Introduction to LHC physics

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special thanks to A.Mazeliauskas, P.Monni, U.Wiedemann

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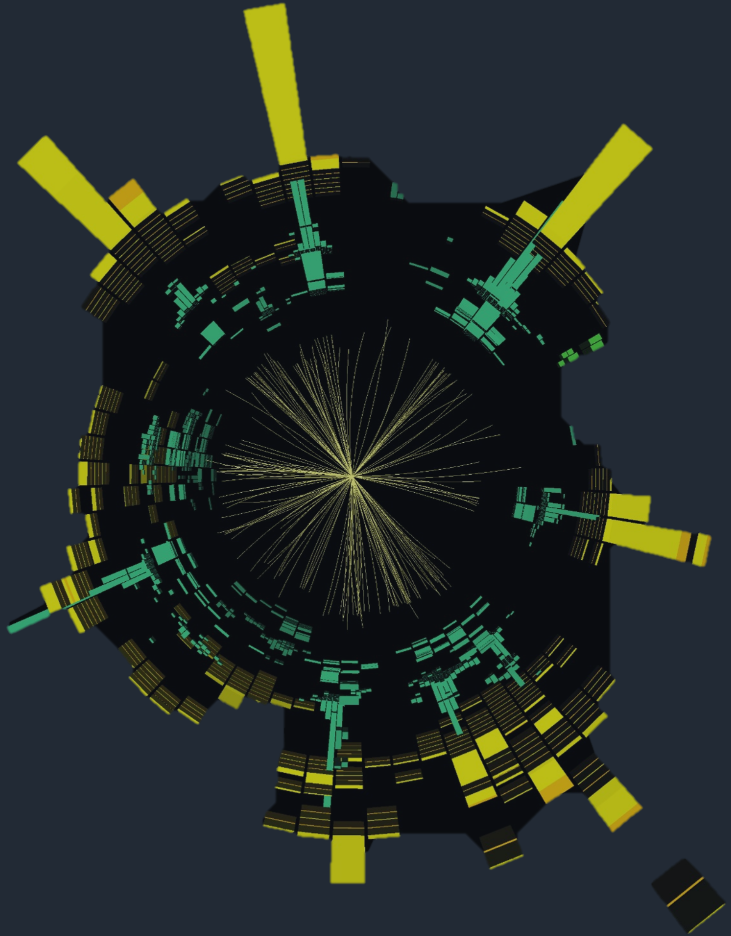
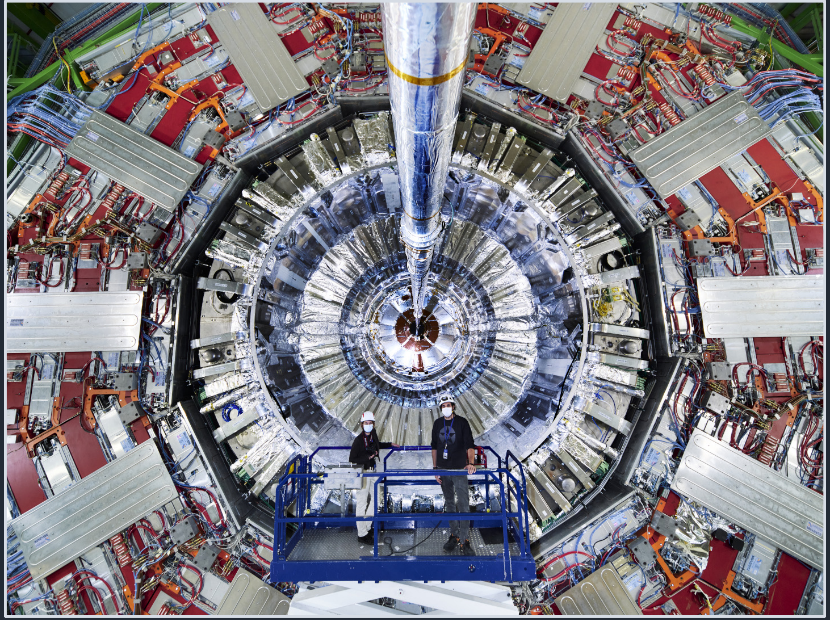
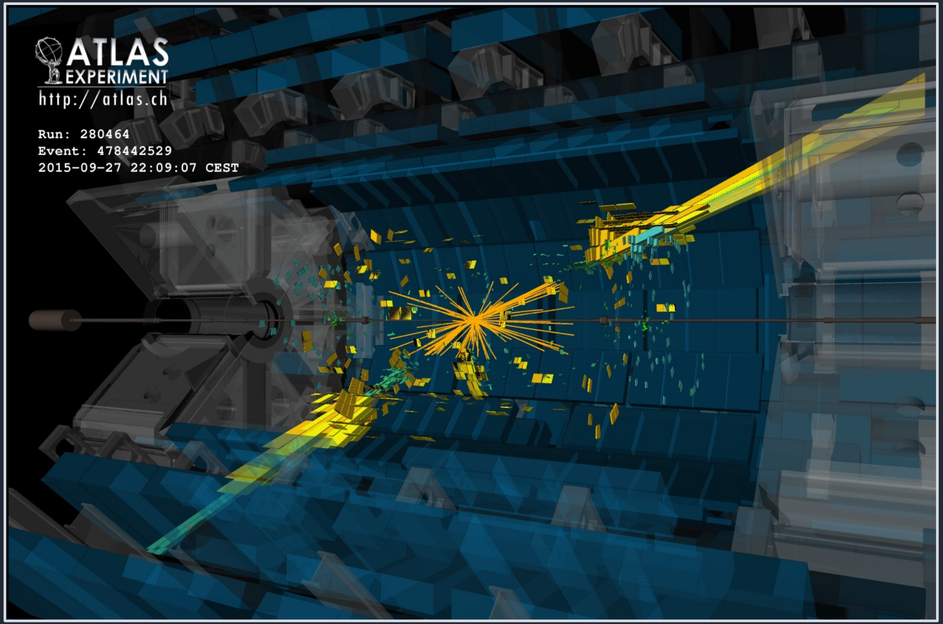
1. LHC: Stress-testing the SM







images: home.cern

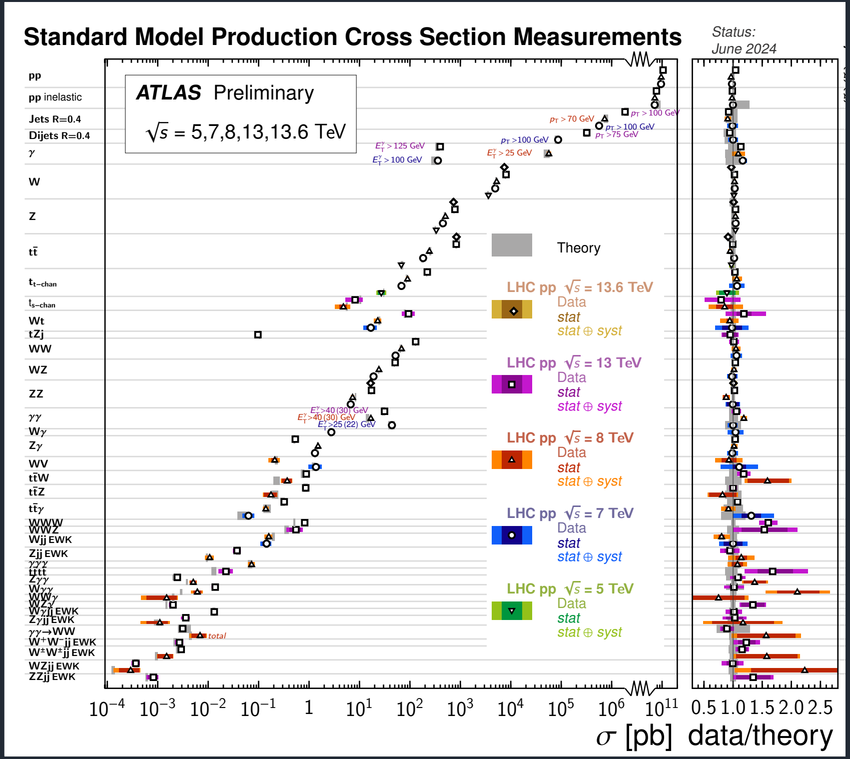
The Standard Model

- no free parameters (since M_H)

  → fully predictive

- Stress-testing the SM at LHC

  Very good overall agreement!



[ATL-PHYS-PUB-2024-011]

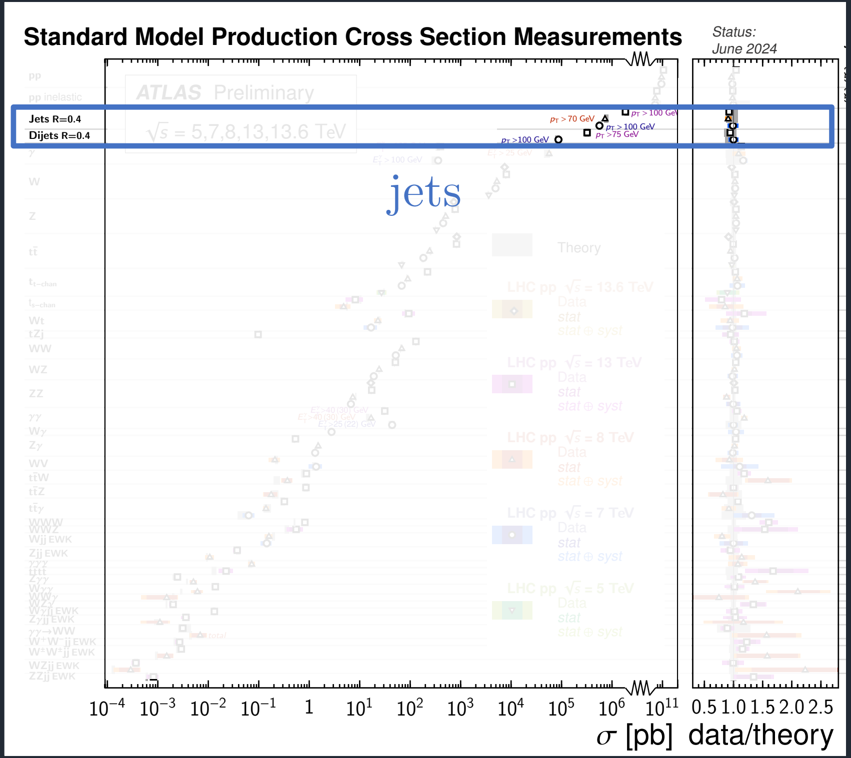
Jet measurements

- Jets: (the most common process)

  background of most SM/BMS process

- Driven by QCD:

  test of perturbative (and non-perturbative) QCD



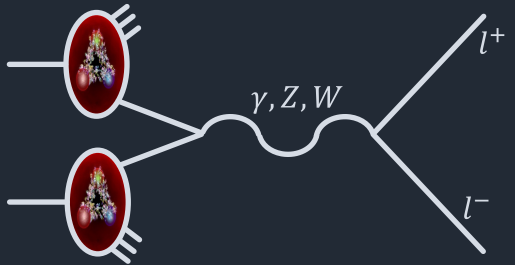
[ATL-PHYS-PUB-2024-011]

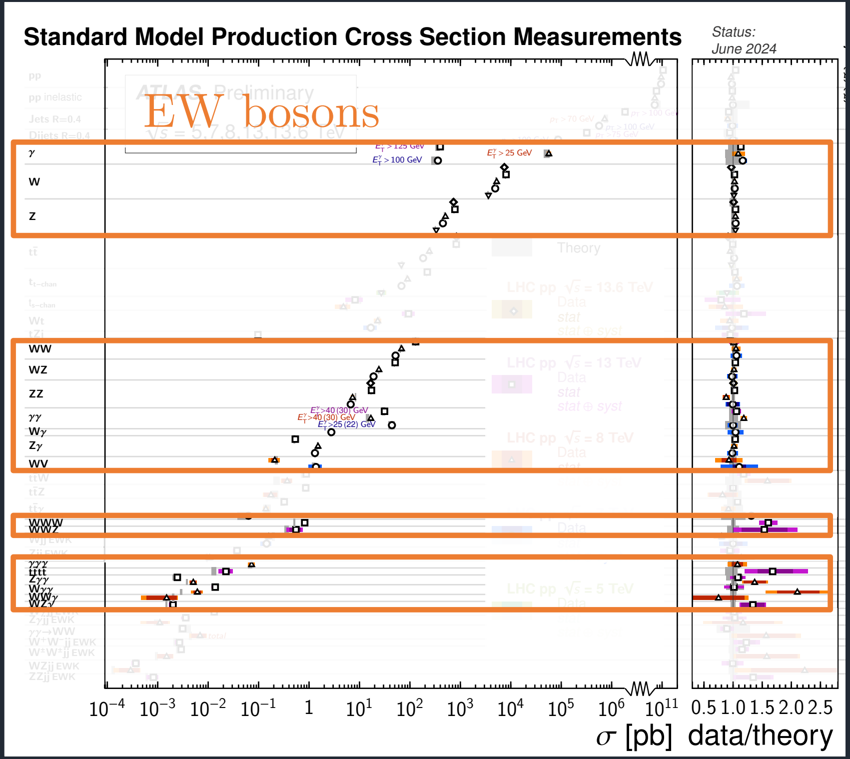
The Standard Model

- **Electroweak bosons**: $\gamma, W^{\pm}, Z$:

  involving 1, 2, or 3 of them

- Clean signatures* ($<$1% unc.)





*QCD contributes at higher orders

[ATL-PHYS-PUB-2024-011]

The Standard Model

- Top quarks: heaviest particle

  small hadronization corr, sensitive to BSM

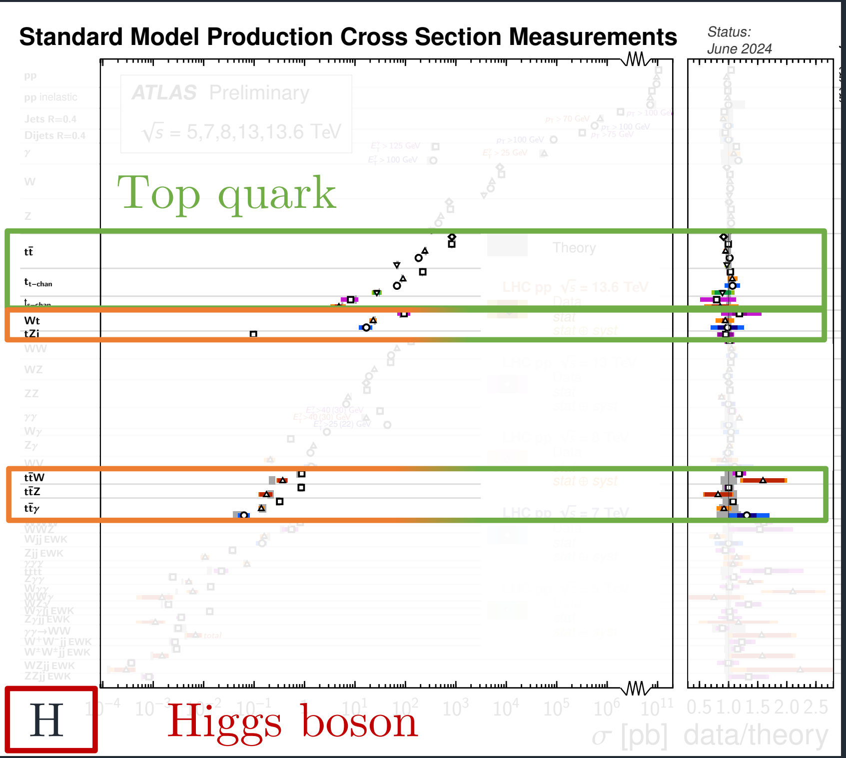
- Higgs boson: priority of LHC

  first non-electrodynamics like interaction

- New physics searches

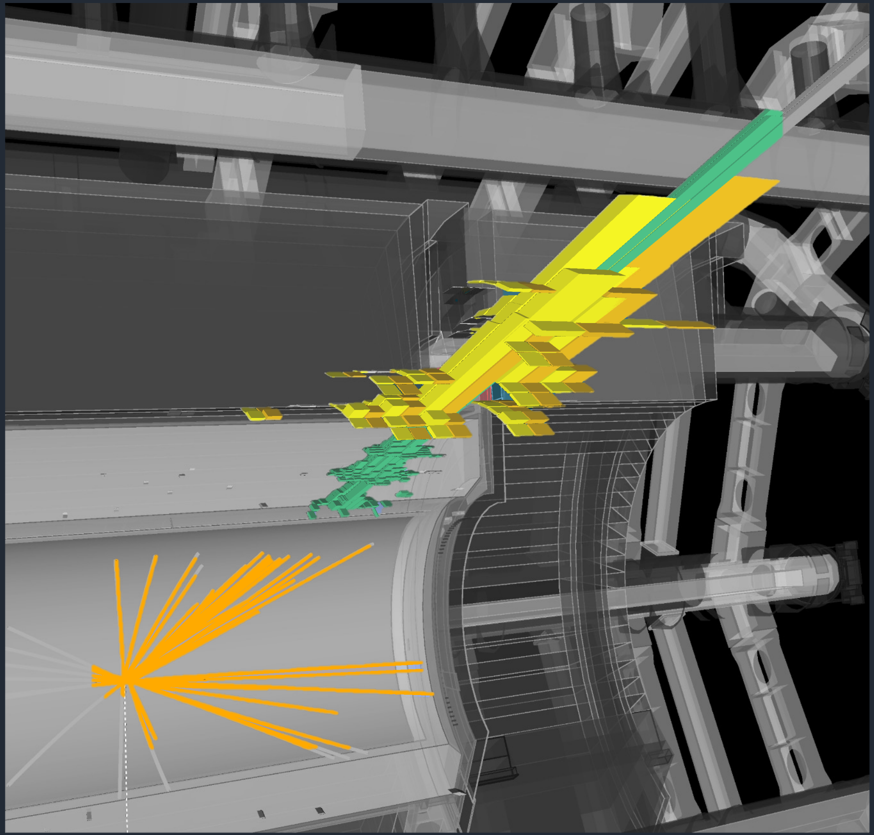
  direct: data driven methods

  indirect: tension in SM ($g_\mu - 2, M_W$)?



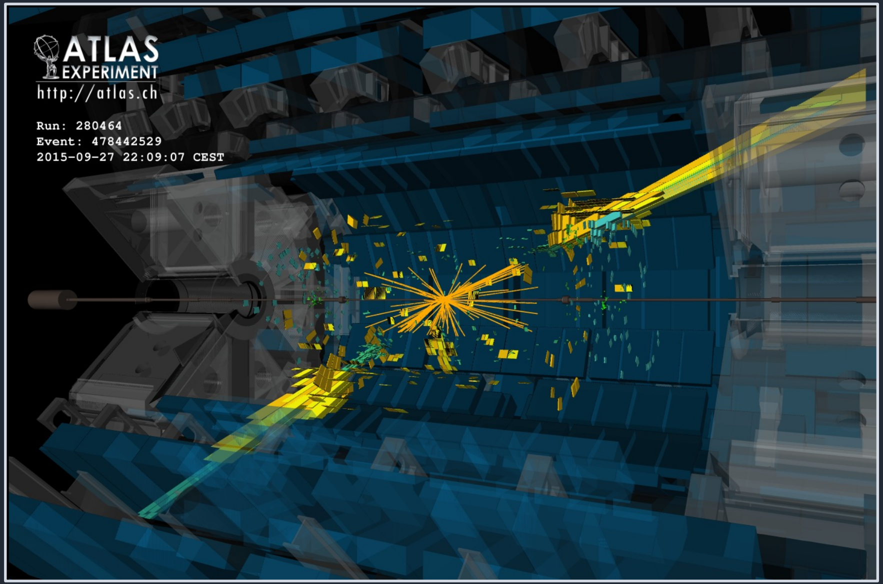
[ATL-PHYS-PUB-2024-011]

2. Precision phenomenology with the SM

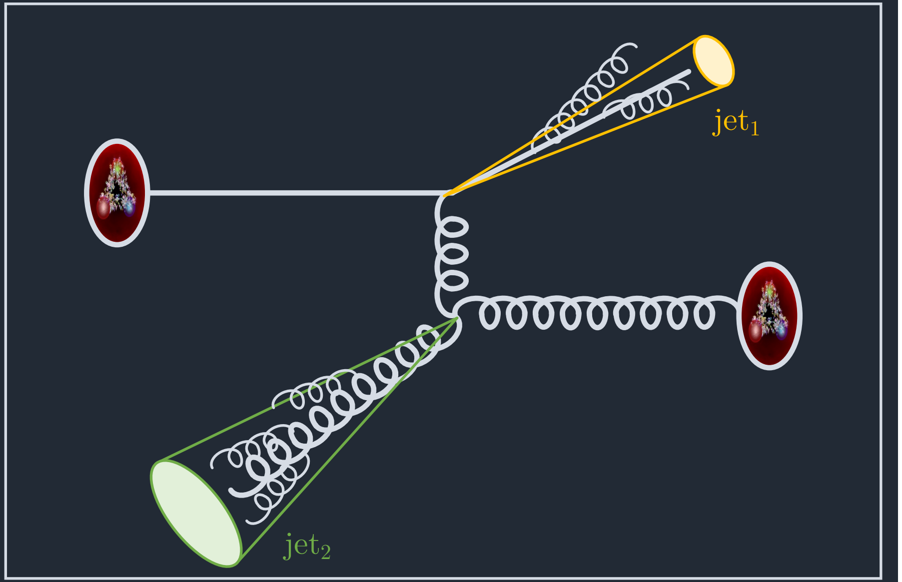


Most* common process: jets

experiment



theory



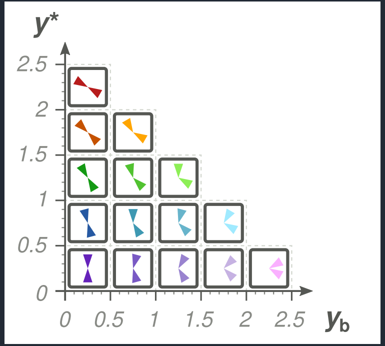
*The most common is when nothing happens...

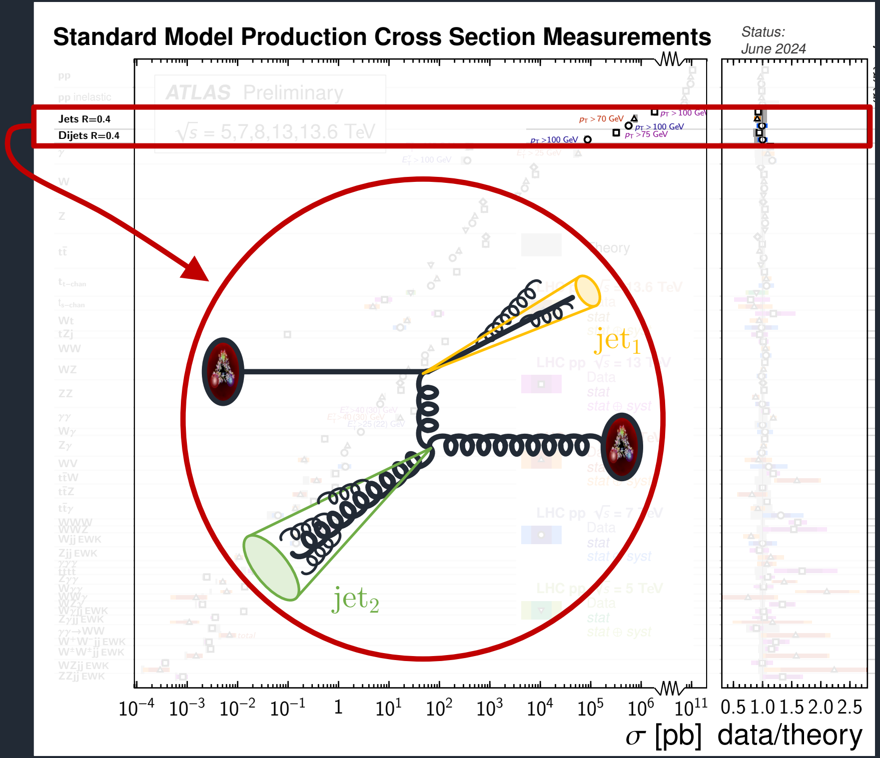
Jet measurements

- Underlying $2 \to 2$ scattering:

  3 independent variables $(+\ \varphi)$

$$\frac{d^3\sigma}{dy^* dy_b dm_{jj}}$$





[ATL-PHYS-PUB-2024-011]

Jet measurements

- Underlying $2 \to 2$ scattering:

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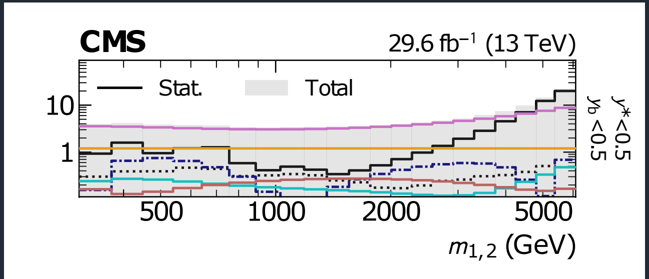
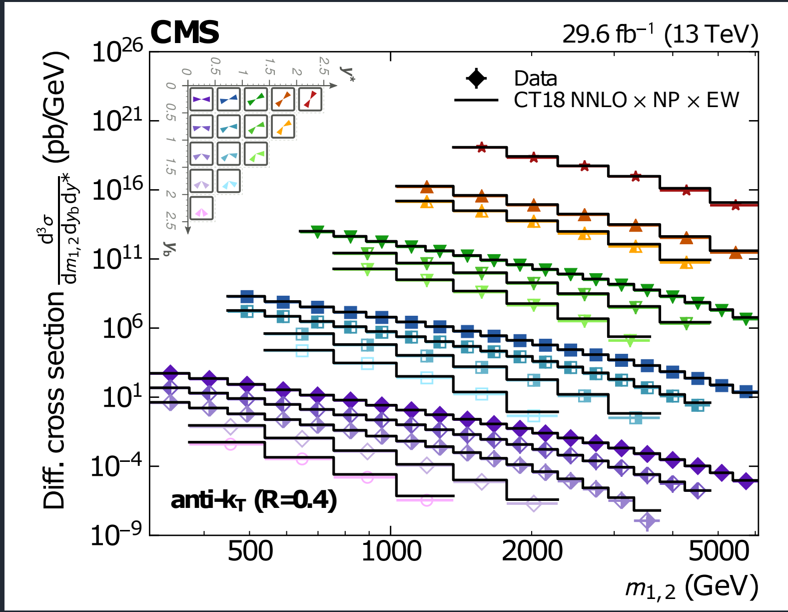
200 bins, few % uncertainty





[CMS 2312.16669]

How to make reliable predictions?

Calculating cross sections

- Observables = combinations of outgoing momenta

$$\frac{d\sigma}{d\mathcal{O}} = \int d\Phi_n \, \sigma_{pp\to n} \, \delta\left(\mathcal{O} - \hat{\mathcal{O}}(p_1, \dots, p_n)\right)$$

phase space of outgoing particles

multileg cross-section

observable = combining final momenta

- Separation of scales: $Q_{hard} \gtrsim Q_{jet} \gg \Lambda_{QCD}$ ⇐ Implied by choosing clever $\mathcal{O}$!

  Collinear factorization:

$$\sigma_{pp\to n} = \int dx_i dx_j \, f_i^p(x_i) \, f_j^p(x_j) \otimes \hat{\sigma}_{ij\to n} \otimes \left[1 + \mathcal{O}\left(\frac{\Lambda}{Q}\right)^p\right]$$

parton distribution in protons

partonic cross sections

power corrections: non-fact, hadronization, etc.

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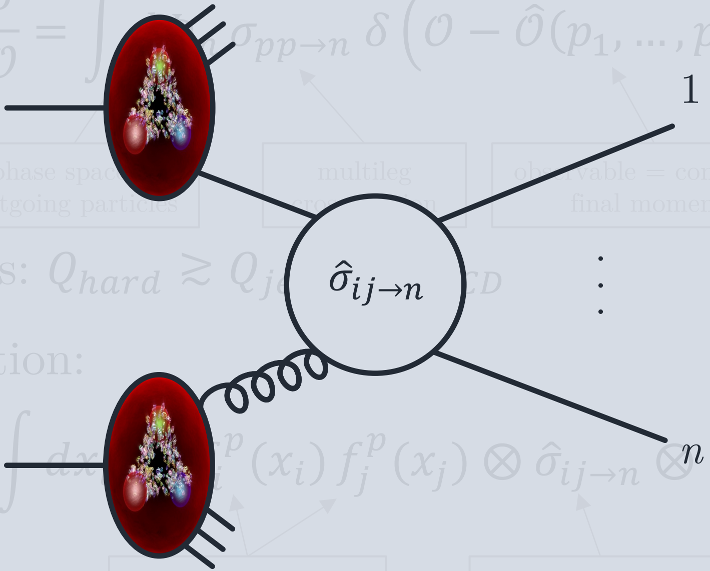
power corrections: non-fact, hadronization, etc.

Cross section in collinear factorization



Evaluate cross sections with precision!

$$\sigma_{pp\to n} = \int dx_i dx_j\, f_i^{h_1}(x_i)\, f_j^{h_2}(x_j) \otimes \hat{\sigma}_{ij\to n} \otimes \left[1 + \mathcal{O}\left(\frac{\Lambda}{Q}\right)\right]$$

pdf

LO $\lesssim$ 20%
NLO $\lesssim$ 10%
N^{2}LO $\lesssim$ 5%

$ij \to n$

LO	$\lesssim$ 40%	LL	$\lesssim$ 100%
NLO*	$\lesssim$ 20%	NLL	$\lesssim$ 20%
N^{2}LO	$\lesssim$ 5%	N^{2}LL	$\lesssim$ 5%

pow. corr.

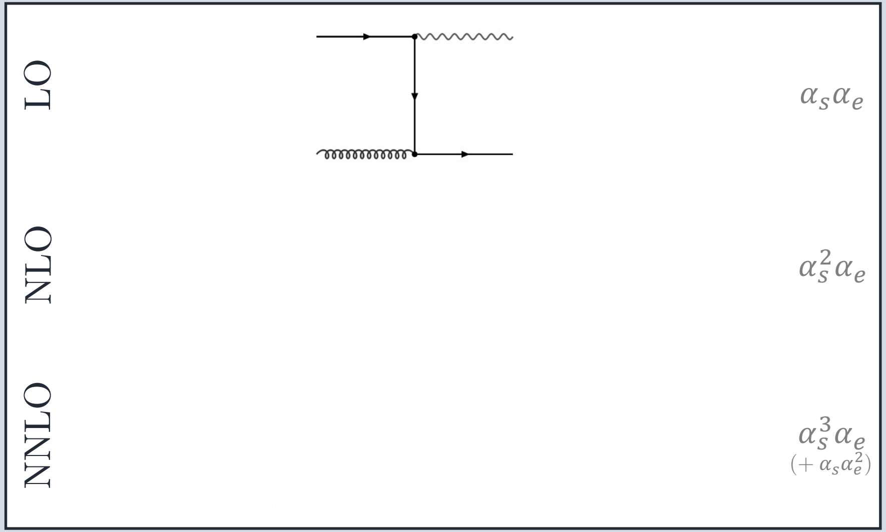
non- fact,
hadronization,
MPI, etc.

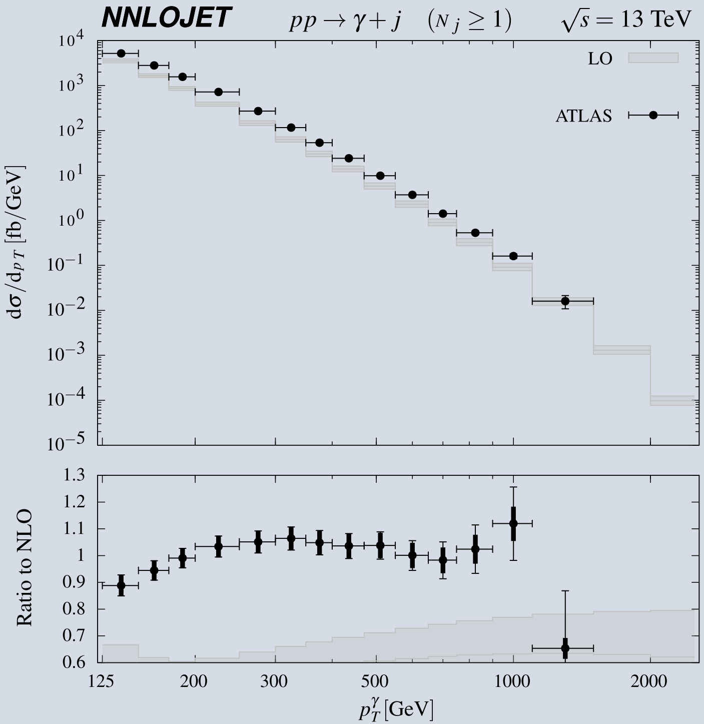
*also mixtures of α_s & α_e!

Case study: photon + jet

[adapted from A.Huss]

Coupling (loop) expansion





[Chen,Ghermann,Glover,Hofer,Huss 1904.01044]

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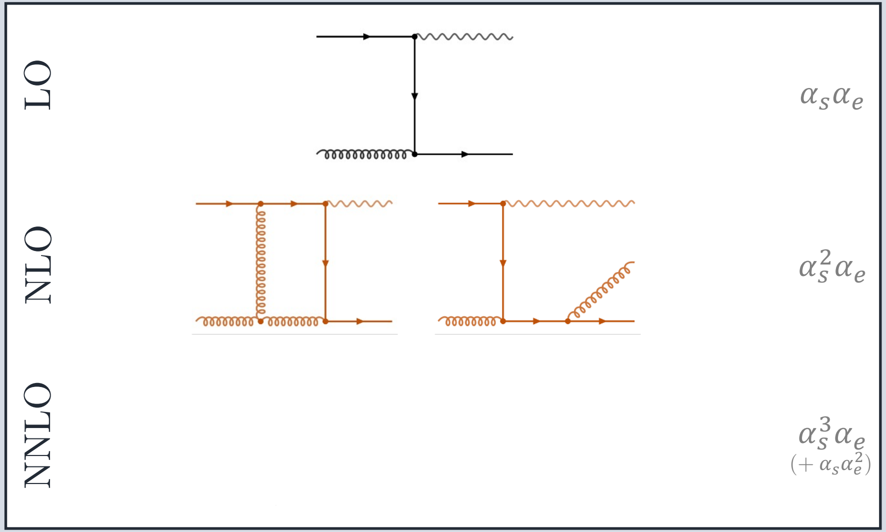

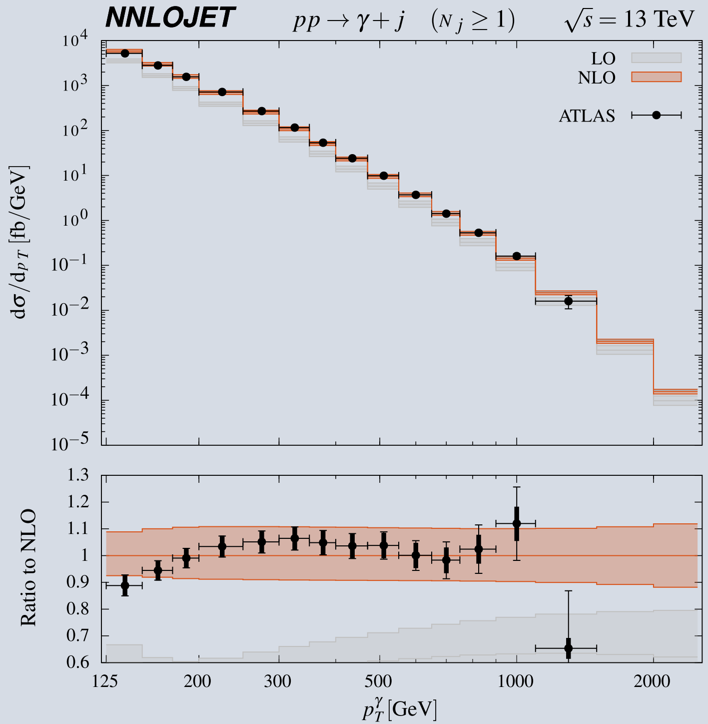

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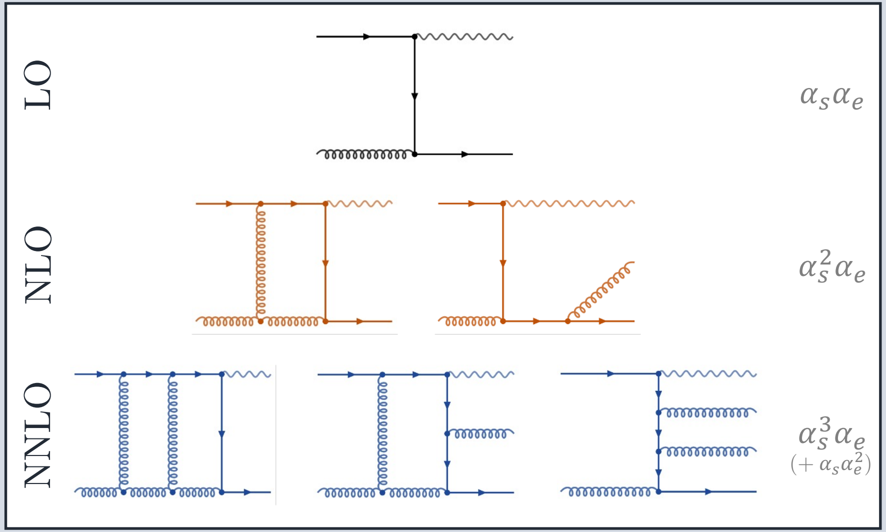
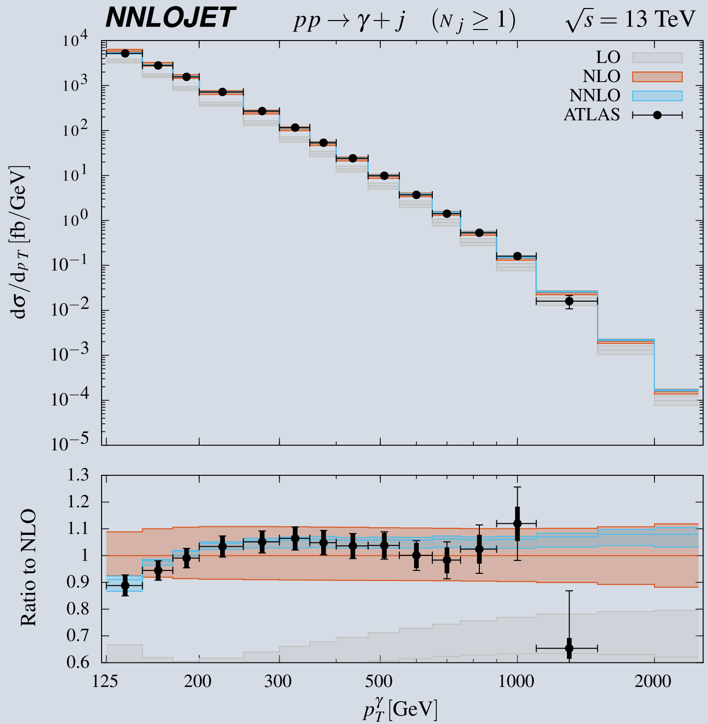




[Chen,Ghermann,Glover,Hofer,Huss 1904.01044]

HL-LHC 1% uncertainty target ($\alpha_s \approx 0.1$, $\alpha_e \approx 0.01$): $\mathcal{O}(\alpha_s^2,\, \alpha_e)$ and $\mathcal{O}(\alpha_s^3, \alpha_s \alpha_e)$.

Case study: photon + jet

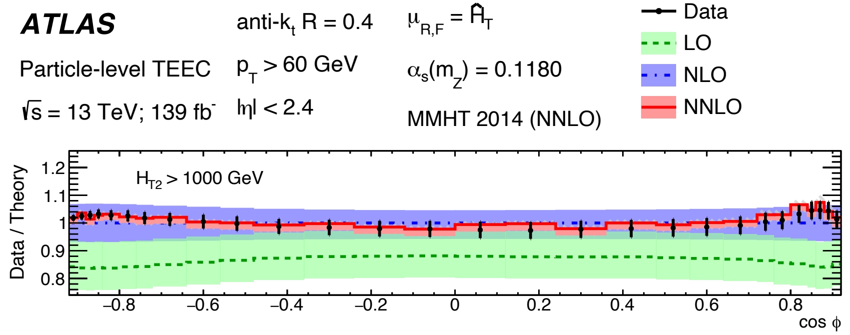
[adapted from A.Huss]

Main challenges:

1. Multi-dimensional integral

   NNLO $pp \to jjj$ needs 100M CPUh to measure α_s.

   [ATLAS 2301.09351]



2. Infrared singularity

   matrix elements are divergent but their sum is finite

3. Multi-loops complexity

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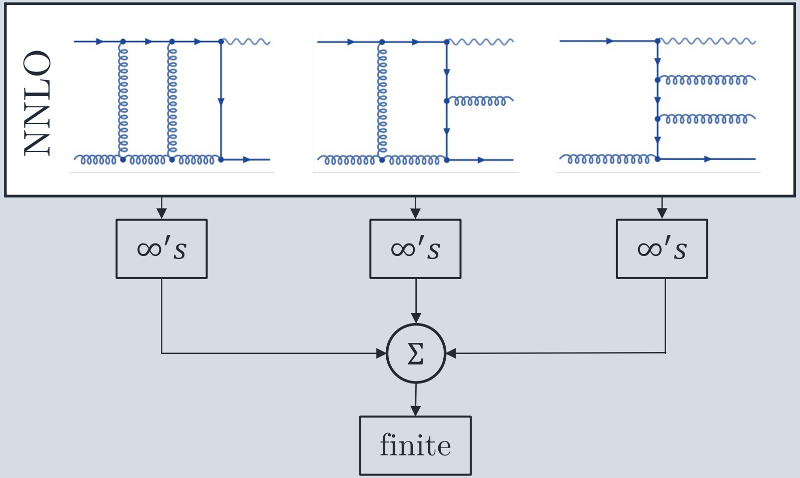
3. Multi-loops complexity

→ Feasible for a few legs ☹



Jet resummation

Separation of scales: $Q_{hard} \gtrsim Q_{jet} \gg \Lambda_{QCD}$

Collinear (to the beam) factorization:

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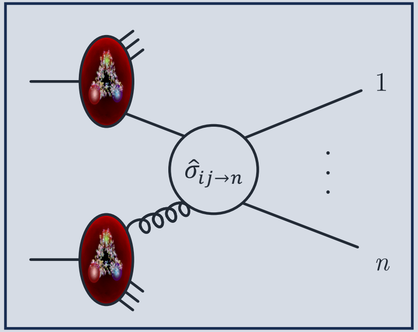

Only for a few legs.

- Additionally: $Q_{hard} \gg Q_{jet} \gg \Lambda_{QCD}$

  Soft or collinear limit (to the jet)

$$\hat{\sigma}_{ij\to(n+1)} = \hat{\sigma}_{ij\to n} \otimes \hat{\sigma}_{1\to 2}$$

Markov-like process → parton shower

For many legs!

Jet resummation and event generators

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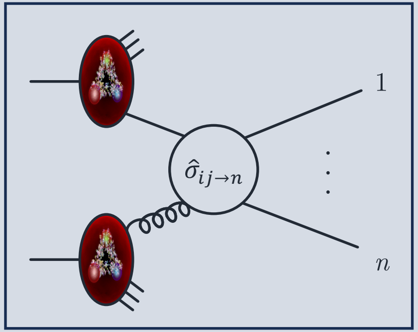

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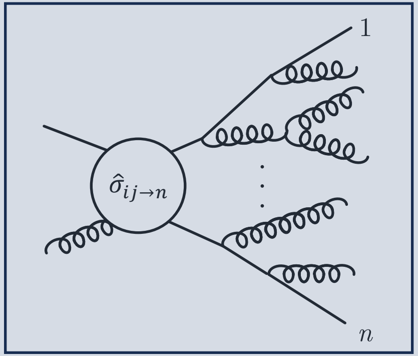

For many legs!

Recent progression in (N)NLL parton showers!

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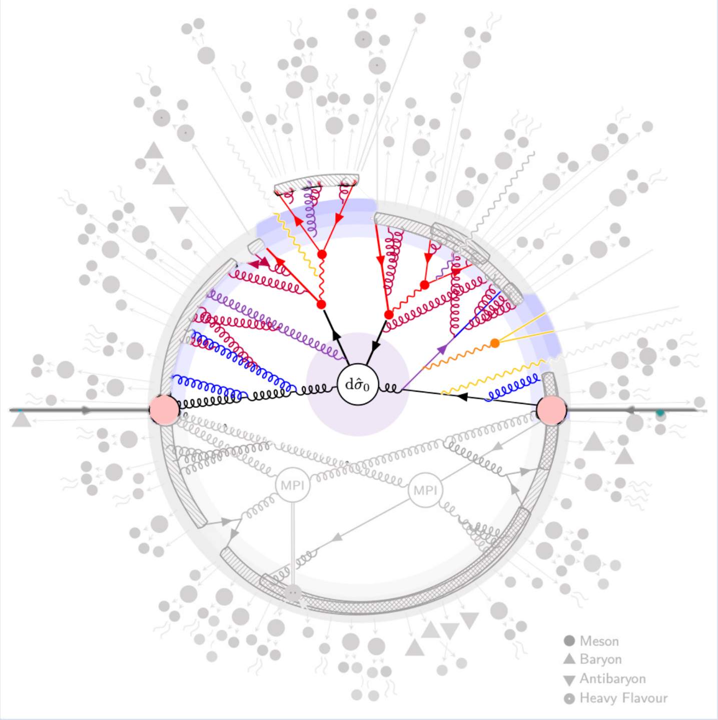
Theory behind **event generators**.



[Pythia8: P. Skands]

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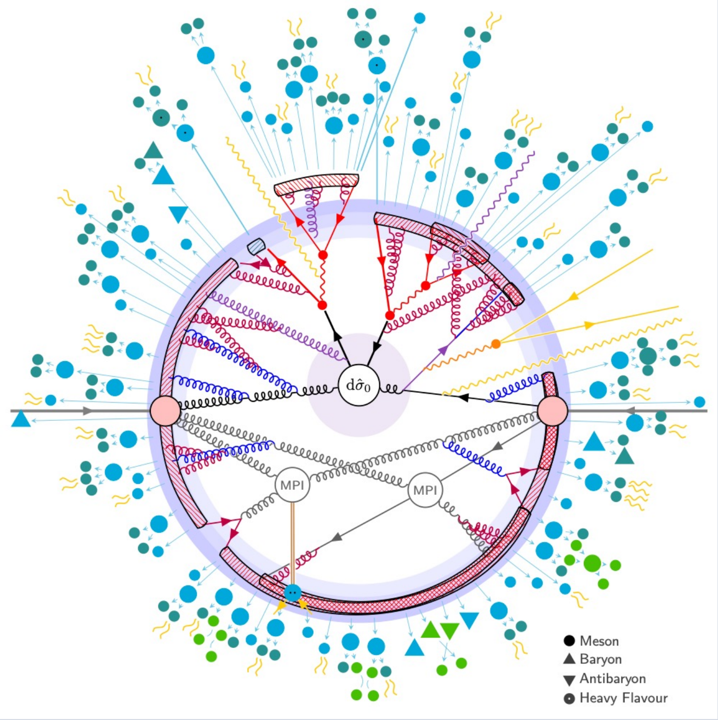
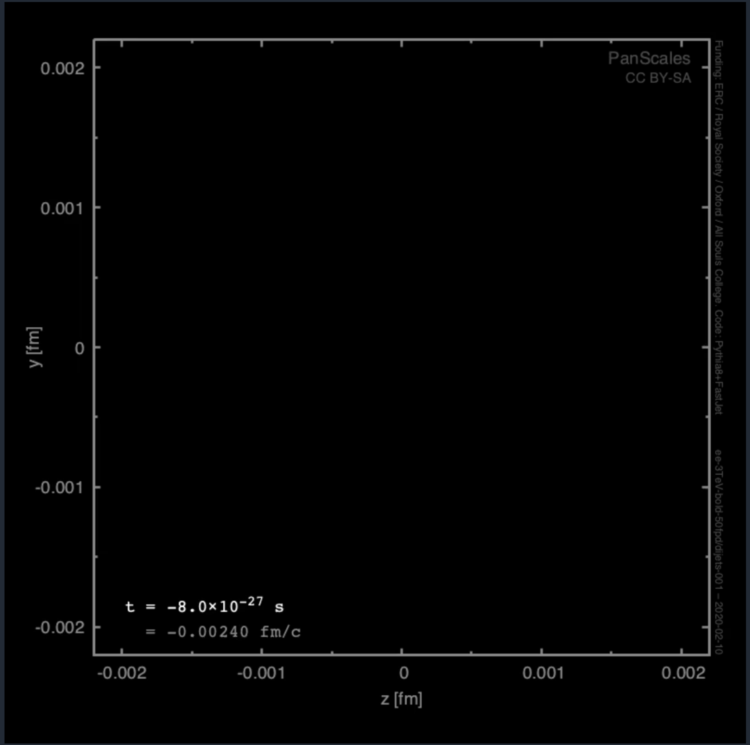
Markov-like process → parton shower

Event generators also include: hadronization, MPI, …

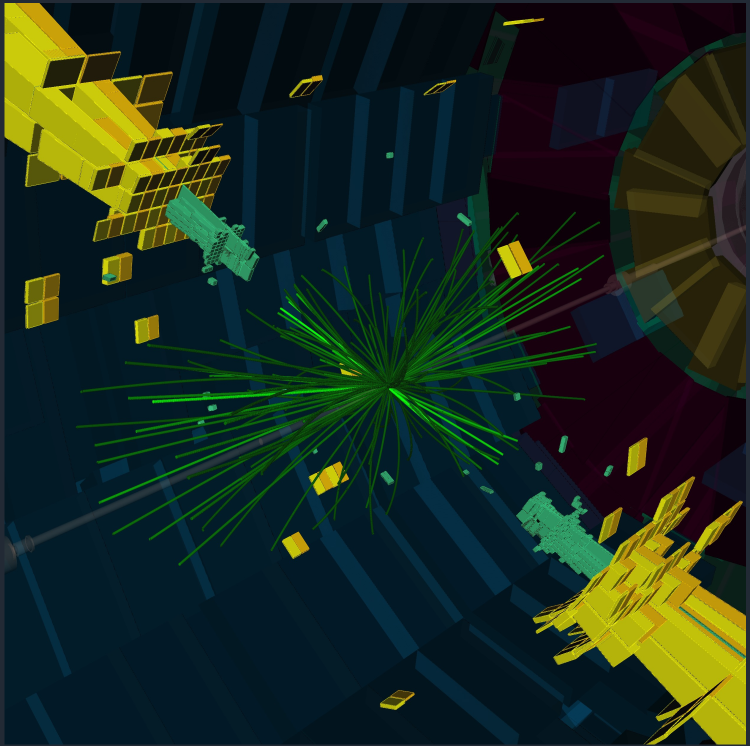


[Pythia8: P. Skands]

Event generator



Experiment

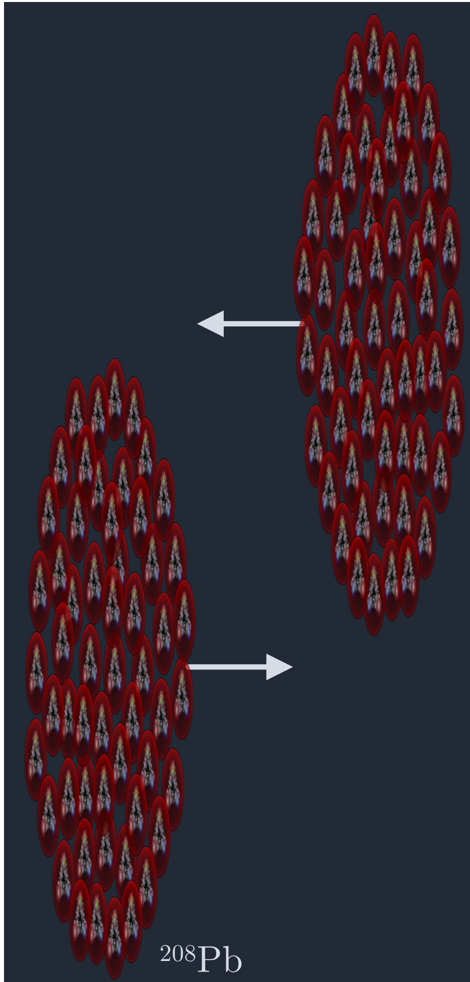


Markov process → parton shower

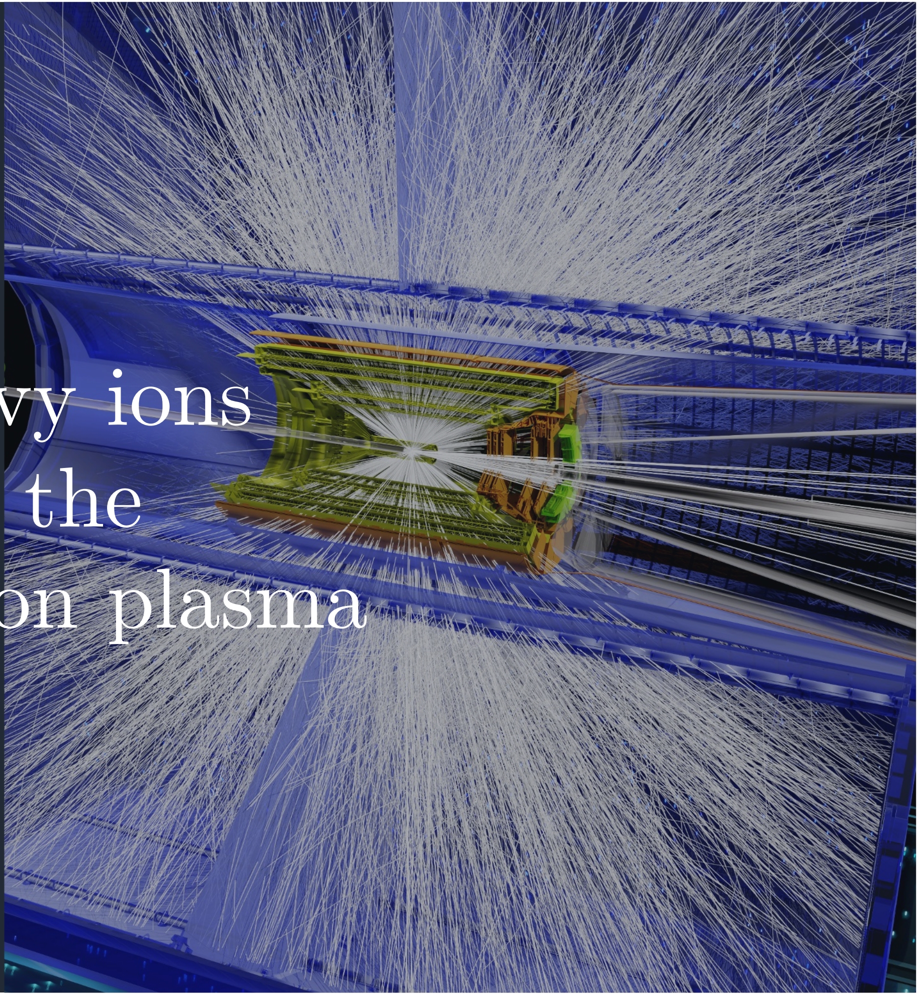
[Pythia8: P. Skands]

Summary of SM studies:

- SM is complete: stress testing with LHC $\rightarrow$ good agreement!
- Predictions are based on perturbation theory.
- At high accuracies QCD & EW diagrams are needed.
- At 1% precision non-perturbative effects also comes to play

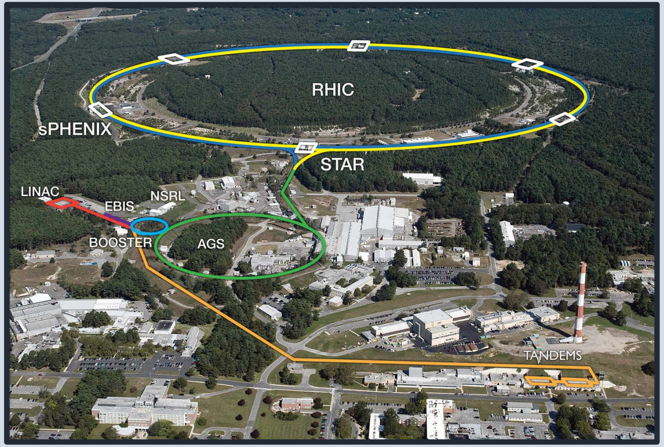


3. Heavy ions and the quark-gluon plasma



Heavy-ion collisions

- Heavy-ion program at LHC and RHIC
- Nuclear matter at high energy
- Discovery of the quark-gluon plasma:
  - **Quenching** (= energy loss)
  - Collective flow
  - Soft photon excess
  - Strangeness enhancement
  - etc.



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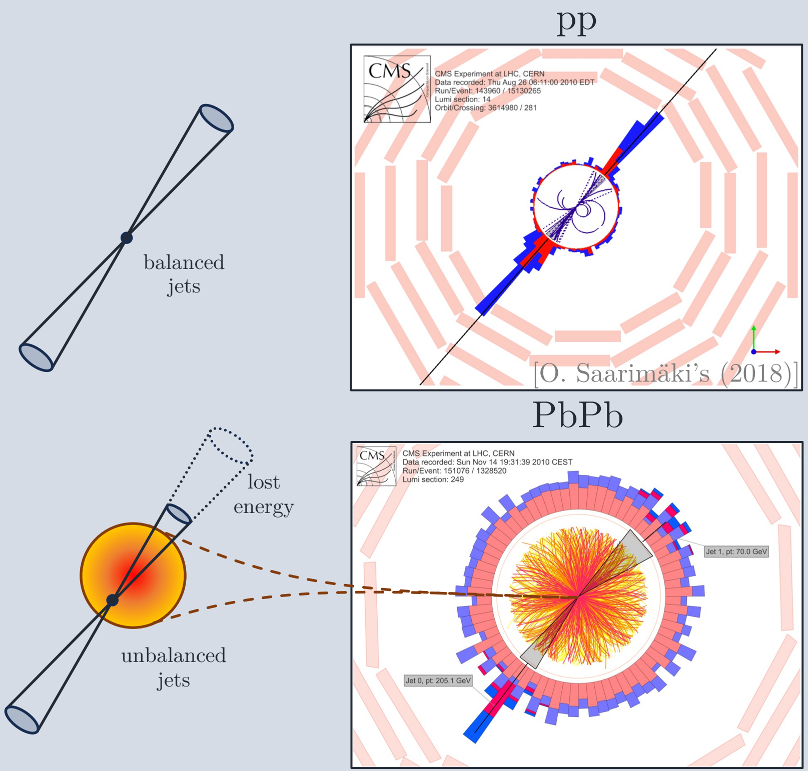

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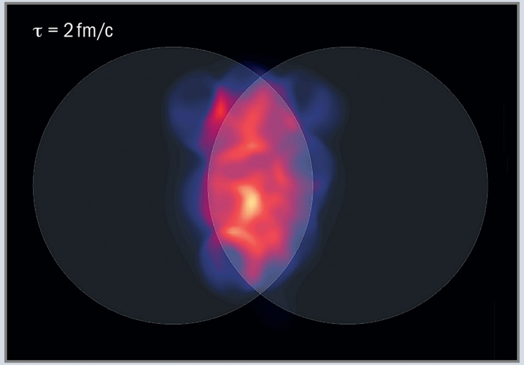

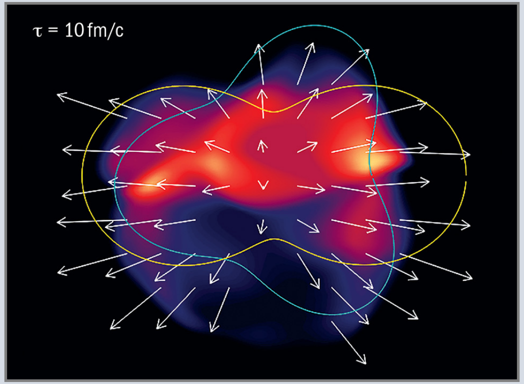

[CERNCourier]

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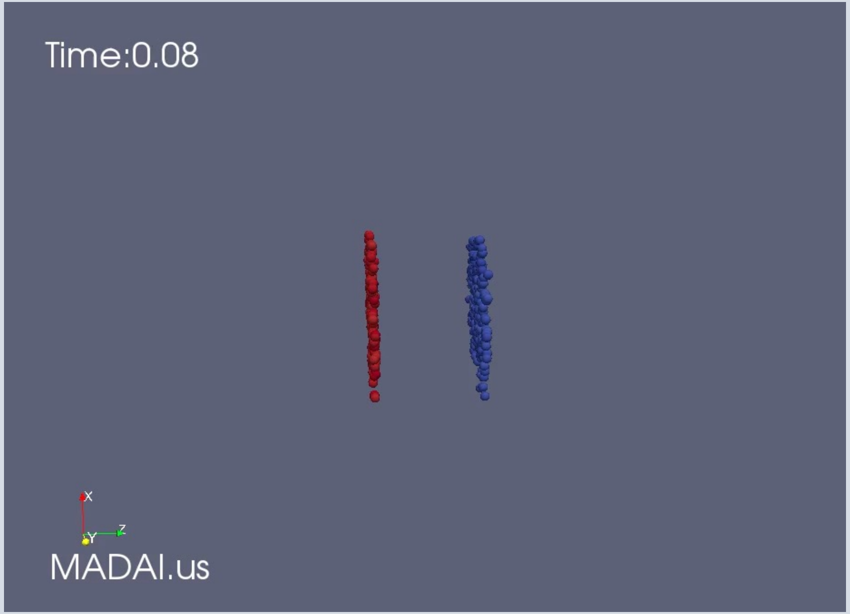
"Hydrodynamic" picture of AA collisions!



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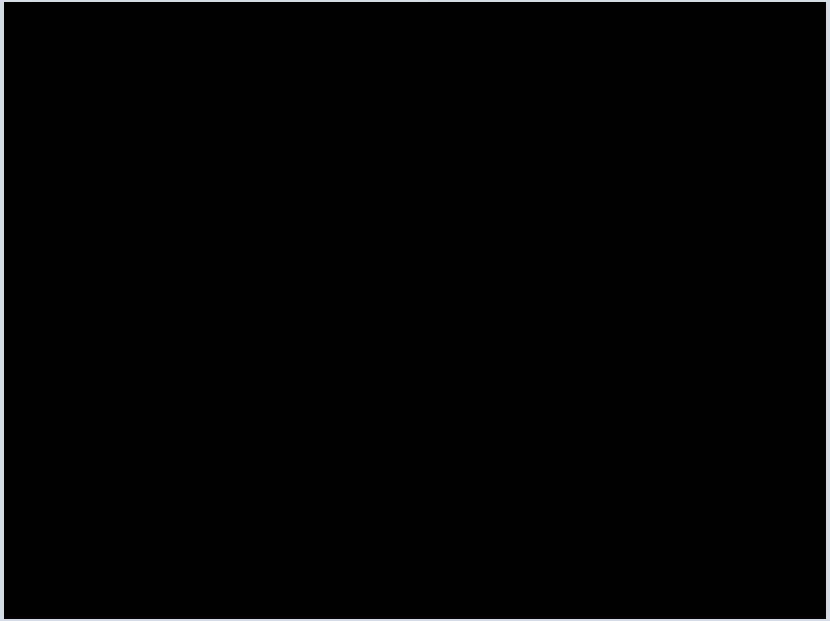
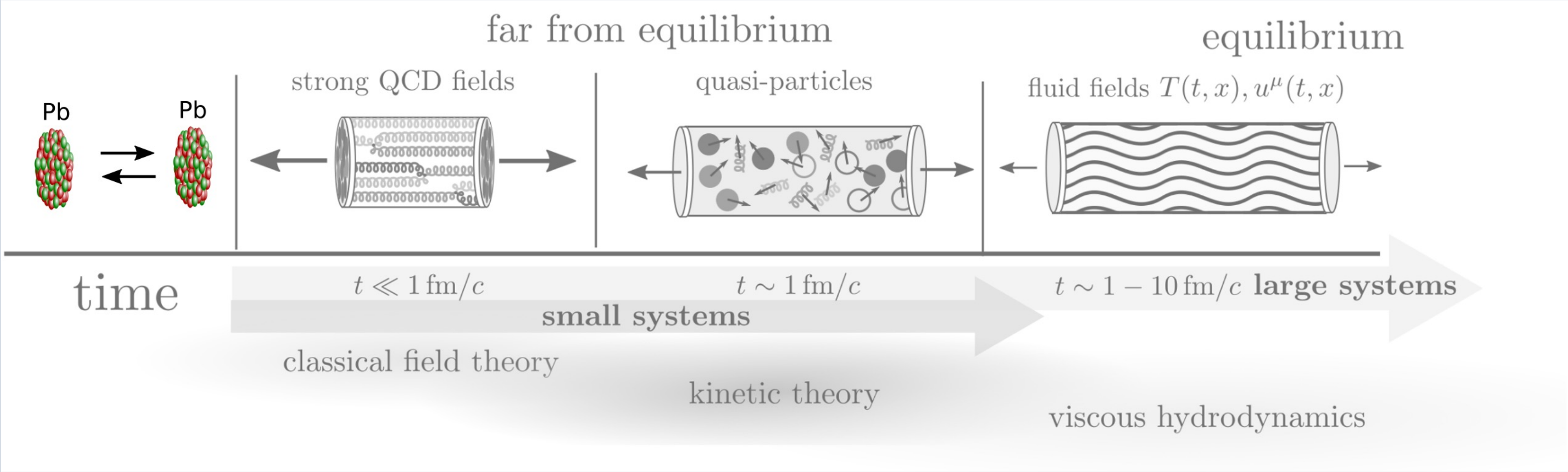


[Chun Shen]

Real-time dynamics of HI collisions

[Berges,Heller,Mazeliauskas,Venugopalan 2005.12299]



1. Initial state:
   - Nucleus geometry
   - (Sub)nucleon structure
   - Fluctuations
2. Reaching-equilibrium:
   - Dense gluon fields (glasma)
   - Far-from-equilibrium evolution
   - Attractor behavior
3. Hydrodynamics:
   - Close to equilibrium
   - Very small viscosity
   - Freeze-out.

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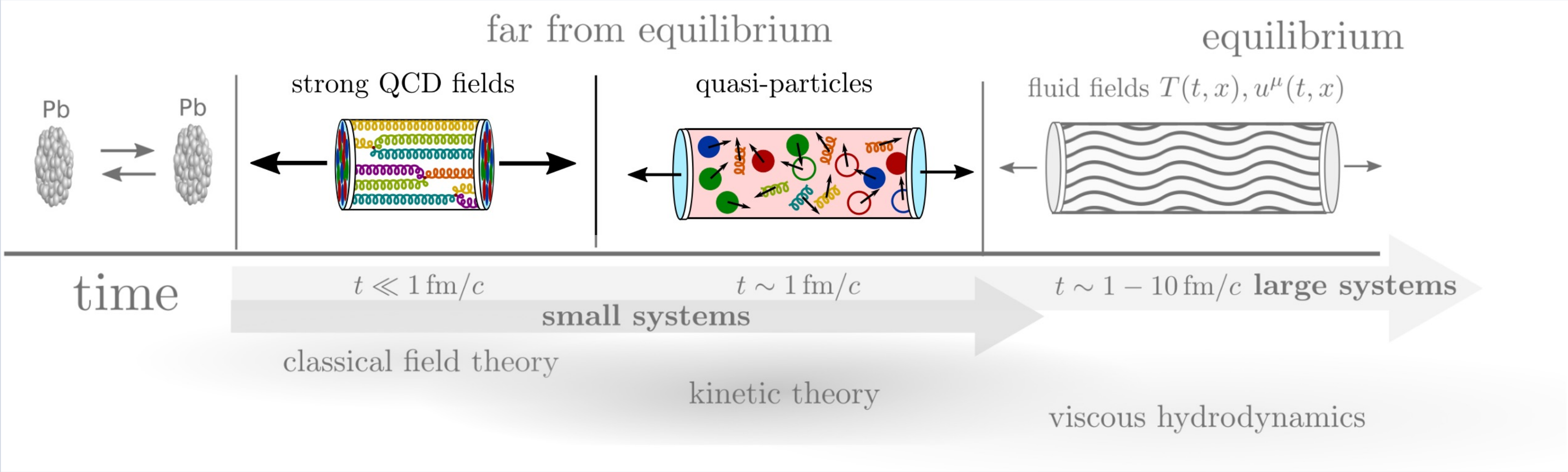

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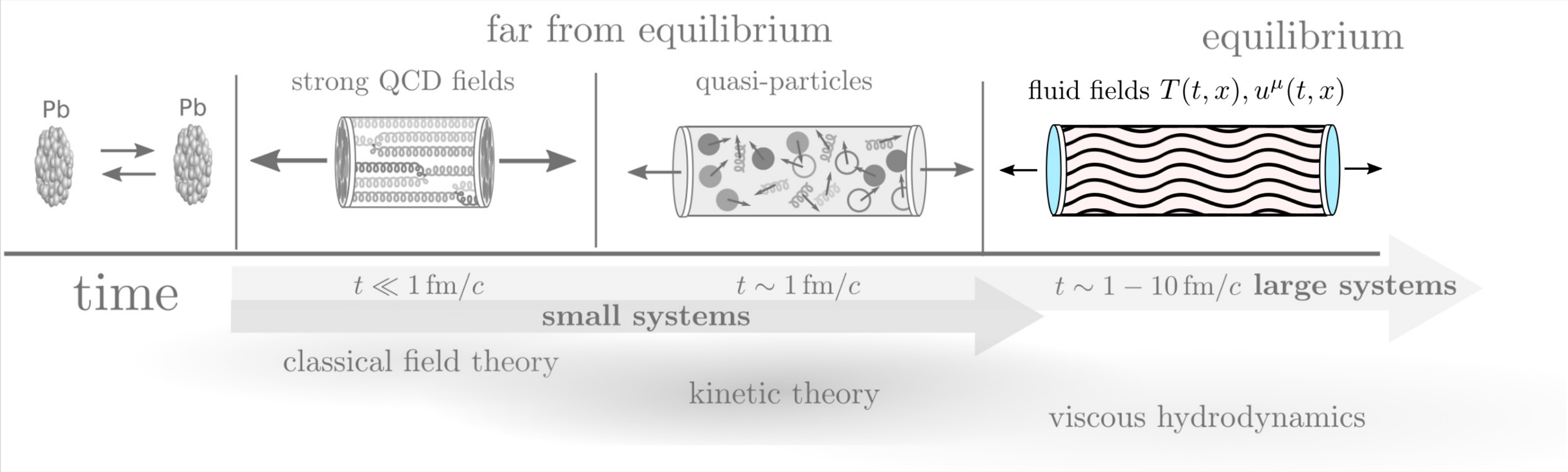

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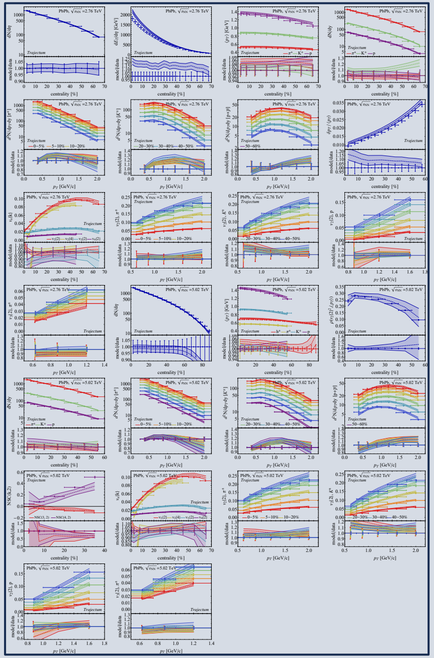
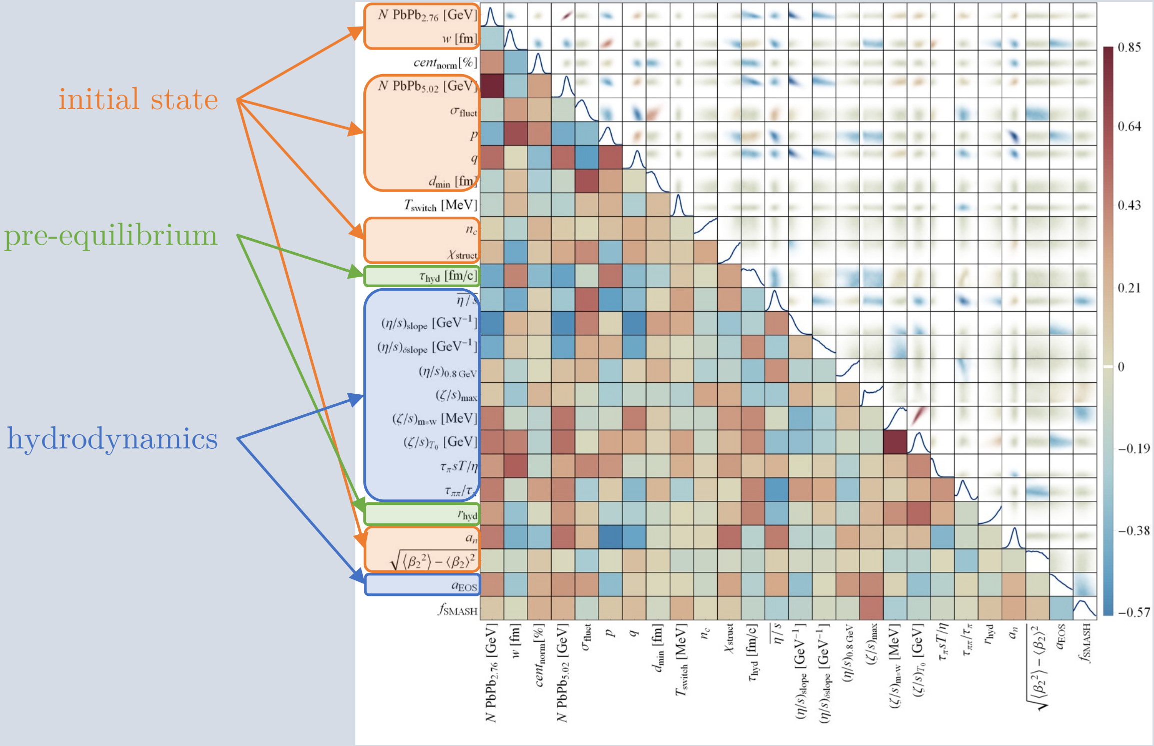
Success of the “hydrodynamic picture”

Bayesian analysis:





[Giacalone,Nijs,van der Schee, PRL 131.202302]

Success of the “hydrodynamic picture”

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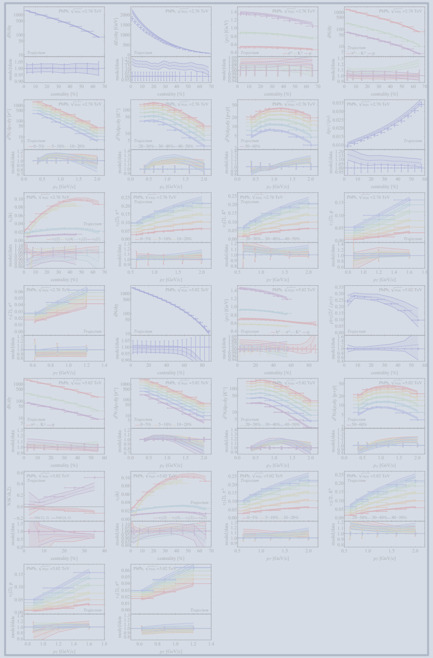

<u>Hydrodynamics:</u>

- density
- temperature
- QCD equation of state
- viscosity
- ...

[Giacalone,Nijs,van der Schee, PRL 131.202302]

Success of the "hydrodynamic picture"

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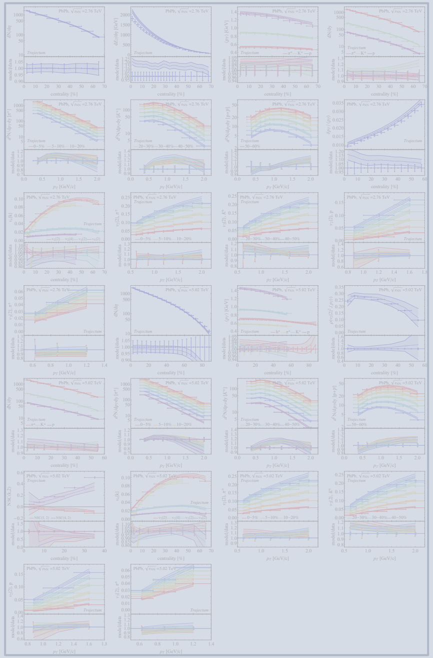


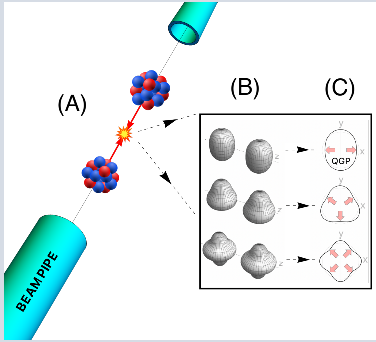
Initial geometry:

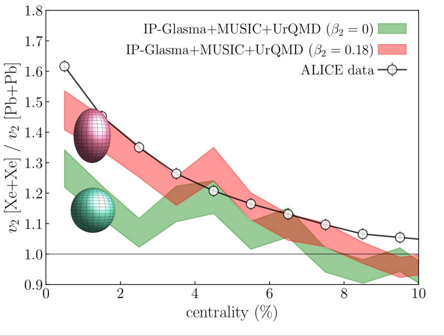
- hydro response is sensitive to the nucleus structure!
- nucleus tomography!

[Giacalone,Nijs,van der Schee, PRL 131.202302]

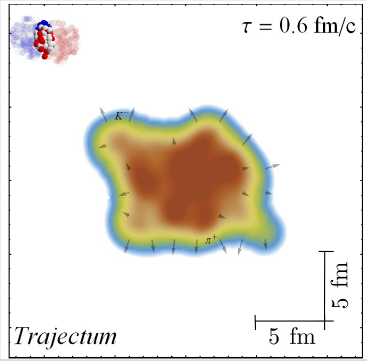
Nucleus structure in heavy-ion collisions

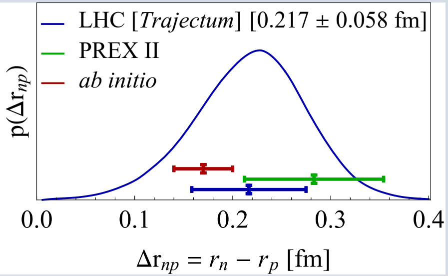
- Hydro response is sensitive to the nucleus shape
- Clever measurements constrains nucleus structures
- State-of-the-art precision in:
  - nucleus shape
  - neutron skin



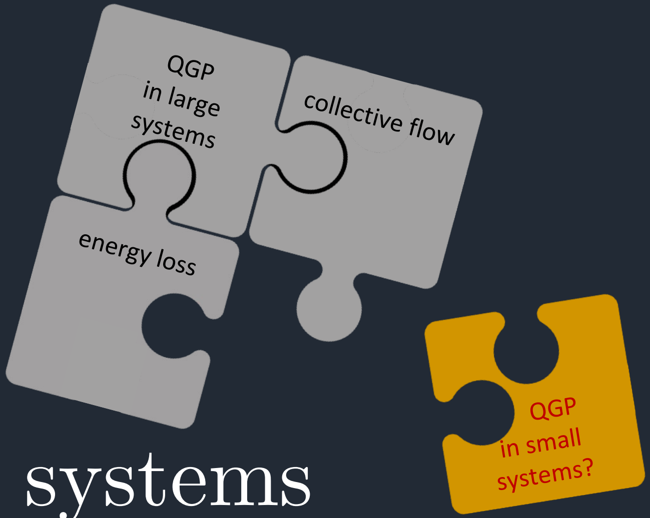


[Xe shape: Bali et al, 2209.11042]





[neutron skin: Giacalone,Nijs,van der Schee, PRL 131.202302]



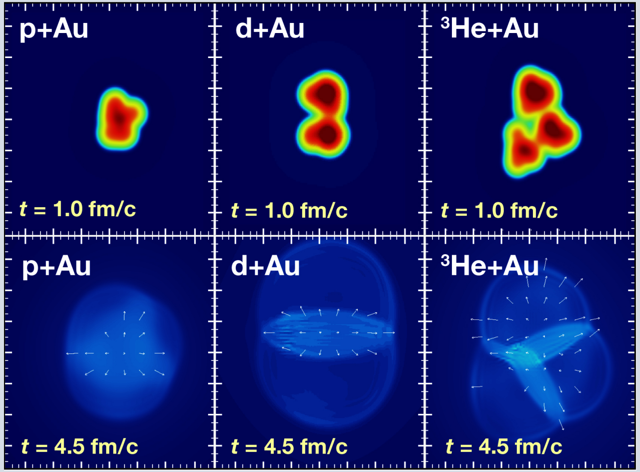
The puzzle of small systems

Small system collectivity

[Grosse-Oetringhaus, Wiedemann 2407.07484]

- **flow**-like signals in: pA, pp, γA
- **strangeness enhancement** in: pA, pp
- Hydro description works!
- **Quenching haven't been observed**
- Why does hydro work?!
- Where is energy loss?

→ precision is needed! (**jets**)



[ALICE: Nature13 (2017)]
[PHENIX pA: Nature15.214]
[STAR pA: PRL.130.242301]
[CMS pp: PRL116.172302]
[ALICE pp: PRL.132.172302]

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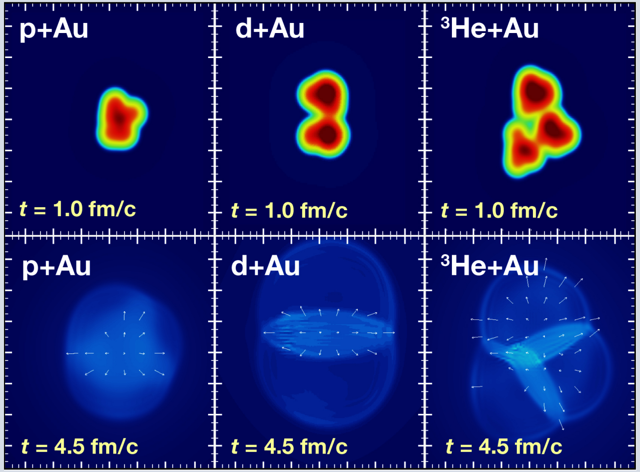

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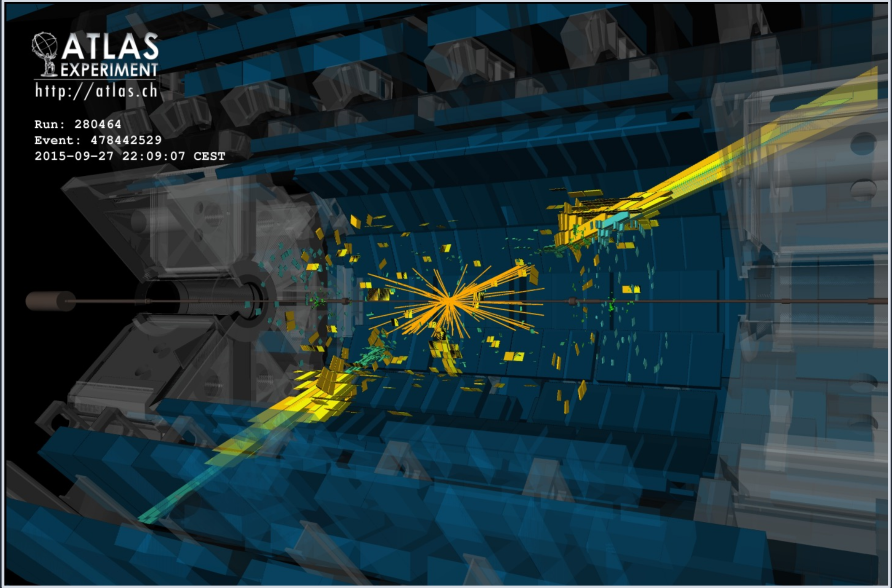
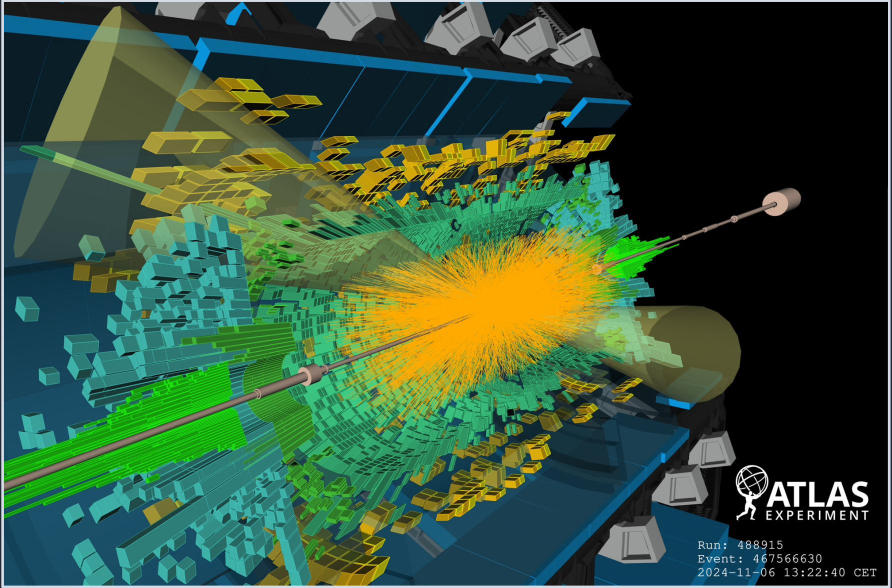


2-jets in pp collision



2-jets in PbPb collision

Use jets to learn about the PbPb, and pPb!

Summary:

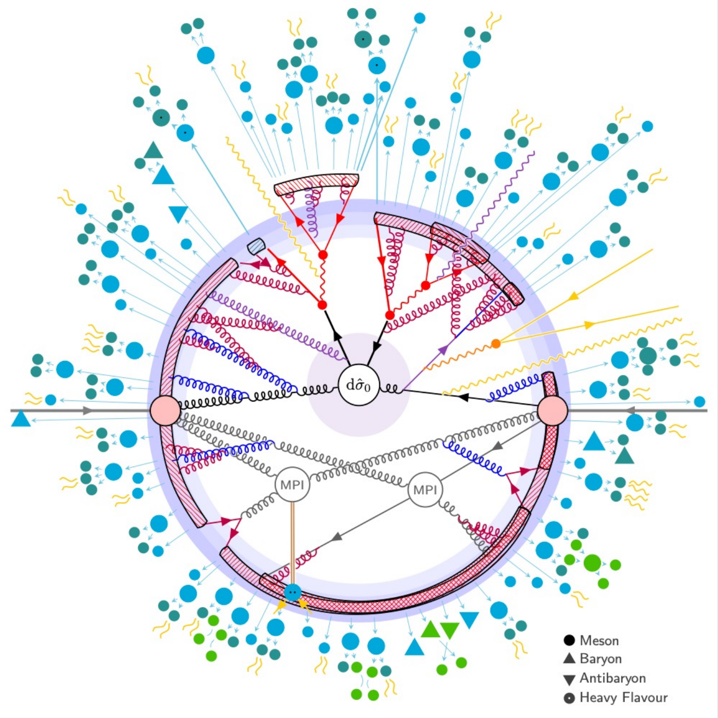
- Heavy-ion collisions → nuclear matter under extreme conditions
- Heavy-ion "standard model" = hydro picture
- Success of hydro:
  - thermodynamic properties of QGP
  - nuclear structure!
- QGP-droplets creates a great challenge for the future

Thank you for your attention!

Precision with jets

- Adding flavor and masses (c-, b-quark jet)
- Identified particles (isolated photons, hadrons)
- mixing QCD & EW corrections
- Resummation at NNLL
- Matching to (N)NLO
- Improve hadronization

+1 Improve underlying event (needed)



[Pythia8: P. Skands]

Early-time dynamics in HI collisions

[Berges,Heller,Mazeliauskas,Venugopalan 2005.12299]