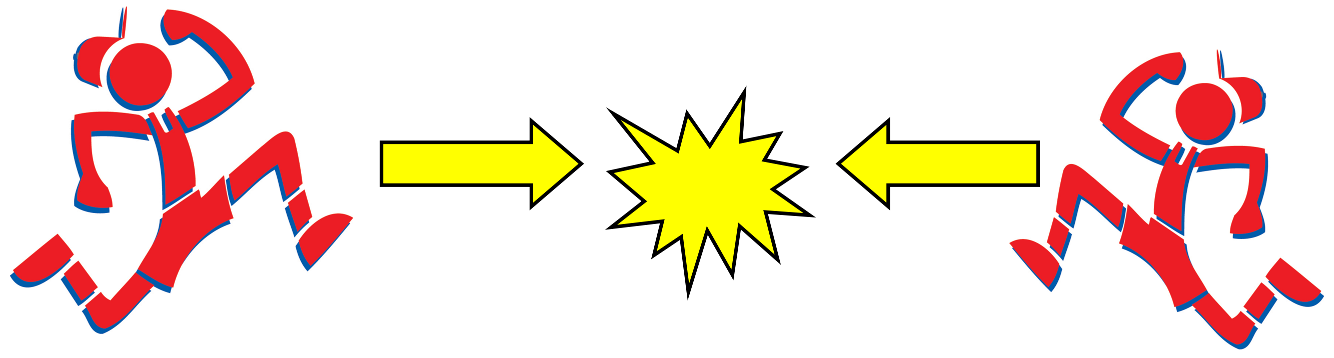
$$-\Delta E \approx \frac{4\pi^2}{3R^2}\left(\frac{E}{mc^2}\right)^4$$

for ring of radius R and energy E

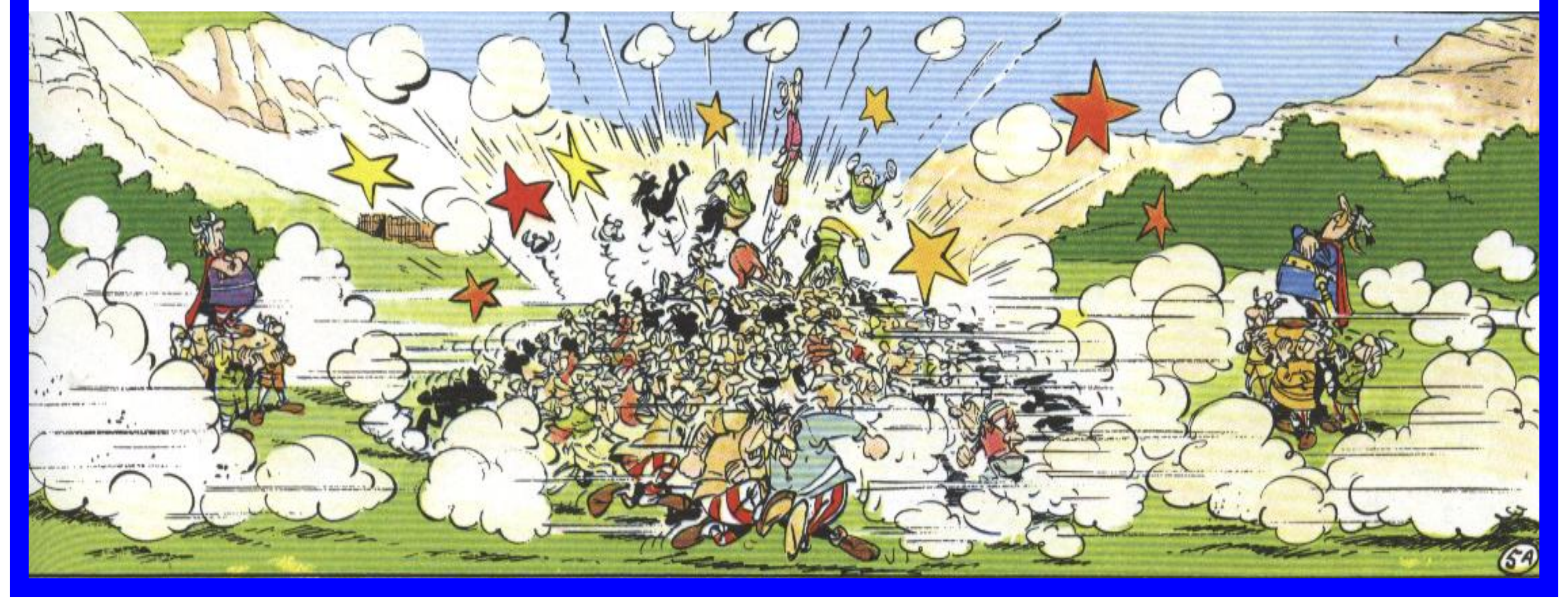
LEPTON AND HADRON COLLIDERS

- **Lepton colliders**
  - electron — positron (so far)
  - All beam energy used to make new particles
  - Can tune center-of-mass energy
  - Energy limited by synchrotron radiation
  - Precision measurements
- **Hadron colliders**
  - Hard collision uses only a fraction of beam energy
  - Can probe high energy, less radiation when accelerated
  - Probe a range of energies at once
  - Discovery machines

Lepton Collider
(collision of two point-like particles)

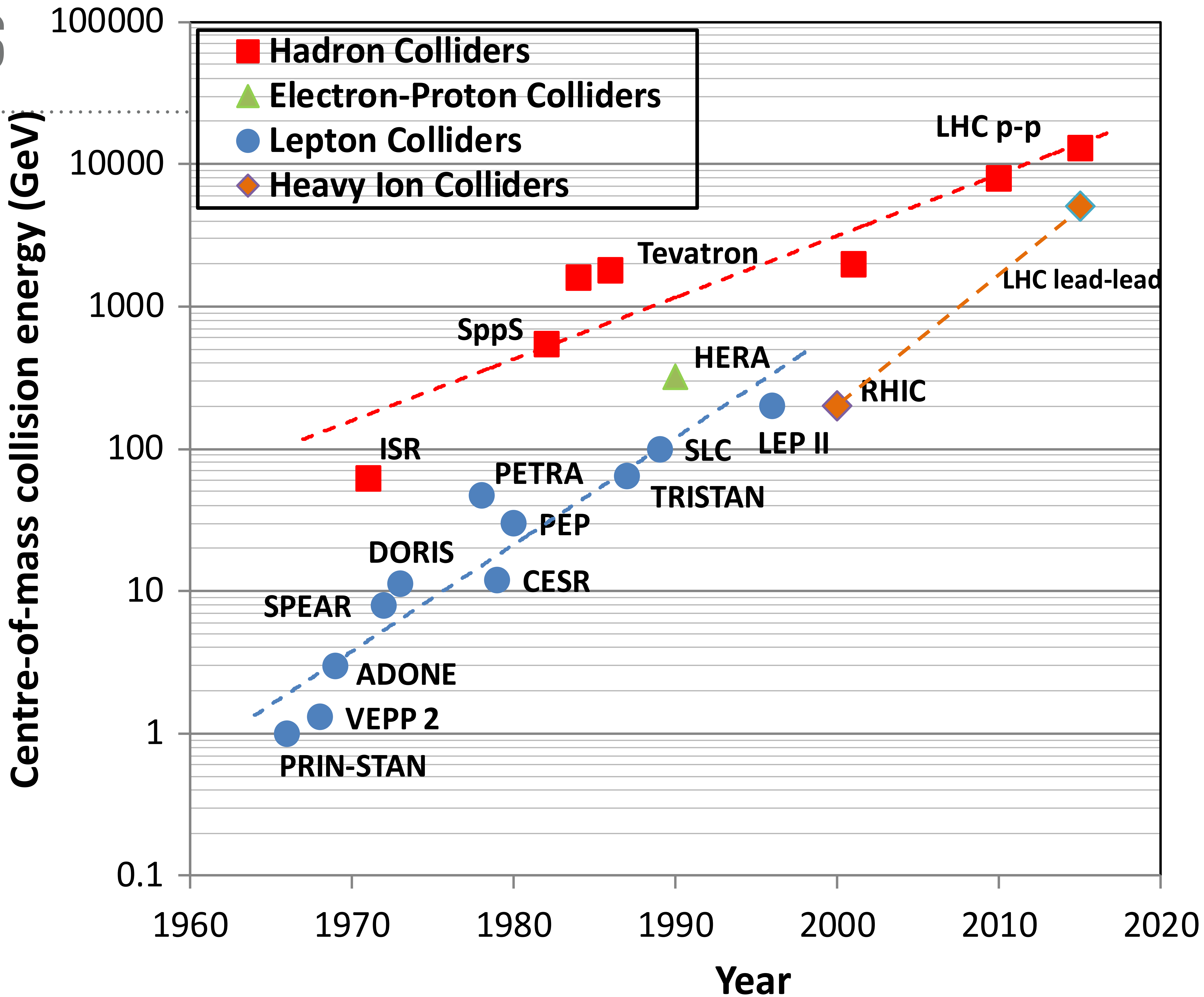


Hadron collider
(collision of ~50 point-like particles)



A BRIEF HISTORY OF COLLIDERS

- Energy, luminosity, and particle species are the main parameters of interest
- So far, exponential growth of center-of-mass energy with time
  - Roughly factor of 4 every 10 years

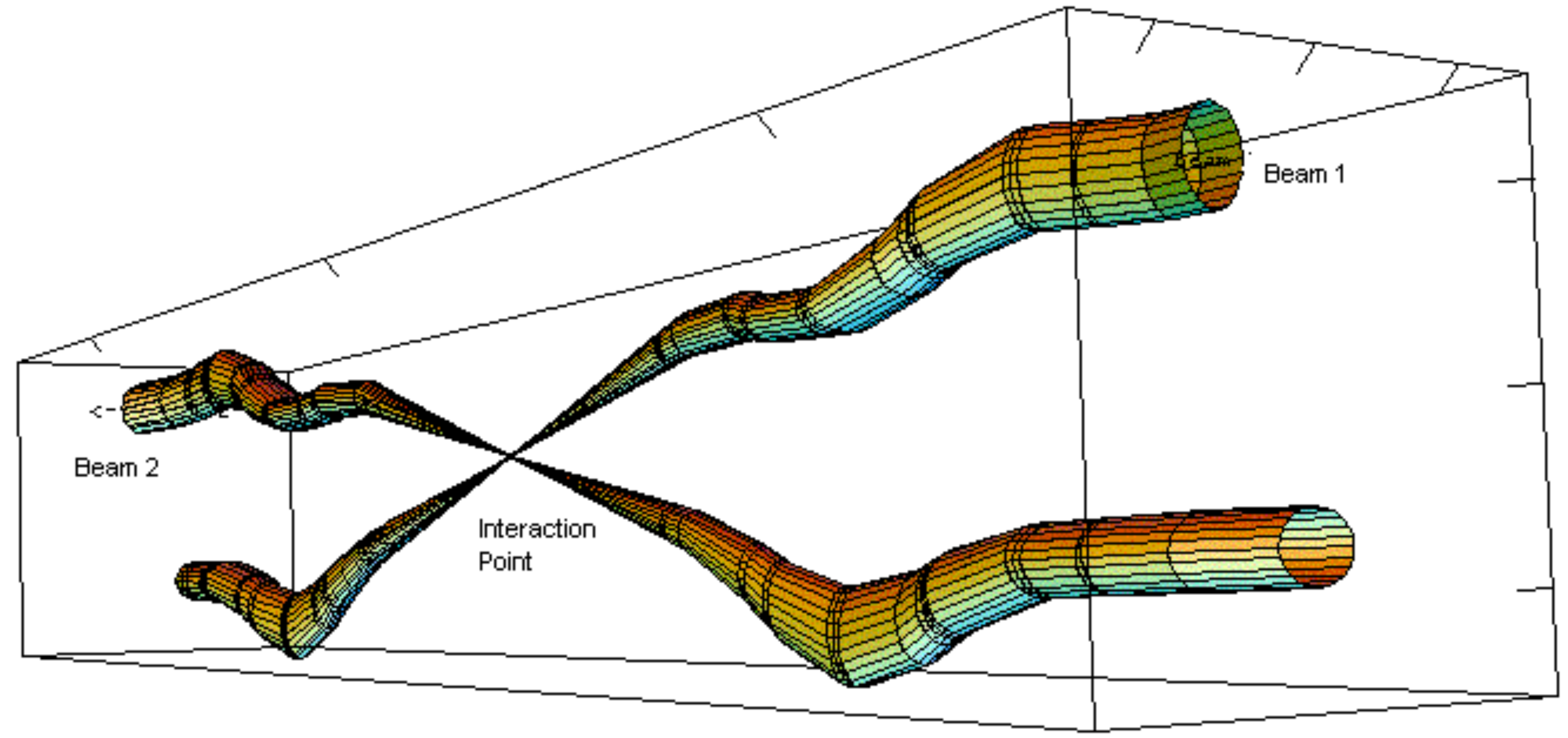


https://doi.org/10.1016/j.nima.2018.01.034

LUMINOSITY

- Drives sensitivity for measurements and searches

$$N_{\text{signal}} = \int L\, dt \;\times \sigma \times BR \times \epsilon$$



Relative beam sizes around IP1 (Atlas) in collision

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \epsilon_n \beta^*} F$$

θ_C = crossing angle

N_b = bunch population (N particles per bunch)

n_b = number of bunches in each beam

f_{rev} = revolution frequency

ϵ_n = normalized emittance at crossing point

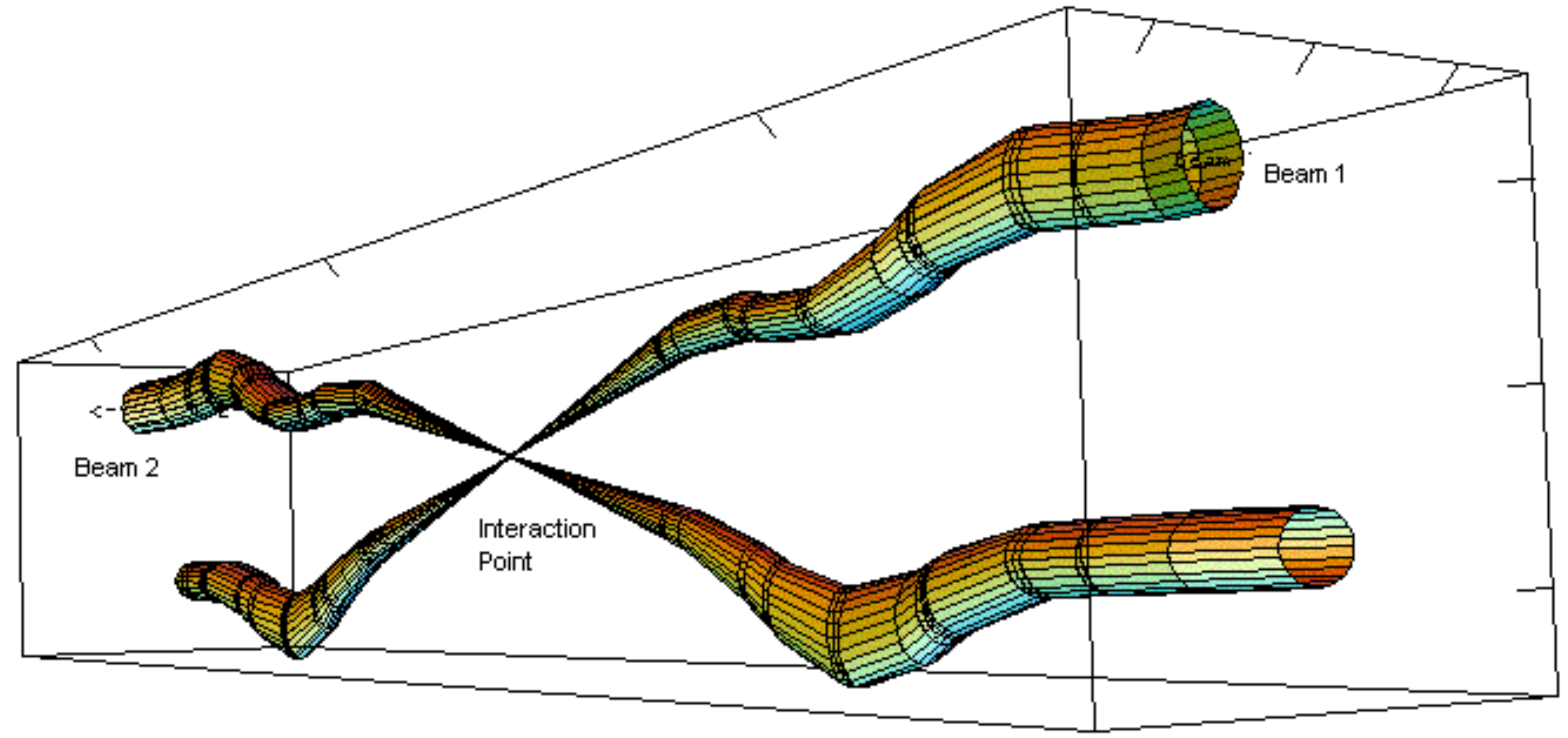
β^* = beta function at crossing point

γ = relativistic factor

$$F = \frac{1}{\sqrt{1 + (\theta_C \sigma_Z / 2\sigma^*)^2}}$$

LUMINOSITY

- Drives sensitivity for measurements and searches



Relative beam sizes around IP1 (Atlas) in collision

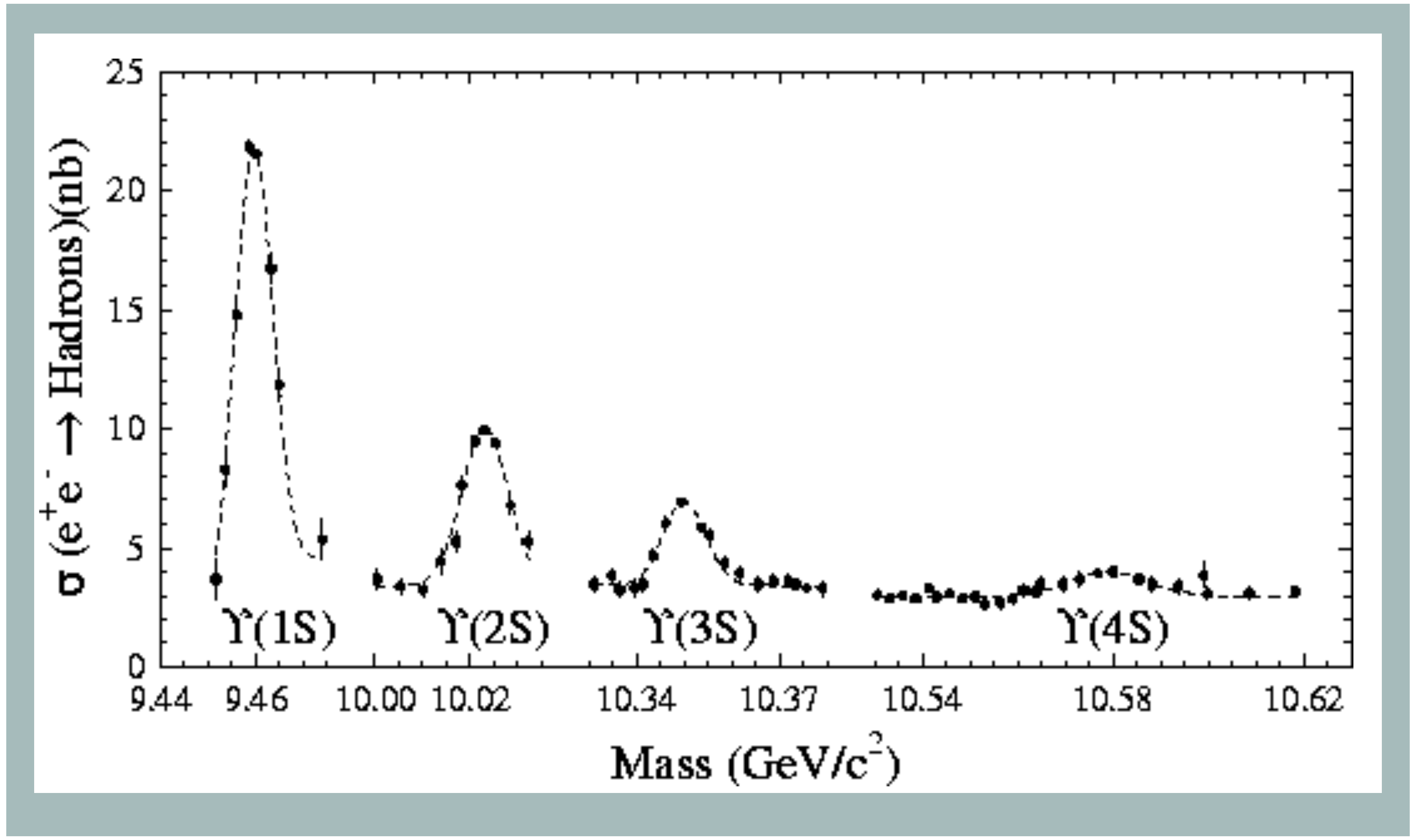
- Toward larger lumi
  - For a given beam stored energy, possible by increasing brilliance of the beams, N_b/ϵ_n, or by crossing beams at small angle and reducing beta function
  - Otherwise increase bunch number and bunch population

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi\epsilon_n \beta^*} F$$

$$E_{\text{beam}} = m_0 c^2 \gamma N_b n_b$$

CURRENT COLLIDERS: SUPER KEKB

- **SuperKEKB**
  - Electron-positron collider at KEK in Tsukuba, Japan with 3 km circumference
  - Target luminosity of 6.5×10^{35} cm^{-2} s^{-1}, first collisions in 2016, record luminosity of 2.4×10^{34} cm^{-2} s^{-1} in 2020
  - Operates close to Υ(4S) resonance, 10.6 GeV
  - Electrons at 7 GeV and positrons at 4 GeV
    - Asymmetry provides a boost to B mesons in the direction of the forward detector



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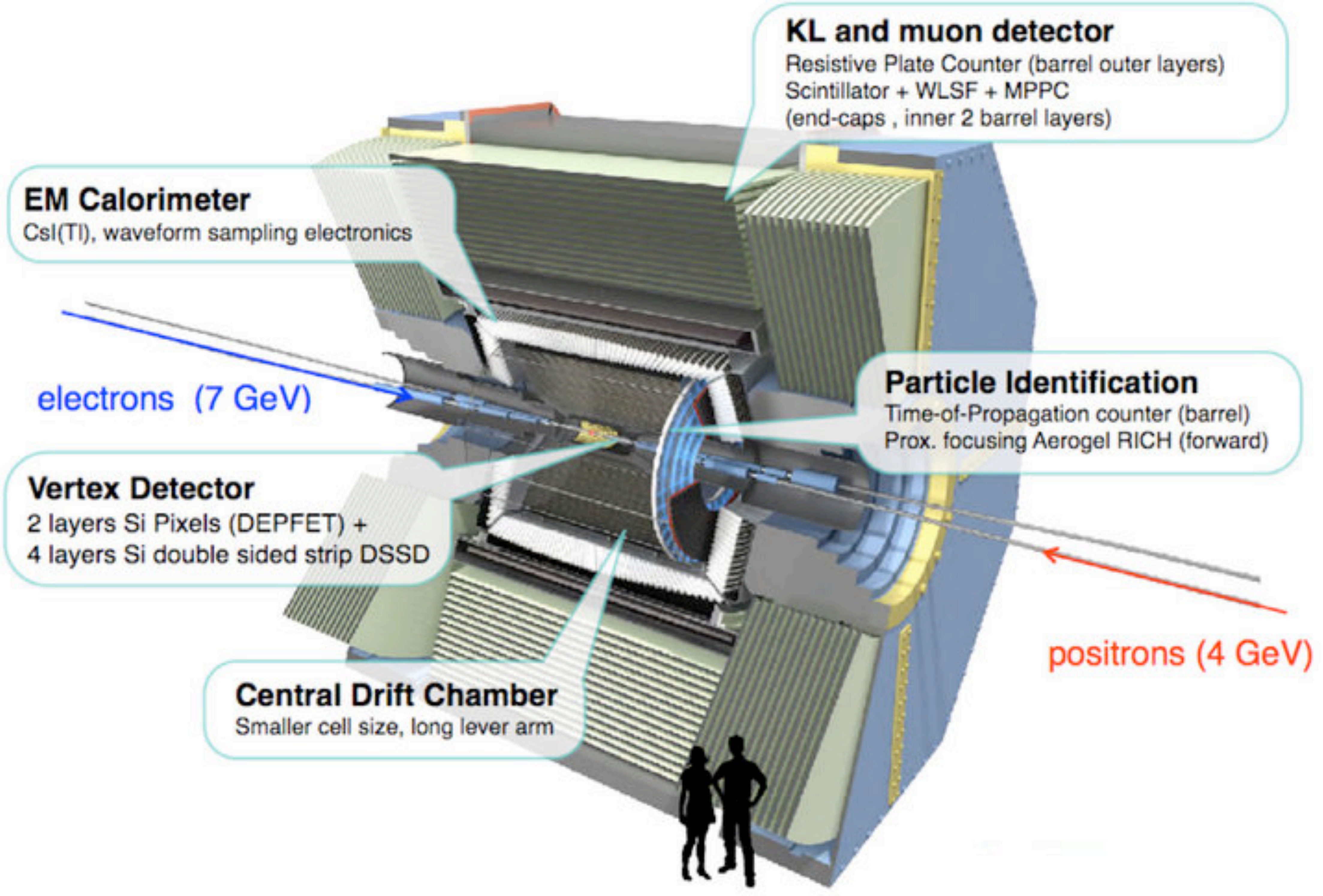
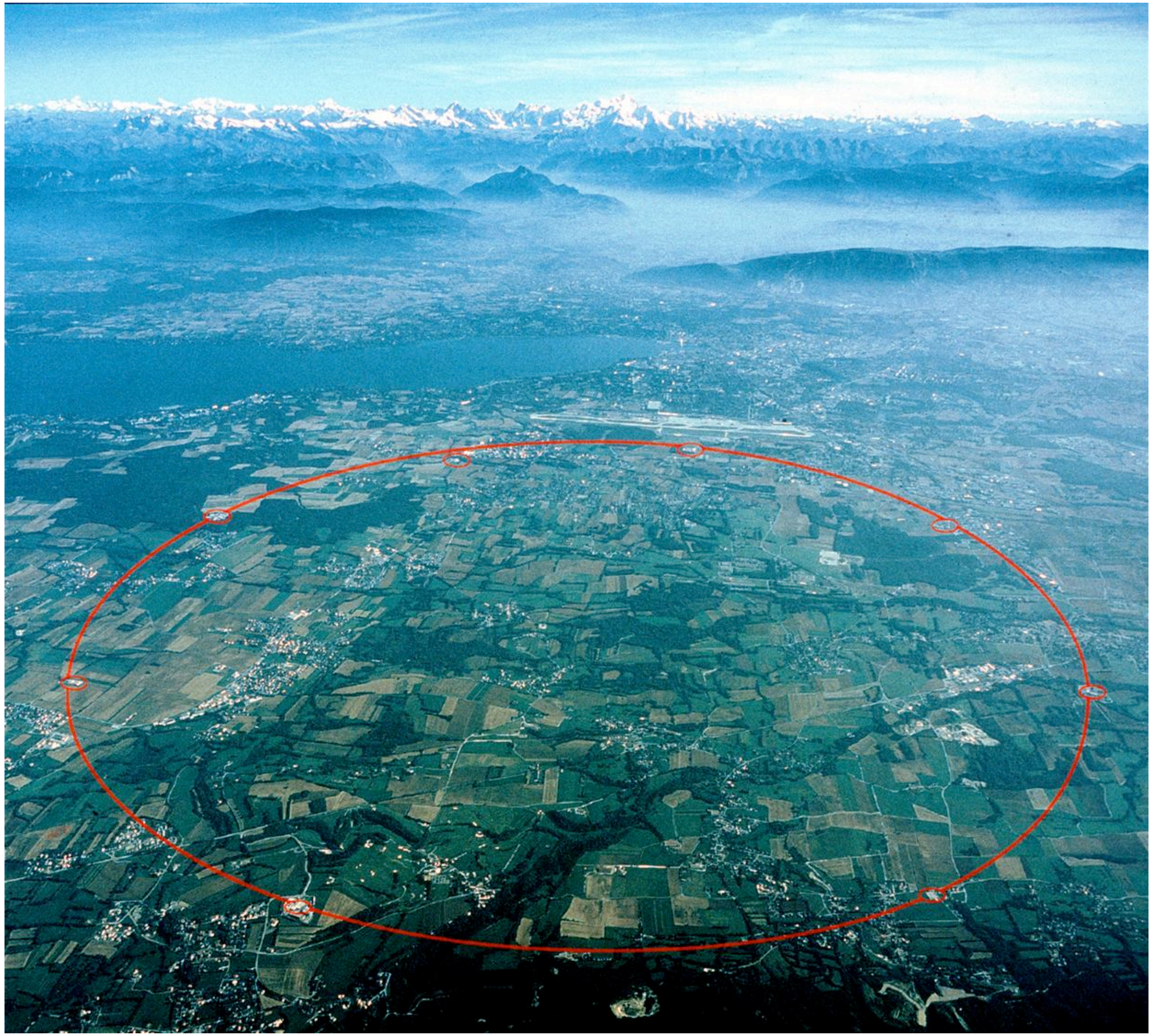
  - Operates close to Υ(4S) resonance, 10.6 GeV
  - Electrons at 7 GeV and positrons at 4 GeV
    - Asymmetry provides a boost to B mesons in the direction of the forward detector
- **Belle II experiment**
  - Precision measurements of CP-violation in heavy quarks and rare decays
  - Targeting 50 ab^{-1} in next five years



CURRENT COLLIDERS: LARGE HADRON COLLIDER



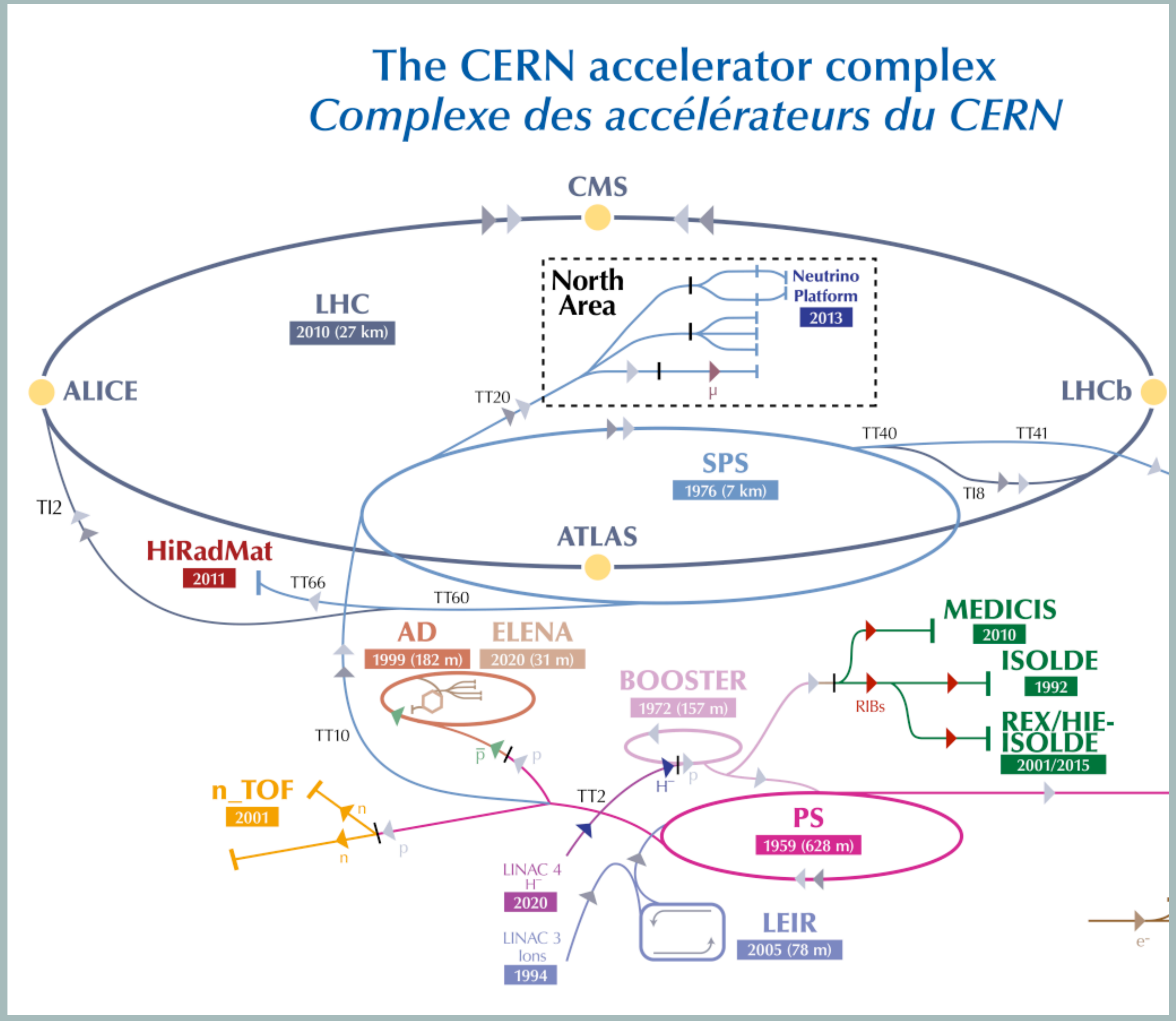
THE LHC

27 km circumference

Bending magnets: 1232 superconducting dipole magnets, each 15 m, B = 8.33 T

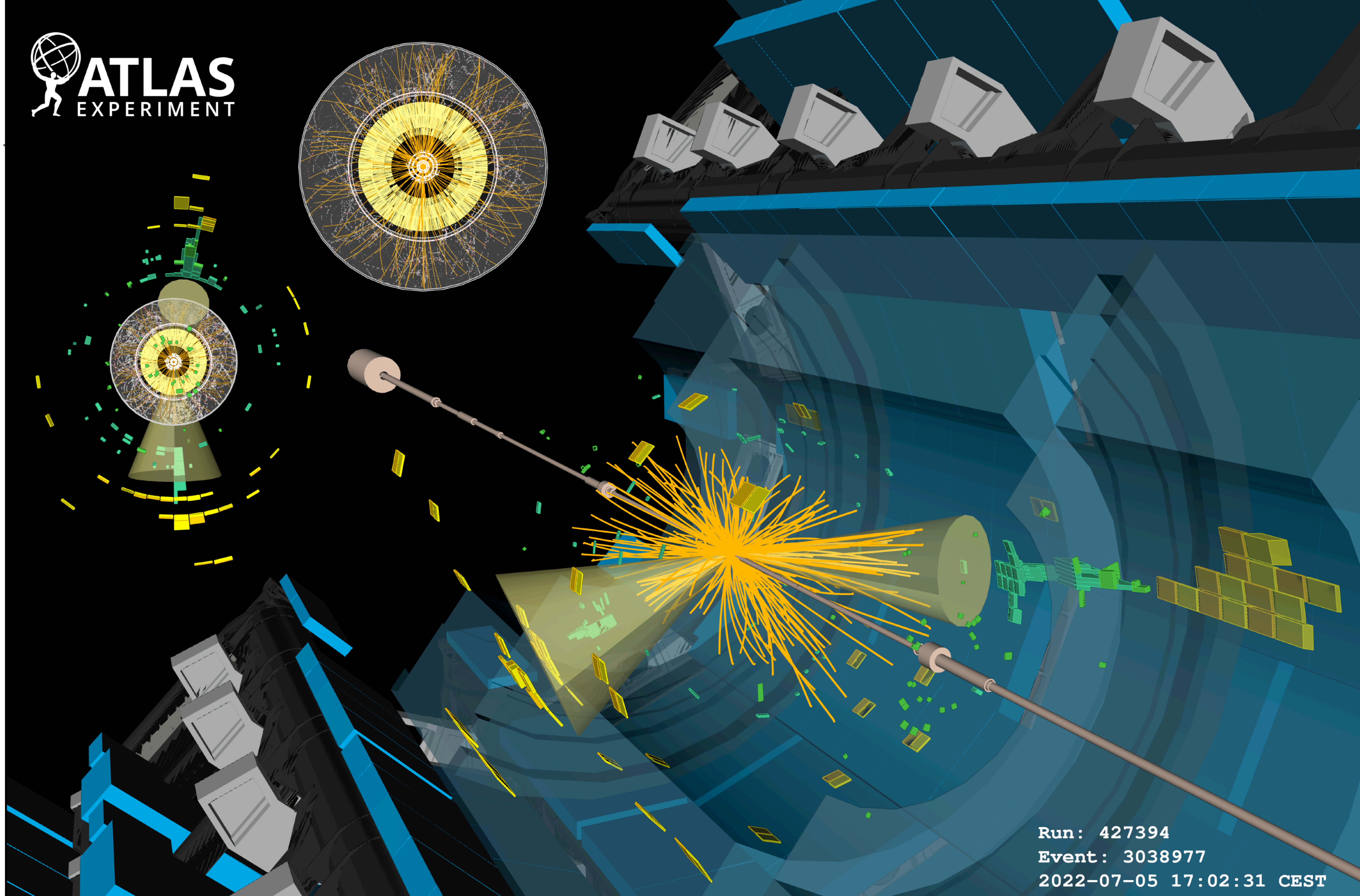
40 MHz beam-crossings

Center-of-mass collisions from 7 TeV (2011) to 13.6 TeV (two days ago!!!)

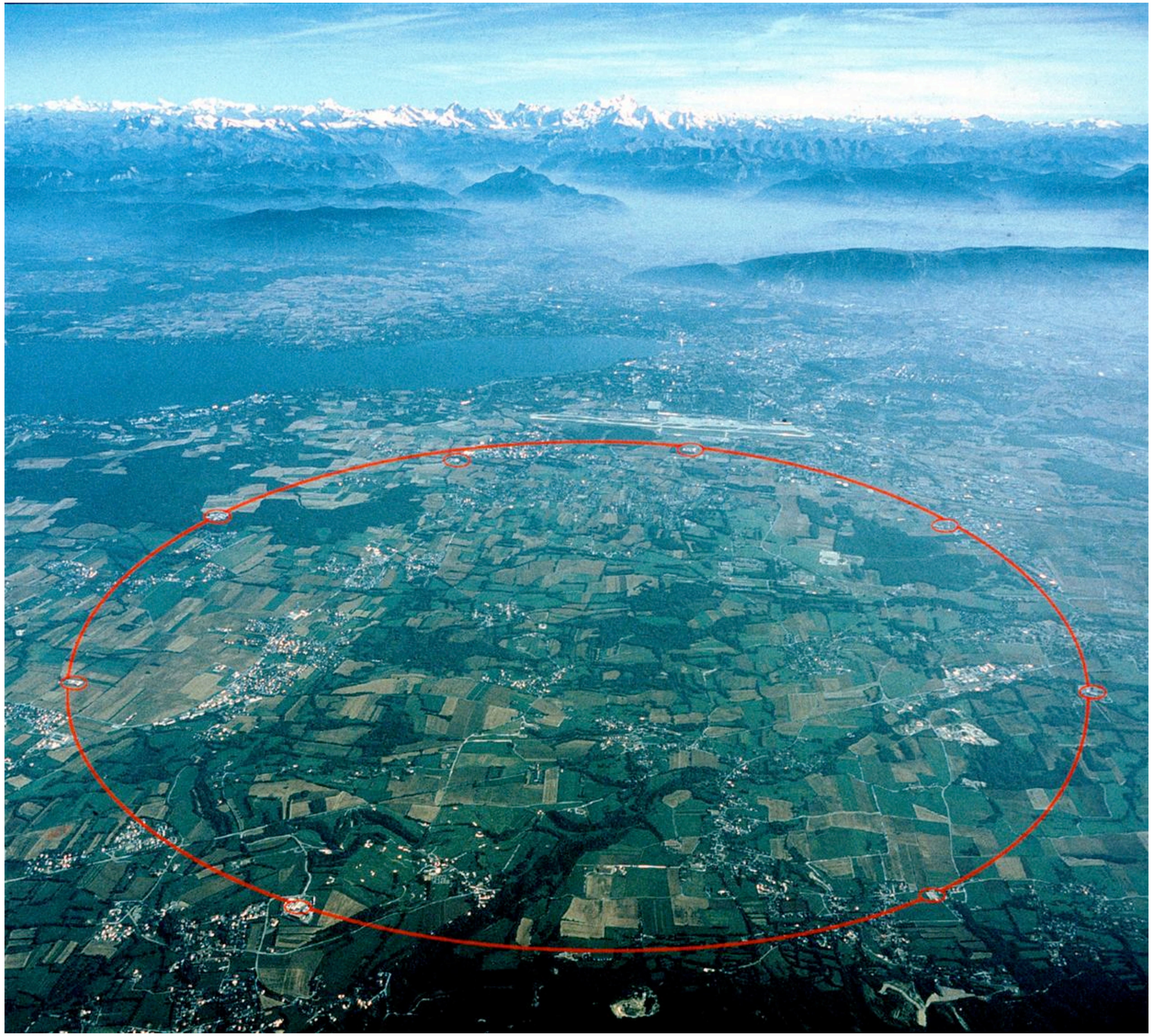


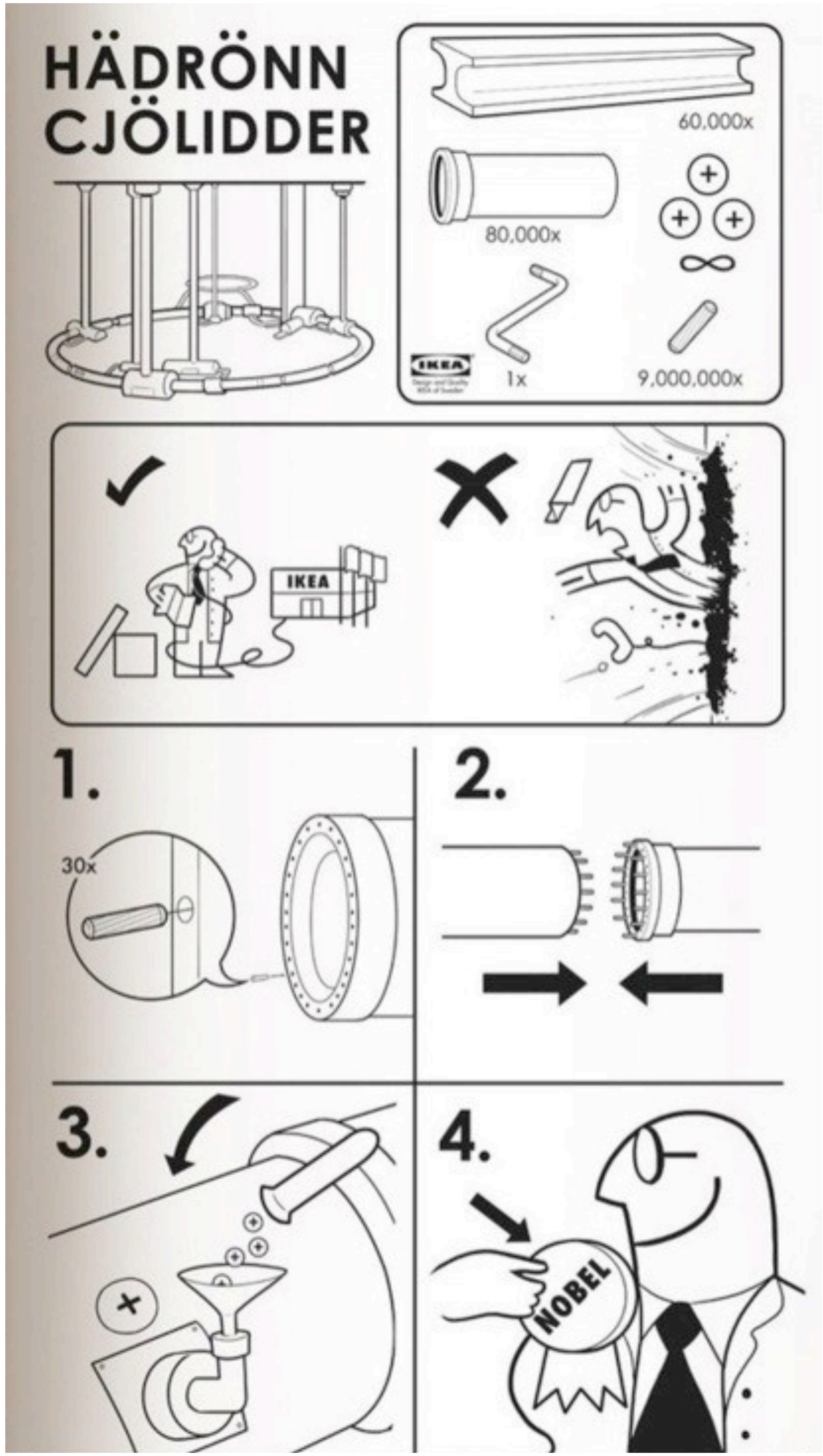
FIRST 13.6 TeV collisions THIS WEEK!!

Highest energy collisions ever produced by people…



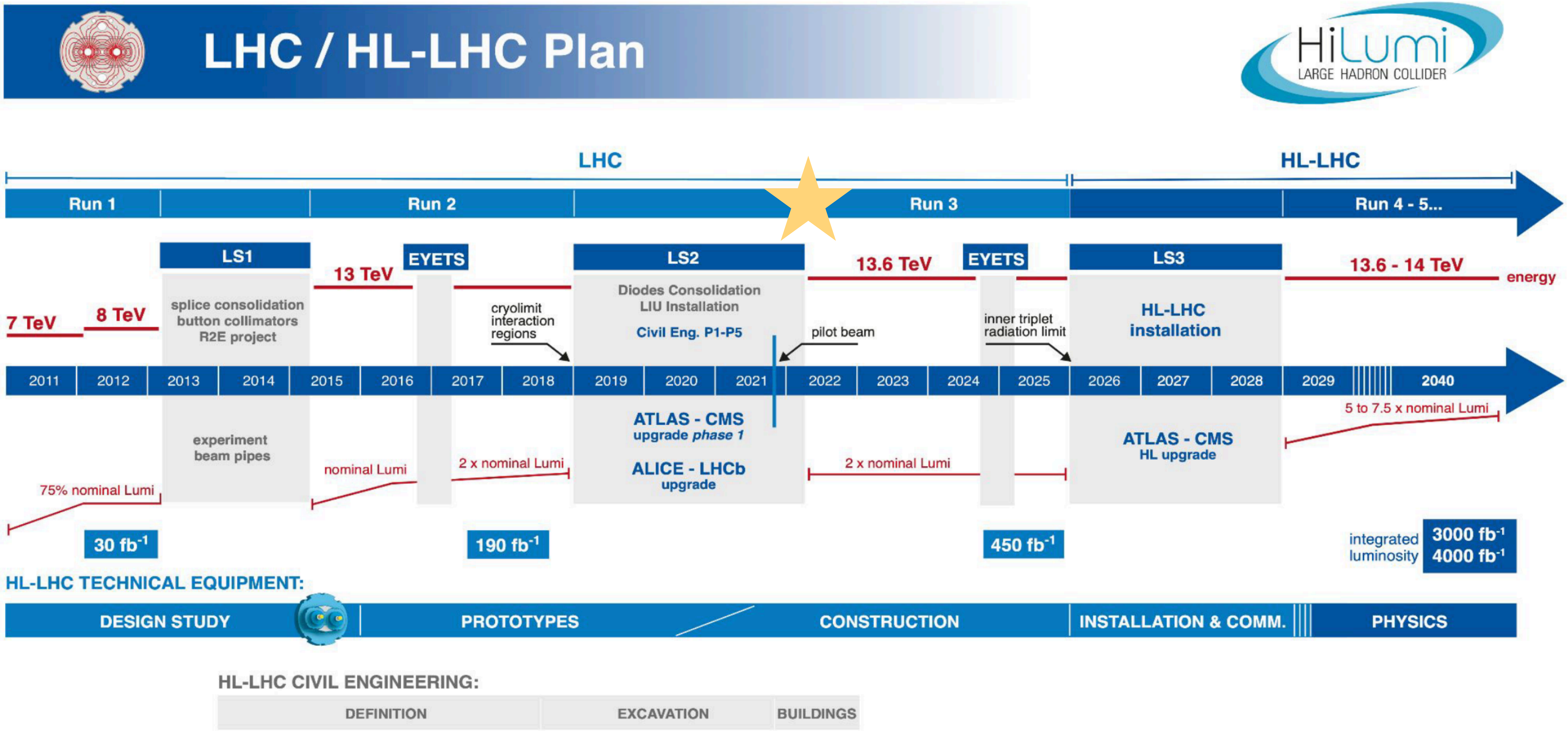
CURRENT COLLIDERS: LARGE HADRON COLLIDER



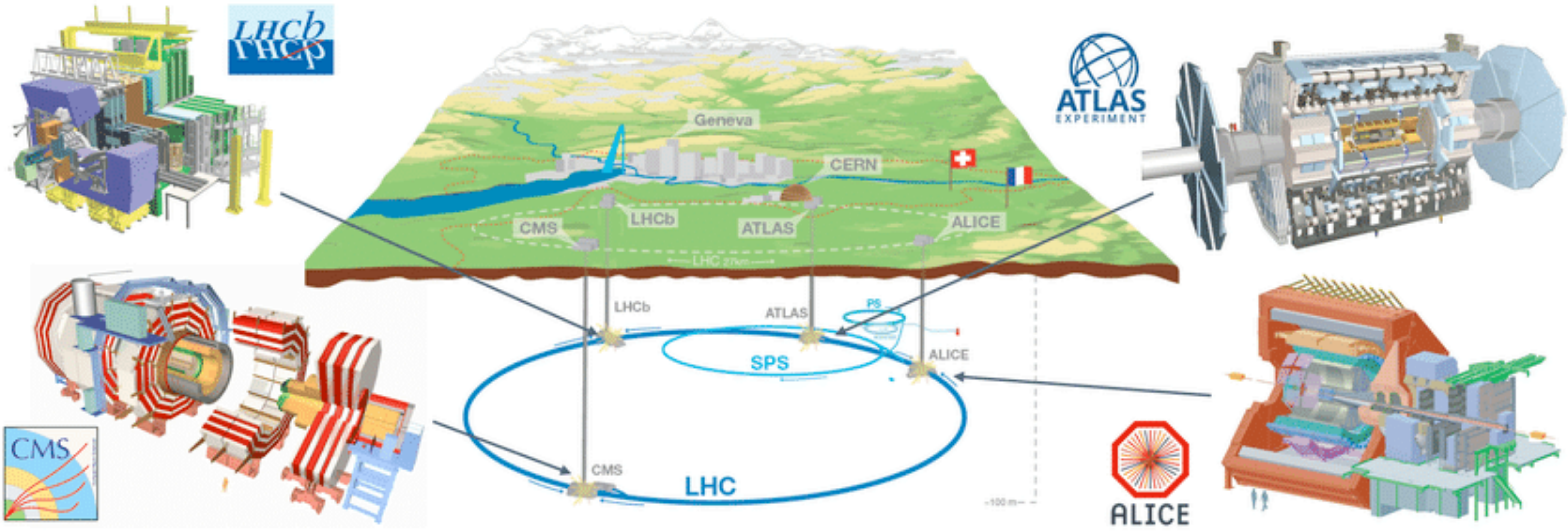


CURRENT COLLIDERS: LARGE HADRON COLLIDER

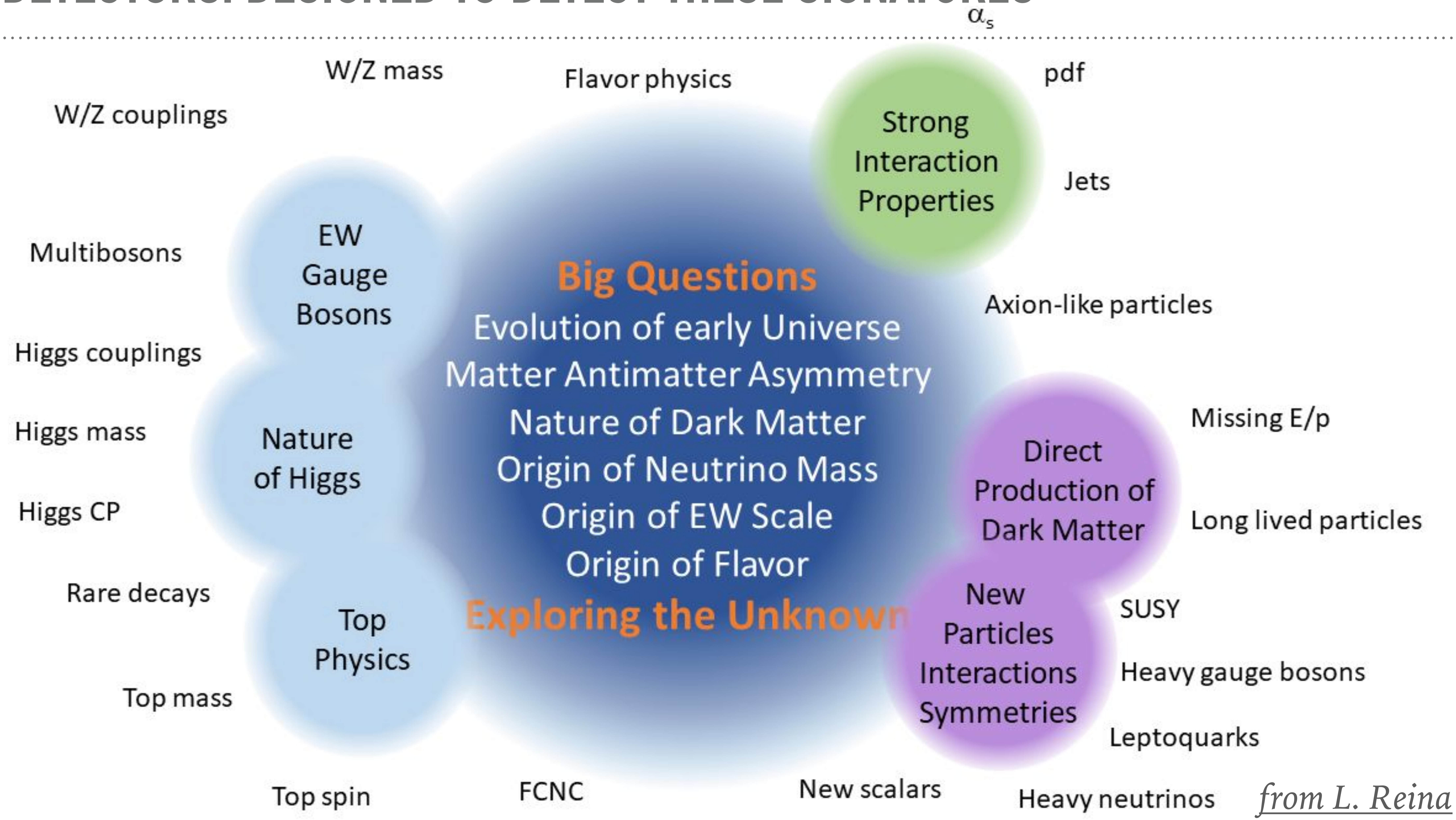
Nominal lumi = 10^{34} $cm^{-2}s^{-1}$



LHC EXPERIMENTS

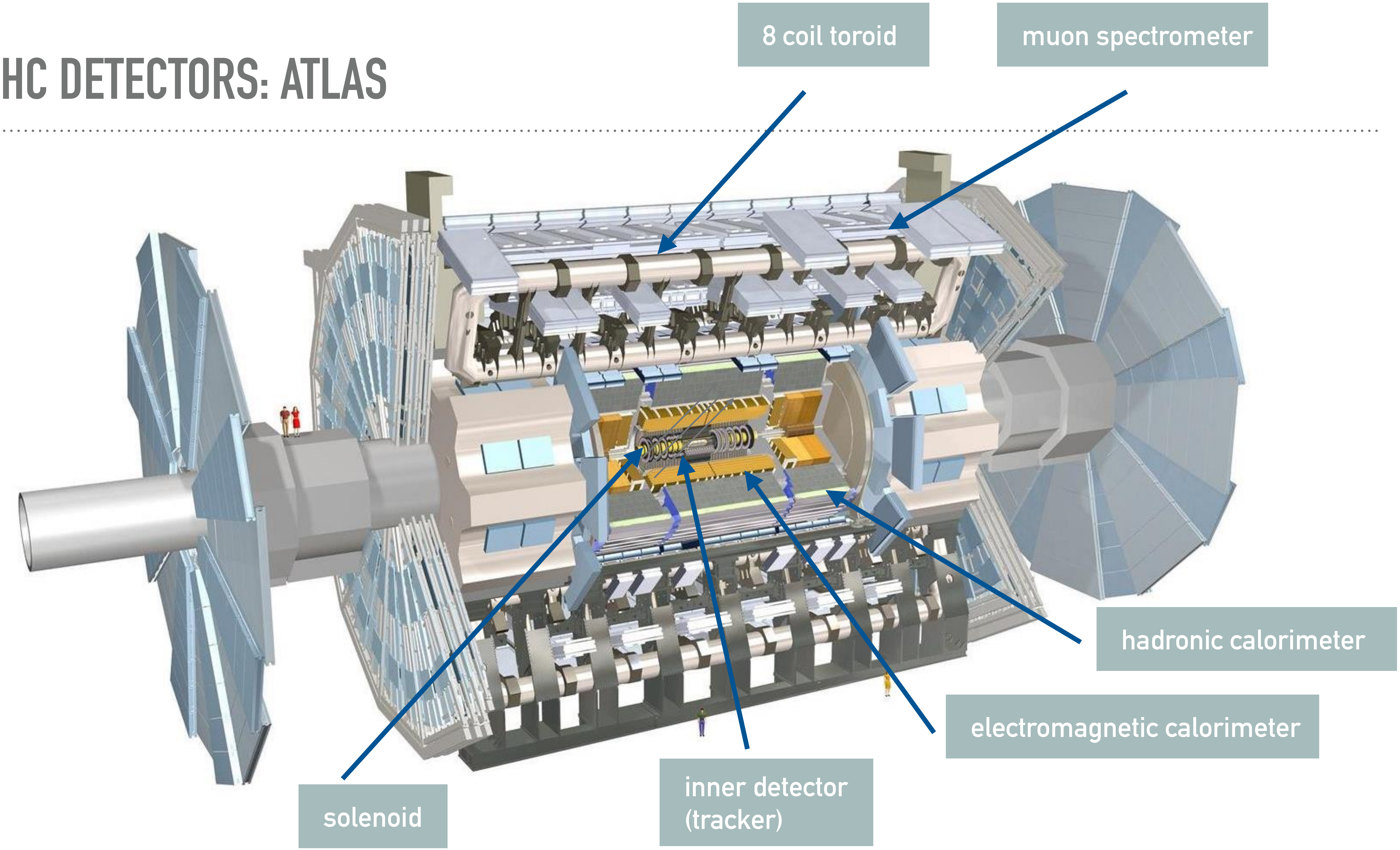


LHC DETECTORS: DESIGNED TO DETECT THESE SIGNATURES



from L. Reina

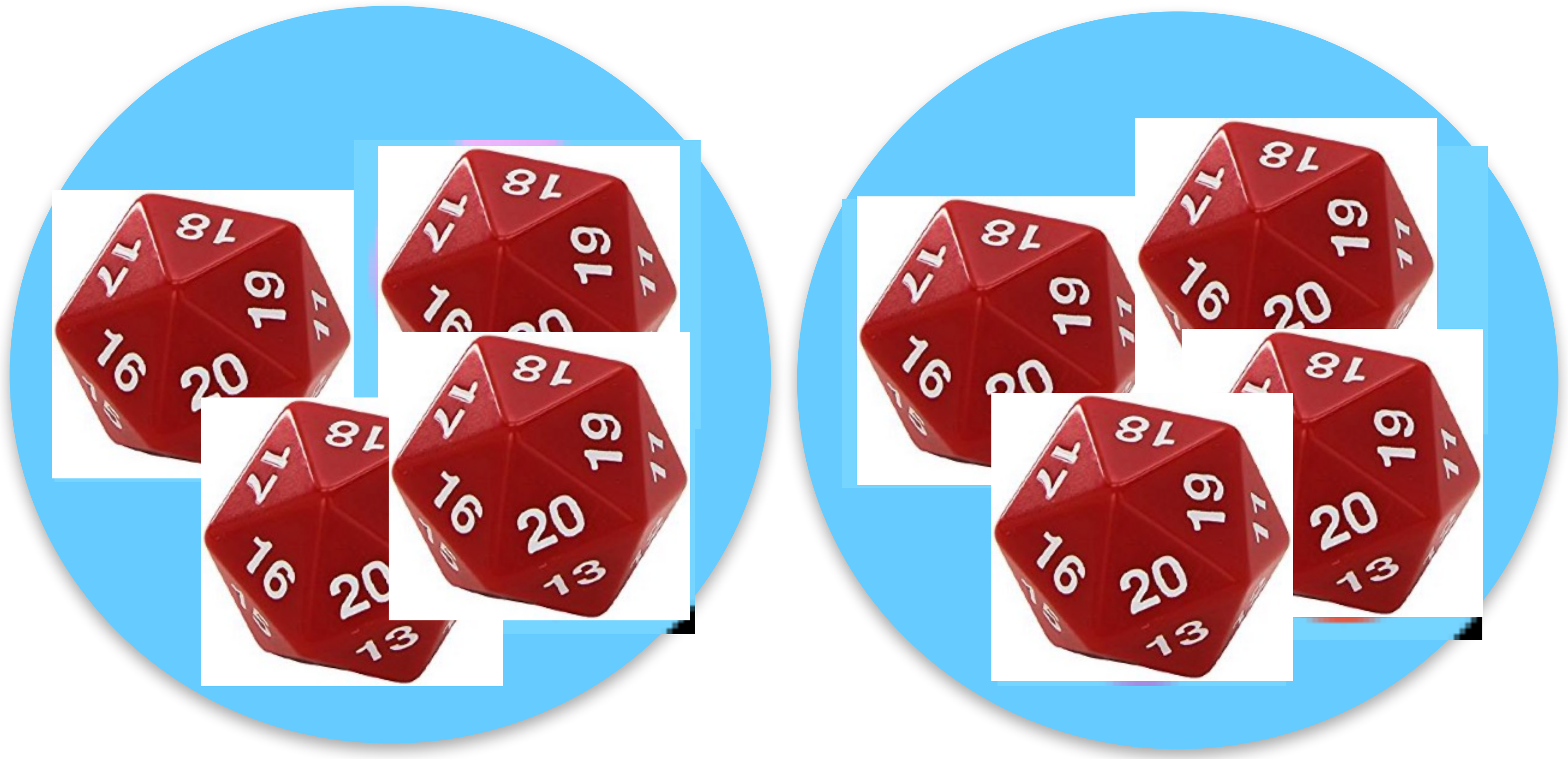
LHC DETECTORS: ATLAS



WHAT HAPPENS WHEN YOU COLLIDE PROTONS?

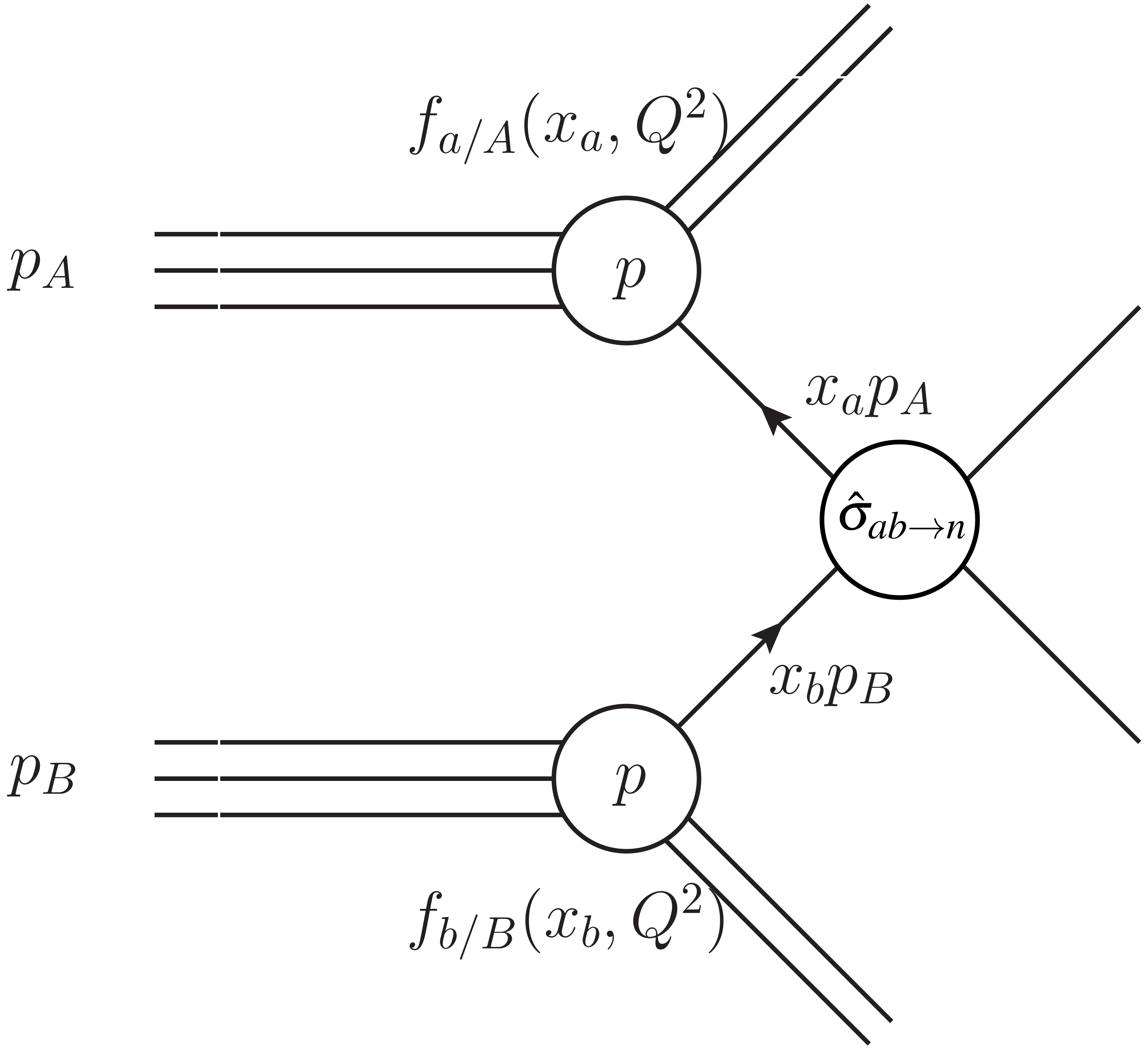
WHAT HAPPENS WHEN YOU COLLIDE PROTONS?

- Probability of interaction with given properties determined by cross-section



CALCULATING A CROSS-SECTION

- Factorization theorem allows separation of cross section into two energy scales
  - parton-parton cross-section, $\hat{\sigma}_{ab \to n}$, at short-distances
  - parton density functions (PDFs) for long-range, non-perturbative description of proton structure
    - $f_{a/A}(x, Q^2)$ PDF for parton a in proton A
    - $x = \dfrac{p_a}{p_A}$ is relative momentum of parton in direction of proton's p
    - Q^2 = energy scale of scattering process $\approx M_X^2 + p_T^2$ if producing particle X
- Scale separating short (cross-section) and long distance (PDF) physics is called factorization scale, μ_F
  - often set μ_F = Q



$$\sigma_{P_A P_B \to n} = \Sigma_{ab} \int dx_a \, dx_b f_{a/A}(x_a, Q^2, \mu_F) f_{b/B}(x_b, Q^2, \mu_F) \hat{\sigma}_{ab \to n}(Q^2, \mu_F^2)$$

CALCULATING A CROSS-SECTION

- Factorization theorem allows separation of cross section into two energy scales
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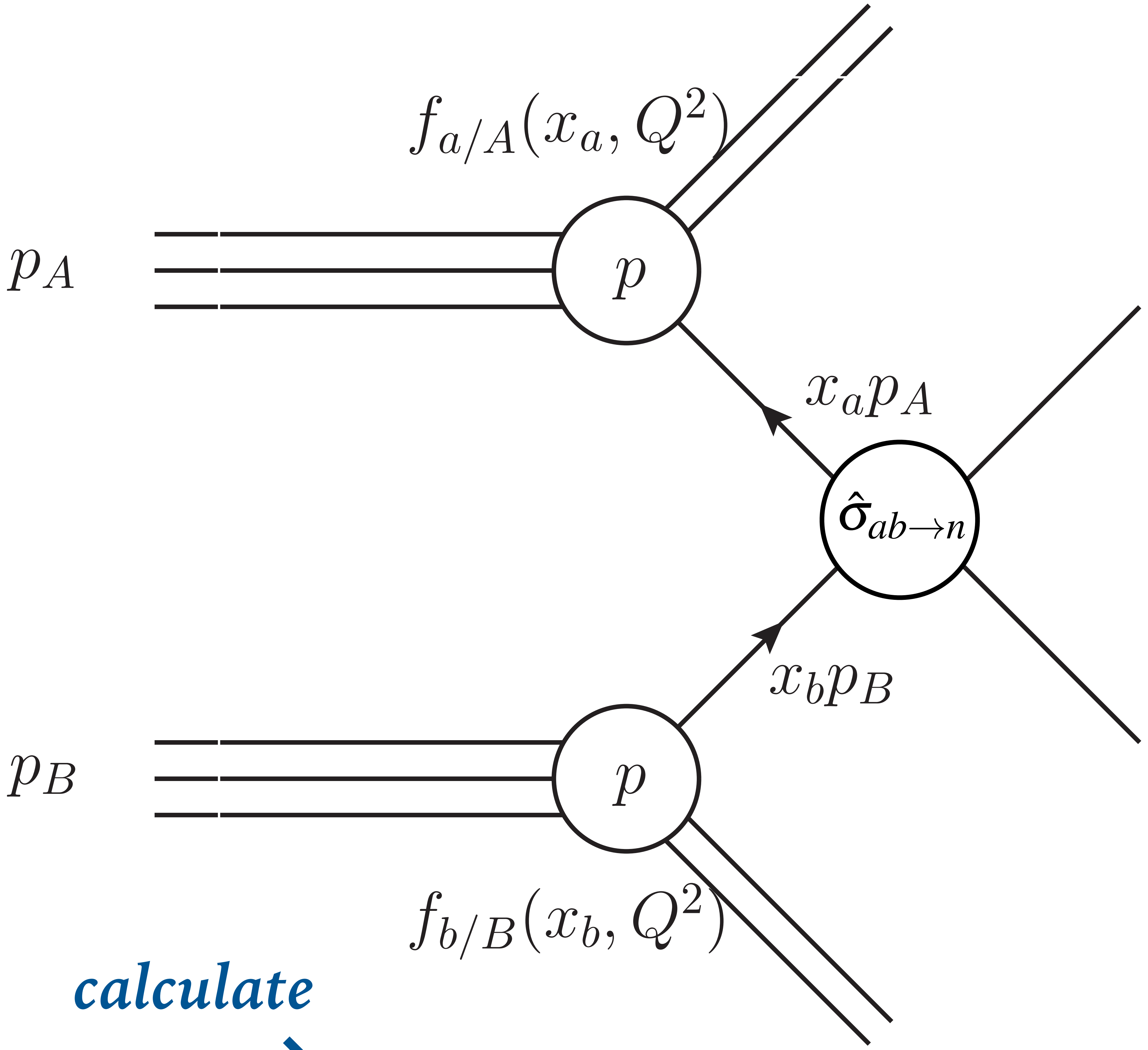
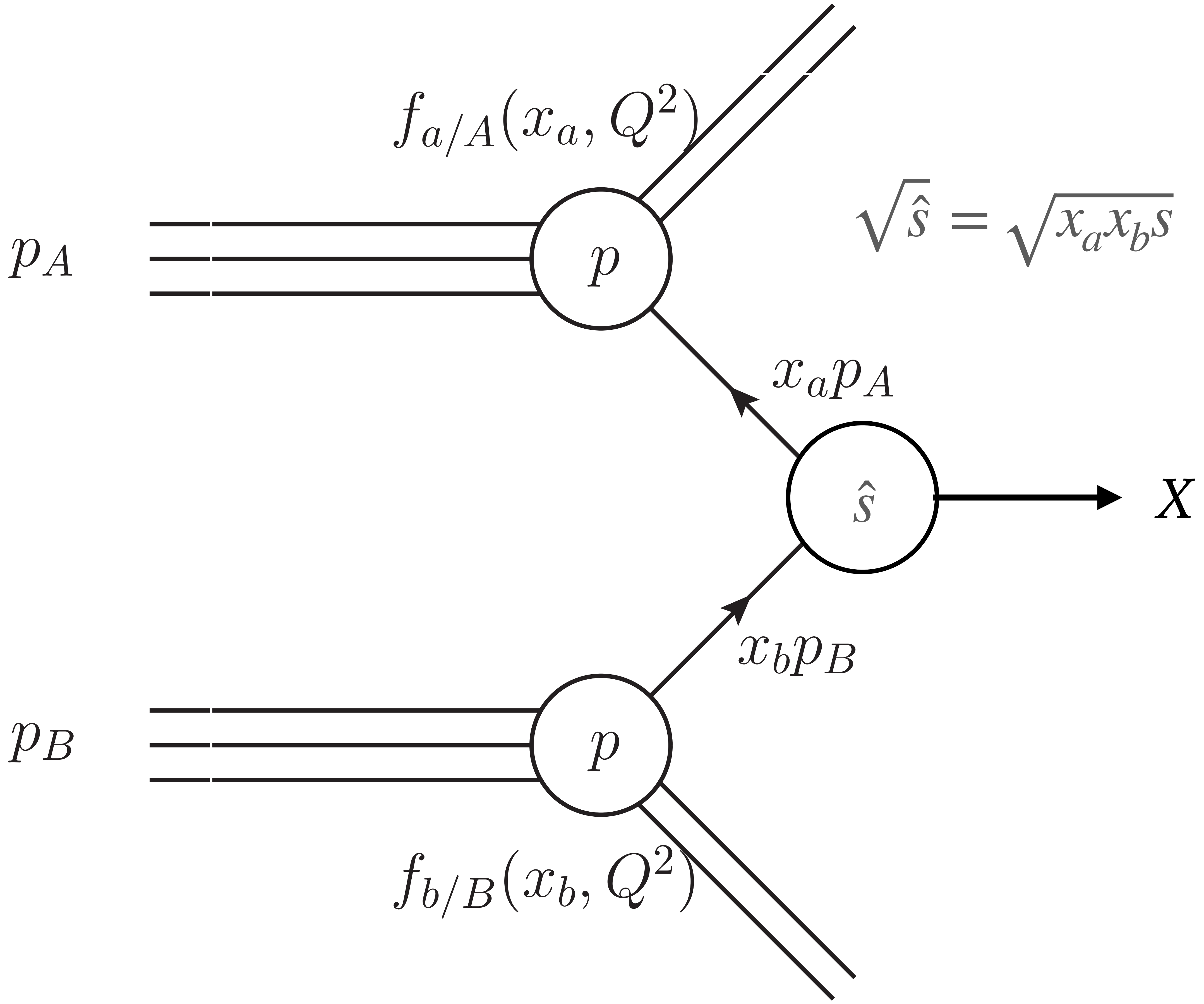


measure *calculate*

$$\sigma_{P_A P_B\to n} = \Sigma_{ab} \int dx_a\, dx_b f_{a/A}(x_a, Q^2, \mu_F) f_{b/B}(x_b, Q^2, \mu_F) \hat{\sigma}_{ab\to n}(Q^2, \mu_F^2)$$

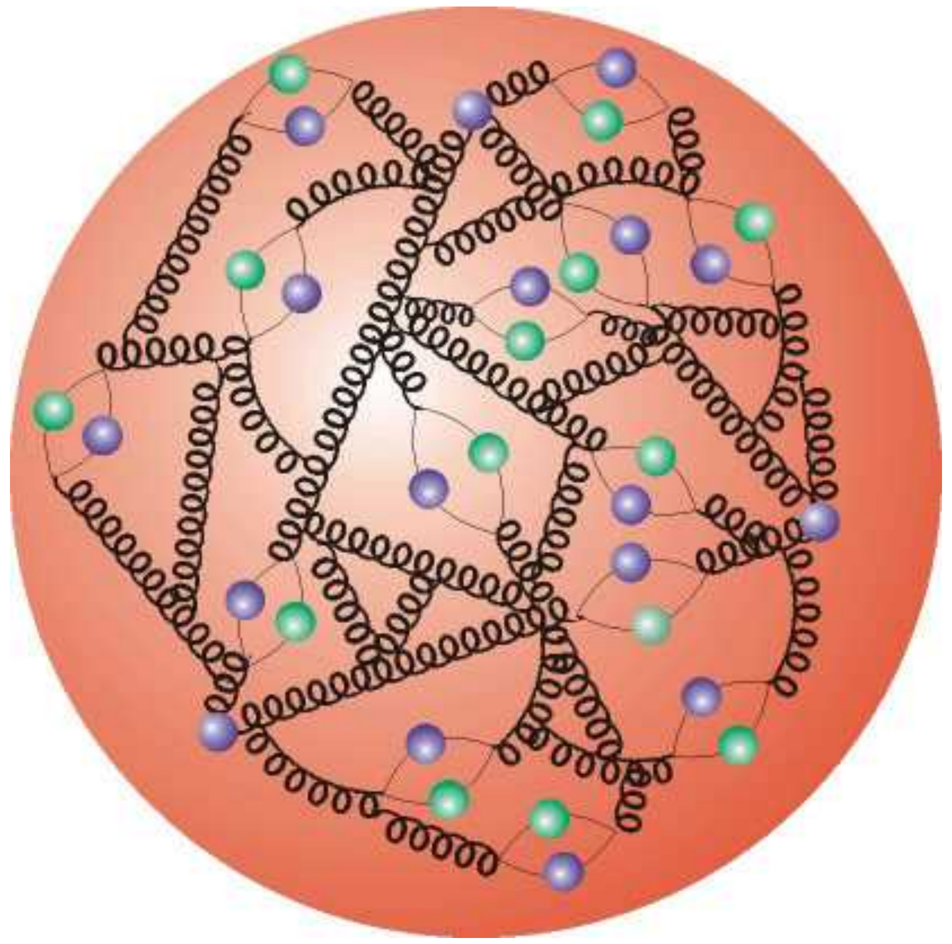
PARTON DISTRIBUTION FUNCTIONS

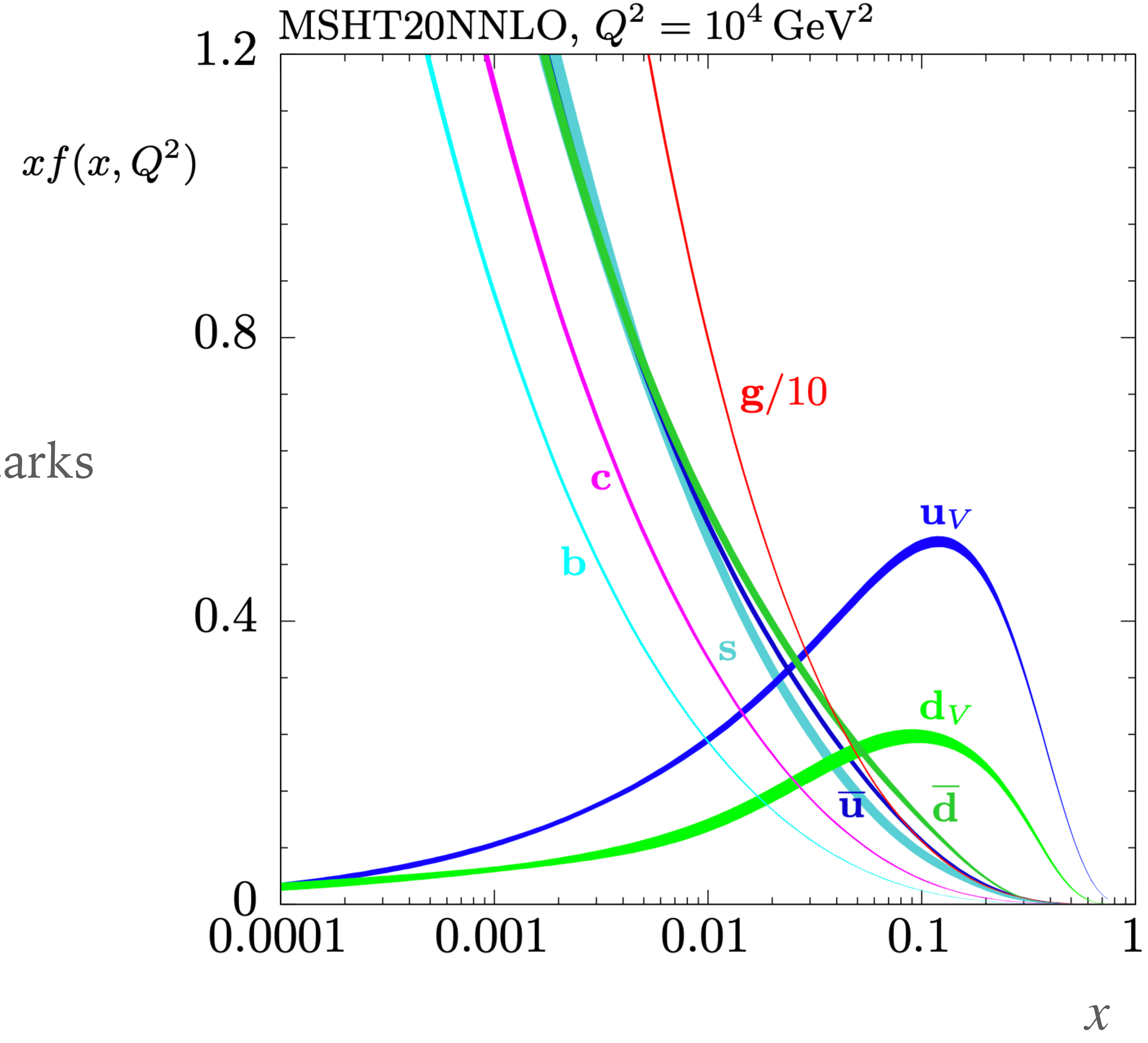
- Parton collision energy for hadron energy s
  - $\hat{s} = x_a \cdot x_b \cdot s$
  - $M_x = \sqrt{\hat{s}}$



PARTON DISTRIBUTION FUNCTIONS

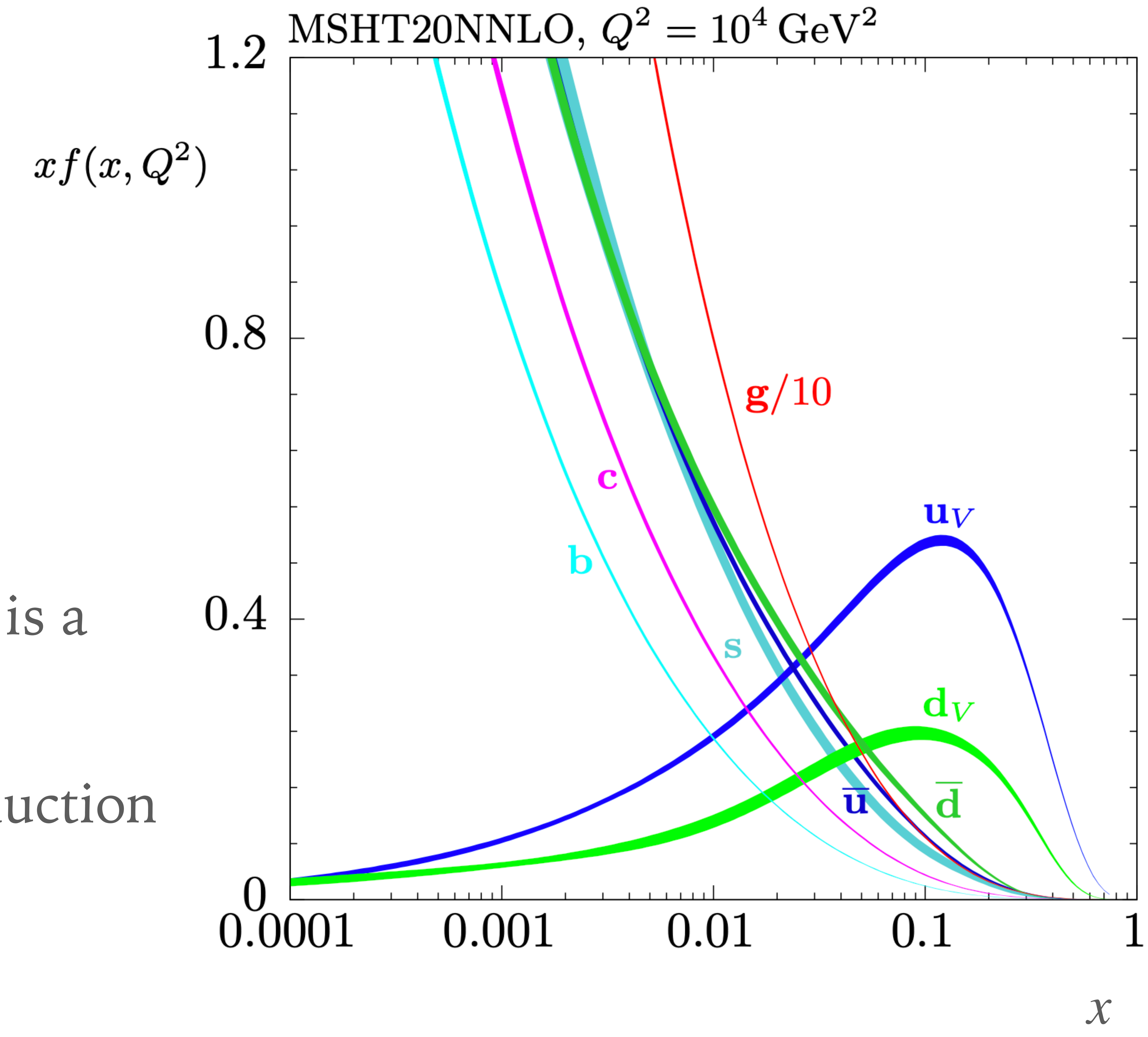
- Parton collision energy for hadron energy s
  - $\hat{s} = x_a \cdot x_b \cdot s$
  - $M_x = \sqrt{\hat{s}}$
- Proton composition is complicated
  - mixture of valence quarks, gluons, sea quarks
  - exact mixture depends on Q^2 and x





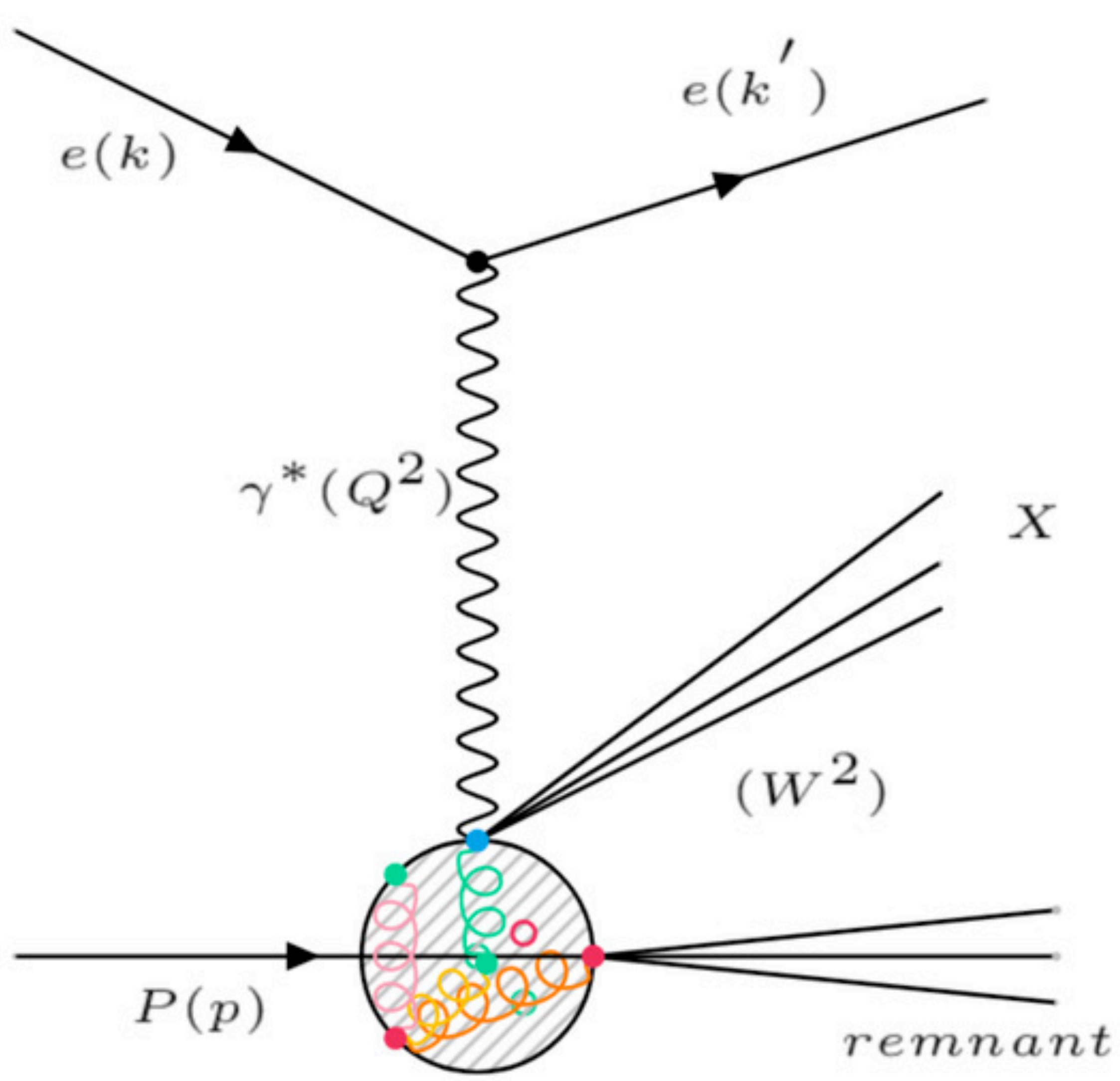
PARTON DISTRIBUTION FUNCTIONS

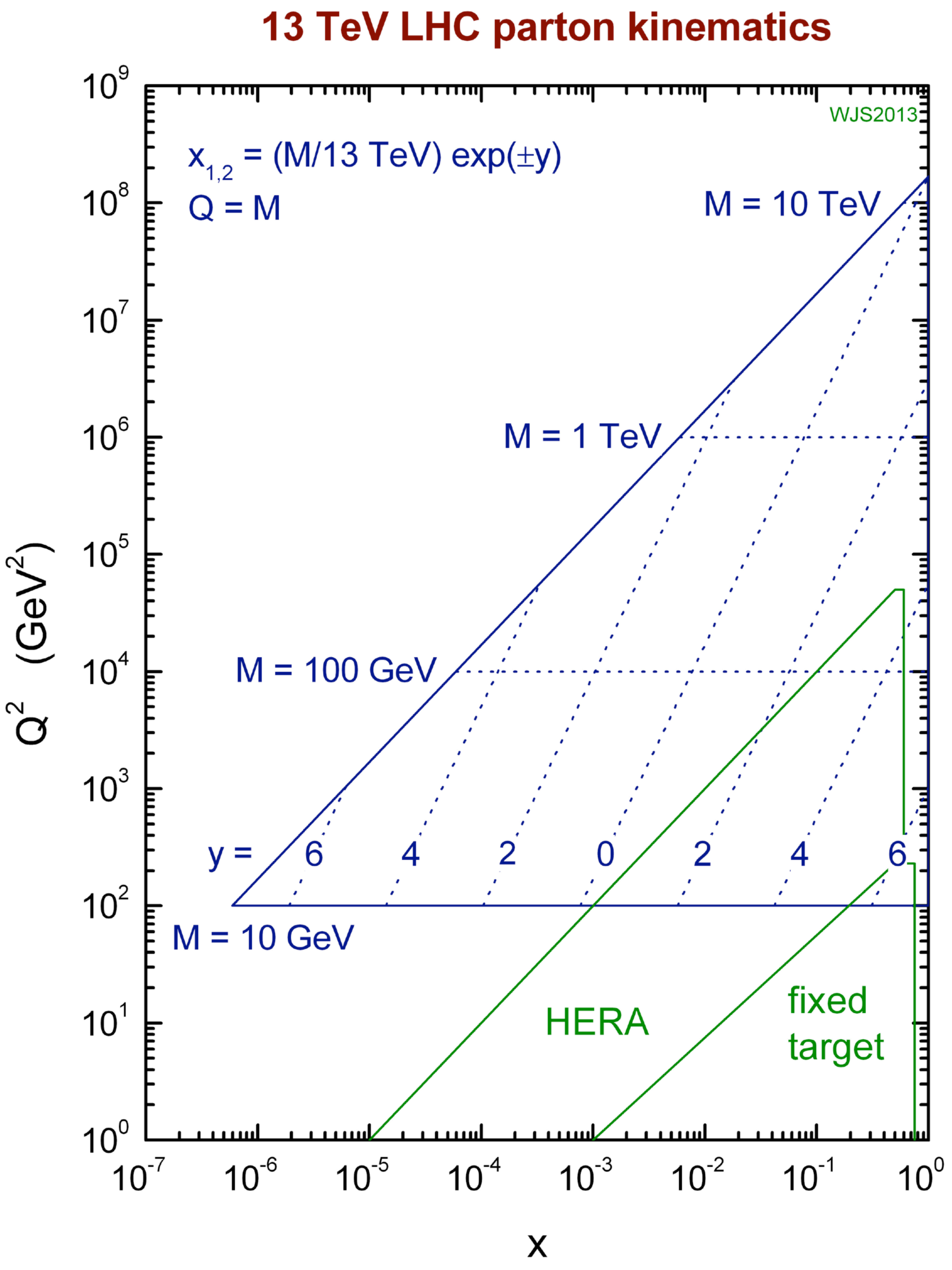
- Examples from LHC
  - 125 GeV Higgs:
    - $< x_p > \approx 125/13000 \approx 0.01$
  - 2 TeV Gluino, pair-produced
    - $< x_p > \approx 4000/13000 \approx 0.3$
- For SM and all but heaviest BSM, LHC is a gluon collider
- Steep rise of partons at low x —> production rates strongly decrease with M_x



MEASURING PDFS

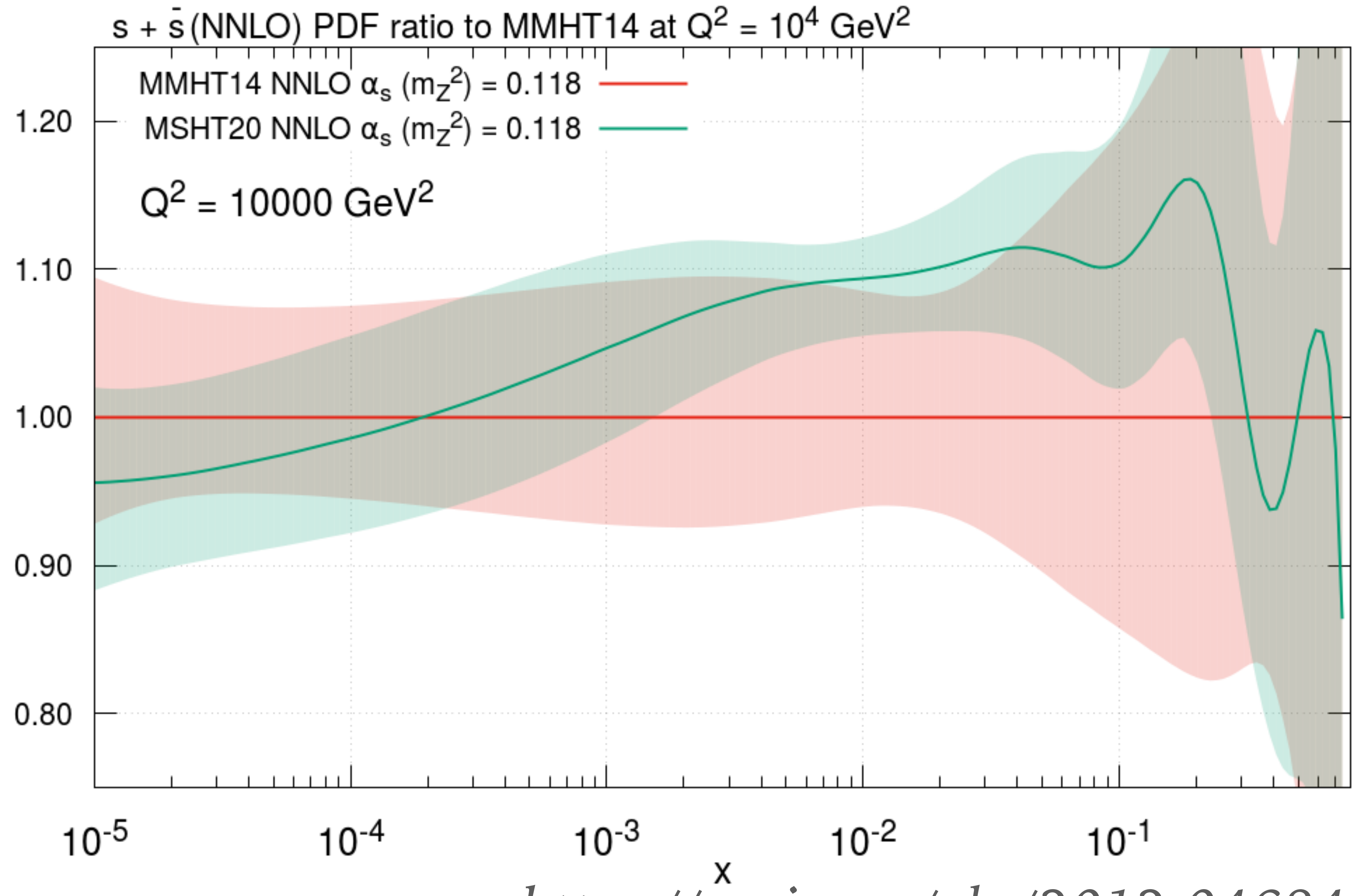
- **Lepton-hadron colliders**
  - HERA, electron-proton collider at DESY (1992-2007)
  - Measured full x range, at $Q^2 \approx 20$ or less
  - Use DGLAP evolution equations to extrapolate to higher energy scales





MEASURING PDFS

- Lepton-hadron colliders
- **Constraints from LHC, Tevatron, fixed target experiments**
  - W, Z and $t\bar{t}$ precision measurements at 7, 8 TeV constrain PDFs
    - for example, significant increase in strange quark contribution at $x \approx 0.01$ from ATLAS W measurements



https://arxiv.org/abs/2012.04684

WHAT HAPPENS WHEN YOU COLLIDE PROTONS (PREDICTIONS)

WHAT HAPPENS WHEN YOU COLLIDE PROTONS

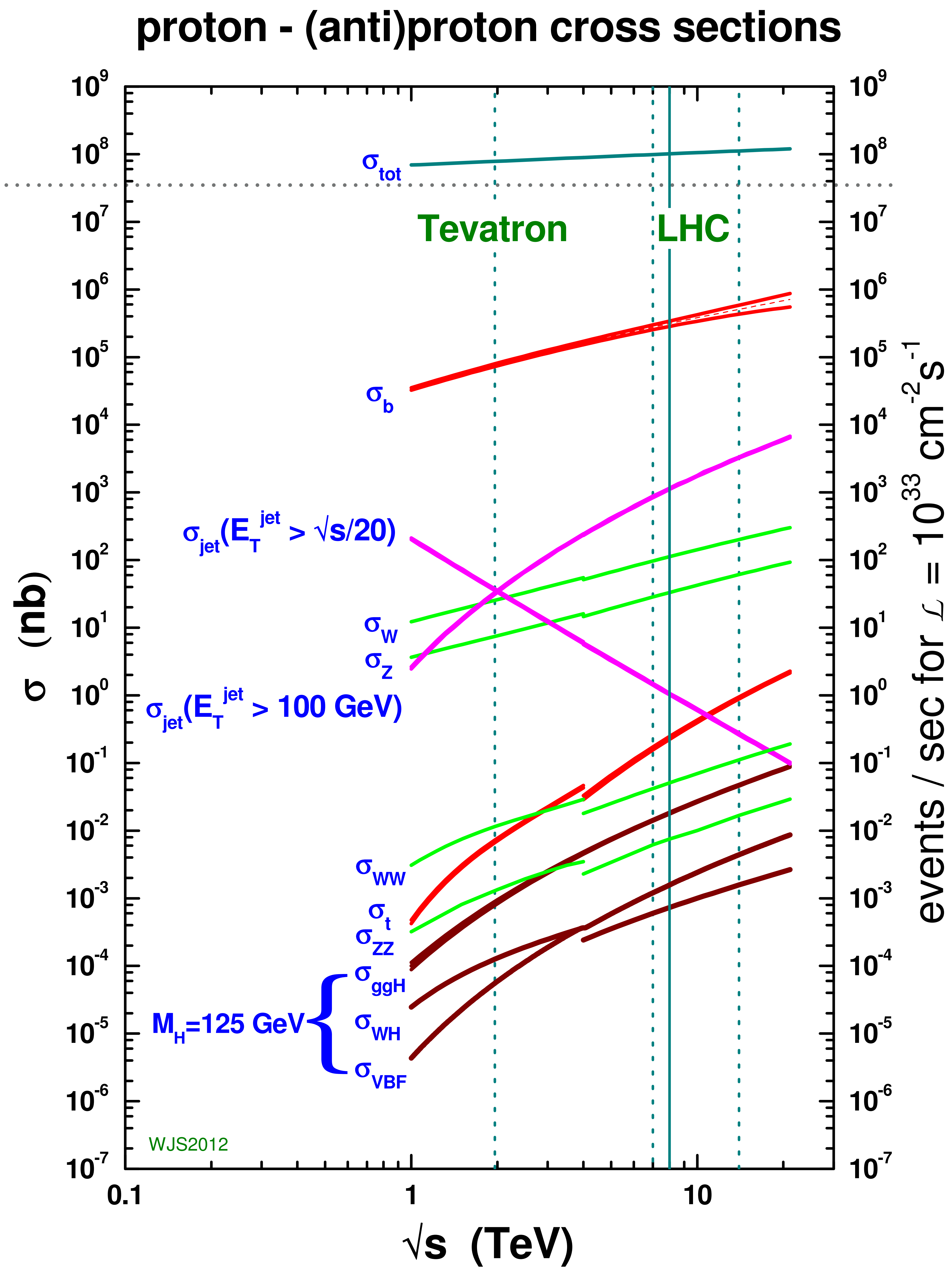
- Steep rise of partons at low x —> production rates strongly decrease with M_x

Roughly at 13 TeV

Process	Rate at 2 x 10^{34} $cm^{-2}s^{-1}$ [Hz]
any interaction	10^9
bottom production	10^7
jets pT > 100 GeV	5 x 10^4
W bosons	5 x 10^3
top quarks	10
Higgs	1
Higgs —> $\gamma\gamma$	0.002

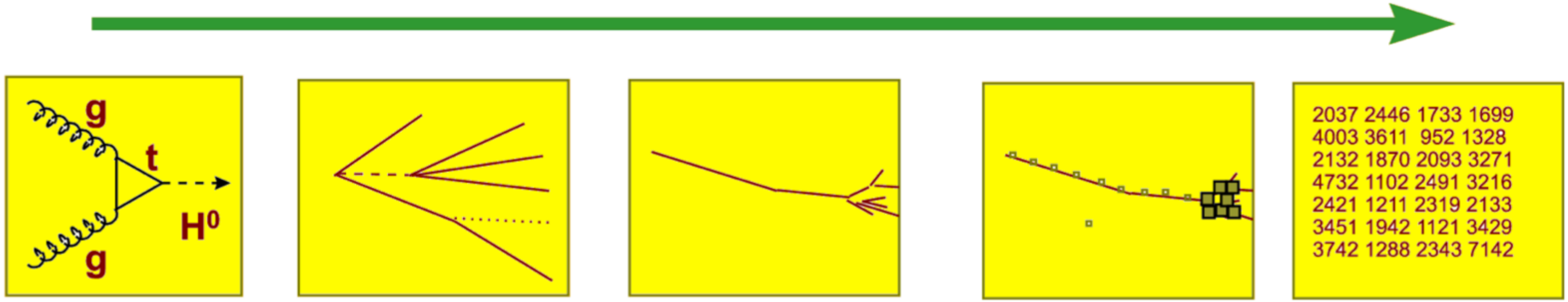
Event Rates at ATLAS

Events	Event Rate [Hz]
Beam crossings	4 x 10^7
Trigger at Level 1	10^5
Recorded to Disk	10^3



WHAT HAPPENS WHEN YOU COLLIDE PROTONS? (MORE CONCRETELY)

FROM PHYSICS TO RAW DATA



Basic physics

Fragmentation, Decay

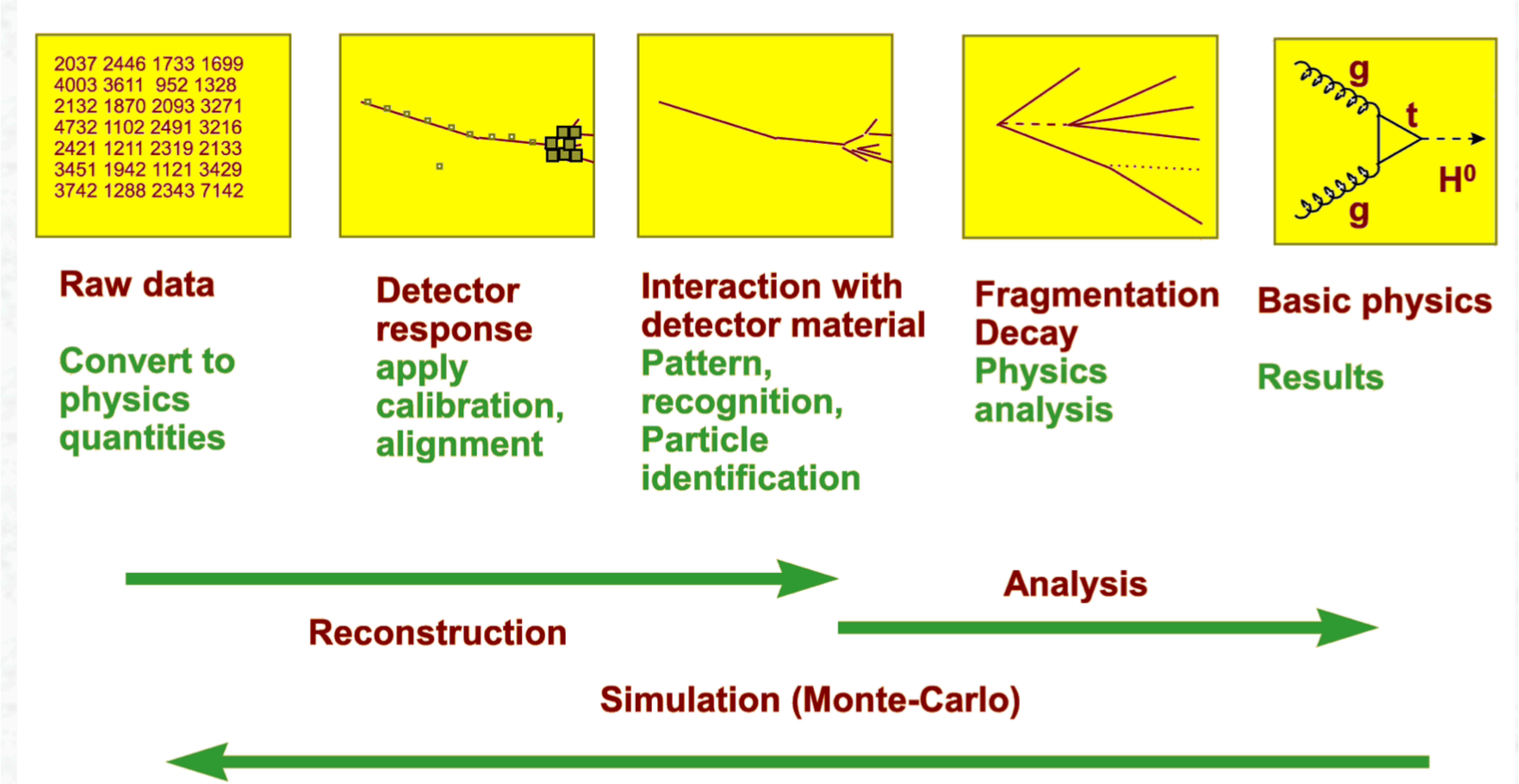
Interaction with detector material
Multiple scattering, interactions

Detector response
Noise, pile-up, cross-talk, inefficiency, ambiguity, resolution, response function, alignment

Raw data

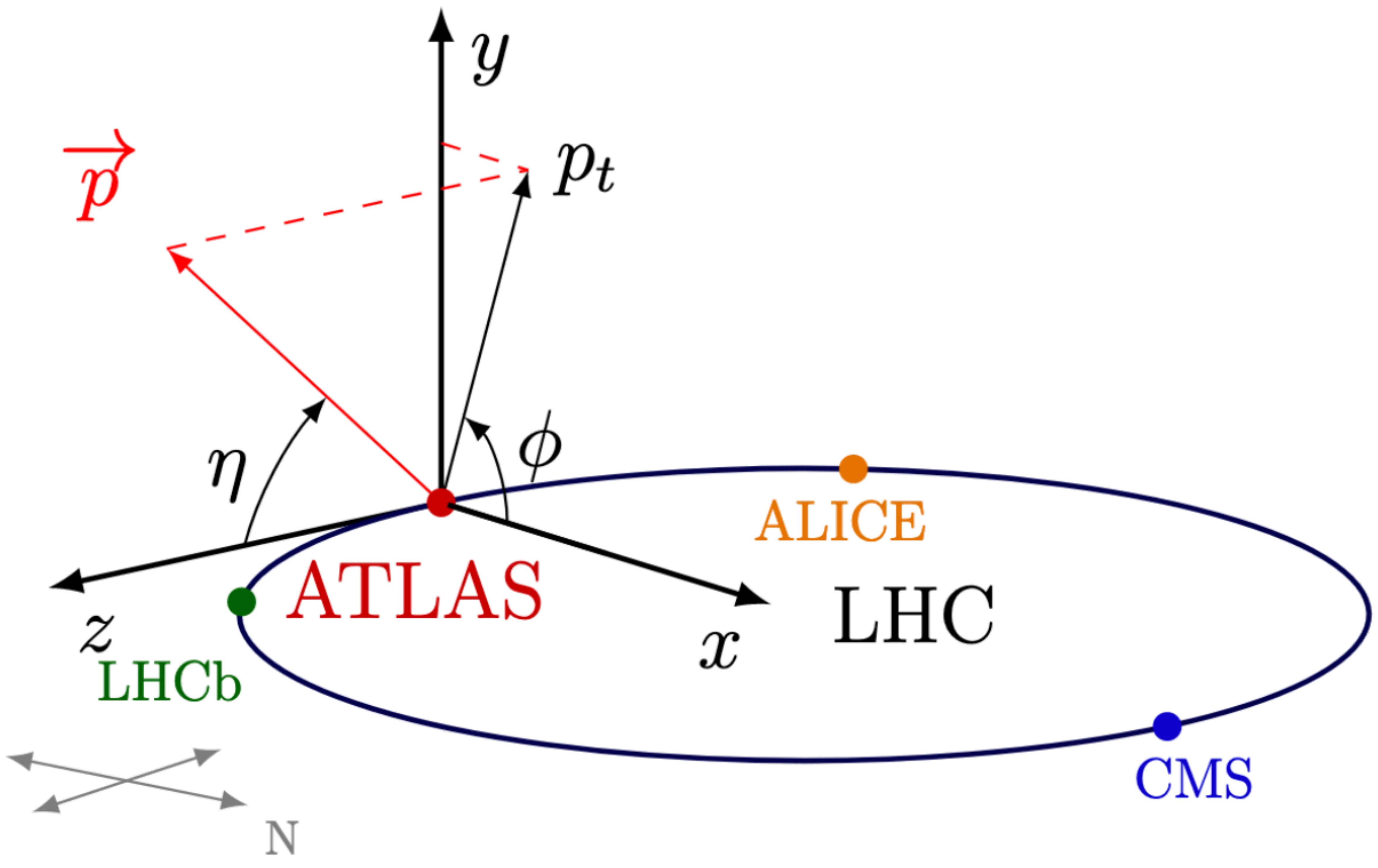
Read-out addresses, ADC, TDC values, Bit patterns

FROM RAW DATA TO PHYSICS



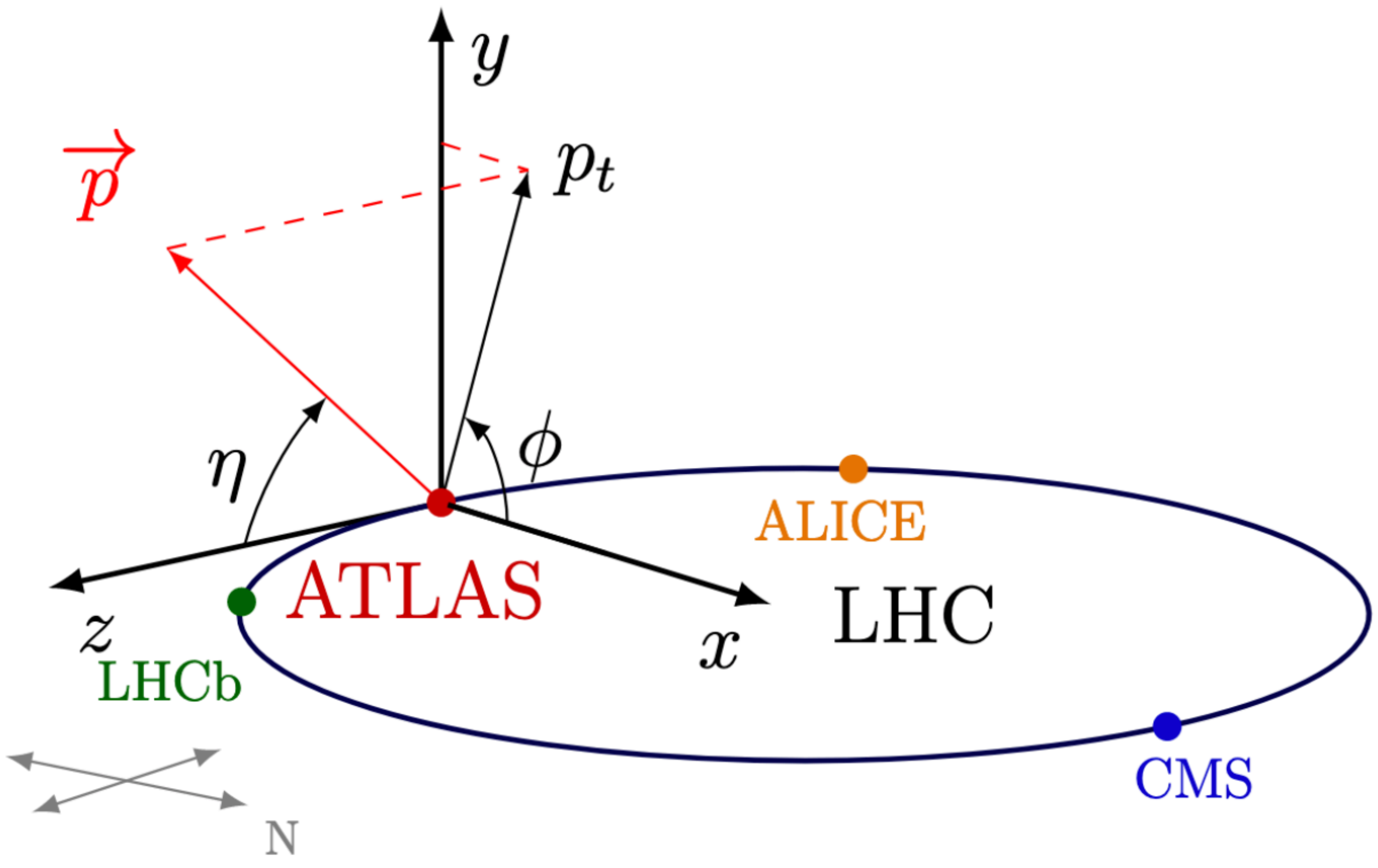
SCATTERING KINEMATICS

- **Detector coordinates: x, y, z or θ, ϕ, R**
  - Polar angle θ
  - Not Lorentz invariant



SCATTERING KINEMATICS

- Detector coordinates: x, y, z or θ, ϕ, R
  - Polar angle θ
  - Not Lorentz invariant
- **Rapidity**
  - $y = \frac{1}{2} \ln \left[\frac{E + p_L}{E - p_L} \right]$
  - where p_L=p along the beam line (z)
  - Δy invariant to boosts along beam line



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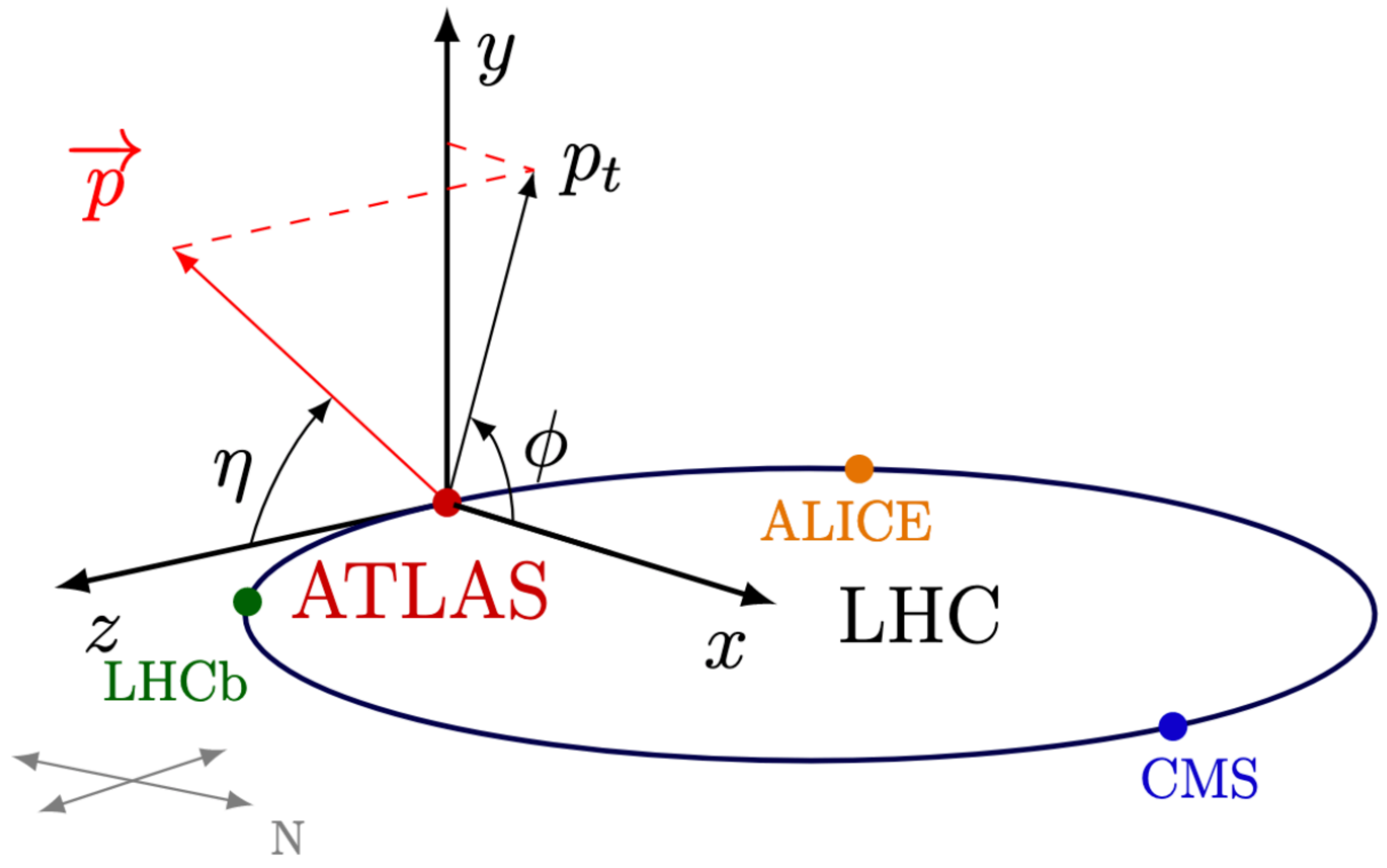
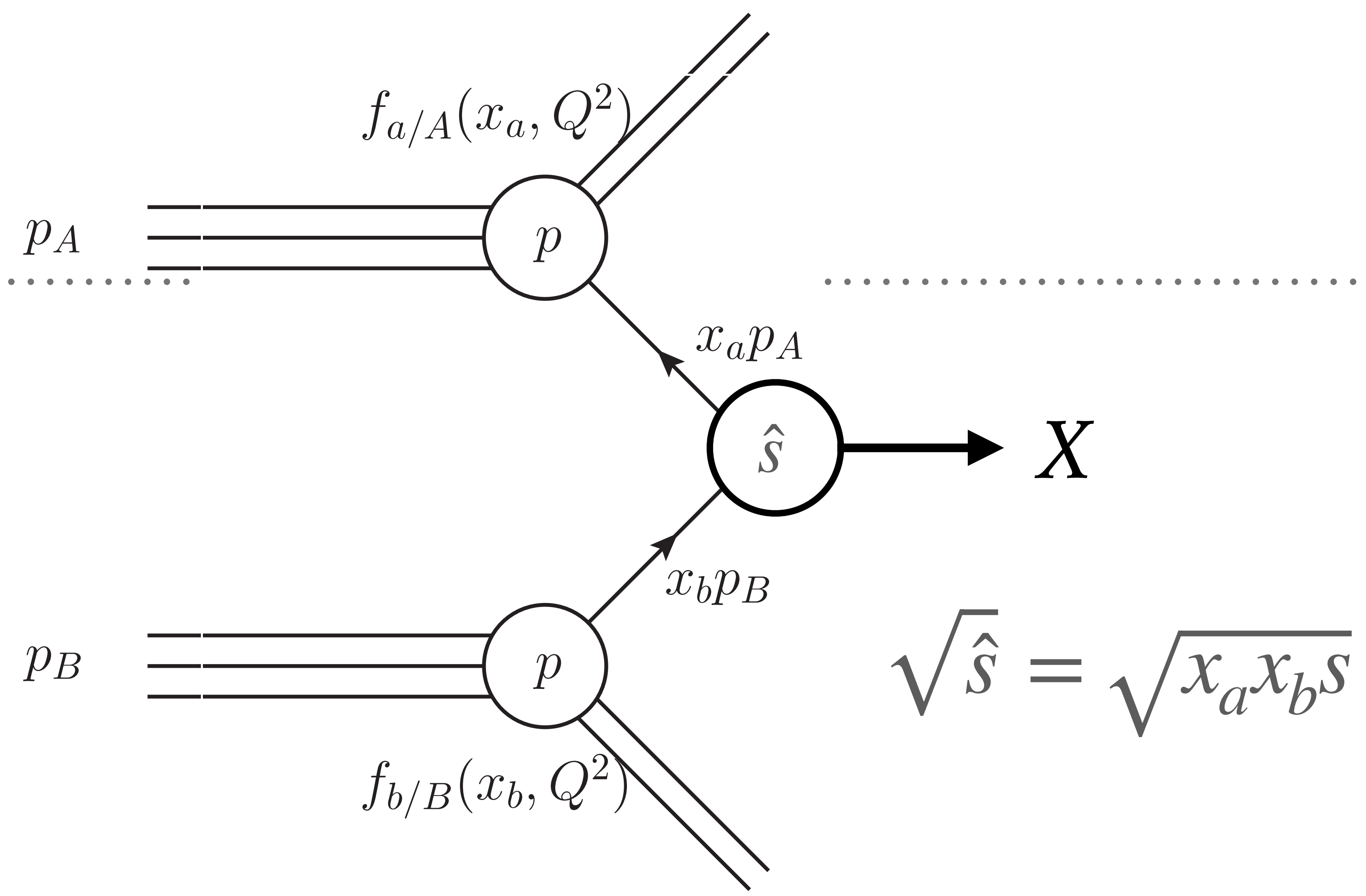
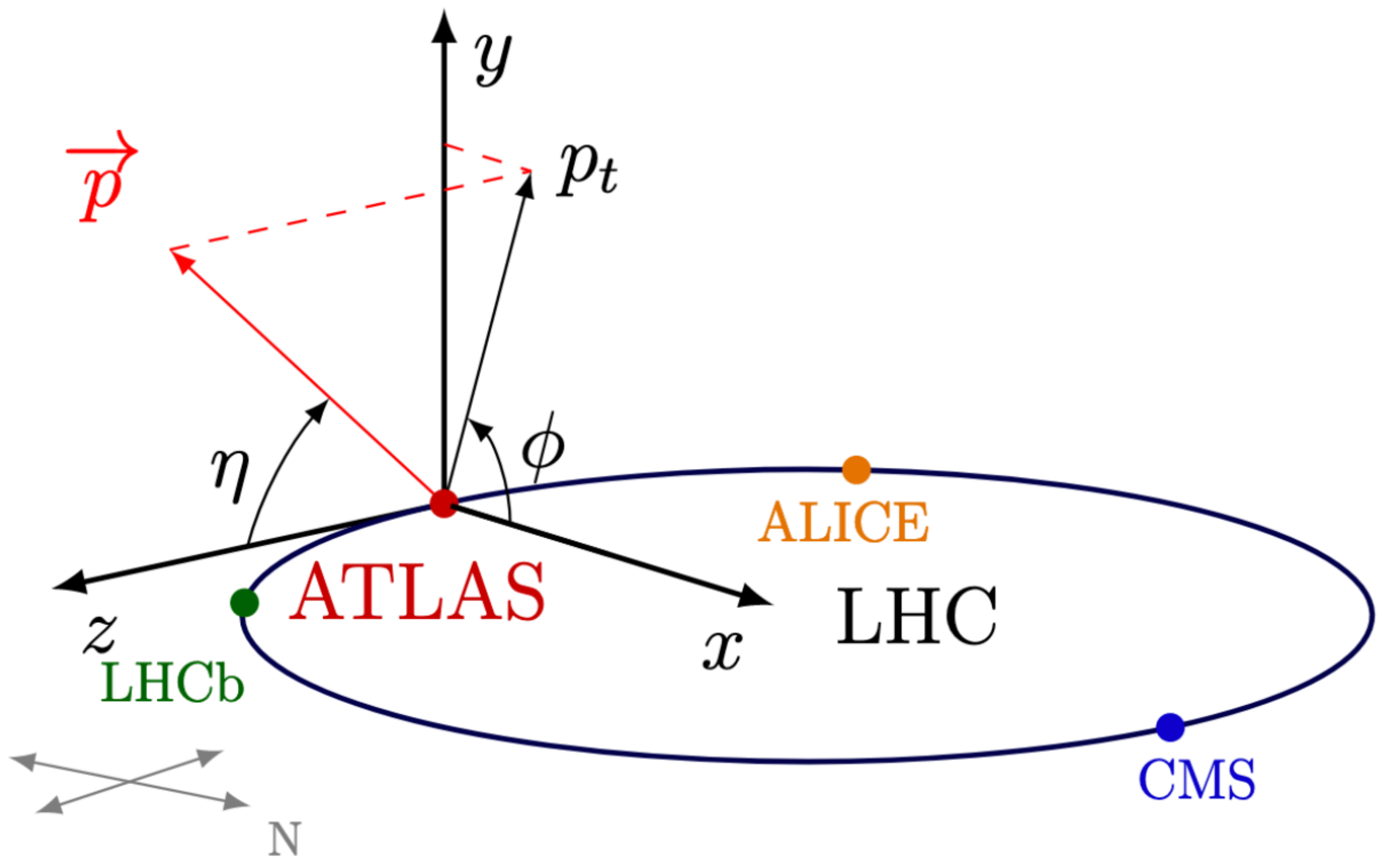
  - where p_L=p along the beam line (z)
  - Δy invariant to boosts along beam line
- **Pseudo-rapidity**
  - For massless particles, $y = \eta$
  - $\eta = -\, ln[\tan(\theta/2)]$



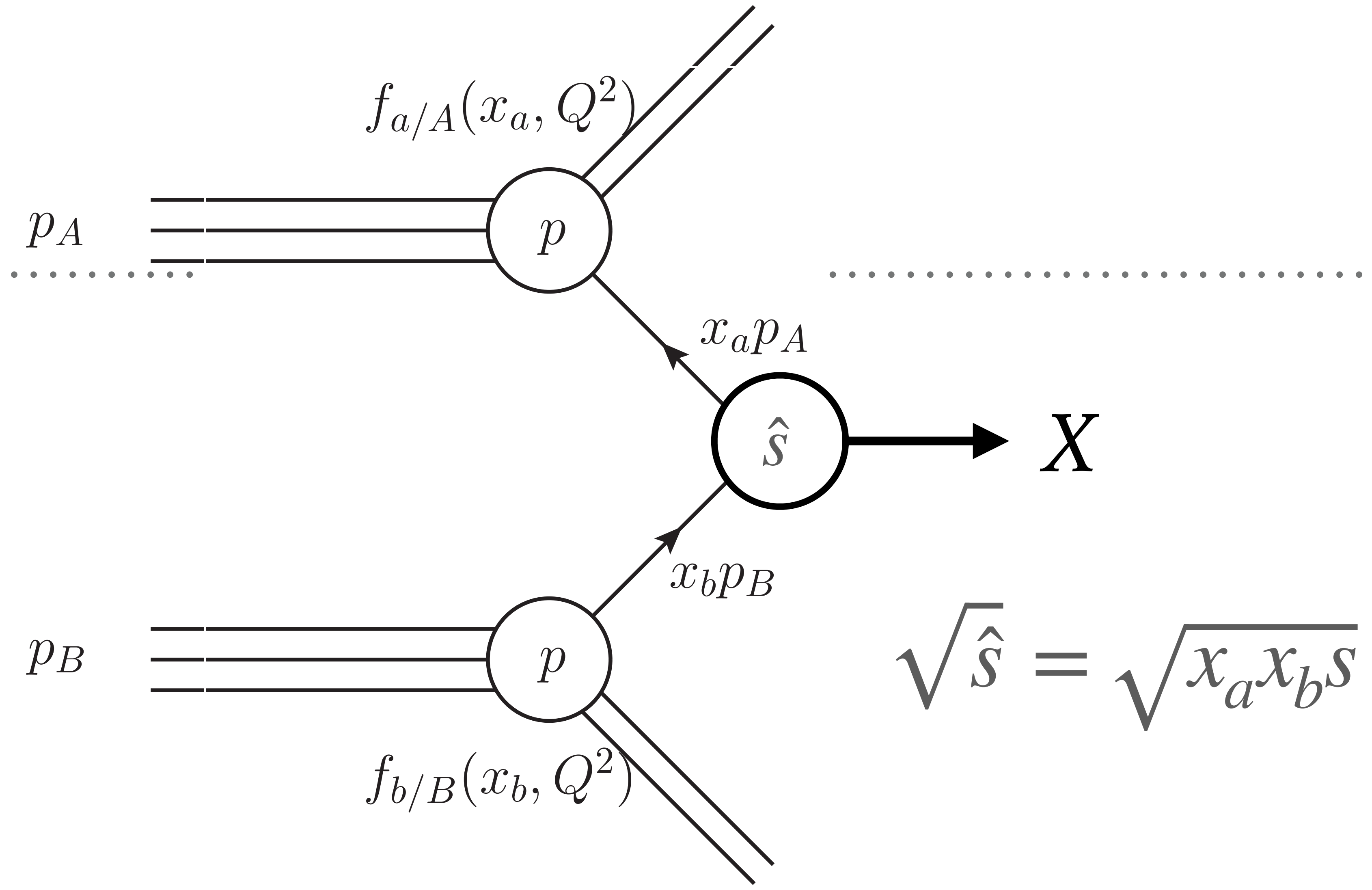
SCATTERING KINEMATICS



- **For production of particle X with mass M_X**
  - $\hat{s} = M_x^2$
  - $e^y = \sqrt{\frac{x_a}{x_b}}$ and $x_{a,b} = \frac{M}{\sqrt{s}} e^{\pm y}$
  - Large M
    - both x have to be large and not too dissimilar
    - $e^y \to 1$, ie, $y \to 0$, centrally produced
  - Small M
    - differing x, large boost —> large η



SCATTERING KINEMATICS



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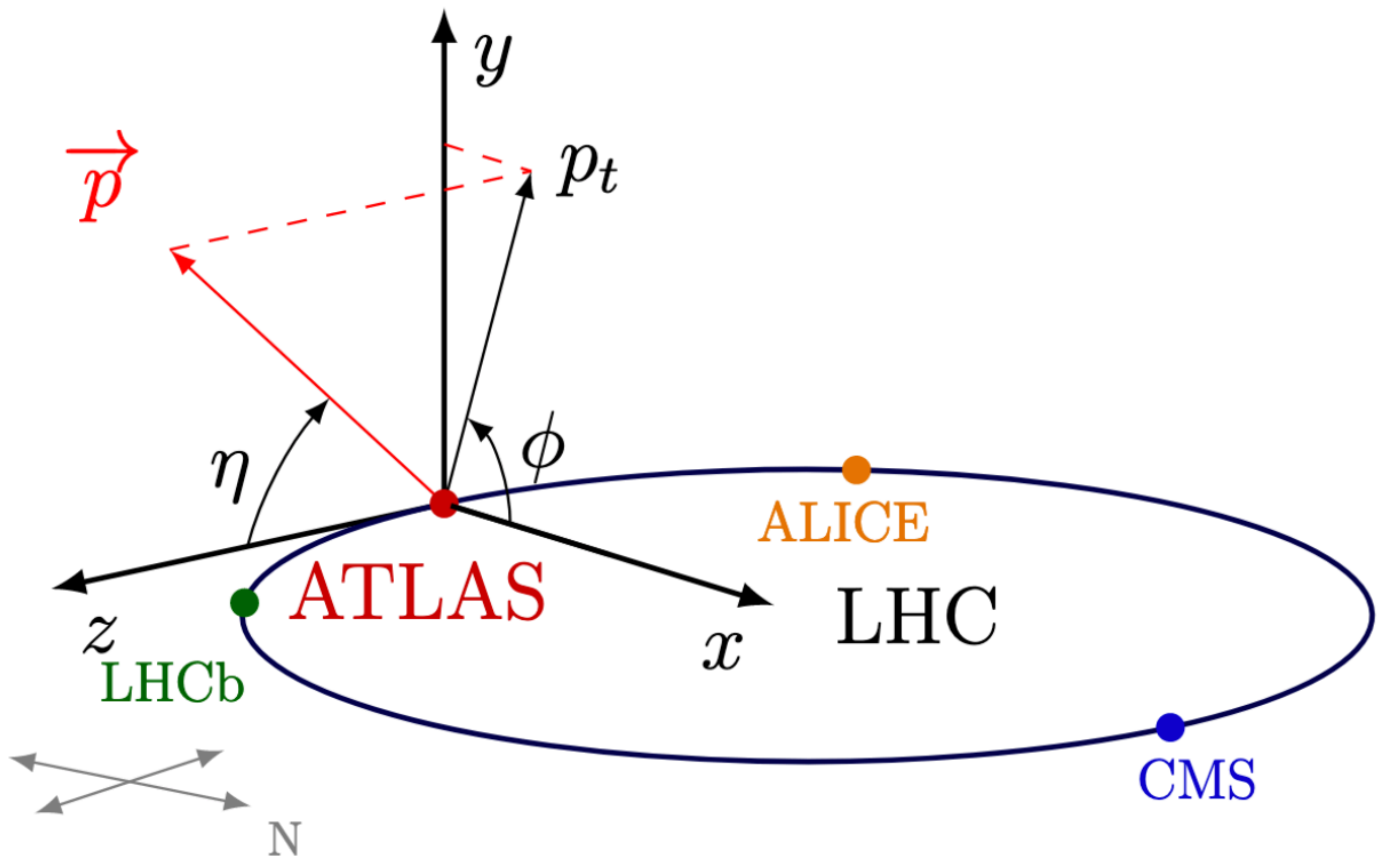
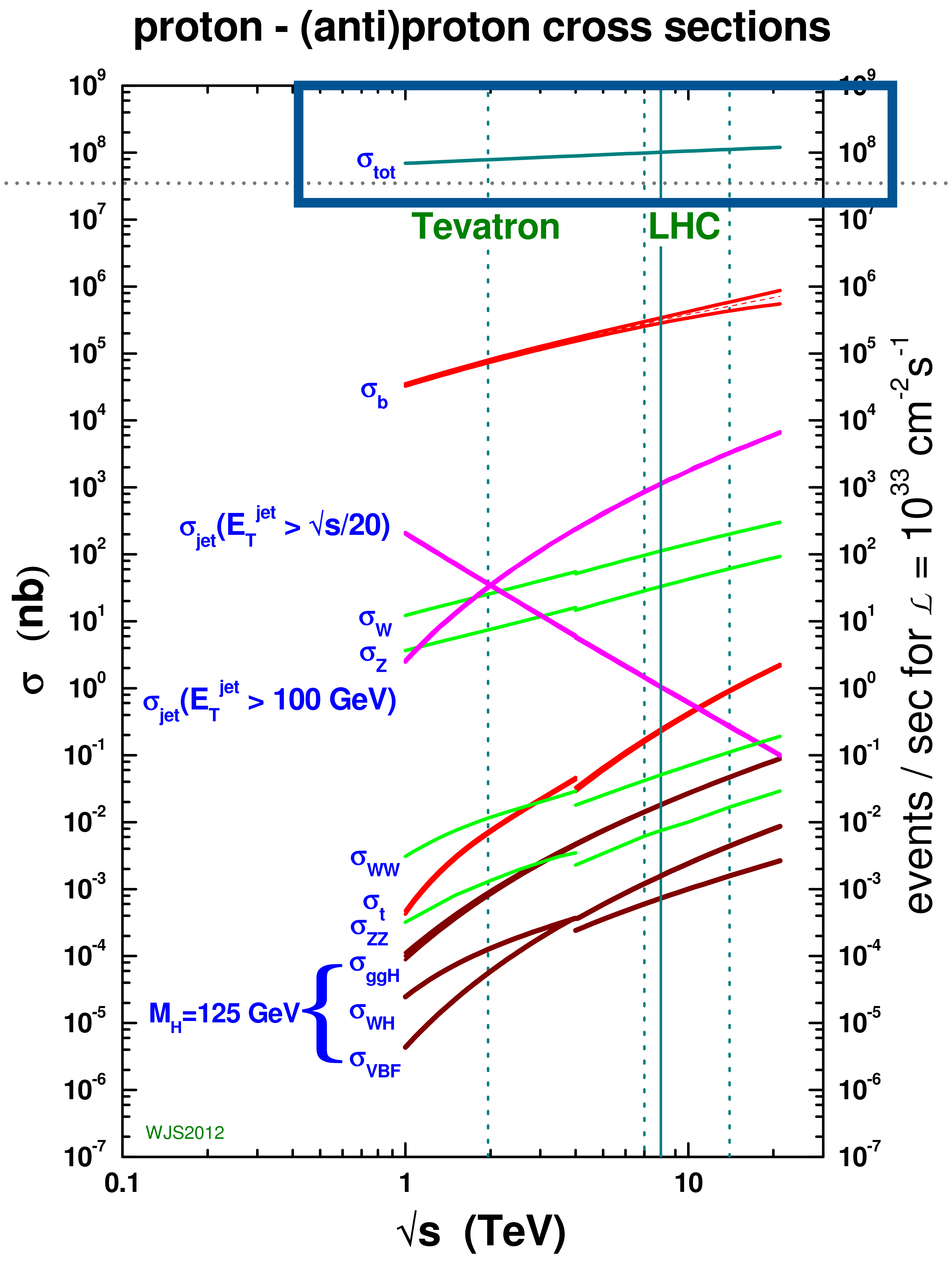
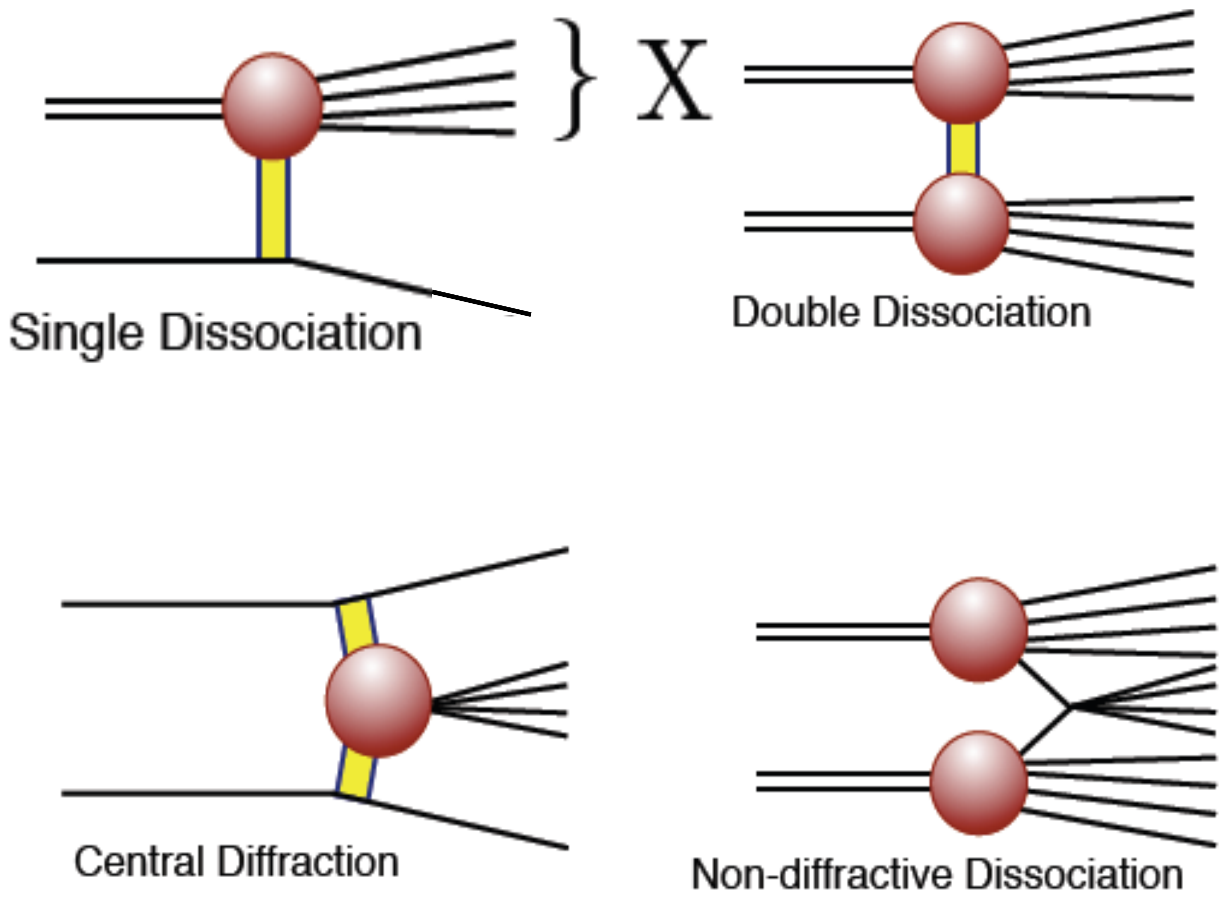
    - $e^y \to 1$, ie, $y \to 0$, centrally produced
  - Small M
    - differing x, large boost —> large η
- **Transverse momentum p_T**
  - Particles that escape detection have $p_T \approx 0$, $\theta < 2^\circ$
  - Visible transverse momentum conserved $\sum_i p_T^i \approx 0$

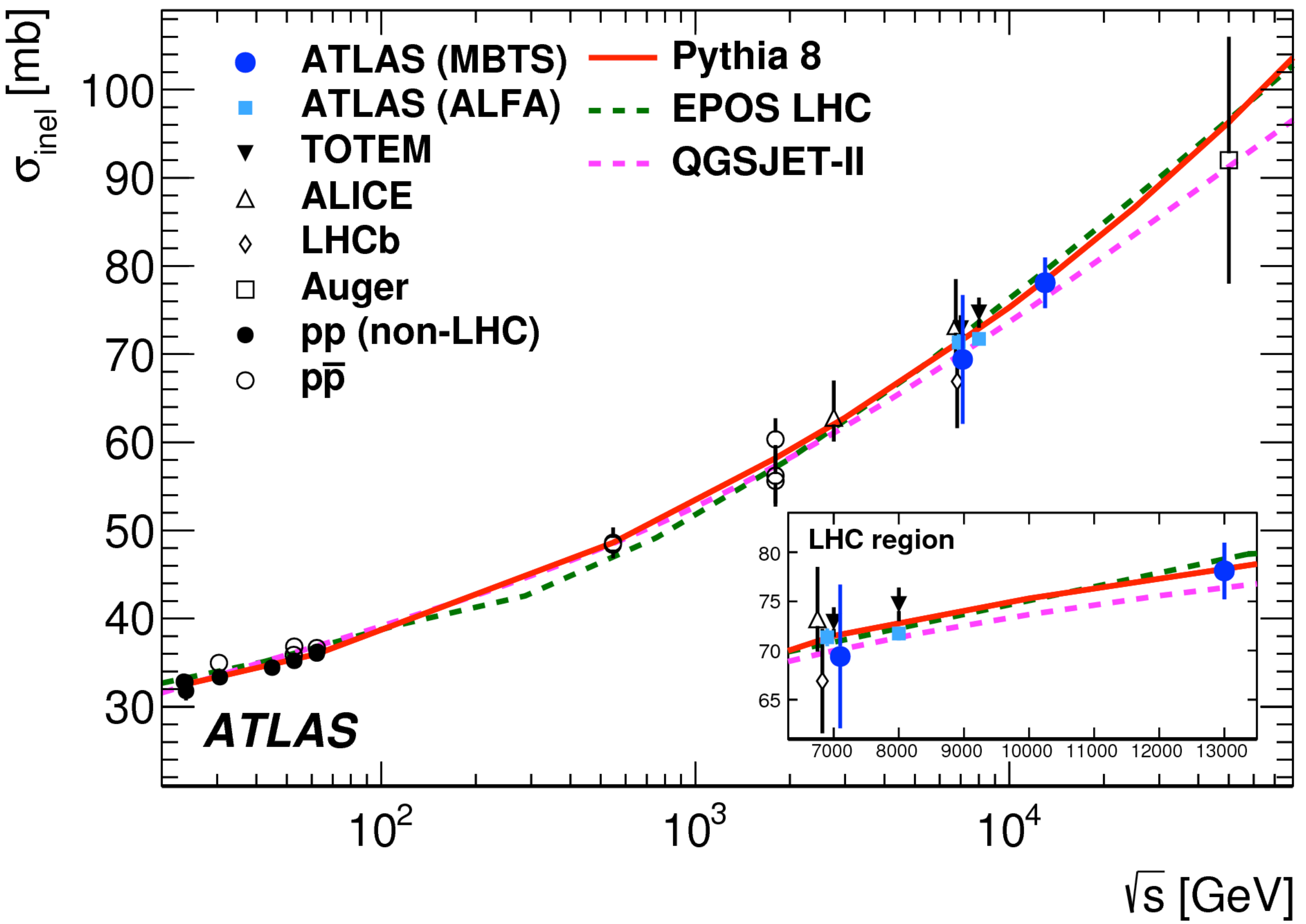



proton - (anti)proton cross sections
σ (nb)
events / sec for ℒ = 10^33 cm^-2 s^-1
√s (TeV)
σtot
Tevatron
LHC
σb
σjet(ET jet > √s/20)
σW
σZ
σjet(ET jet > 100 GeV)
σWW
σt
σZZ
σggH
MH=125 GeV
σWH
σVBF
WJS2012
0.1
1
10

INELASTIC PROTON-PROTON CROSS SECTION AT LHC

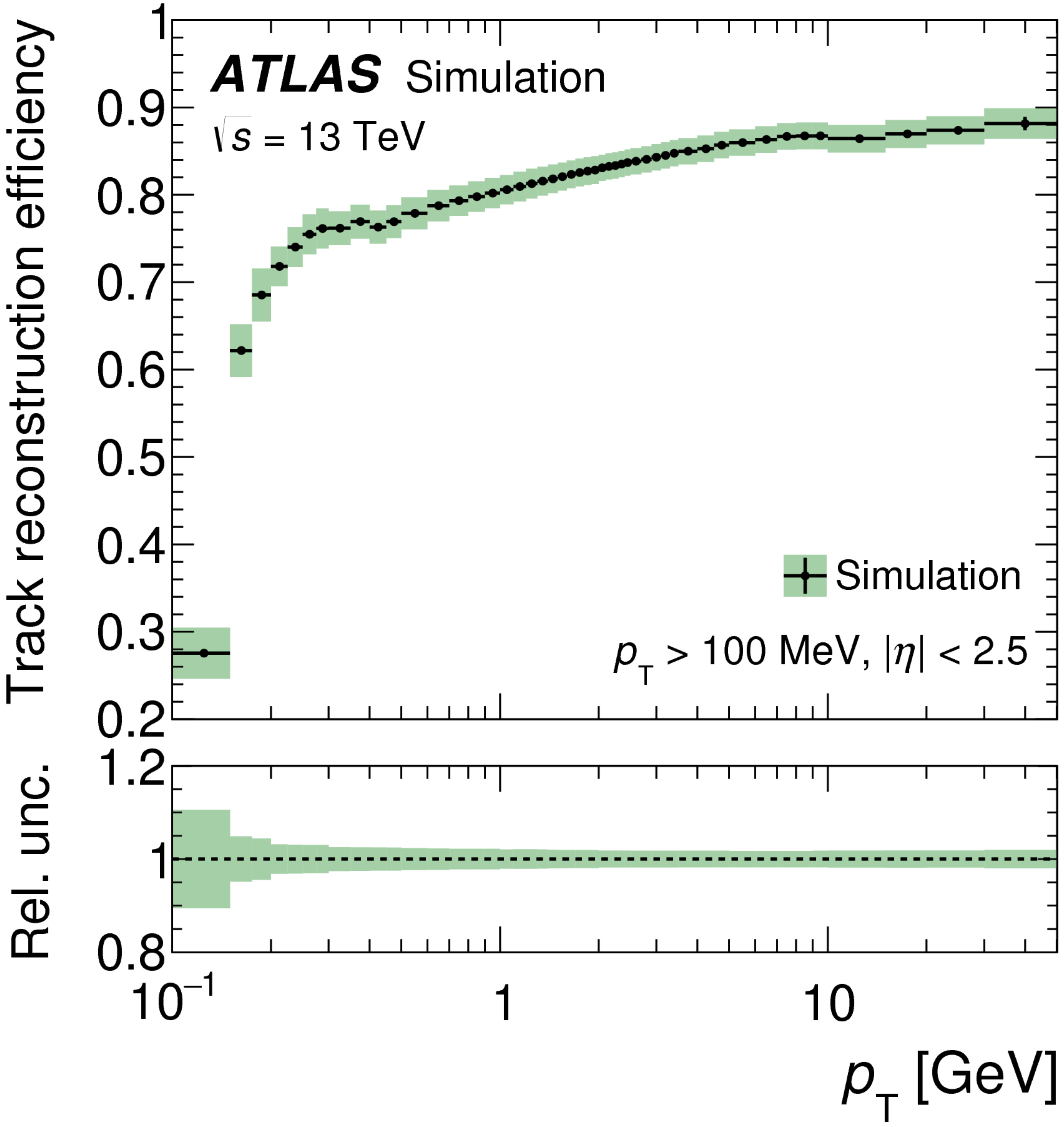
- Inelastic proton-proton collisions
  - pp —> X
  - non-perturbative; can not be calculated to high precision theoretically
- In every LHC event there are 10-70 such interactions (pile-up)





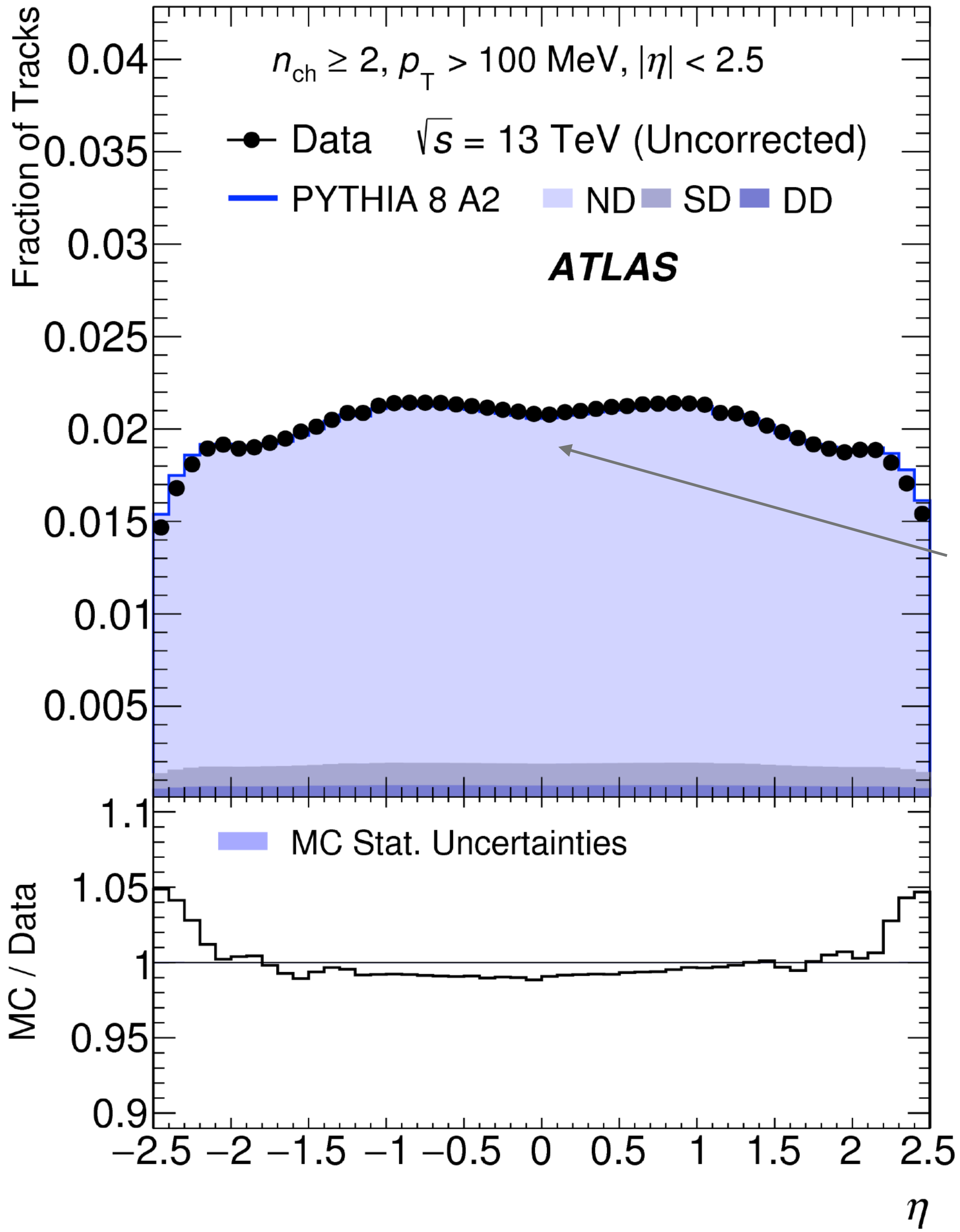
INELASTIC PROTON-PROTON EVENTS

- **What do the bulk of events look like?**
  - Minimum-bias events, selected / defined with "minimum-bas trigger"
- **Study charged particle properties**
  - Look inclusively at tracks
  - Select only "primary" particles
    - Those produced in hard-scatter or from prompt decay of hard-scatter product
  - Select against "secondaries" from decays-in-flight, hadronic interactions, photon conversions, etc.



INELASTIC PROTON-PROTON EVENTS

- What do the bulk of events look like?
- **Study charged particle properties**
  - Relatively flat distribution of charged particles in rapidity up to kinematic boundary of $y \approx 5$, and then sharp drop
  - Roughly 6 charged particles and 2-3 neutrals per unit rapidity per min bias collision
    - —> Order 80-100 particles per collision

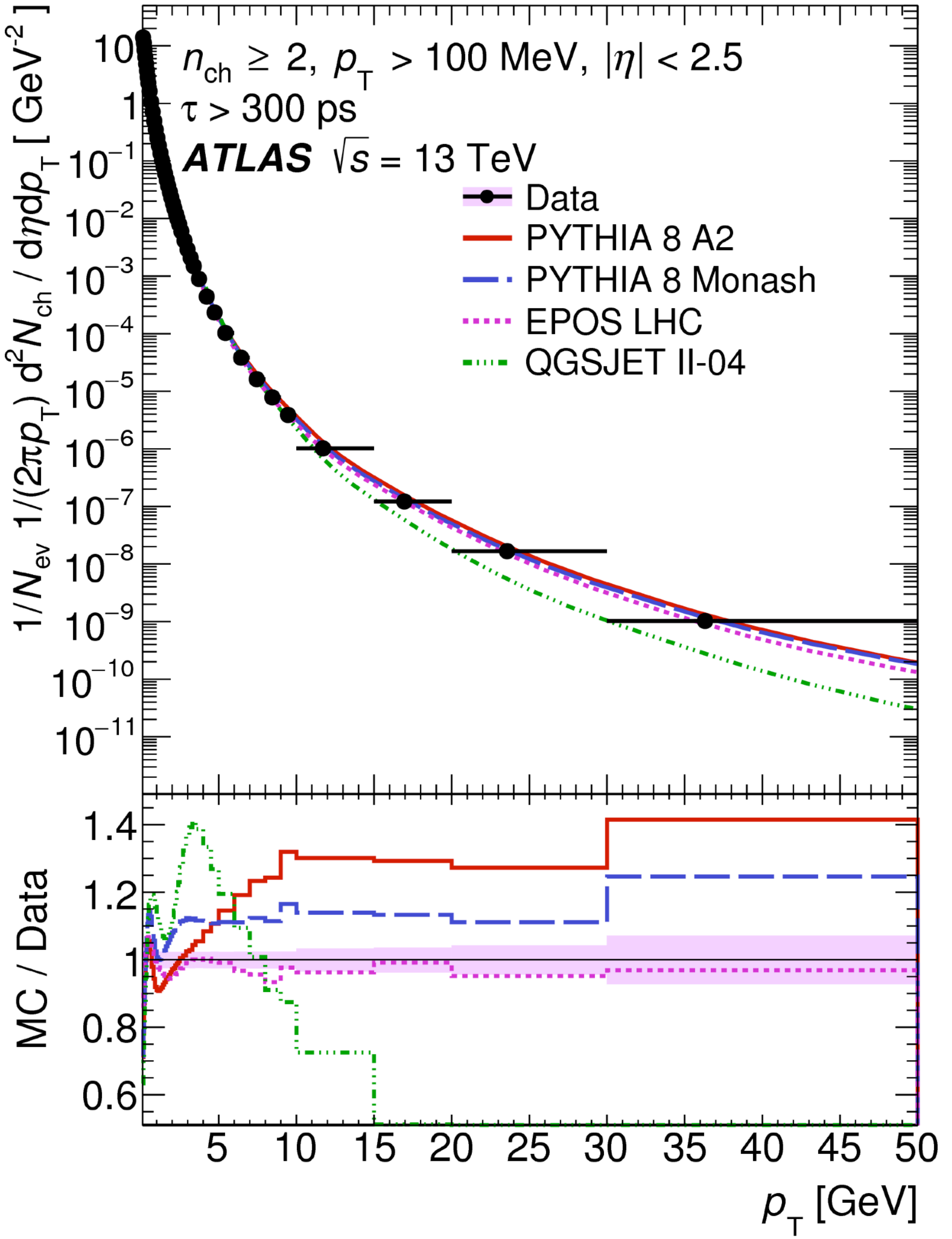


dip at central η because $m \neq 0$, flat in y

non-diffractive (ND), single-diffractive dissociation (SD) and double-diffractive dissociation (DD)

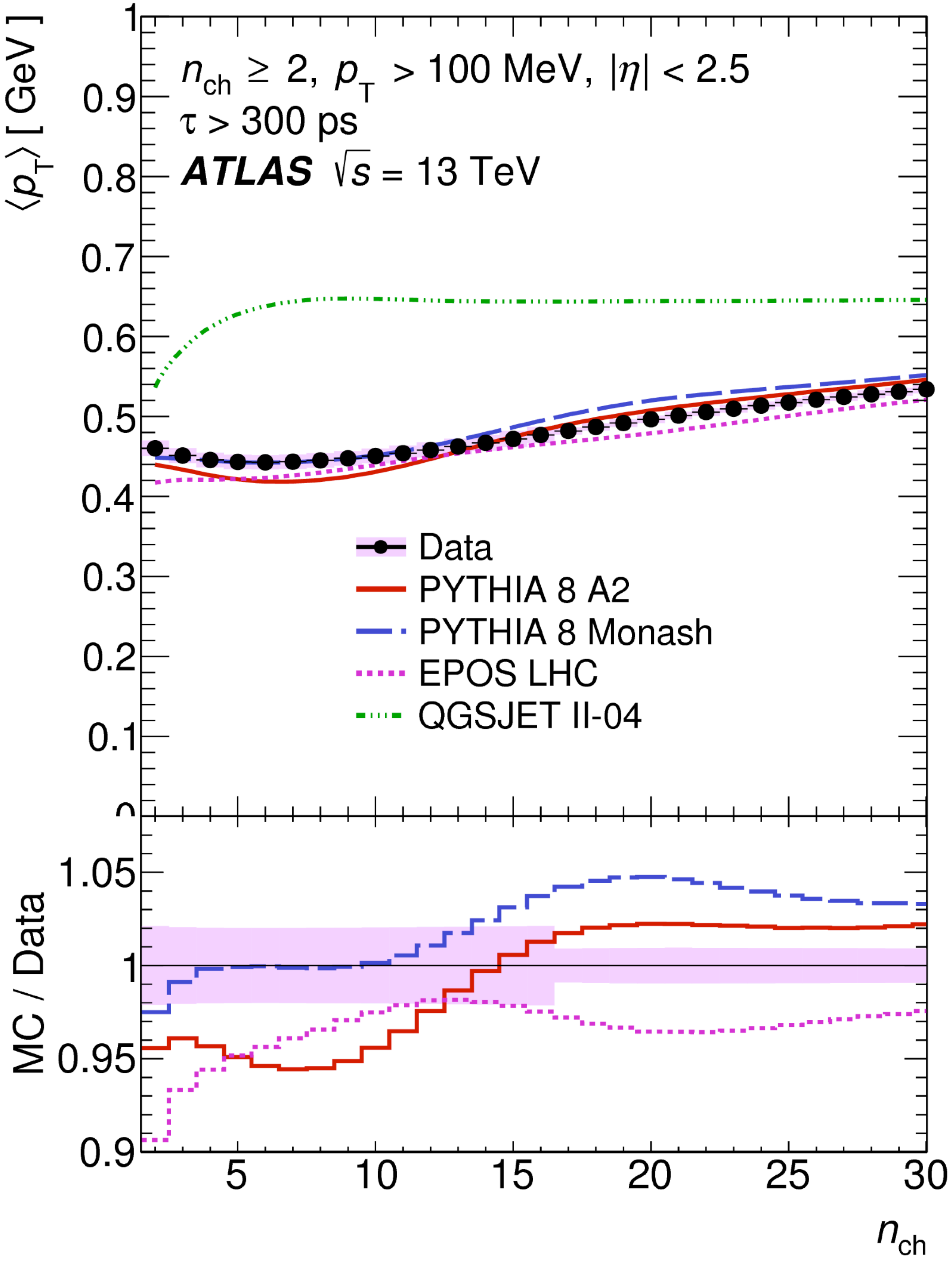
INELASTIC PROTON-PROTON EVENTS

- What do the bulk of events look like?
- **Study charged particle properties**
  - Steeply falling distribution in p_T above threshold of $p_T > 100$ MeV
  - Bending radius determined by:
    - $p[\text{GeV}] = 0.3R[\text{m}]B[\text{T}]$
    - For tracking detectors of ≈ 1 m and $B \approx 2-4$ T, particles with p < 0.6 (1.2) GeV will curl/loop inside tracker
      - Detector design choice on B, R to determine occupancy of tracker versus calorimeters



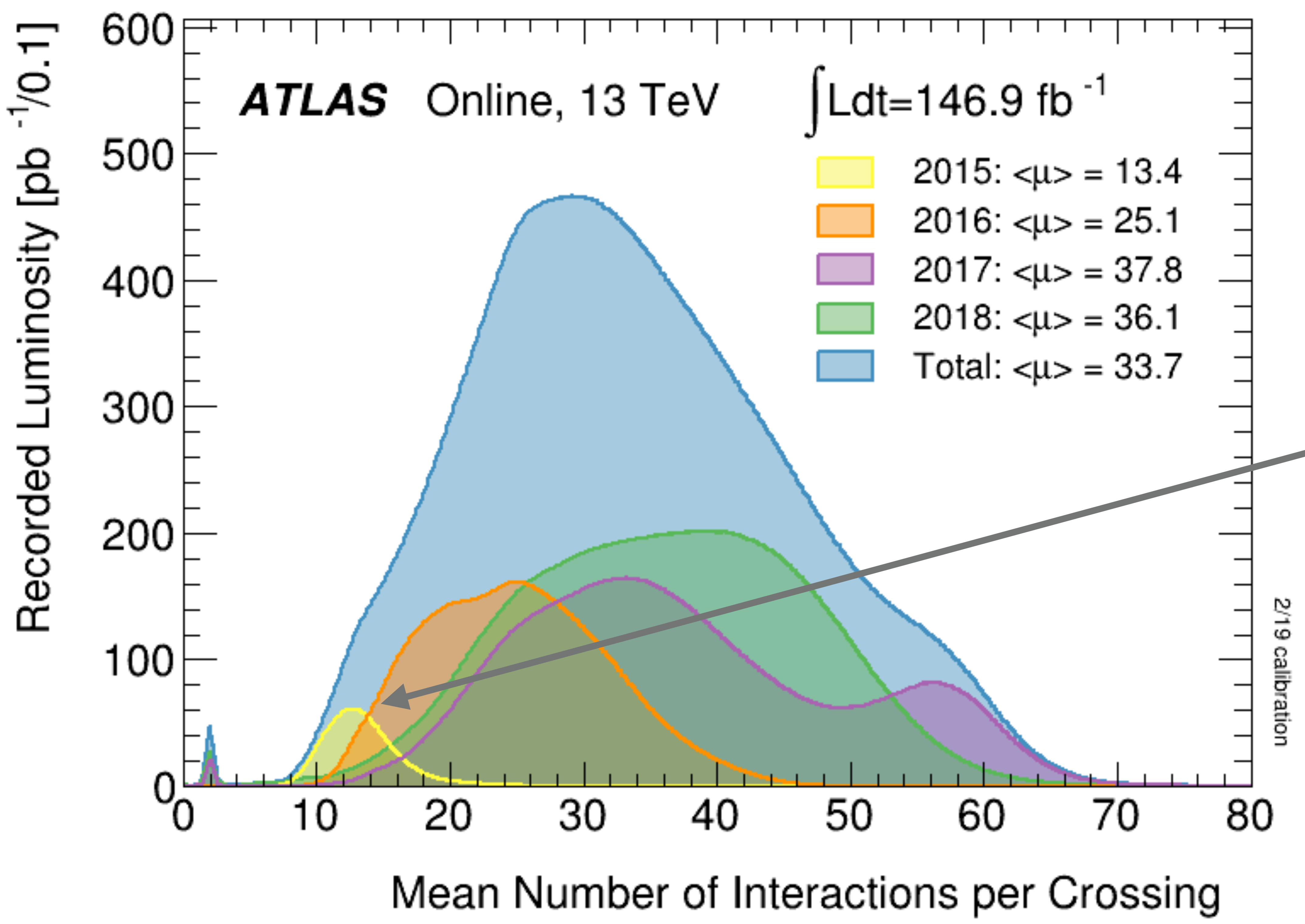
INELASTIC PROTON-PROTON EVENTS

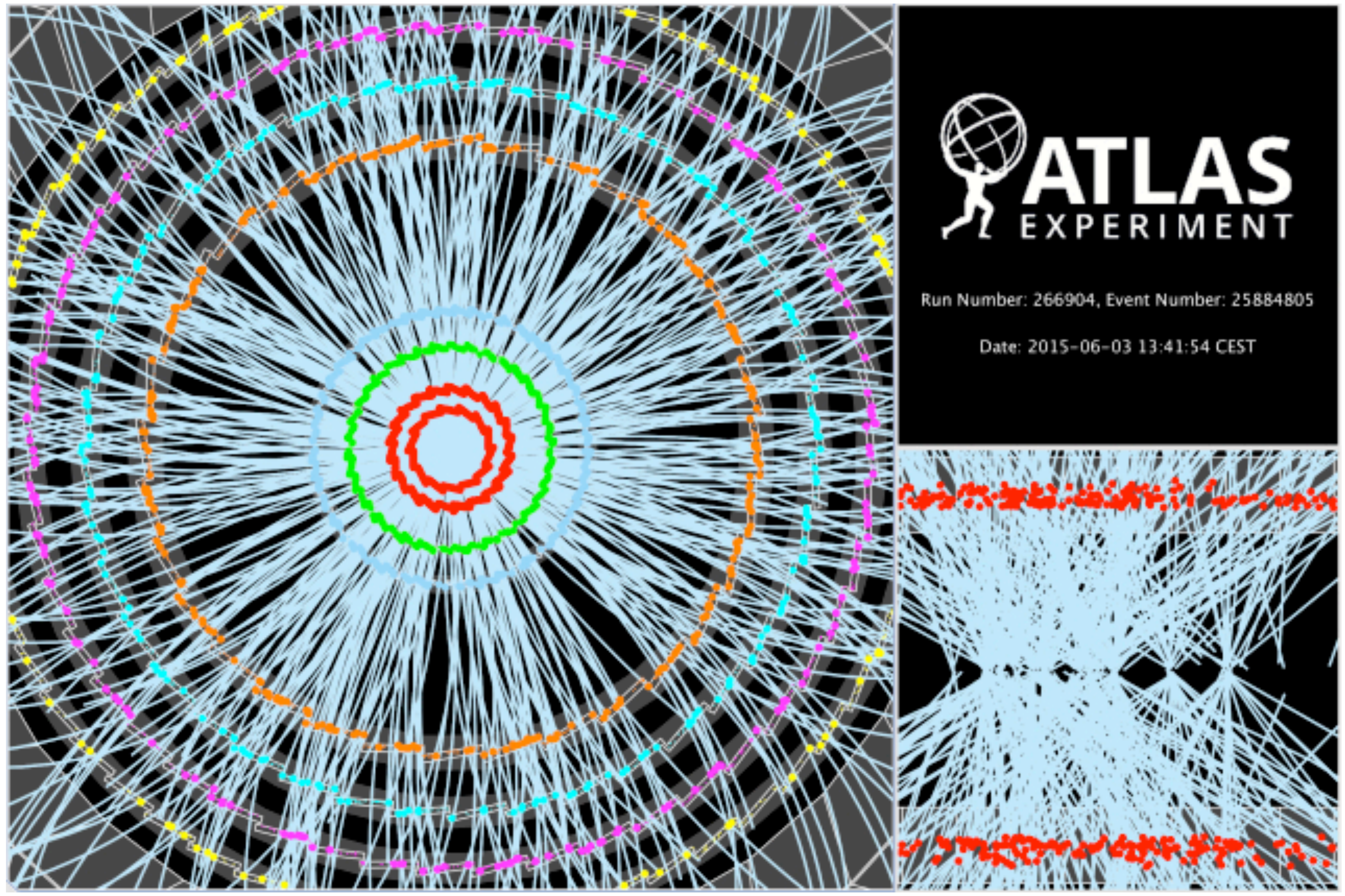
- What do the bulk of events look like?
- **Study charged particle properties**
  - Steeply falling distribution in p_T above threshold of $p_T > 100$ MeV
  - Average p_T of charged particles ≈ 0.5 GeV
  - —> Order (100 x 0.5 =) 50 GeV p_T per minimum bias event
  - Important to measure these properties and tune MC
    - soft QCD, not possible to calculate precisely
    - Necessary to get right for modeling 99.99xx% of collisions
      - Pile-up!



PILE-UP AT LHC

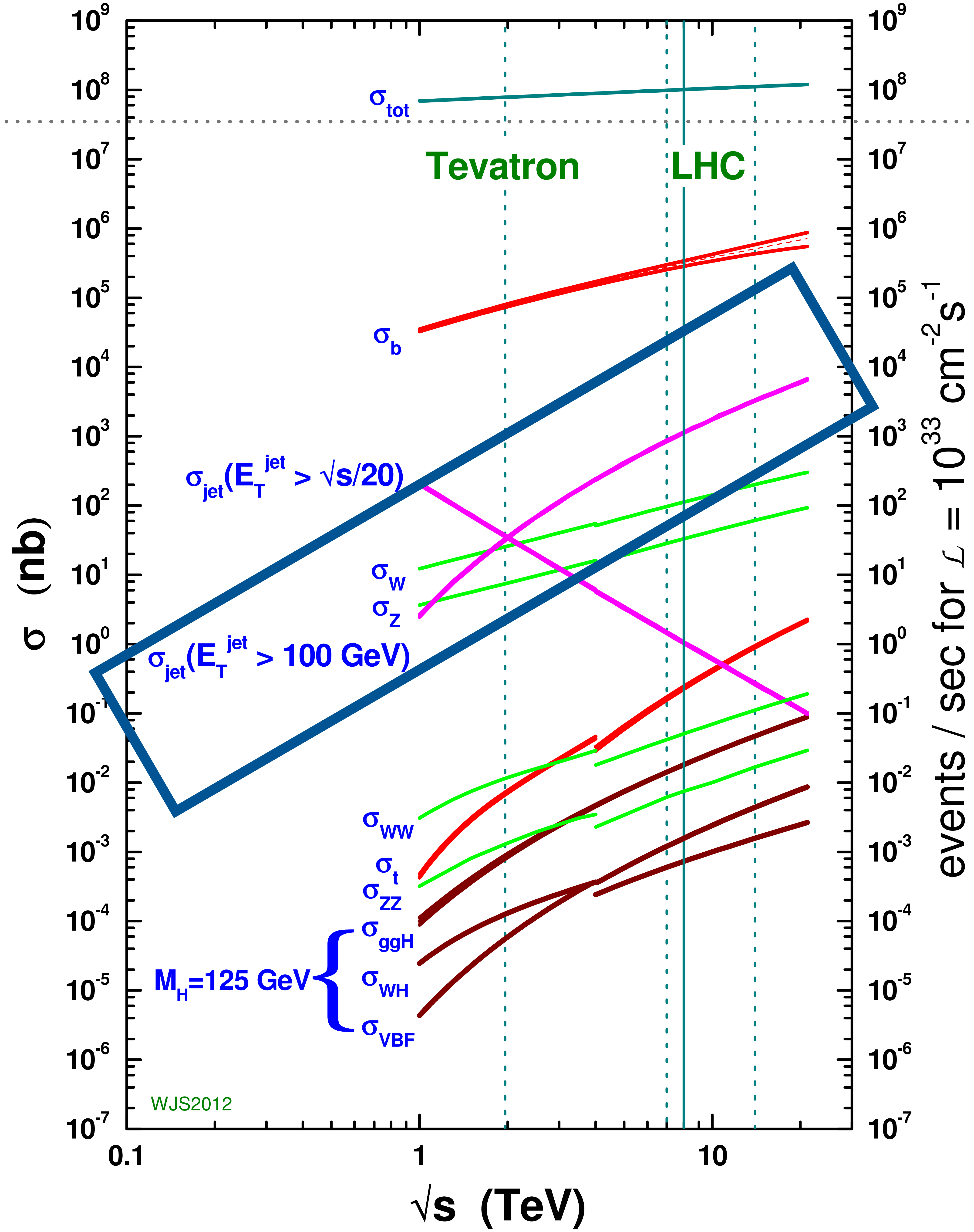
- Challenge for detector performance and object reconstruction
  - In-time pileup (same bunch crossing)
  - Out-of time pileup (different bunch crossing than collision of interest)
    - some detectors have readout window larger than one bunch-crossing
    - can interfere with energy / hit collection even if not





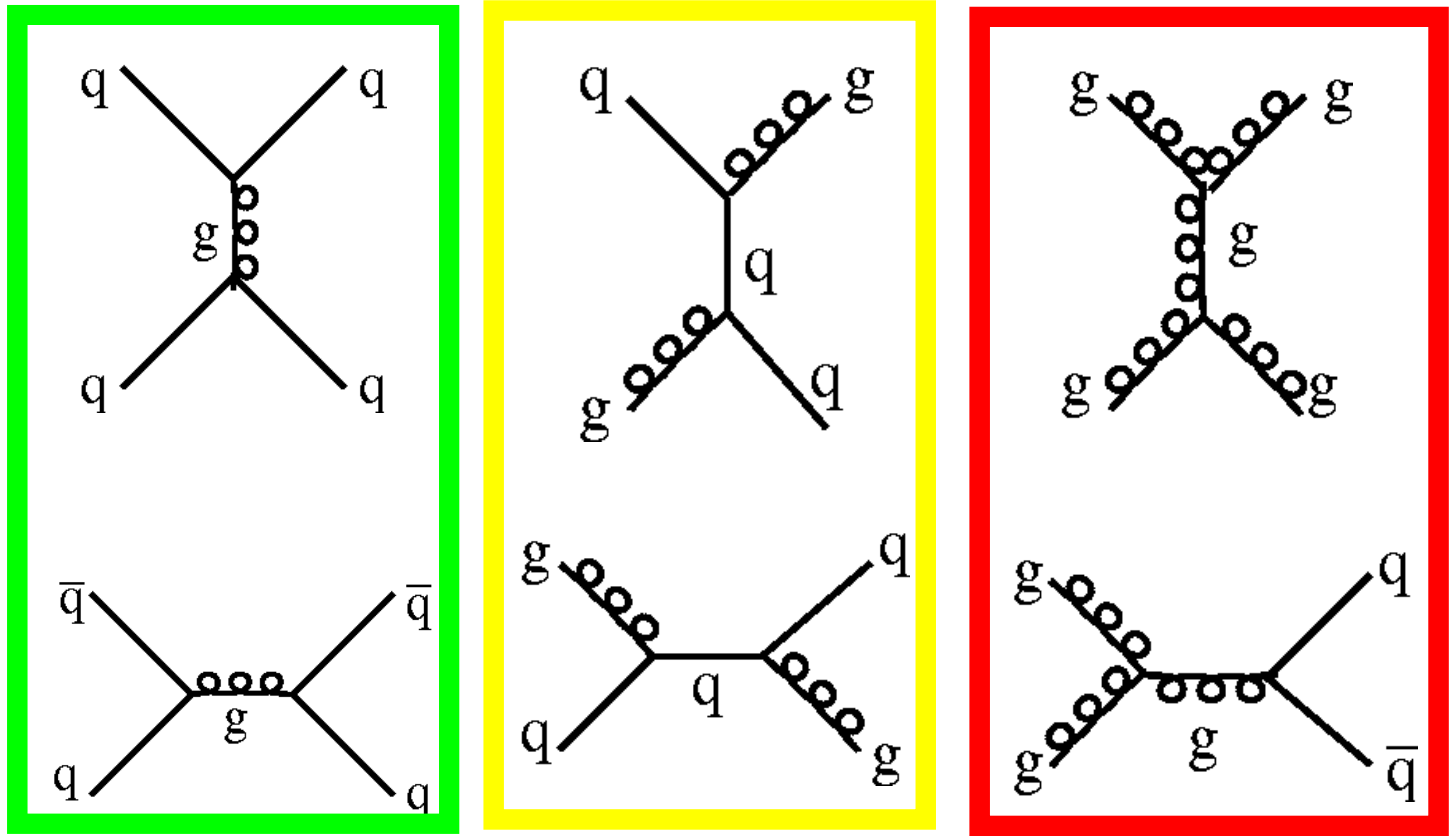
$p_T > 500\ MeV, \ <\mu> \approx 10$

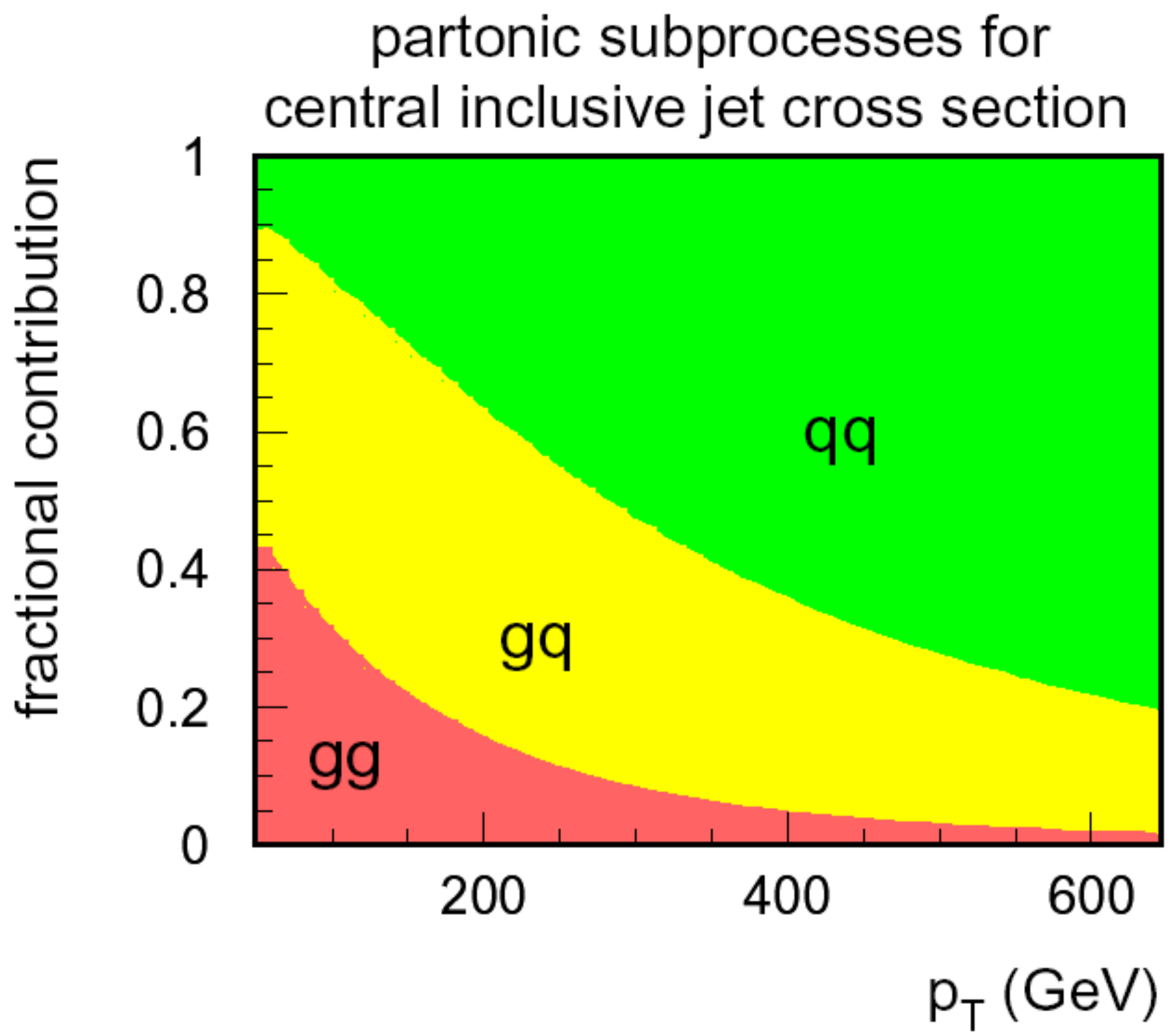
proton - (anti)proton cross sections



JET PRODUCTION AT LHC

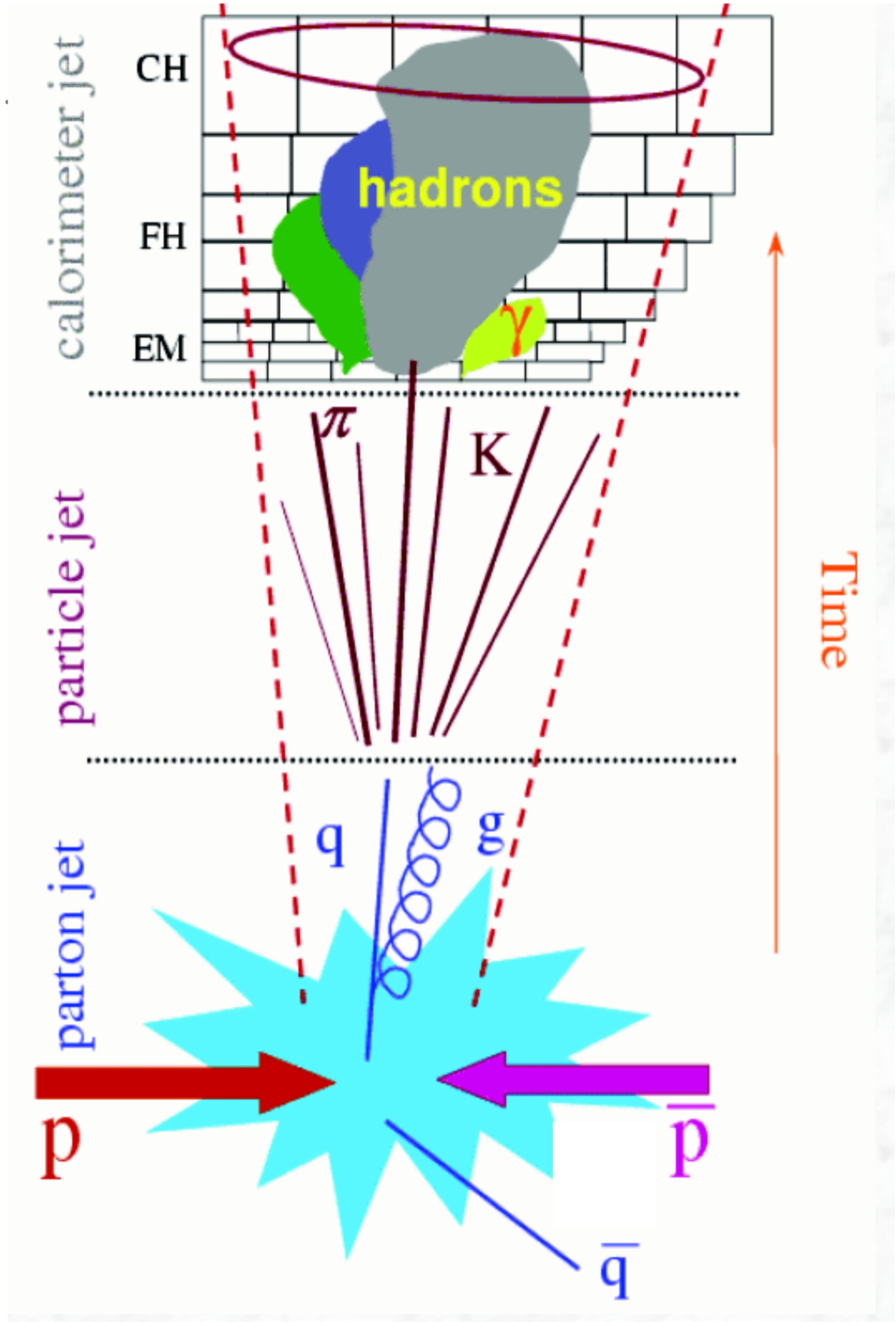
- Hard scattering processes dominated by QCD processes, originating from qq, qg, and gg scattering
- Cross-sections can be calculated in QCD using perturbation theory
- Measuring cross-sections and comparing to predictions an important test of QCD
  - Deviations could be a sign of quark substructure, etc…





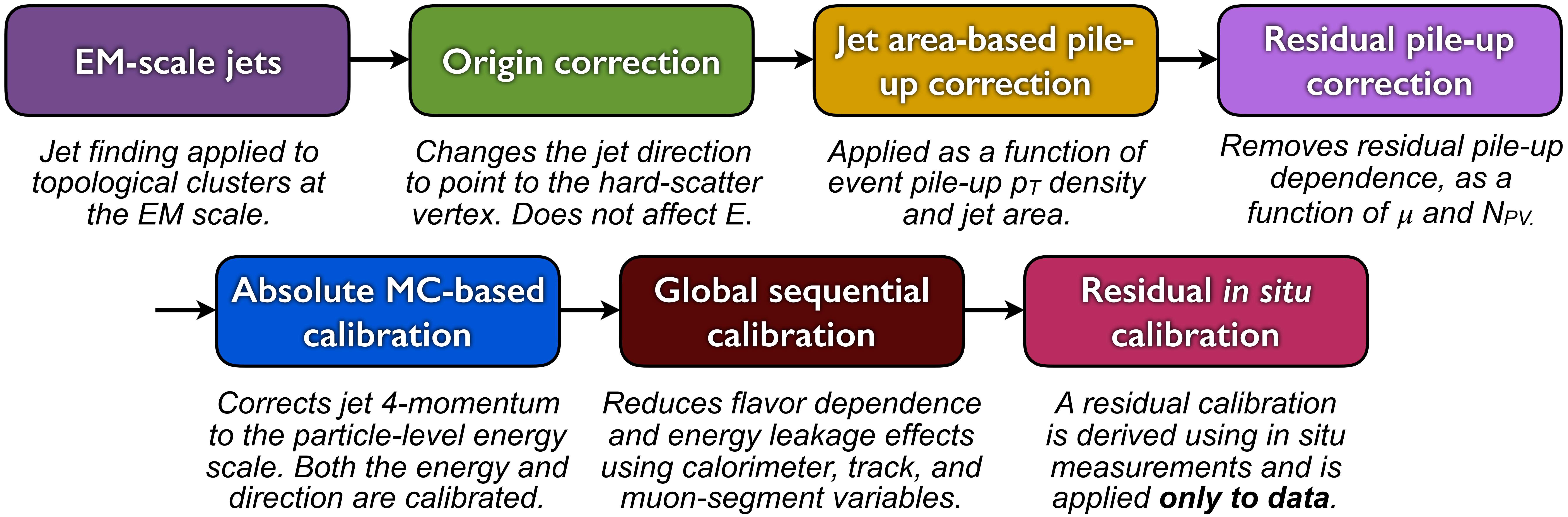
JET RECONSTRUCTION AT LHC

- A jet is not a uniquely or well-defined object
  - Fragmentation, gluon radiation, detector response all folded-in
  - Detector response different for electrons/photons, hadrons —> correct calorimeter energy response to “particle level”
- Many jet algorithms exist, desired features include
  - Collinear safe: jet definition independent of presence of partons radiated collinear to quark
  - Infrared safe: jet defintion independent of soft radiation
  - k_T family of algorithms satisfies these criteria, commonly used

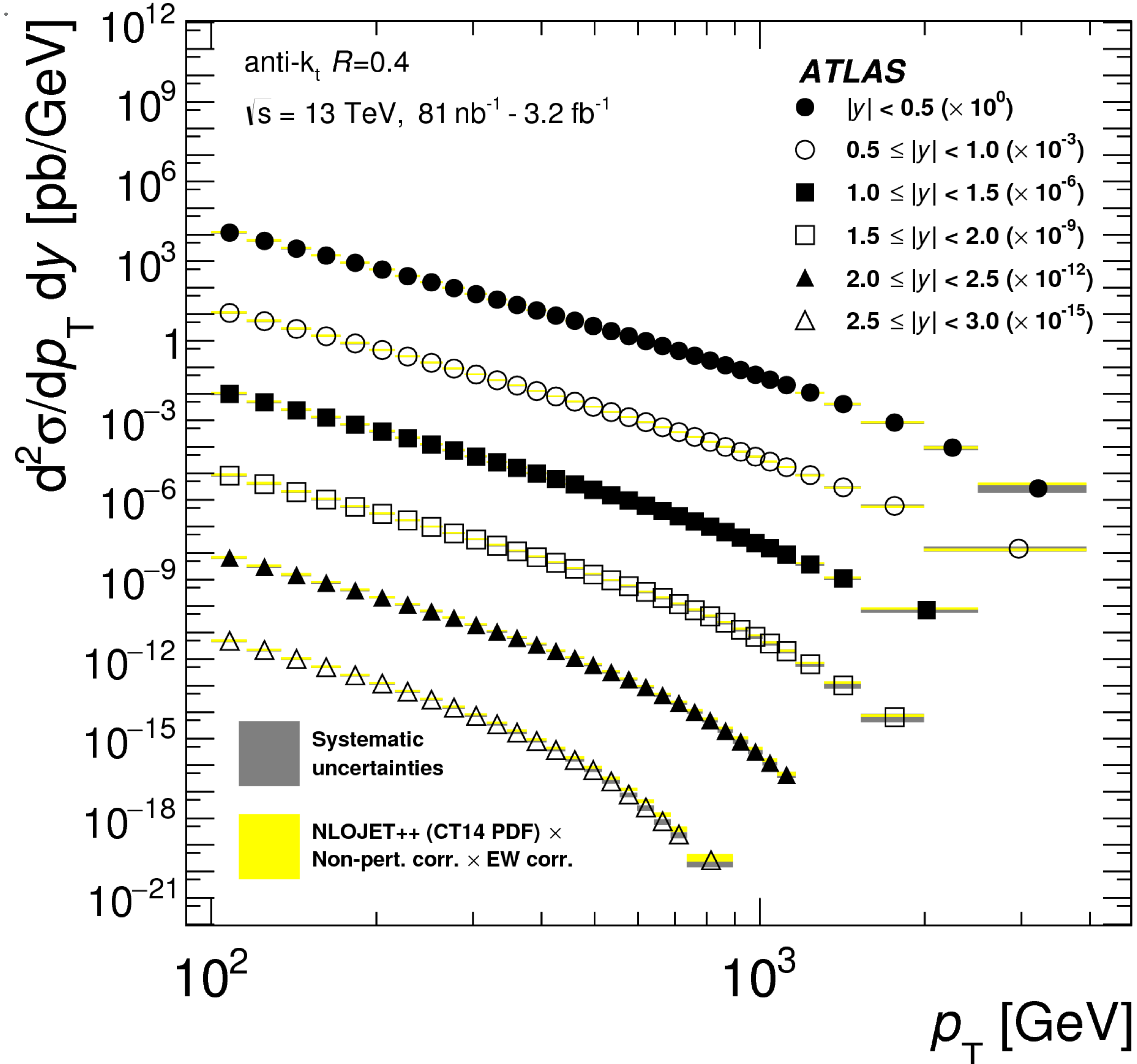


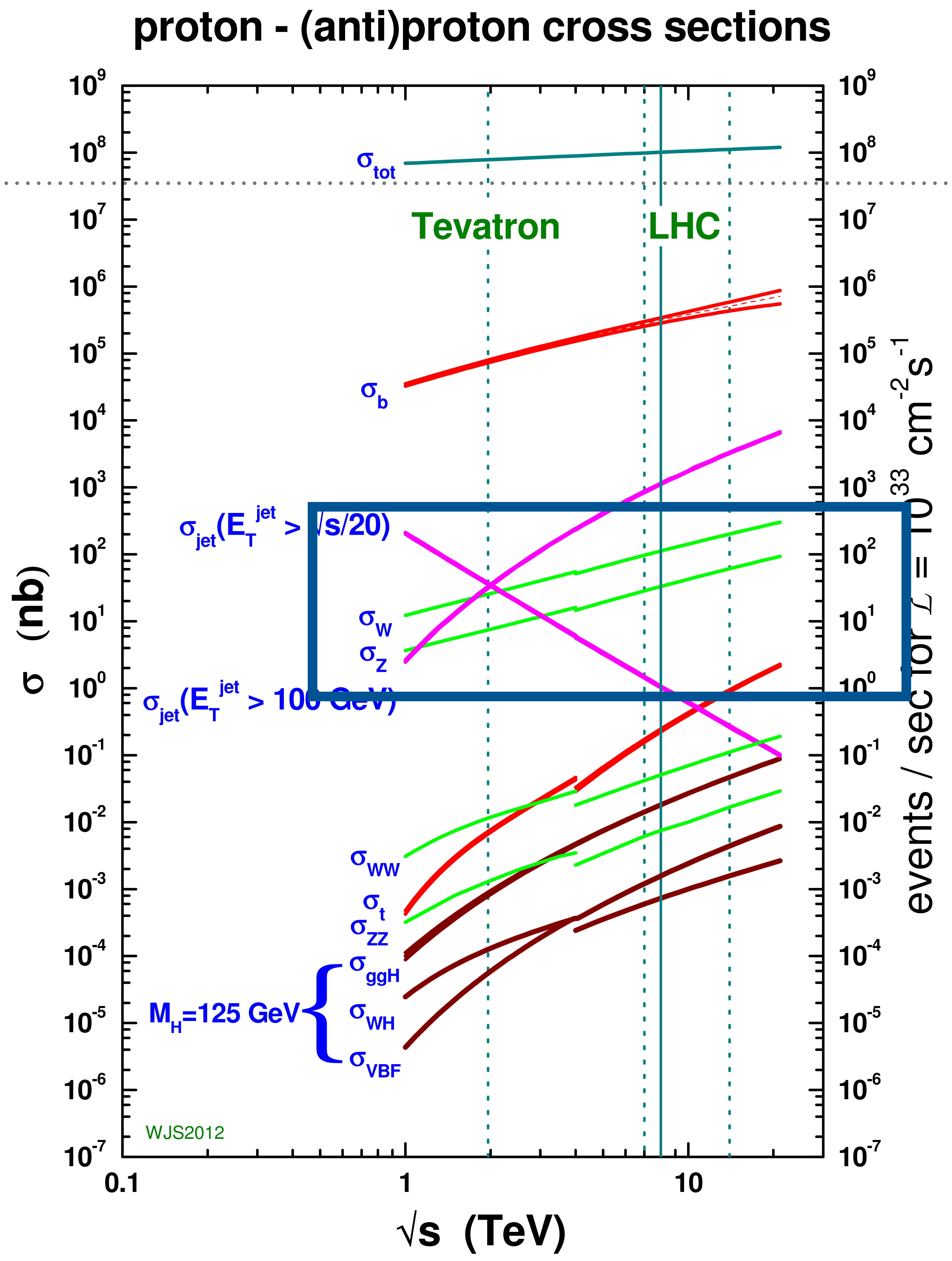
JET CALIBRATION AT LHC

- Calibrate jet energy scale, resolution, and uncertainties
  - Use a combination of simulation, test-beam results, and in-situ measurements
  - Rely on transverse energy balance between jet and other object: Z boson, photon, or other jet



JET CROSS-SECTIONS AT LHC

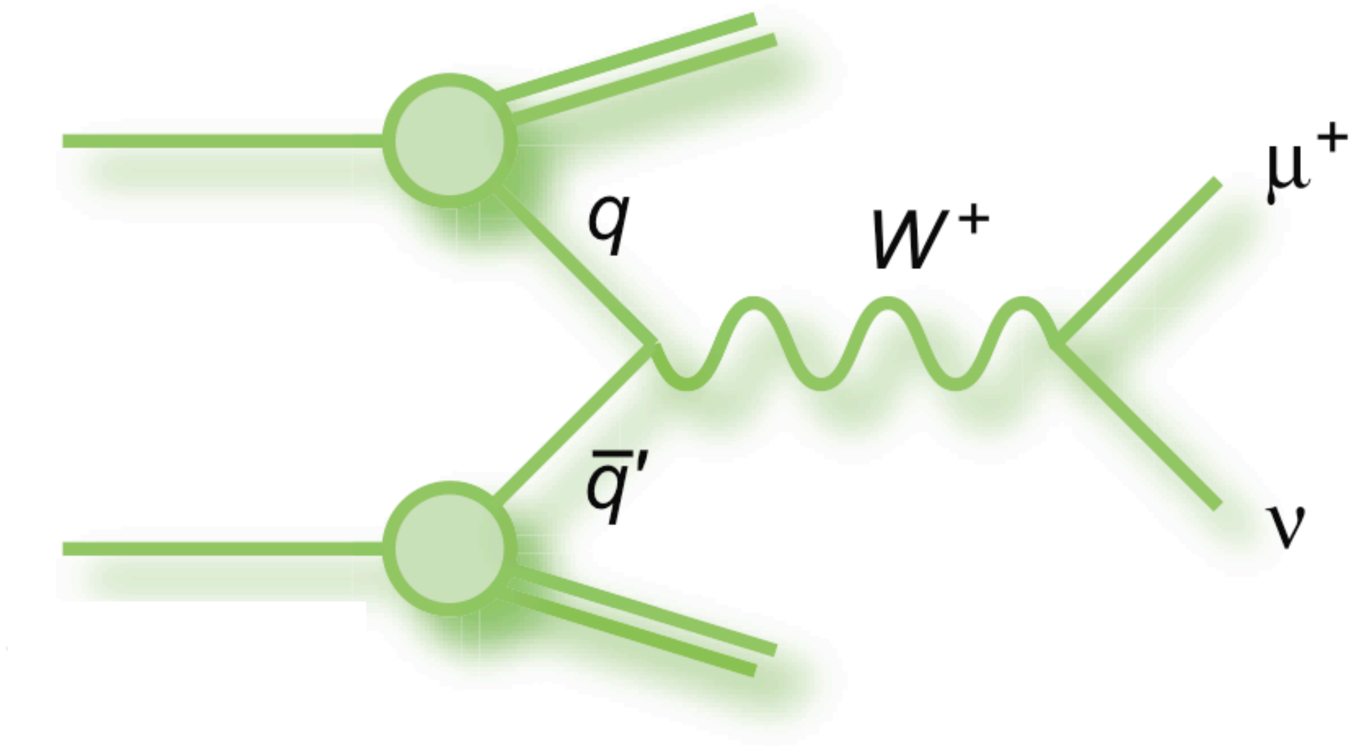




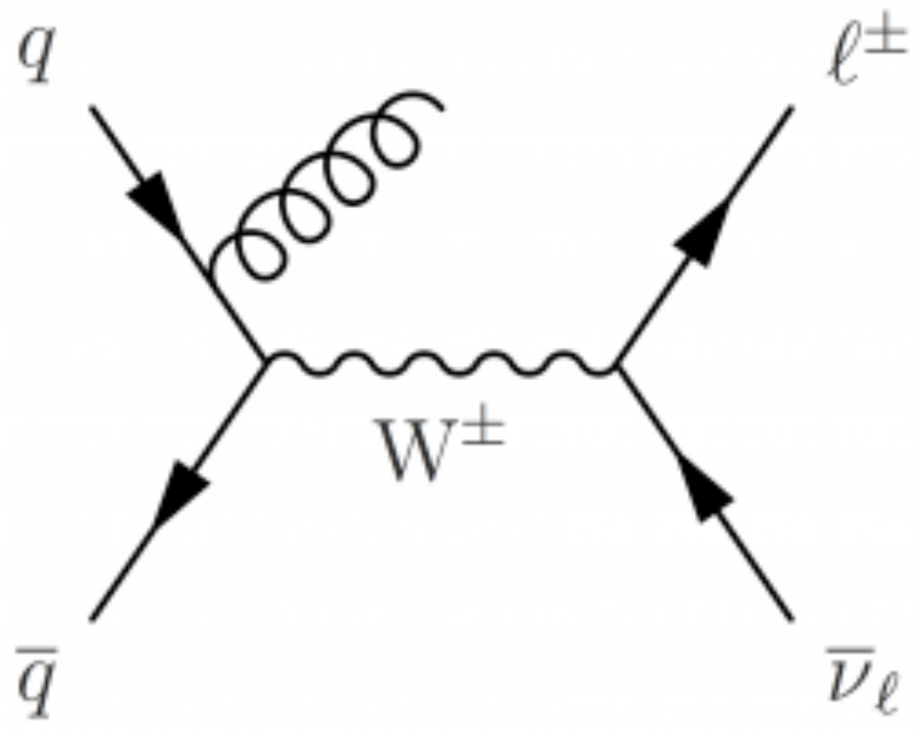
proton - (anti)proton cross sections
σ (nb)
events / sec for $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1}
√s (TeV)
Tevatron
LHC
σ_{tot}
σ_b
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/20)$
σ_W
σ_Z
$\sigma_{jet}(E_T^{jet} > 100$ GeV)
σ_{WW}
σ_t
σ_{ZZ}
M_H=125 GeV
σ_{ggH}
σ_{WH}
σ_{VBF}
WJS2012

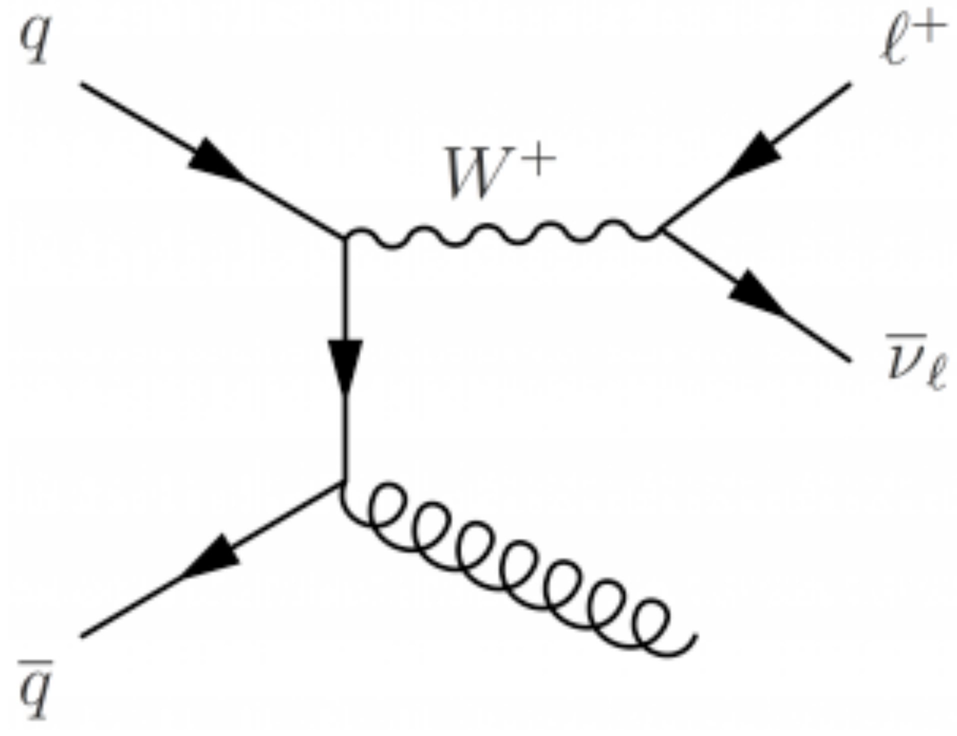
W AND Z PHYSICS

- **Essential in many tests of SM and new physics**
  - Understanding electroweak symmetry breaking key goal of LHC
  - Diboson scattering important test of SM (and Higgs)
  - Many new physics decays to vector bosons
  - Important background to most searches for new particles



- **Excellent experimental handle**
  - Use W's and Z's to calibrate:
    - Electron energy scale
    - Track momentum scale
    - Lepton ID and trigger efficiencies
    - Missing ET resolution
    - Luminosity, …





…

MEASURING A CROSS SECTION, IN PRINCIPLE

$$\sigma = \frac{N_{\text{signal}}}{\int L\,dt \;\times BR \times \epsilon}$$

- Event rates determined by

$$N_{\text{signal}} = \int L\,dt \;\times \sigma \times BR \times \epsilon$$

- where

$$N_{\text{signal}} = \text{Number of observed signal events} = N_{\text{data}} - N_{\text{background}}$$

$$\int L\,dt \;= \text{Integrated Luminosity}$$

$$\epsilon = \text{Efficiency}$$

- Total efficiency ϵ can be factored into

$$\varepsilon = C \cdot A = \frac{N^{\text{selected}}_{\text{reco.}}}{N^{\text{selected}}_{\text{gen.}}} \cdot \frac{N^{\text{selected}}_{\text{gen.}}}{N^{\text{all}}_{\text{gen.}}} = \frac{N^{\text{selected}}_{\text{reco.}}}{N^{\text{all}}_{\text{gen.}}}$$

$C = \text{Detector Correction Factor}$ $\quad$ $A = \text{(Fiducial) Acceptance}$

Measure

- N_{data}
- C
- $\int L\,dt$
- $N_{background}$ *(if data-driven)*

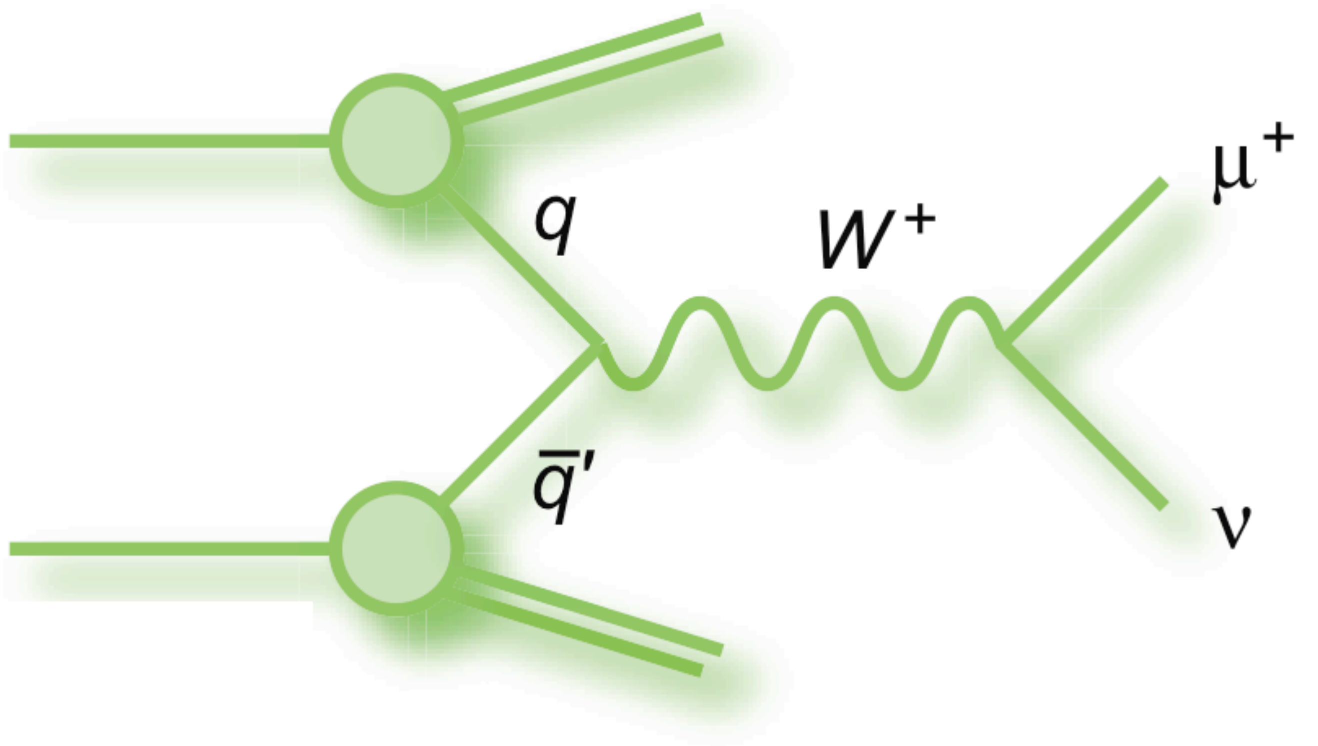
Calculate (from MC)

- A
- BR
- $N_{background}$ *(if using MC)*

MEASURING A CROSS SECTION, IN PRACTICE

EXAMPLE: W CROSS-SECTION

- Signature
  - Focus on leptonic (muon, electron) decays due to large background from QCD diet background
  - 1 lepton, $p_T > 20$ GeV
  - large imbalance in transverse momentum
    - Signature of neutrino (or other undetected particle)
    - Missing $E_T > 25$ GeV
  - Transverse mass $m_T > 40$ GeV



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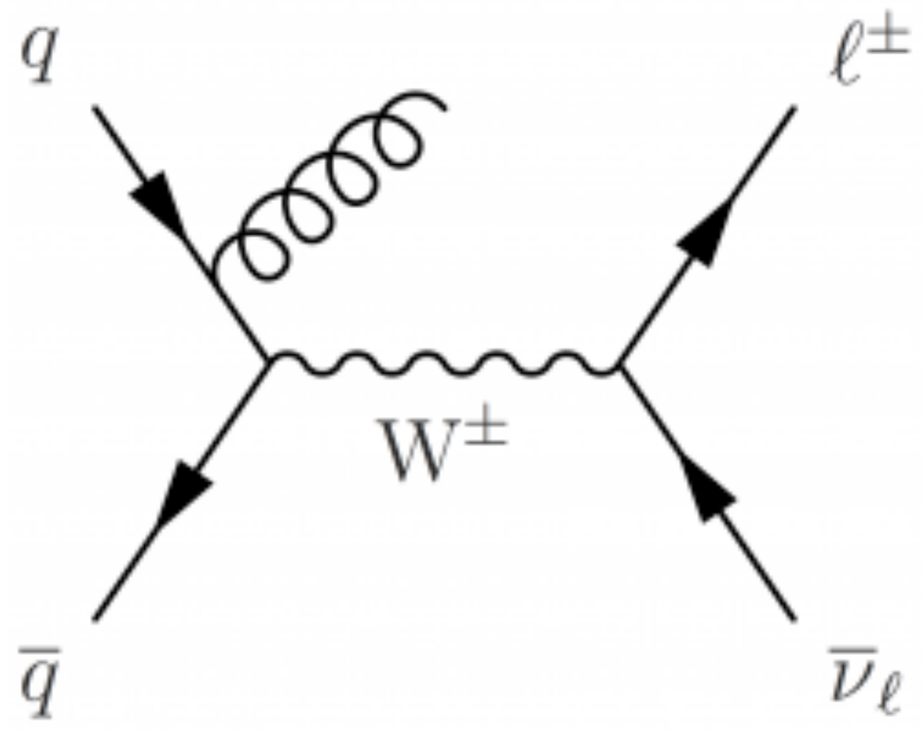

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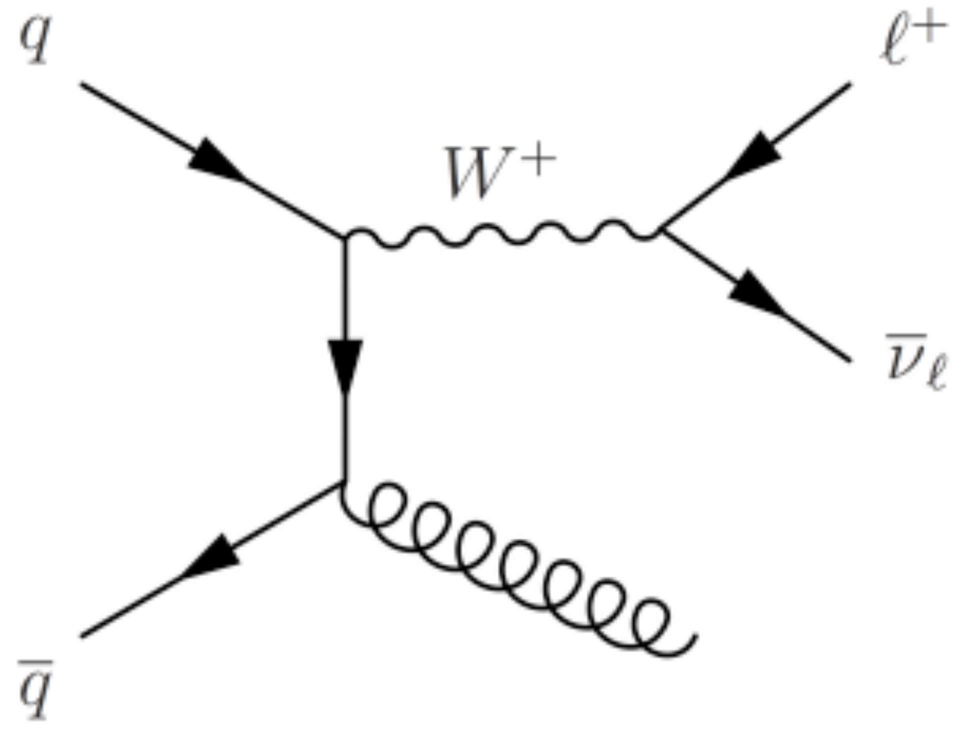

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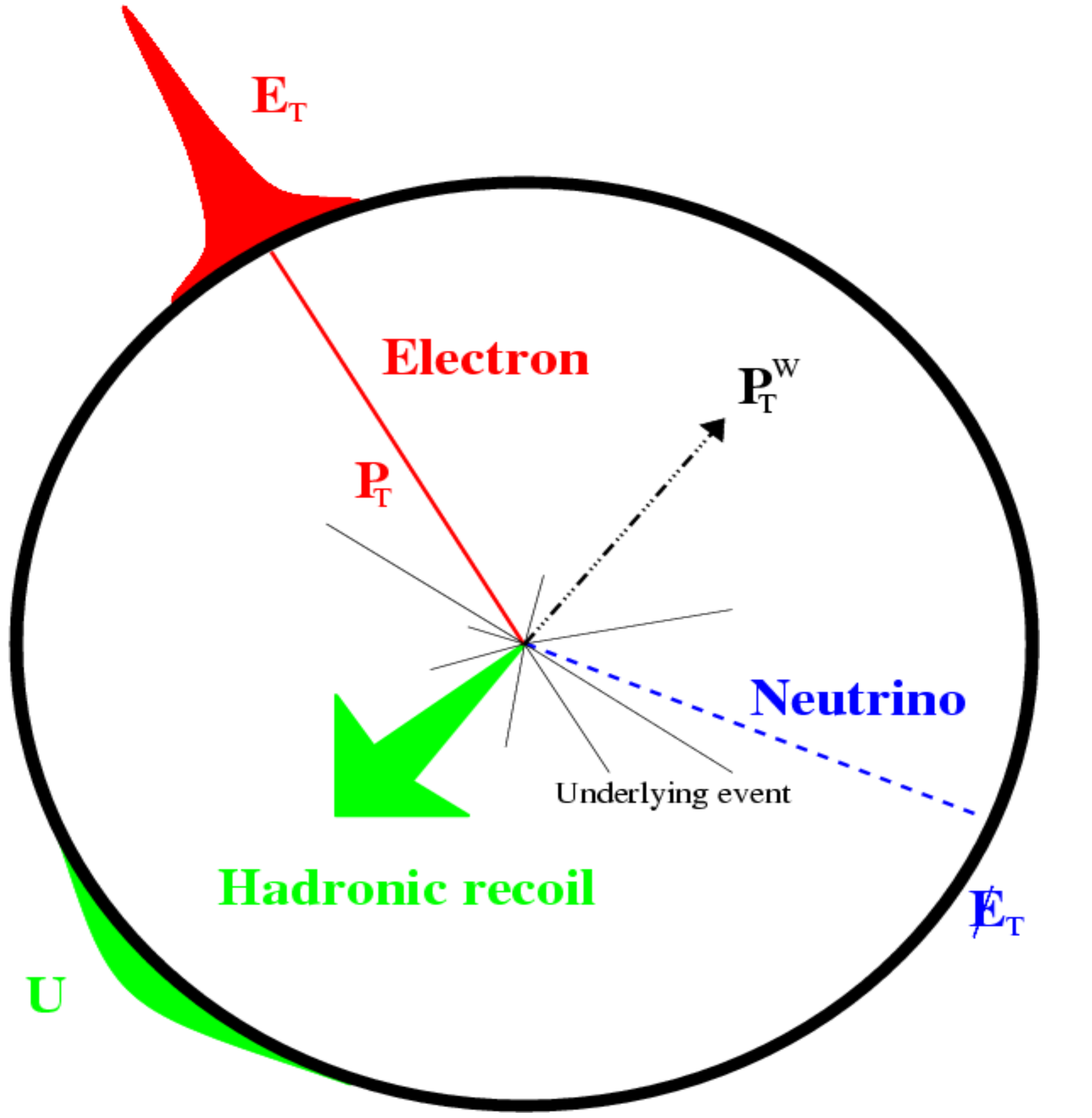


$$\overrightarrow{E_T}^{miss} = -\sum_i \overrightarrow{p}_T(i)$$

$$m_{\mathrm{T}} = \sqrt{2\, p_{\mathrm{T}}^{\ell}\, E_{\mathrm{T}}^{\mathrm{miss}}\, (1 - \cos\Delta\phi)}$$

MEASURING A CROSS SECTION, IN PRACTICE

EXAMPLE: W CROSS-SECTION

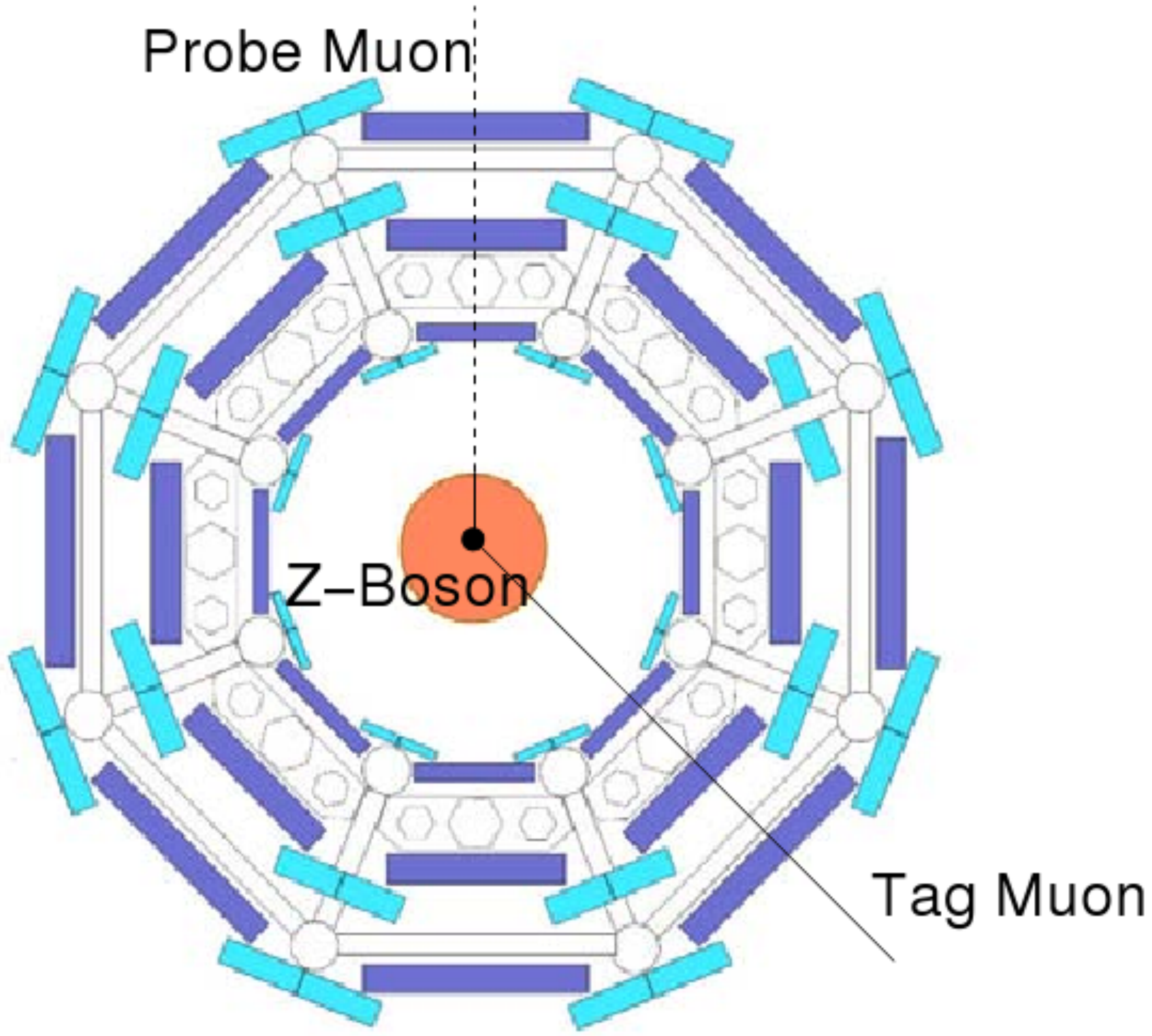
- **Generate Monte Carlo**, both signal and background processes
  - Used to define analysis selections
  - Estimate background
  - Extrapolate phase space (calculate A)
  - Measure correction factors (C and others)
  - Used in estimating many uncertainties

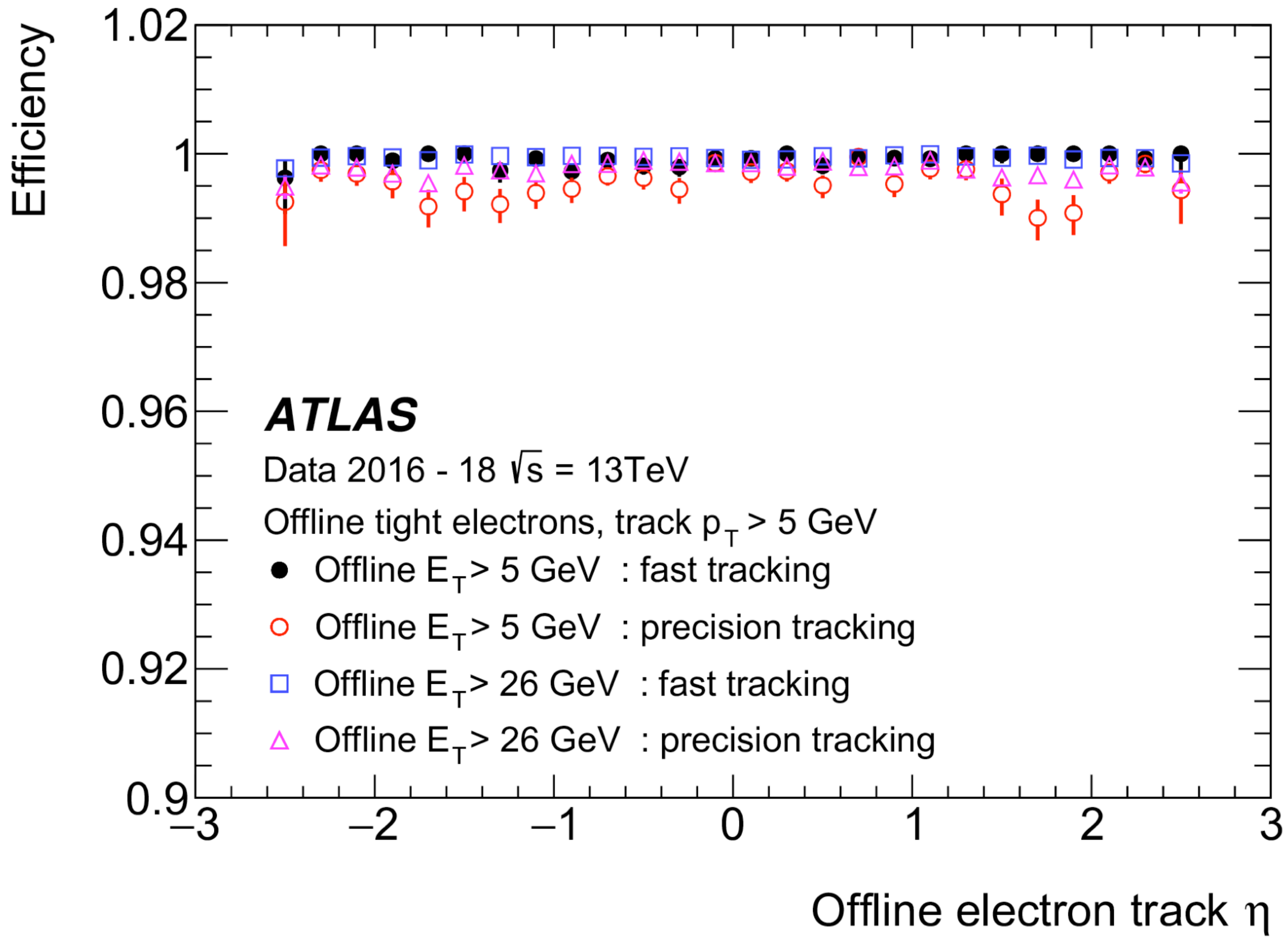
Physics process	Generator	$\sigma \cdot$ BR [nb]		
$W \to \ell\nu \quad (\ell = e, \mu)$	PYTHIA [25]	10.46±0.52	NNLO	[5,8]
$W^+ \to \ell^+\nu$		6.16±0.31	NNLO	[5,8]
$W^- \to \ell^-\overline{\nu}$		4.30±0.21	NNLO	[5,8]
$Z/\gamma^* \to \ell\ell \quad (m_{\ell\ell} > 60$ GeV)	PYTHIA	0.99±0.05	NNLO	[5,8]
$W \to \tau\nu$	PYTHIA	10.46±0.52	NNLO	[5,8]
$W \to \tau\nu \to \ell\nu\nu\nu$	PYTHIA	3.68±0.18	NNLO	[5,8]
$Z/\gamma^* \to \tau\tau \quad (m_{\ell\ell} > 60$ GeV)	PYTHIA	0.99±0.05	NNLO	[5,8]
$t\bar{t}$	MC@NLO [26,27], POWHEG [31]	0.16±0.01	NLO+NNLL	[28–30]
Dijet (e channel, $\hat{p}_{\mathrm{T}} > 15$ GeV)	PYTHIA	1.2×10^6	LO	[25]
Dijet (μ channel, $\hat{p}_{\mathrm{T}} > 8$ GeV)	PYTHIA	10.6×10^6	LO	[25]
$b\bar{b}$ (μ channel, $\hat{p}_{\mathrm{T}} > 18$ GeV, $p_{\mathrm{T}}(\mu) > 15$ GeV)	PYTHIA	73.9	LO	[25]
$c\bar{c}$ (μ channel, $\hat{p}_{\mathrm{T}} > 18$ GeV, $p_{\mathrm{T}}(\mu) > 15$ GeV)	PYTHIA	28.4	LO	[25]

MEASURING A CROSS SECTION, IN PRACTICE

EXAMPLE: W CROSS-SECTION

- Generate Monte Carlo, both signal and background processes
- **Select (design) trigger**
  - Lowest threshold (p_T or E_T) possible to fit within allocated event rate, ie, electron $E_T > 20$ GeV
  - Measure efficiency in data, parameterized as needed
  - For leptons, can use "tag and probe" method





MEASURING A CROSS SECTION, IN PRACTICE

EXAMPLE: W CROSS-SECTION

- Generate Monte Carlo, both signal and background processes
- Select (design) trigger
- **Object definition and performance**
  - **Reconstruction**: baseline output of reconstruct algorithms

Lepton Reconstruction

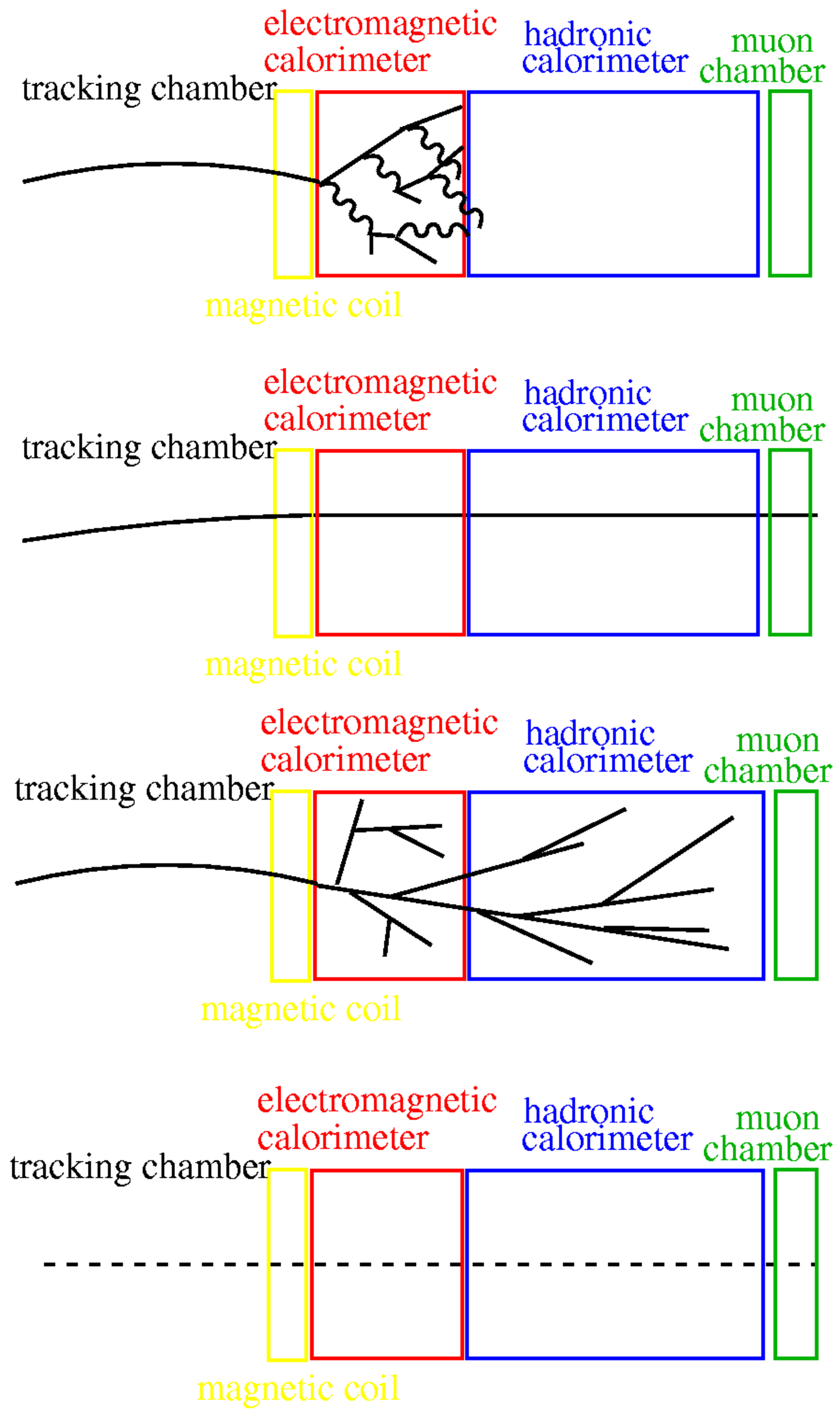
Electrons:
Compact EM cluster in calo
Matched to Track

Muons:
Track in muon chamber
Matched to Track

Taus:
Narrow jet
Matched to 1 or 3 tracks

Neutrinos:
Missing transverse momentum
Calculated from total p_T measured

$$\overrightarrow{E_T}^{miss} = -\sum_i \vec{p}_T(i)$$



MEASURING A CROSS SECTION, IN PRACTICE

EXAMPLE: W CROSS-SECTION

- Generate Monte Carlo, both signal and background processes
- Select (design) trigger
- **Object definition and performance**
  - **Reconstruction:** baseline output of reconstruct algorithms
  - **Identification**: additional selections to tag signal objects
    - Often includes cuts on impact parameters, number of hits, etc to select primary versus secondaries and reject combinatoric background
    - Can include additional selections like isolation to distinguish leptons from boson decay versus leptons from hadron decay inside jets

Example Lepton ID requirements

– **"Loose":** this basic selection uses EM shower shape information from the second layer of the EM calorimeter (lateral shower containment and shower width) and energy leakage into the hadronic calorimeters as discriminant variables. This set of requirements provides high and uniform identification efficiency but a low background rejection.

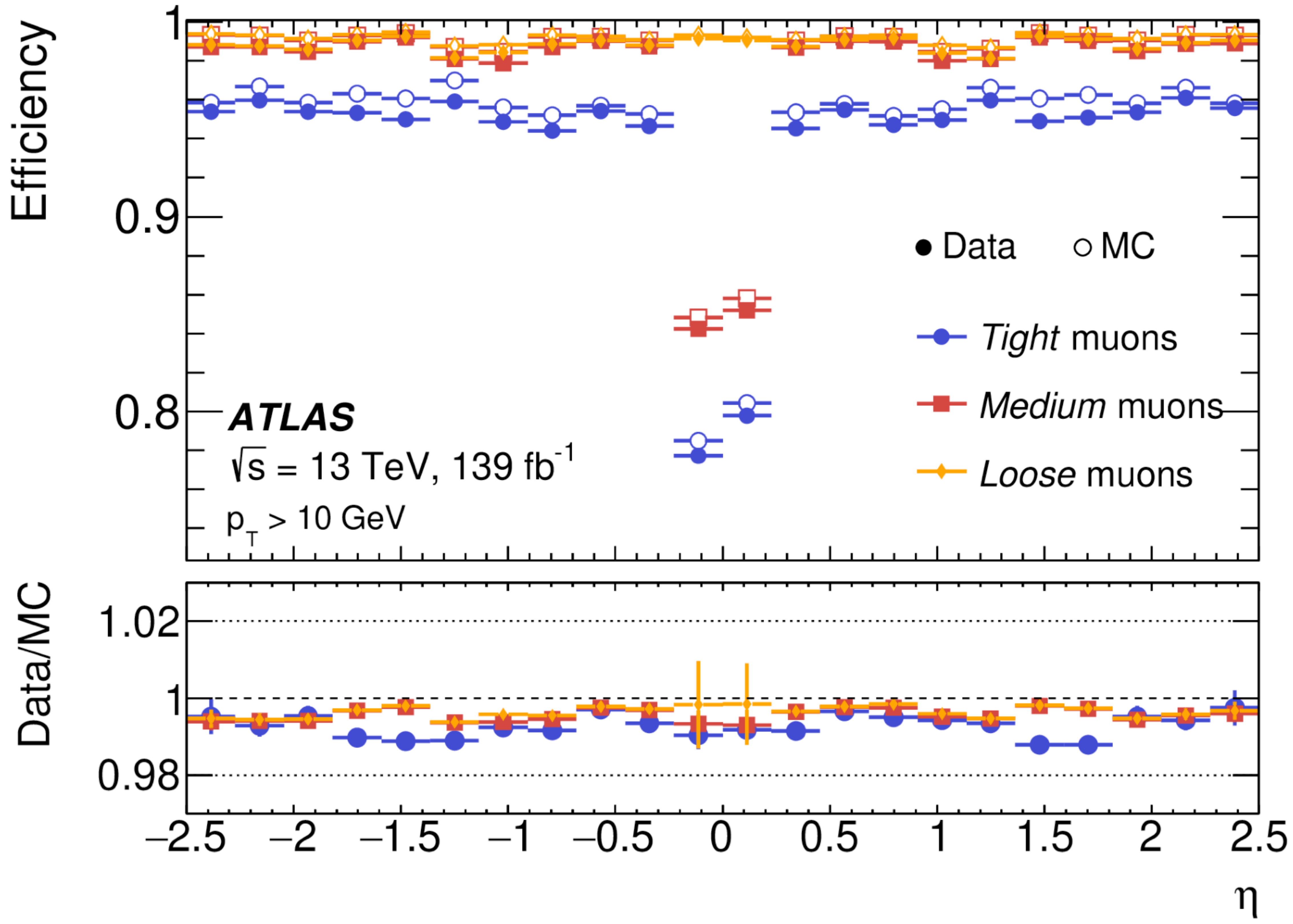
– **"Medium":** this selection provides additional rejection against hadrons by evaluating the energy deposit patterns in the first layer of the EM calorimeter (the shower width and the ratio of the energy difference associated with the largest and second largest energy deposit over the sum of these energies), track quality variables (number of hits in the pixel and silicon trackers, transverse distance of closest approach to the primary vertex (transverse impact parameter)) and a cluster-track matching variable ($\Delta\eta$ between the cluster and the track extrapolated to the first layer of the EM calorimeter).

– **"Tight":** this selection further rejects charged hadrons and secondary electrons from conversions by fully exploiting the electron identification potential of the ATLAS detector. It makes requirements on the ratio of cluster energy to track momentum, on the number of hits in the TRT, and on the ratio of high-threshold hits[2] to the total number of hits in the TRT. Electrons from conversions are rejected by requiring at least one hit in the first layer of the pixel detector. A conversion-flagging algorithm is also used to further reduce this contribution. The impact-parameter requirement applied in the medium selection is further tightened at this level.

MEASURING A CROSS SECTION, IN PRACTICE

EXAMPLE: W CROSS-SECTION

- Generate Monte Carlo, both signal and background processes
- Select (design) trigger
- **Object definition and performance**
  - Reconstruction: baseline output of reconstruct algorithms
  - Identification: additional selections to tag signal objects
  - Measure efficiency, scale, and resolution of objects in data and MC
    - Parameterize as needed ($p_T, \phi, \eta, < \mu > , \ldots$)
    - Often done using tag and probe from "standard candle" such as $Z \rightarrow ll$ or object E_T balance in jet events
    - Calibrate object performance
    - Calculate scale factors for data/MC performance
    - Calculate uncertainties



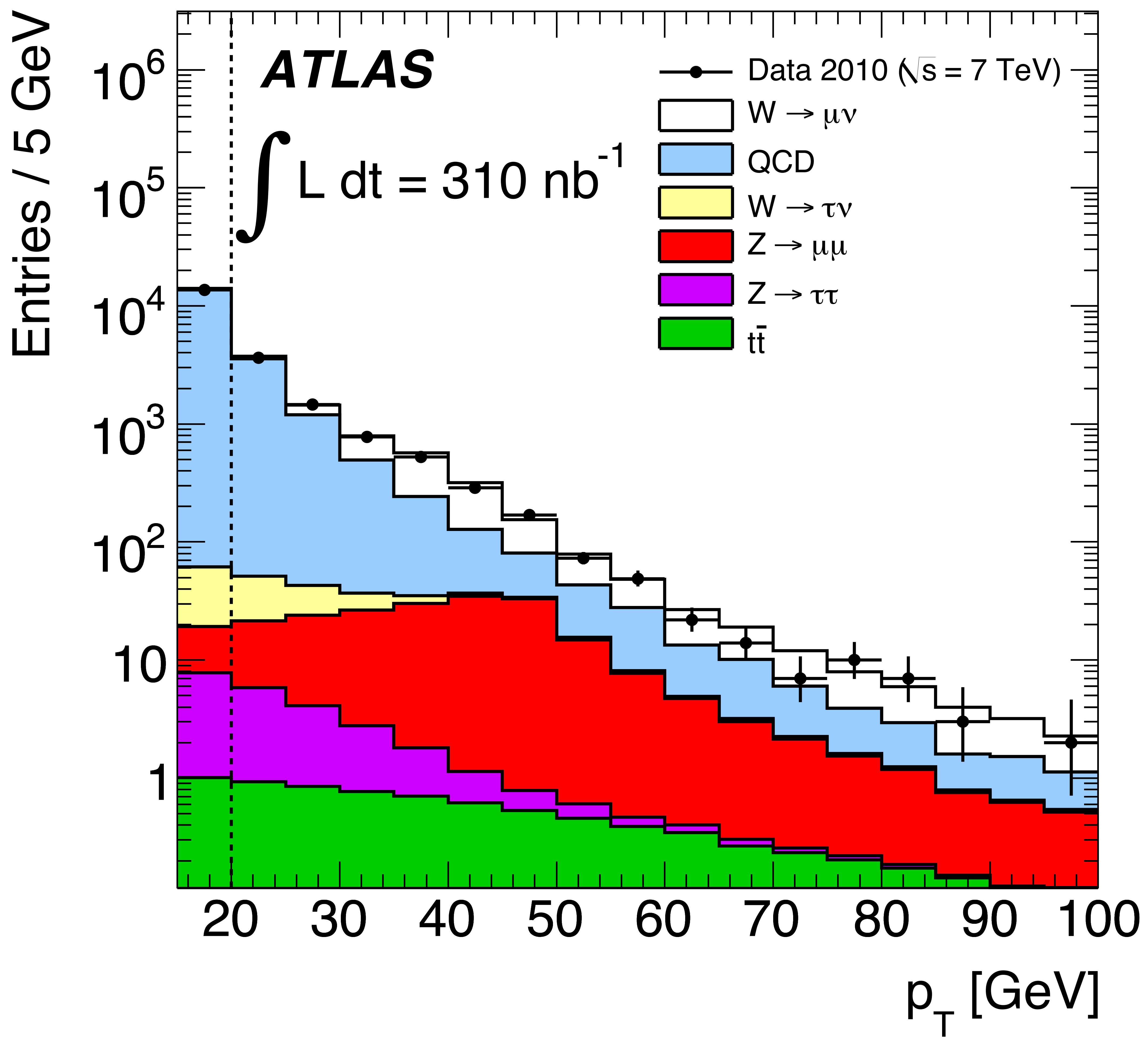
MEASURING A CROSS SECTION, IN PRACTICE

EXAMPLE: W CROSS-SECTION

- Generate Monte Carlo, both signal and background processes
- Select (design) trigger
- Object definition and performance
- **Design event selection**
  - Optimize signal significance
    - Gaussian approximation for significance:

$$Z = \frac{n - b}{\sqrt{b + \sigma^2}}$$

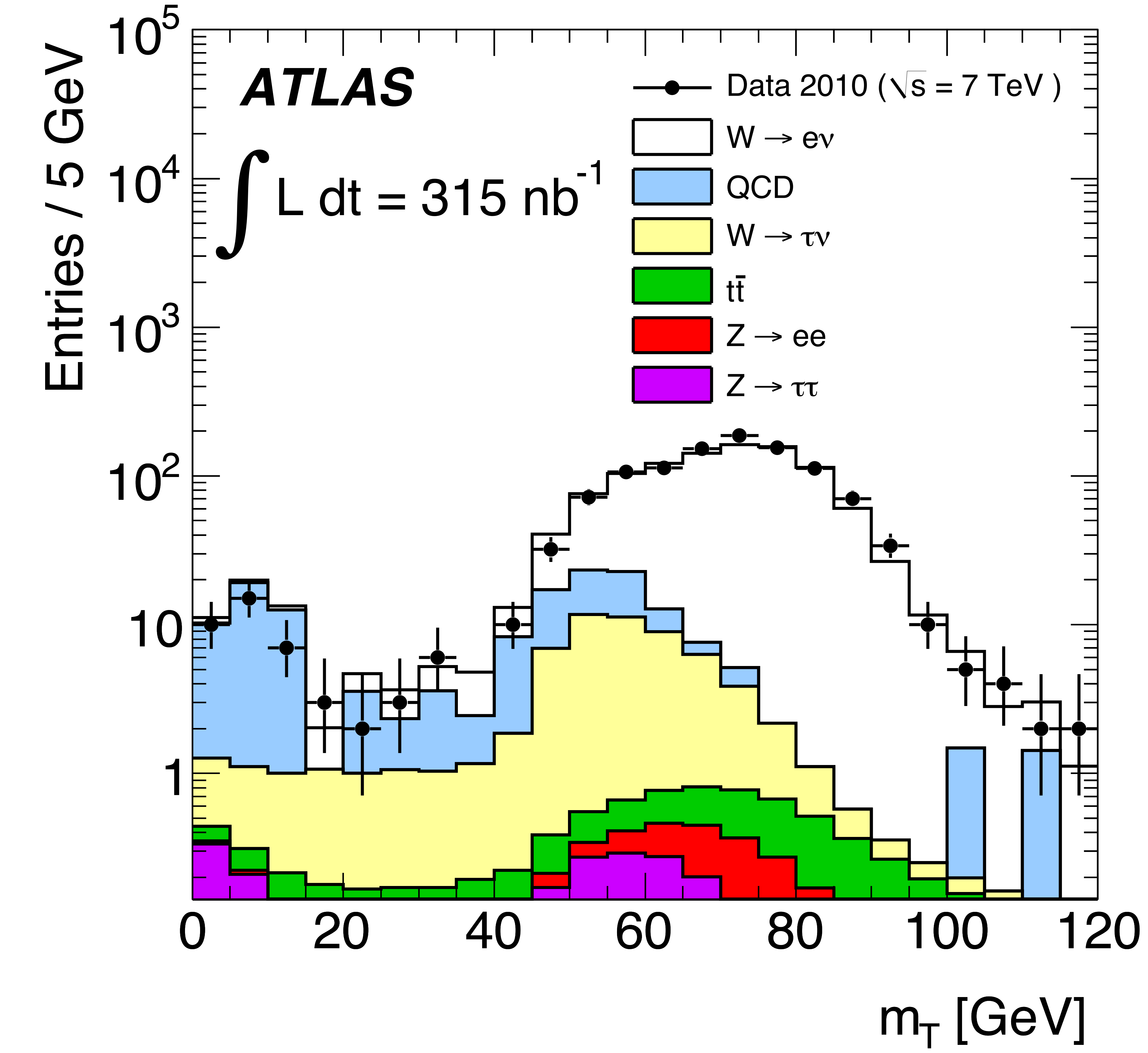
    - where n = number of signal
    - b = number of background
    - σ = uncertainty on b
    - Include large uncertainties if possible
    - Many dimensional phase-space and limited knowledge of background —> as much an art as science



MEASURING A CROSS SECTION, IN PRACTICE

EXAMPLE: W CROSS-SECTION

- Generate Monte Carlo, both signal and background processes
- Select (design) trigger
- Object definition and performance
- Design event selection
- **Estimate background**
  - Backgrounds well modeled by MC can be directly taken from MC and normalized by σ
  - Partially data-driven: invert some signal region selections to maximize background in nearby kinematics, normalize MC in this "control region" and extrapolate normalization to signal region
  - Fully data-driven
    - Many techniques for estimating background from data for backgrounds not well modeled by MC or limited by MC stats
    - Ie, "fake factor" method for estimating non-prompt lepton sources: $N_{\text{SR tight}} = \frac{N_{tight}}{N_{loose}} \cdot N_{\text{SR loose}}$



MEASURING A CROSS SECTION, IN PRACTICE

EXAMPLE: W CROSS-SECTION

- Generate Monte Carlo, both signal and background processes
- Select (design) trigger
- Object definition and performance
- Design event selection
- **Calculate A, measure C, and uncertainties**
  - Calculate A from MC (phase space extrapolation)
  - Measure C from MC and data
  - Spend most of time on calculating uncertainties

$$C_W = \epsilon^W_{event} \cdot \epsilon^W_{lep} \cdot \epsilon^W_{trig} \cdot SF$$

$$SF = \frac{\epsilon^{data}_{trig}}{\epsilon^{MC}_{trig}} \cdot \frac{\epsilon^{data}_{lep\ reco}}{\epsilon^{MC}_{lep\ reco}} \cdot \frac{\epsilon^{data}_{event\ reco}}{\epsilon^{MC}_{event\ reco}}$$

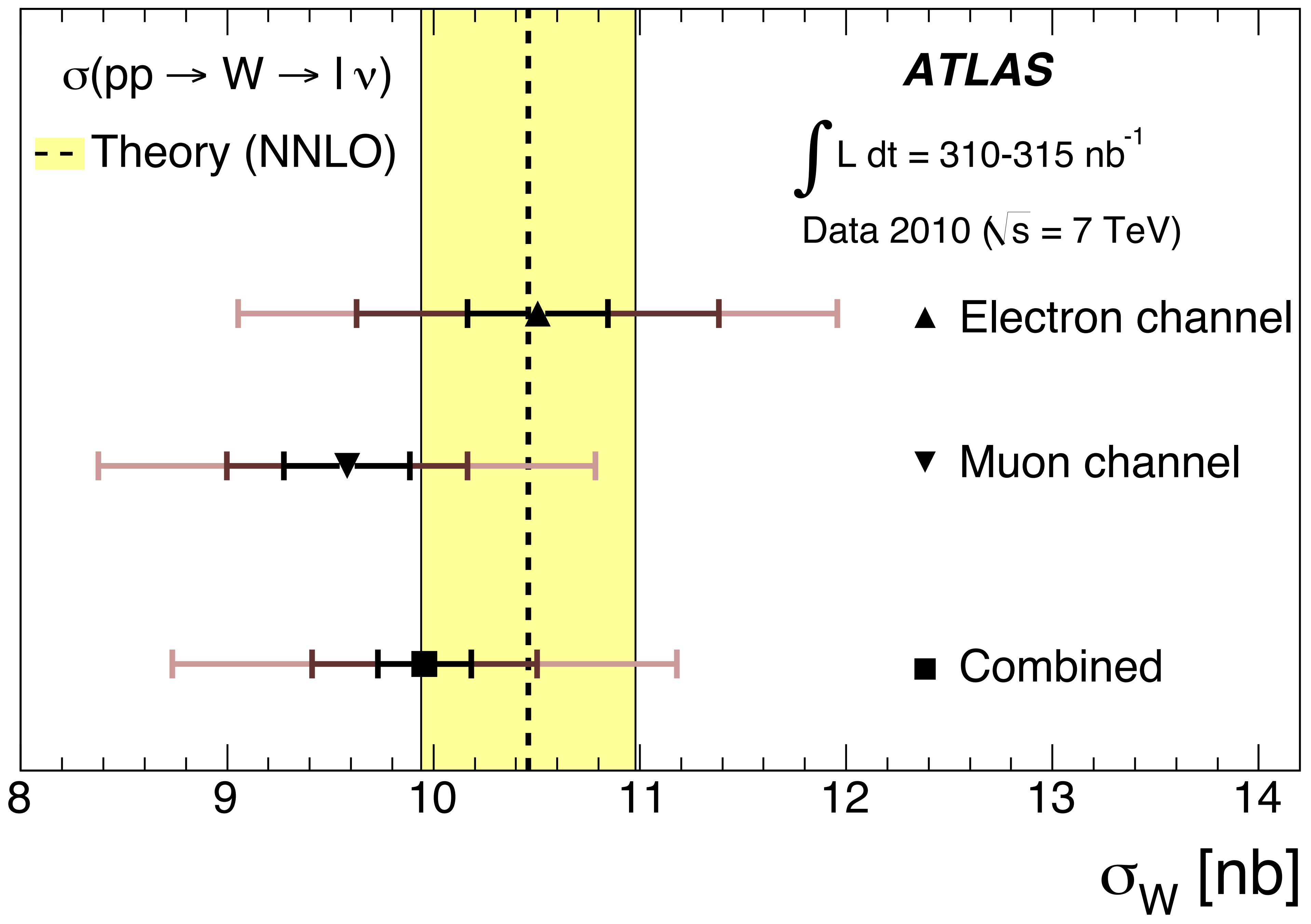
Parameter	$\delta C_W / C_W (\%)$
Trigger efficiency	1.9
Reconstruction efficiency	2.5
Momentum scale	1.2
Momentum resolution	0.2
E_T^{miss} scale and resolution	2.0
Isolation efficiency	1.0
Theoretical uncertainty (PDFs)	0.3
Total uncertainty	4.0

MEASURING A CROSS SECTION, IN PRACTICE

EXAMPLE: W CROSS-SECTION

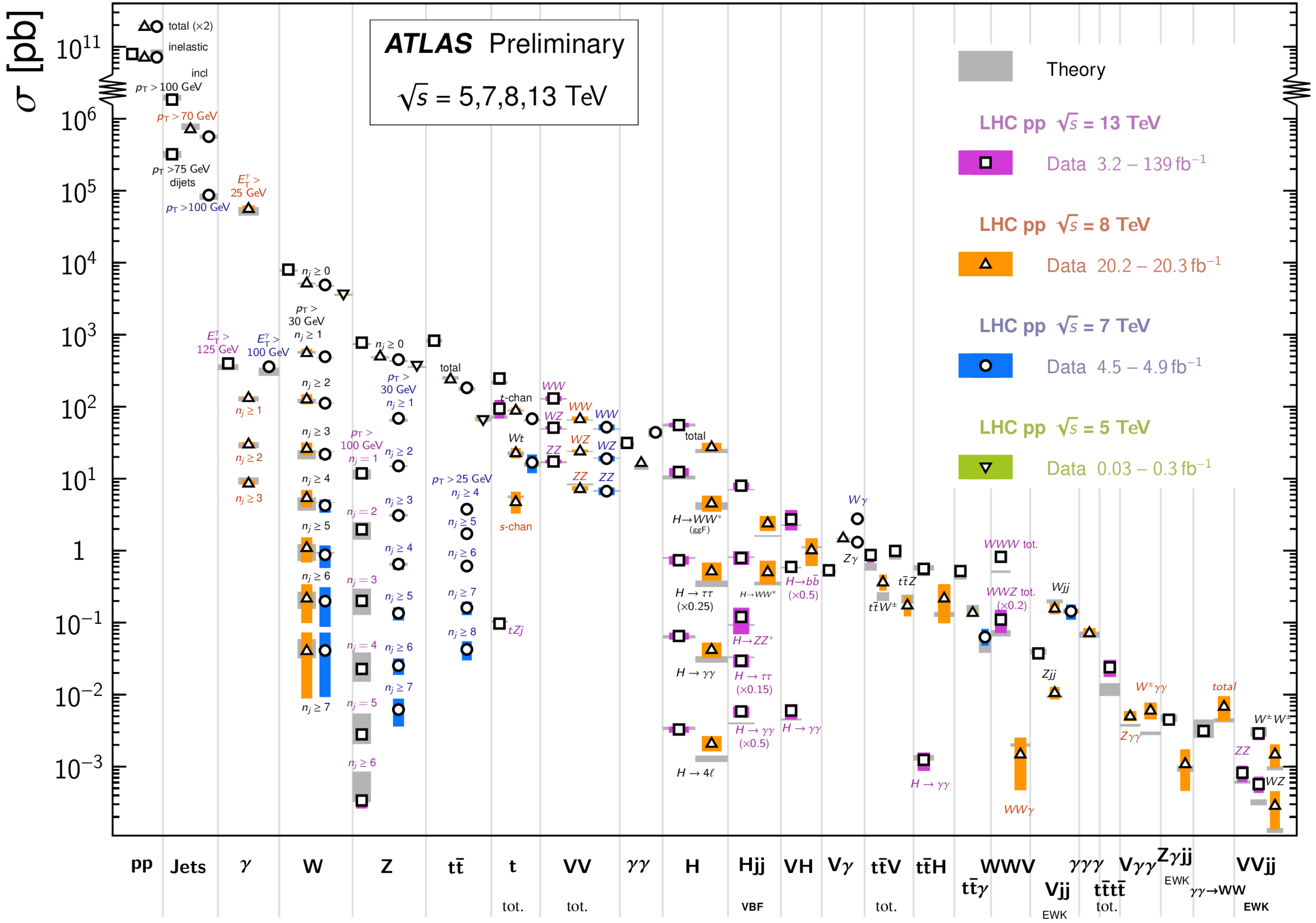
- Generate Monte Carlo, both signal and background processes
- Select (design) trigger
- Object definition and performance
- Design event selection
- Calculate A, measure C, and uncertainties
- **Statistical analysis**
  - Combine electron and muon channel
  - Decide how to treat leptonic decays of tau
  - Usually performed with a likelihood fit
    - Include uncertainties with nuisance parameters
  - Measure separately
    - fiducial cross-section (no A)
    - total cross-section (extrapolate to full phase space)

$$L(N^i_{obs}; N^i_s + N^i_b) = \frac{e^{-(N^i_s+N^i_b)} \times (N^i_s + N^i_b)^{N^i_{obs}}}{(N^i_{obs})!}$$

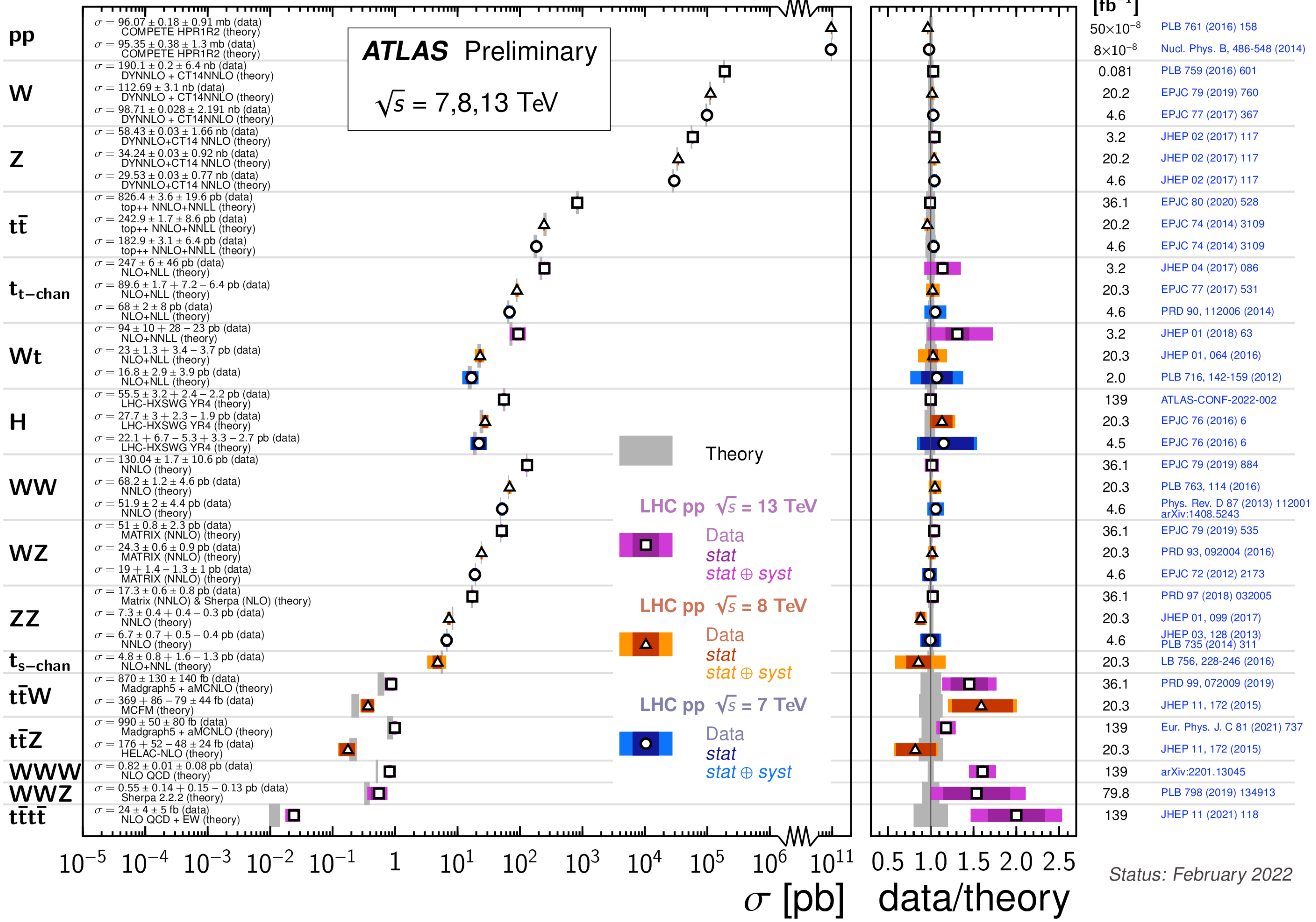


Standard Model Production Cross Section Measurements

Status: February 2022



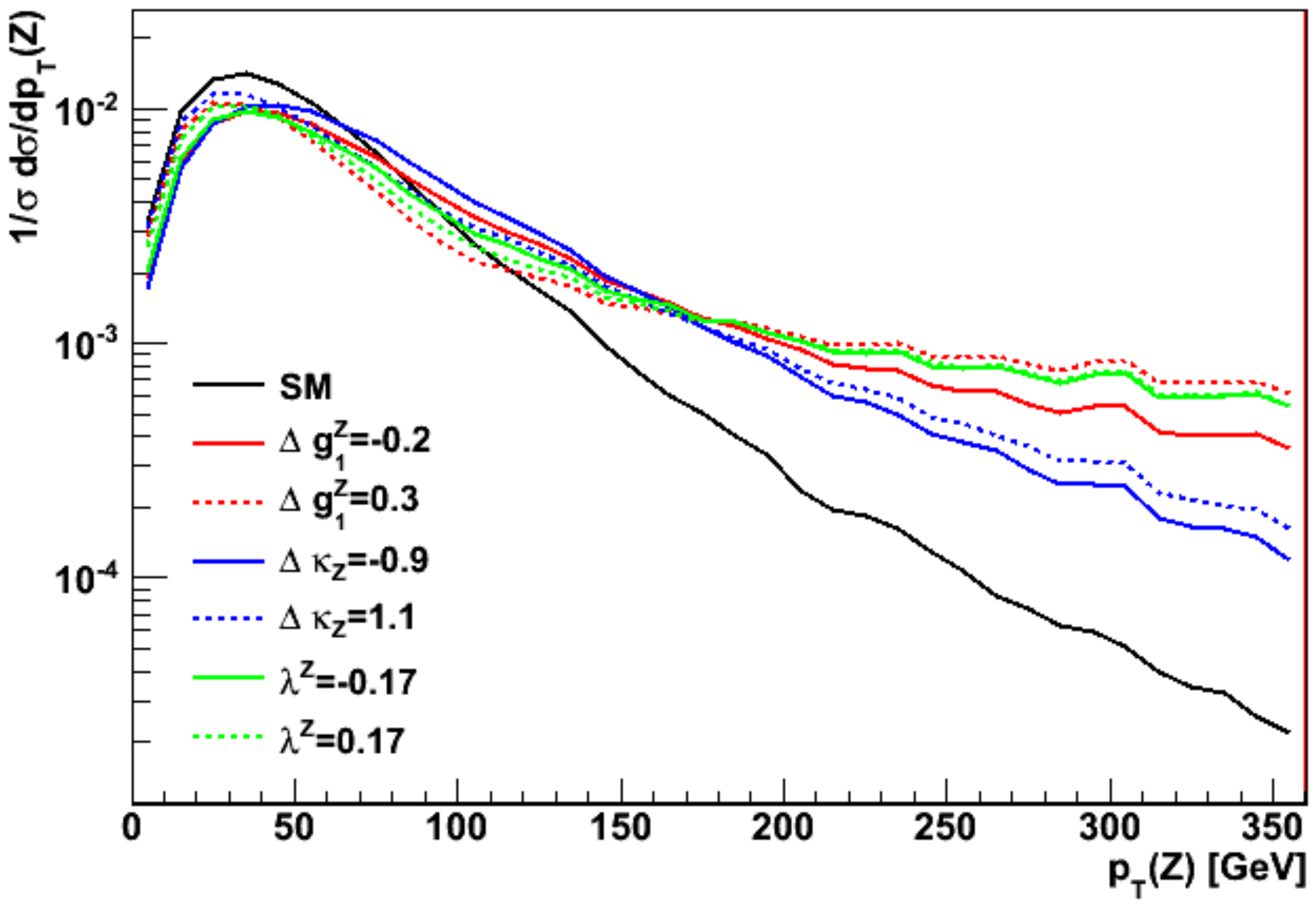
Standard Model Total Production Cross Section Measurements



MEASURING CROSS-SECTIONS, NEXT STEPS

- Measure differential quantities
  - Search for new physics
  - Constrain PDFs
  - Tune MC

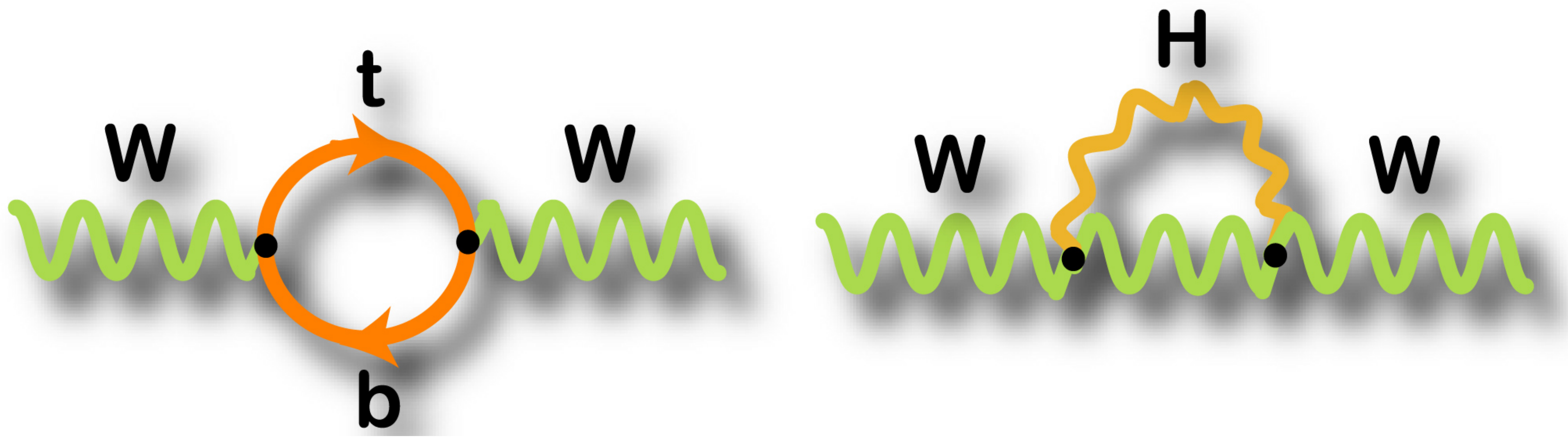
- Measure other properties
  - Mass, spin, lifetime, etc..
  - Compare to predictions
    - Combination of theory + other measurements

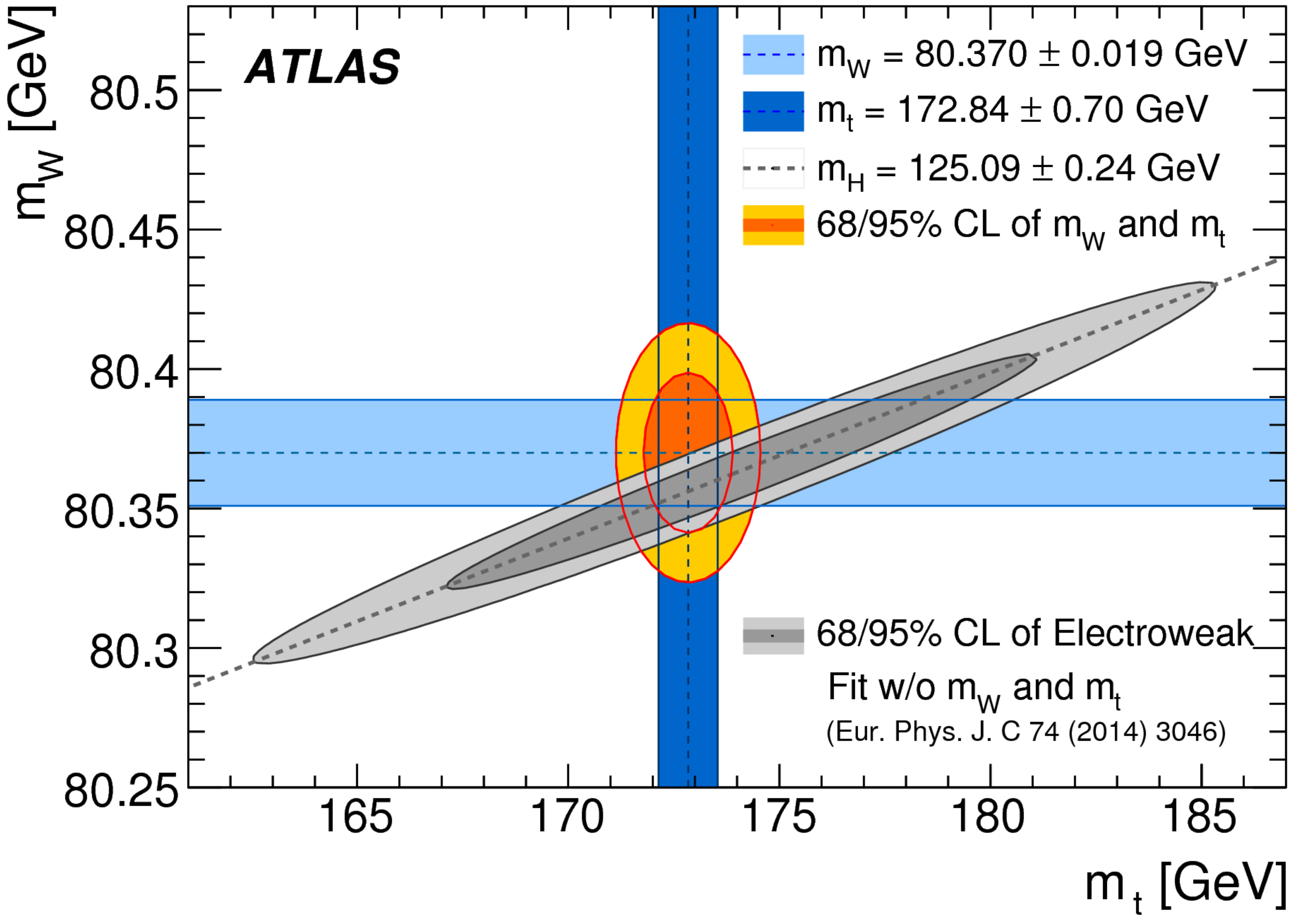


Zp_T in WZ events could be modified at high p_T by anomalous gauge couplings

W MASS MEASUREMENT

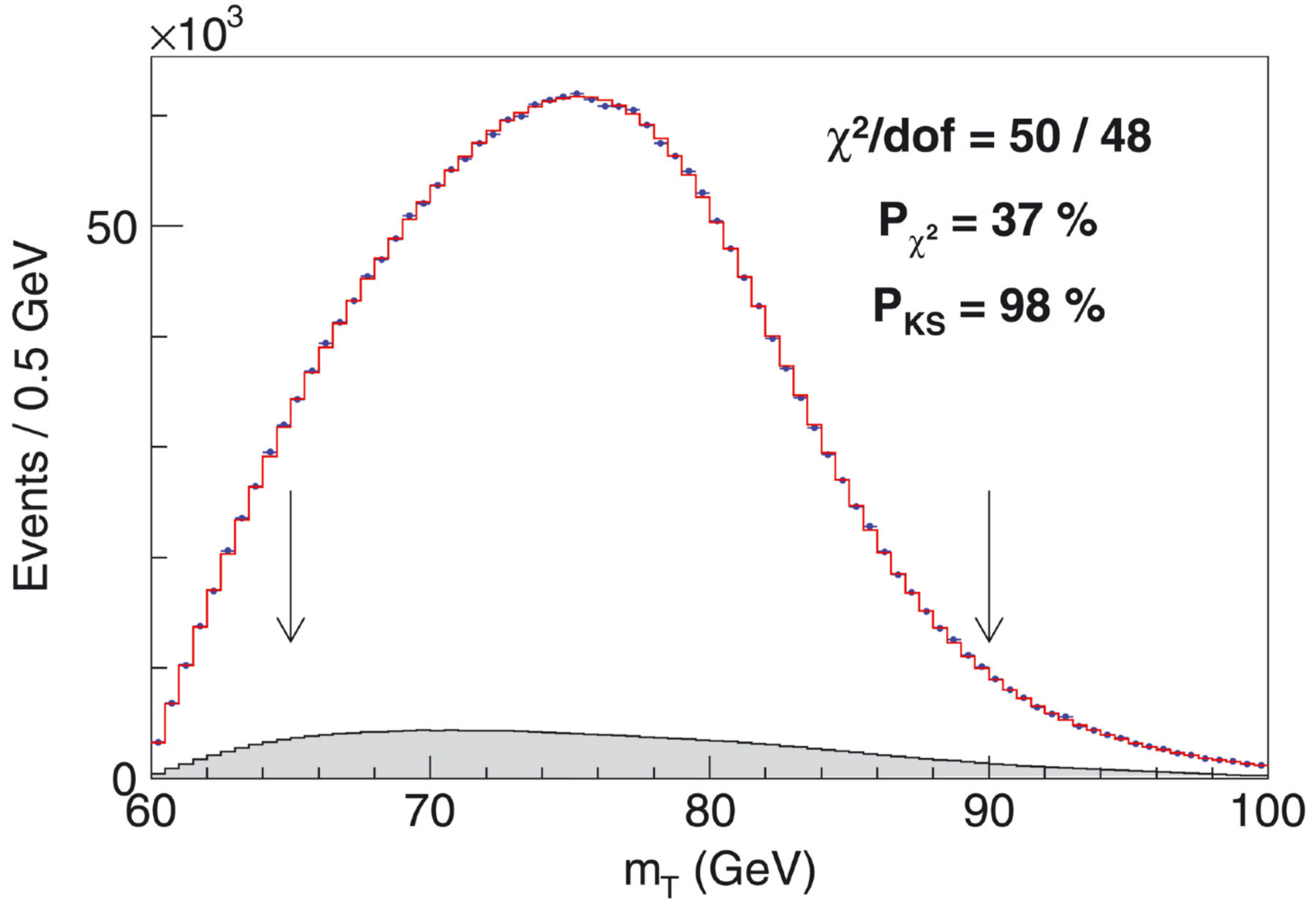
- ➤ Motivation
  - ➤ Top, W, and Higgs Boson masses all connected via radiative corrections
    - ➤ Absolute value of masses is not a prediction of the SM but their relationship is
    - ➤ New particles or interactions might change the relation
- ➤ Measurement
  - ➤ Extremely precise measurement needed to test predictions and probe for new physics
  - ➤ Requires dedicated and precise calibration of object efficiencies, resolutions, scale, uncertainties… very difficult measurement

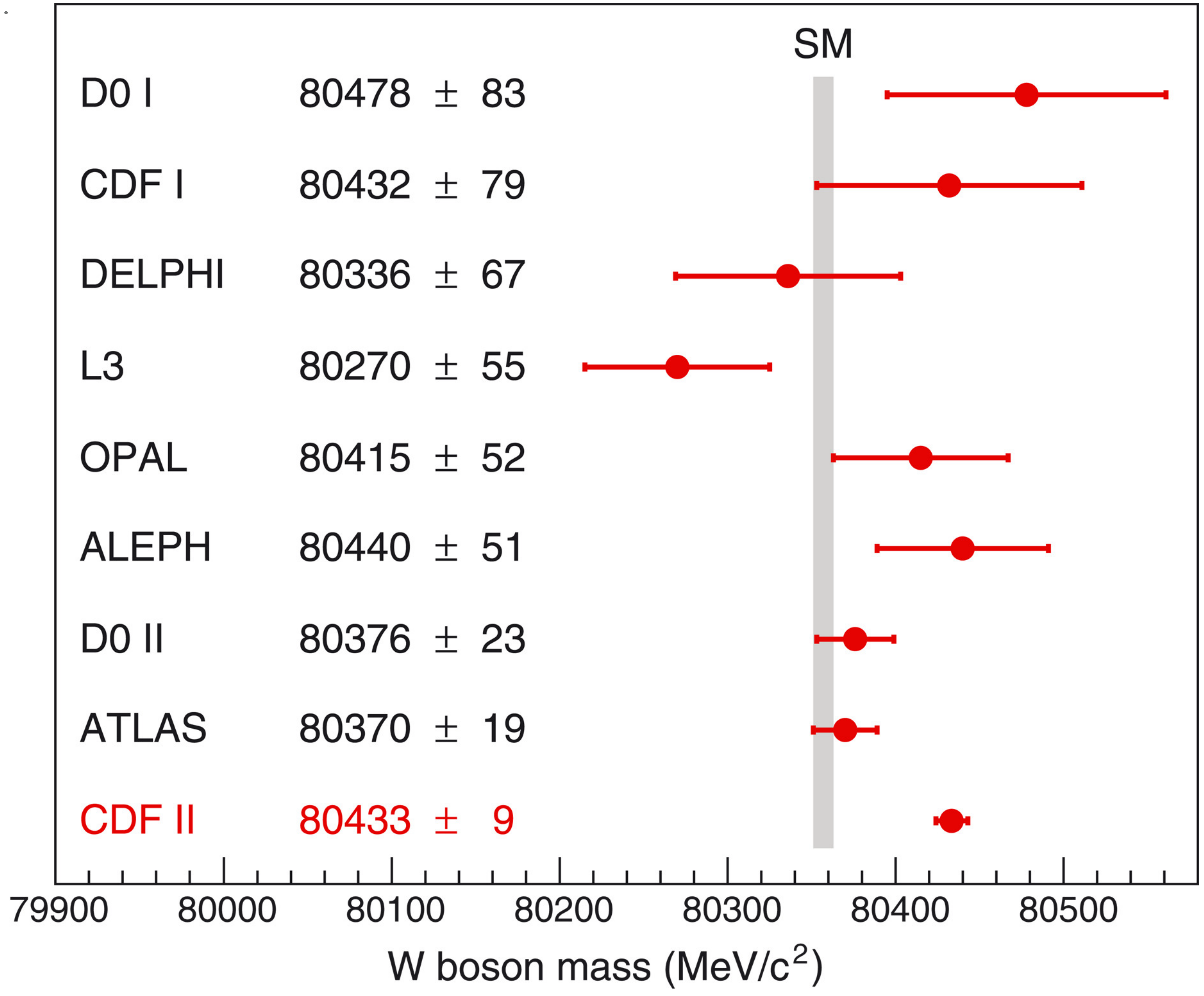




CDF W MASS MEASUREMENT

- Precision to 9 MeV!
  - Uncertainty from PDFs alone dropped from 10 to 3.9 MeV due to constraints from LHC measurements
- 7-sigma tension with SM fit!





CDF W MASS MEASUREMENT

- ➤ Pointing to new physics?
- ➤ Or experimental or theoretical issue?
- ➤ Another motivation for direct searches for new physics
- ➤ Emphasizes the importance of precision measurements
- ➤ More on these tomorrow!