Collective phenomena and critical transitions

from plasma to complex socio-ecological systems

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Environmental
Institute

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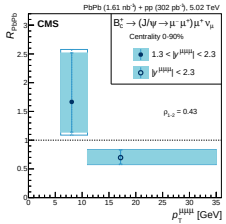
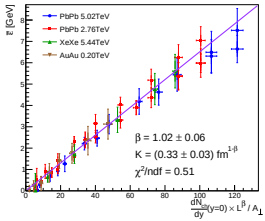
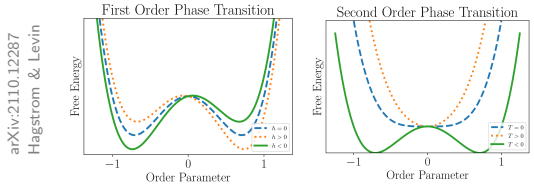
Between physics and ecology

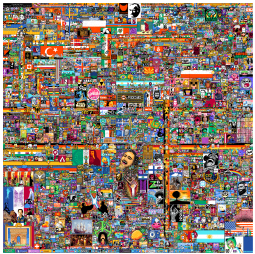




- PhD on QGP: B_c meson in PbPb, high-p_T radiative energy loss

- Postdoc: critical transitions in socio-ecological complex systems





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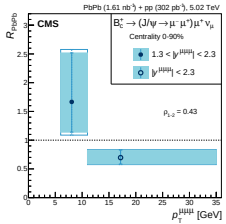

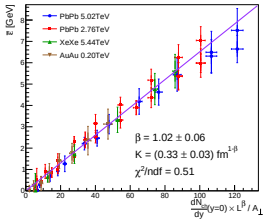

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???

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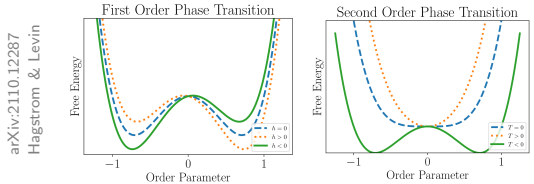
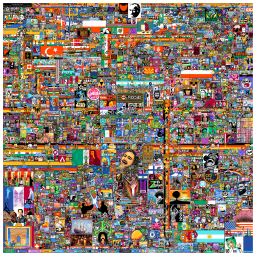
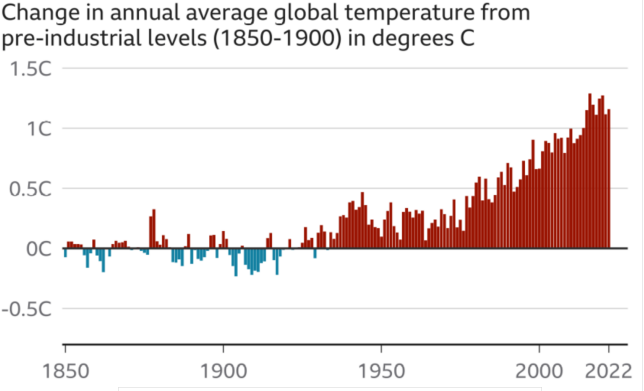
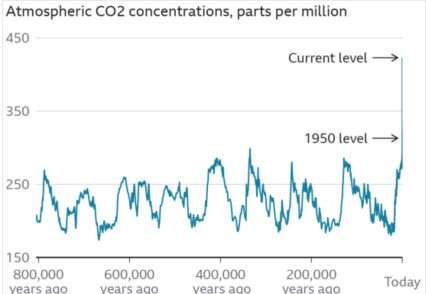
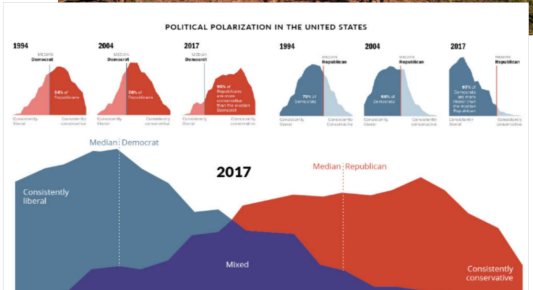




Credits: Guillaume Falmagne


Change in annual average global temperature from pre-industrial levels (1850-1900) in degrees C
1.5C
1C
0.5C
0C
-0.5C
1850
1900
1950
2000
2022


Atmospheric CO2 concentrations, parts per million
450
350
250
150
Current level
1950 level
800,000 years ago
600,000 years ago
400,000 years ago
200,000 years ago
Today


POLITICAL POLARIZATION IN THE UNITED STATES
1994
Democrat
2004
Democrat
2017
Democrat
1994
Republican
2004
Republican
2017
Republican
Median Democrat
2017
Median Republican
Consistently liberal
Mixed
Consistently conservative

Elementary brick or many-agents system?

- QGP links:
  - The world of particle physics:
    why? → more elementary components
  - and that of statistical physics:
    why? → system perspective, many agents

- *More is different*,
  Phil Anderson, 1972

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

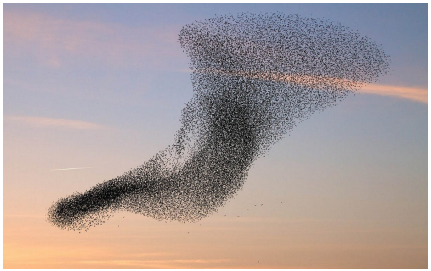
X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
⋮	⋮
psychology	physiology
social sciences	psychology

But this hierarchy does not imply that science X is "just applied Y."

- Emergent phenomena: interactions between many simple agents (*i.e.* complex systems) lead to original system properties, far from those of a single agent.
  Example: phase transitions!

Plasma and collectivity

- QGP = a *"state of matter"*, a *"medium"* ...
  as can be ensembles of living beings

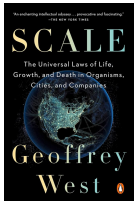


- Continuity of approaches from "elementary" particles (*first principles*) to their collective behaviour:
  - agent-based models
  - spin models
  - statistical physics
  - dynamical models (diff. equations)
  - scaling laws
  - networks
  - evolutionary game theory

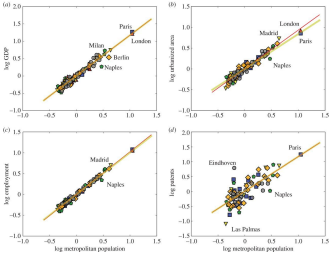
- Historically:
  - thermodynamics *then* particle physics
  - bird biology *then* flocks

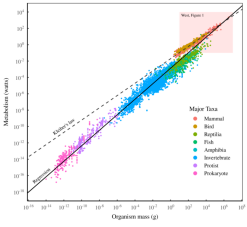
Sociophysics, scaling laws, networks

- Sociophysics = humans as particles? 
- Interdisciplinarity = *complementary* approach, not replacement
- Example success stories with complex systems (including from Santa Fe Institute):

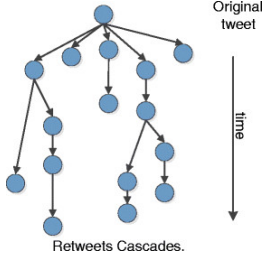


Scaling laws / allometry (urbanization, animal morphology, businesses ...)



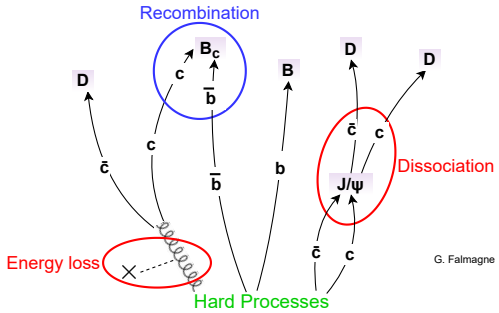


Networks: influence of structure on dynamics (Internet, disease and opinion propagation ...)



Effects of the QGP on B_c mesons

- Dissociation: screening of heavy-quark potential
  B_c: binding energy between J/ψ and $\Upsilon(1S)$



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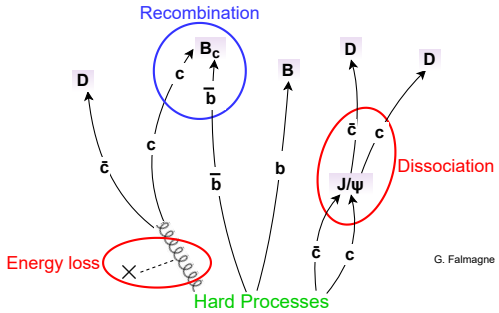
- Recombination: many $c\bar{c}$ produced in PbPb + small $\sigma(B_c)$ in pp
  → large enhancement at $p_T \lesssim m_{B_c}$?



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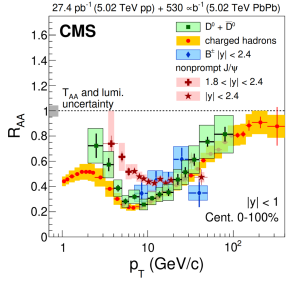
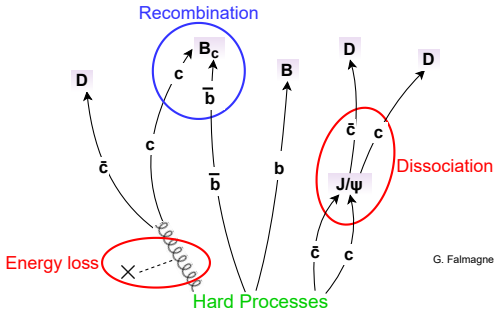
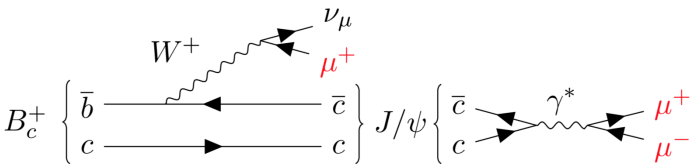
- Recombination: many $c\bar{c}$ produced in PbPb + small $\sigma(B_c)$ in pp
  → large enhancement at $p_T \lesssim m_{B_c}$?
- Energy loss: universal at high p_T,
  mass and color charge dependence at low-mid p_T





Challenges for first observation of B_c in heavy ions

- Semi-leptonic channel $B_c^+ \to (J/\psi \to \mu\,\mu)\,\mu^+\nu_\mu$
  - Signal = a slightly displaced vertex of three muons, with an opposite-sign pair in the J/ψ mass peak region



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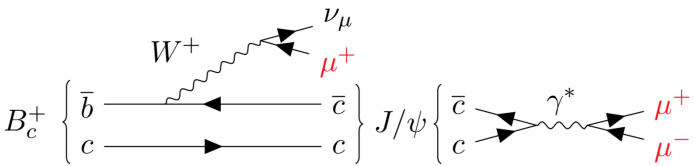
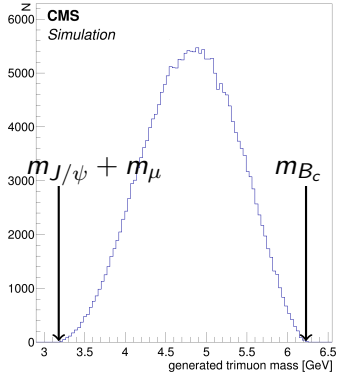
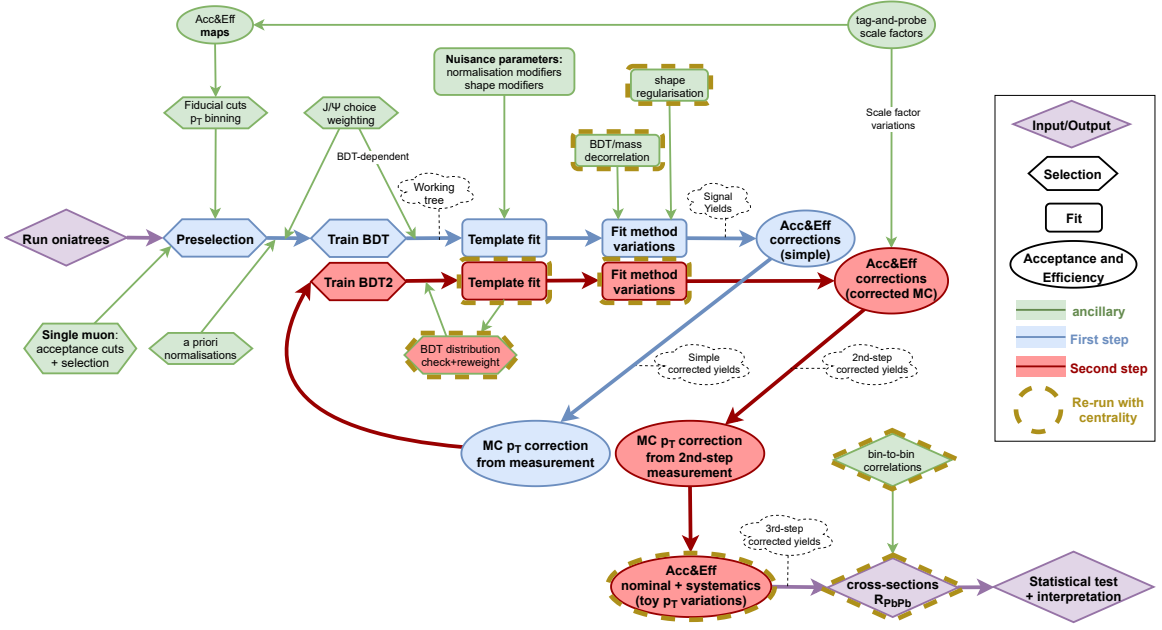
  - Signal = a slightly displaced vertex of three muons, with an opposite-sign pair in the J/ψ mass peak region
  - Partially reconstructed
    → use visible trimuon kinematics and trimuon mass $\in [3.2, 6.3]$ GeV
    → Need good understanding of backgrounds

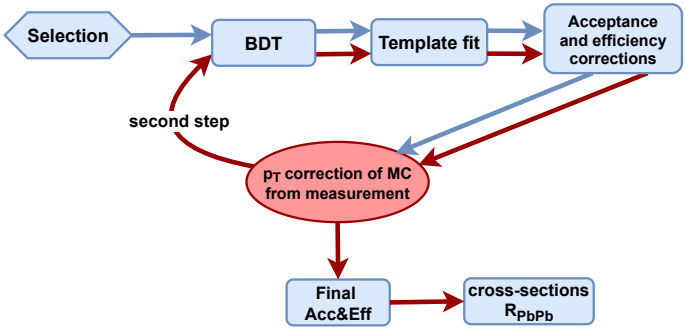





Acc&Eff maps
tag-and-probe scale factors
Nuisance parameters: normalisation modifiers shape modifiers
shape regularisation
Fiducial cuts p_T binning
J/Ψ choice weighting
BDT-dependent
BDT/mass decorrelation
Scale factor variations
Working tree
Signal Yields
Run oniatrees
Preselection
Train BDT
Template fit
Fit method variations
Acc&Eff corrections (simple)
Train BDT2
Template fit
Fit method variations
Acc&Eff corrections (corrected MC)
Single muon: acceptance cuts + selection
a priori normalisations
BDT distribution check+reweight
Simple corrected yields
2nd-step corrected yields
MC p_T correction from measurement
MC p_T correction from 2nd-step measurement
bin-to-bin correlations
3rd-step corrected yields
Acc&Eff nominal + systematics (toy p_T variations)
cross-sections R_{PbPb}
Statistical test + interpretation
Input/Output
Selection
Fit
Acceptance and Efficiency
ancillary
First step
Second step
Re-run with centrality

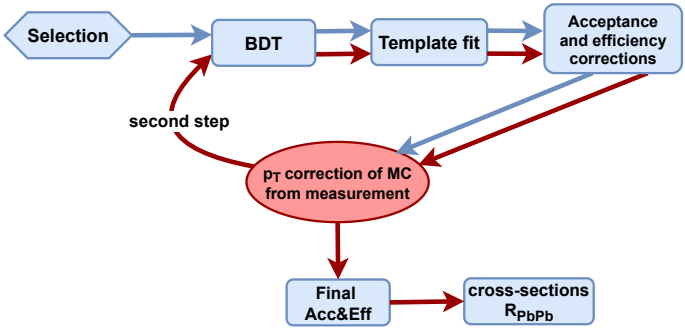
Analysis strategy

- Selection + BDT training



Analysis strategy

- Selection + BDT training
- Trimuon mass templates
  for background and signal
- Template fit of trimuon mass



Analysis strategy

- Selection + BDT training
- Trimuon mass templates
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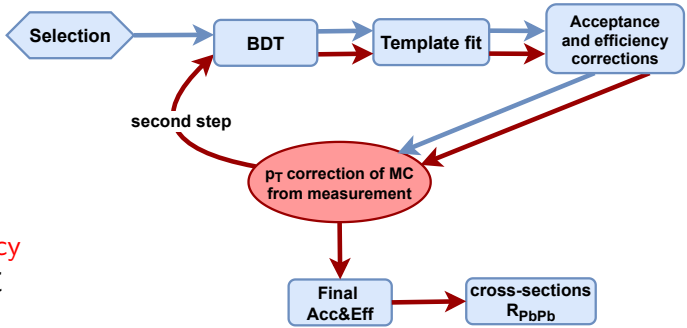
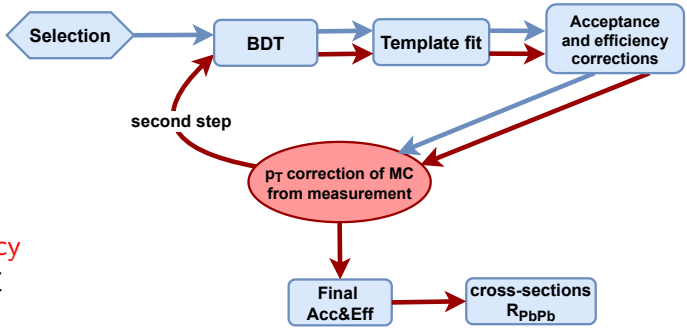
- Template fit of trimuon mass
- Correct for acceptance and efficiency
  → p_T spectrum correction of MC
- Second step of analysis, using corrected MC



Analysis strategy

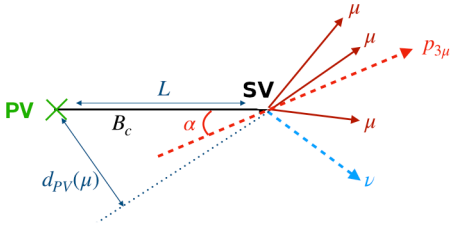
- Selection + BDT training
- Trimuon mass templates
  for background and signal
- Template fit of trimuon mass
- Correct for acceptance and efficiency
  → p_T spectrum correction of MC
- Second step of analysis, using corrected MC
- Result: $R_{PbPb}(B_c)$ in two p_T or centrality bins

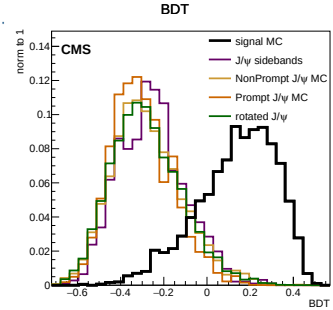


Note: Blinding 3/4 of PbPb data signal region until a late stage, to limit analyser bias.

Selection and BDT

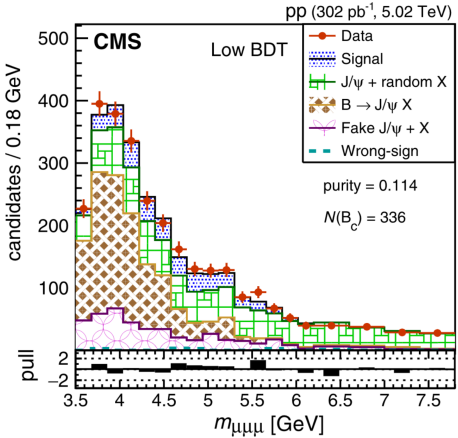
- CMS data from 2018 pp and PbPb, dimuon trigger (fired by ≥ 2 muons)
- Weighting strategy for the 1 or 2 dimuons in the $m_{\mu\mu}$ signal or sidebands regions
- Selection variables: vertexing, displacement, angle topology, p_T imbalance, ...
- BDT trained on 8 variables.
  Not used for selection: fit in 3 BDT ranges.
  Separate training for 2 analysis bins.





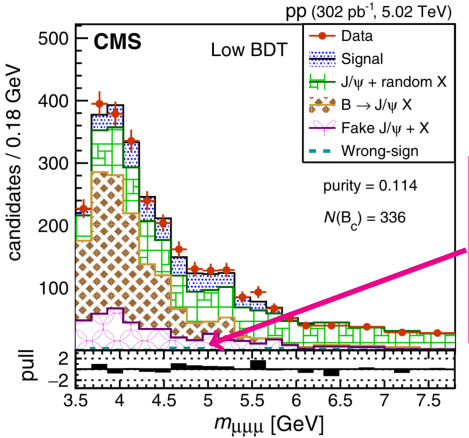
PbPb

Background shapes



pp p_T-integrated fit (background-enriched BDT bin)

Background shapes

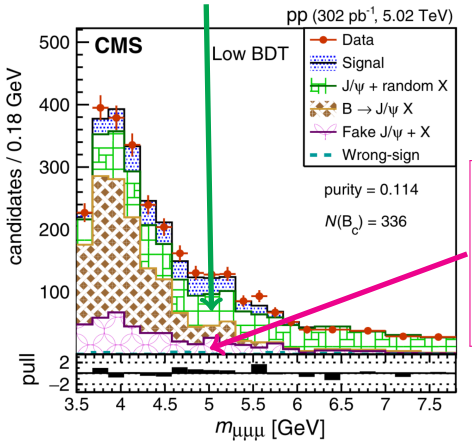


- Fake J/ψ
  → dimuon mass sidebands
  → data-derived normalisation

pp p_T-integrated fit (background-enriched BDT bin)

Background shapes

- $J/\psi - \mu$ from $\neq$ vertices → use rotated J/ψ sample (data-driven)



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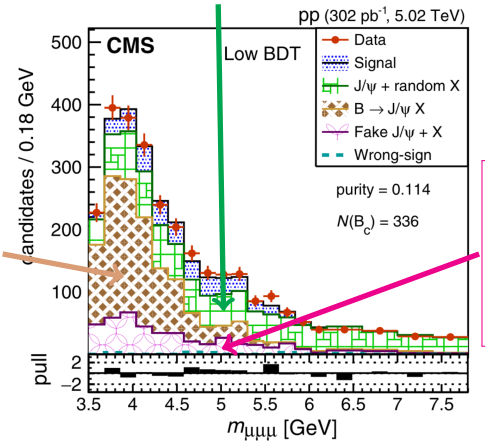
pp p_T-integrated fit (background-enriched BDT bin)

Background shapes

- $J/\psi - \mu$ from $\neq$ vertices → use rotated J/ψ sample (data-driven)

- J/ψ and (mostly fake) muon from same B decay: from MC
  → $\sim$ the only free bkg normalisation in the fit



- Fake J/ψ
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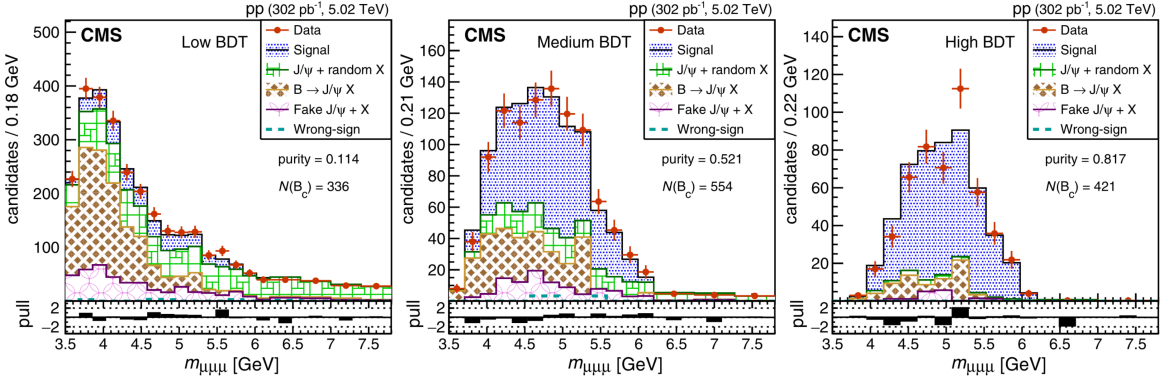
pp p_T-integrated fit (background-enriched BDT bin)

Template fit (pp, p_T-integrated)

- Likelihood fit, simultaneous over 3 BDT bins + 2 p_T or centrality bins
- Nuisance parameters to account for background uncertainties

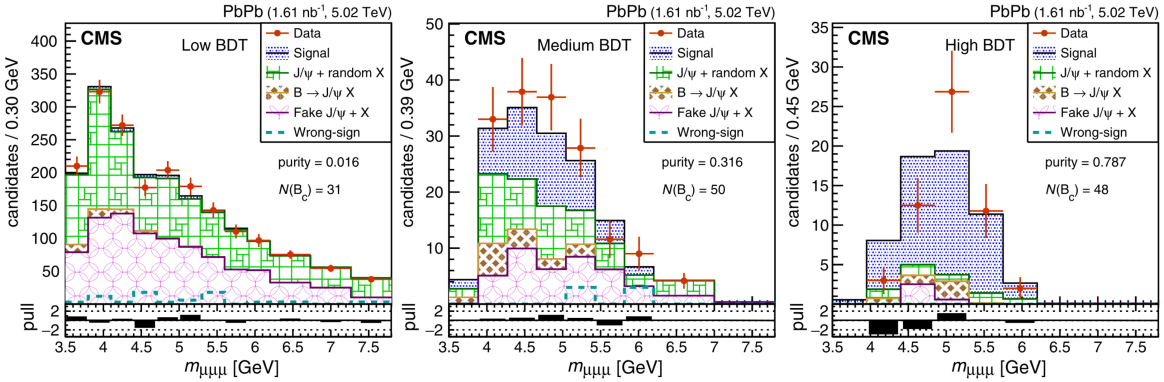
pp, centrality- and p_T-integrated



Template fit (PbPb, p_T-integrated)

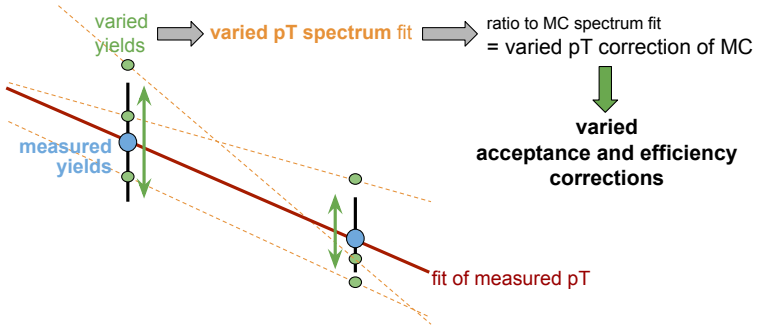
- Likelihood fit, simultaneous over 3 BDT bins + 2 p_T or centrality bins
- Nuisance parameters to account for background uncertainties

PbPb, centrality- and p_T-integrated

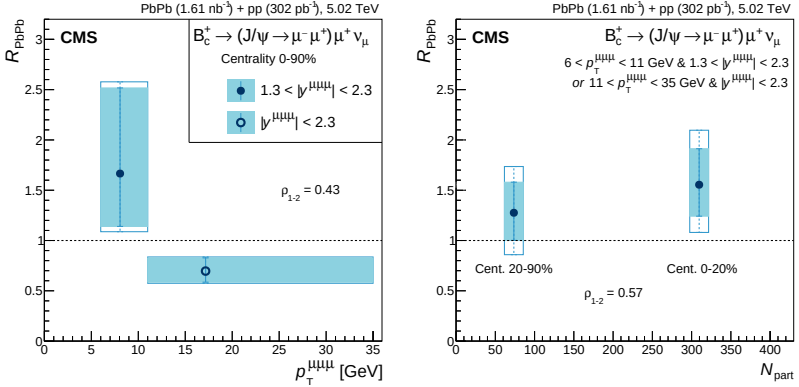


Acceptance and efficiency: iterative procedure

- Wide bins → $\alpha \times \varepsilon$ is sensitive to the assumed p_T spectrum shape
- Correct *with our measurement* the p_T spectrum of MC
- Re-run the whole analysis with corrected MC
- Uncertainty:



First $R_{\mathrm{PbPb}}(B_c)$!

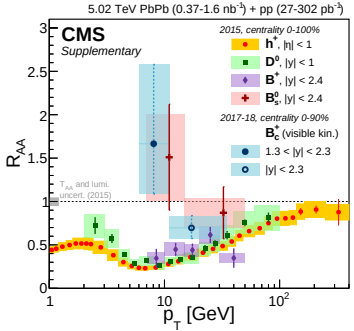


- Observation in PbPb: 6.8σ significance
- Difference between two p_T bins:
  - Consistent with softening of p_T spectrum
  - Consistent with large enhancement of integrated production due to recombination

Comparison with heavy flavour at CMS

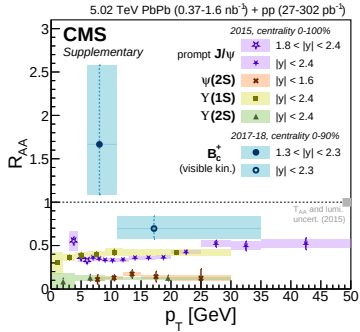
Open HF

- Less suppression than light $h^{\pm}$, B and D
- Low/mid-p_T: mass and color charge dependence + recombination effects?
- High p_T: universal radiative energy loss



Hidden HF

- B_c less suppressed than quarkonia
  → $\neq$ mechanisms at play than in hidden HF, despite similar quark content?
- Pointing to more recombination than in J/ψ

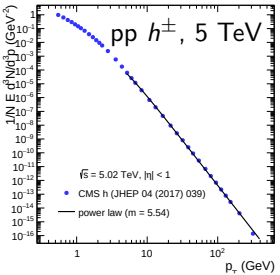


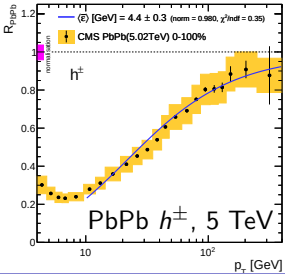
Hadron suppression from radiative energy loss

- Start from model of BDMPS radiative energy loss *only* (Arleo PRL119, 2017)
- Extract mean hadron energy loss $\bar{\varepsilon} = \langle z \rangle \langle \varepsilon \rangle$ from high-p_T R_{AA} data
- Universal shape of $R_{AA}(\frac{p_T}{n\bar{\varepsilon}})$ at high p_T:

$$R_{AA}(p_T, \bar{\varepsilon}, n) = \int_0^\infty \mathrm{d}x \frac{\bar{P}(x)}{\left(1 + x\frac{\bar{\varepsilon}}{p_T}\right)^n} \simeq f\left(u = \frac{p_T}{n\,\bar{\varepsilon}}\right)$$

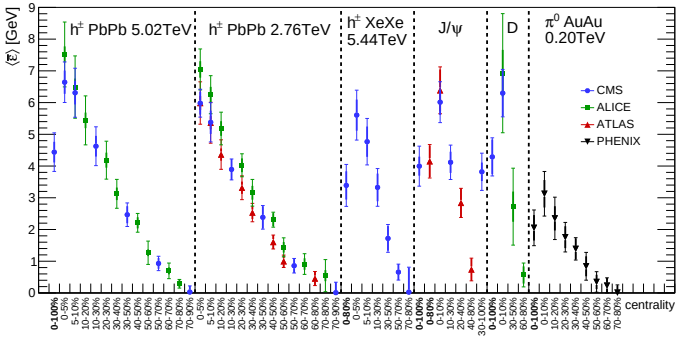
- Fraction $\langle z \rangle$ of parton momentum carried away by the hadron
- pp spectrum is $\sim$ power law at high p_T
- Rescaled quenching weight $\bar{P}(x = \frac{\varepsilon}{\bar{\varepsilon}}) = \bar{\varepsilon}\, P(\varepsilon)$

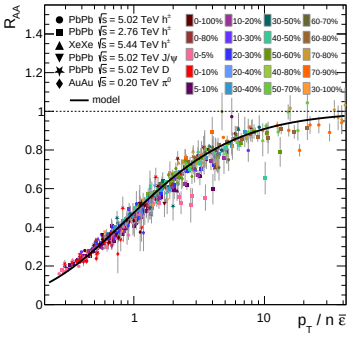




R_{AA} fits to obtain $\bar{\varepsilon}$

- $p_{\mathrm{T}} > 8$ to 13 GeV depending on system. Distinguish bin-to-bin (un)correlated errors
- Correct for peripheral bias from Loizides and Morsch (PLB 773, 2017) (affects centralities $> 50\%$)
- 62 fits (3 particles, 4 energies, 4 experiments, many centralities), all consistent with model





Energy loss vs medium geometry and density

- Salgado and Wiedemann (PRL89, 2003) model the decreasing medium density with $\hat{q} = \hat{q}_0 \left(\frac{\tau_0}{\tau}\right)^{\alpha}$

  → equivalent transport coefficient in static medium:

  $$\langle \hat{q} \rangle \simeq \frac{2}{2-\alpha} \hat{q}_0 \left(\frac{\tau_0}{L}\right)^{\alpha} \qquad (\tau_0 \ll L \text{ is the QGP formation time})$$

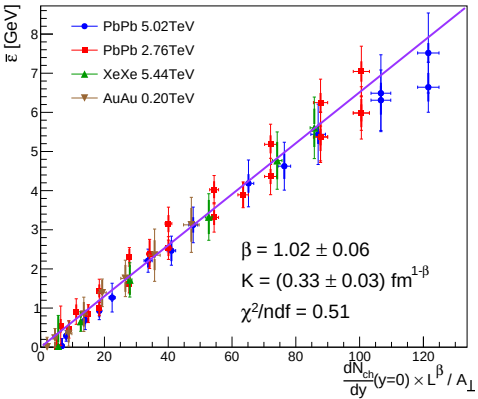
- We use a Bjorken initial density → parametric energy loss:

  $$\hat{q}_0 \propto n \propto \frac{dN_{ch}}{dy} / A_\perp \tau_0 \rightarrow \varepsilon \propto \langle \hat{q} \rangle L^2 \propto \frac{\frac{dN_{ch}}{dy}}{A_\perp} L^{2-\alpha} \propto L^{\beta \neq 2}$$

  - ε from R_{AA} fits
  - Multiplicity $\left.\frac{dN_{ch}}{dy}\right|_{y=0}$ from measurements
  - Path length L and $A_\perp$ from 4 different Glauber models:
    - MC Glauber from Loizides et al., PRC97 (2018)
    - Pure hard spheres, constant density, fully analytic
    - 2 custom optical Glauber's: hard spheres or Woods Saxons

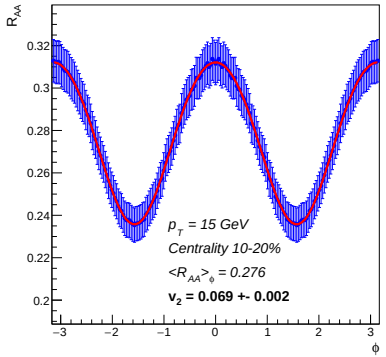
Energy loss scales with medium geometry and density

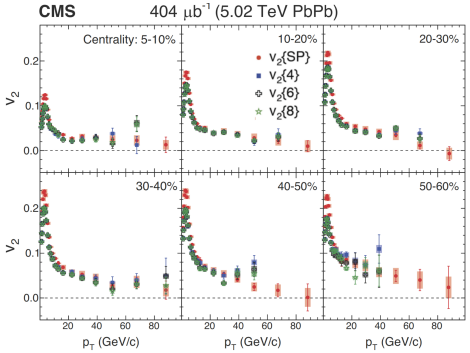
- Multiple systems scale!
- $\beta = 2 - \alpha = 1.02^{+0.09}_{-0.06}$
  with fit and Glauber uncertainties
  → compatible with longitudinal expansion ($\alpha = 1$)
- Knowing $\frac{dN_{ch}}{dy}$, can predict $R_{AA}(h^{\pm})$ at high p_T in any system!
  Did so for oxygen-oxygen at 7 TeV:
  $R_{AA}^{MB}(p_T = 15\ \mathrm{GeV}) \simeq 0.8$
- No significant change using a 2-flavor (gluon and quark) model instead of single parton flavor



$R_{AA}(\phi)$ gives us v_2...

- The custom Glauber model provides $\langle L \rangle(\phi) \rightarrow \bar{\varepsilon}(\phi) \rightarrow R_{AA}(\phi) \rightarrow v_2$ at high p_T!
- We will assume $L(\phi) = L(1 - e\cos(2\phi))$ with eccentricity e and use the scaling $R_{AA}(u, \phi) = f(u \times \left(\frac{L}{L(\phi)}\right)^{\beta})$ with $u = p_{\mathrm{T}}/\bar{\varepsilon}$





And a scaling of v_2/e!

- Approximating v_2 as:

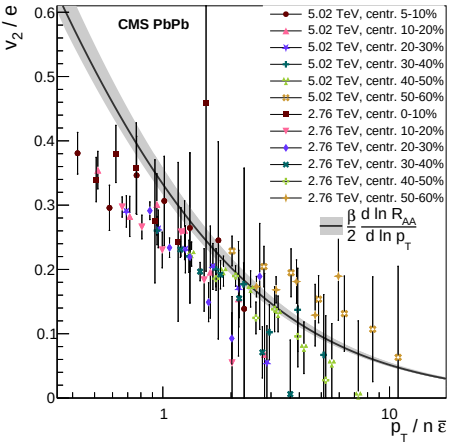
$$2v_2 \approx \frac{R_{AA}(\phi = 0) - R_{AA}(\phi = \pi/2)}{R_{AA}(0) + R_{AA}(\pi/2)}$$

gives

$$\frac{v_2}{e} \simeq \frac{\beta}{2} \frac{\partial \ln f(u)}{\partial \ln u} \simeq \frac{\beta}{2} \frac{p_T}{R_{AA}} \frac{\mathrm{d}R_{AA}}{\mathrm{d}p_T}$$

(with an expansion in e)

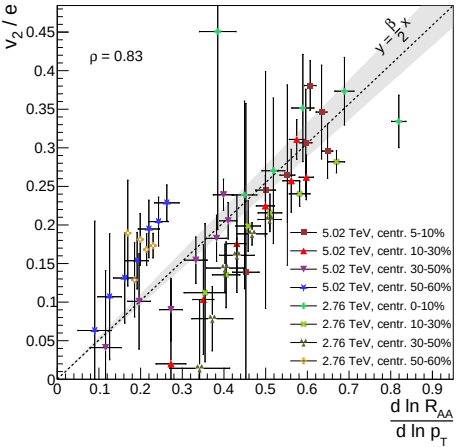
→ Scaling $\frac{v_2}{e}(p_T, \bar{\varepsilon}, n) = g(p_T/n\bar{\varepsilon})$ with same variable than R_{AA}!



- Consistent with CMS data at high p_T
- Simultaneous universal understanding of R_{AA} and v_2 at high p_T

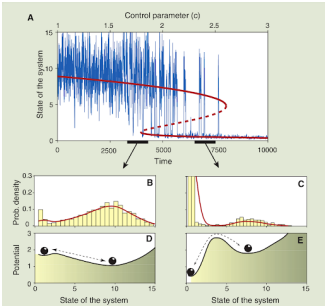
v_2 only from R_{AA} data

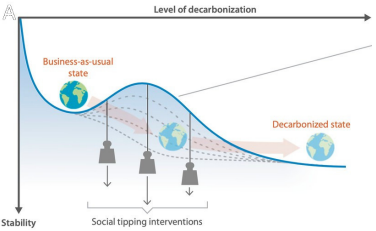
- Can check that $\frac{v_2}{e} \simeq \frac{\beta}{2} \frac{\partial \ln R_{AA}(p_T)}{\partial \ln p_T}$ with only an agnostic fit of R_{AA}
- Consistent with data (large uncertainties) and ε scaling
- Very precise measurements of R_{AA} and v_2 of $h^{\pm}$ could give an independent measurement of β... (Run 3?)

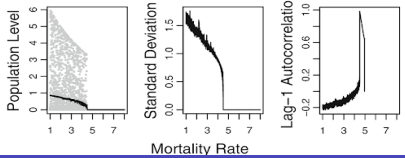


Critical transitions, social tipping points, EWS

- Critical transitions / tipping points / regime shifts / bifurcations:
  - Brutal change of state with a minor perturbation
  - (Sometimes) linked to phase transitions, criticality, hysteresis
  - Need to avoid them in ecology and climate...
    and trigger them for social transformations to cooperation
- How and when do they occur? → early warning signals (EWS)
  - Some standard EWS in ecological systems
    (critical slowing down)
  - Here: use large-scale collaborative game (with humans)
    to find generalizable properties of EWS

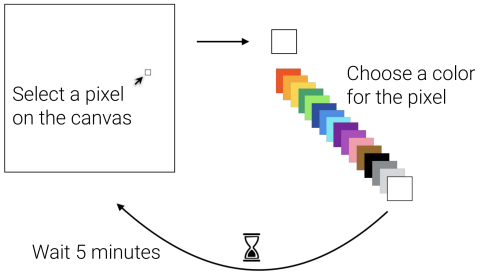






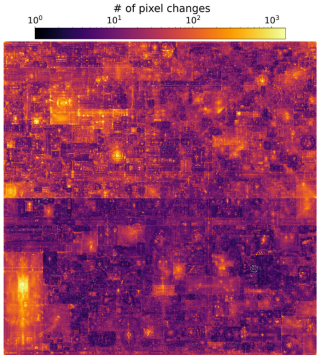
Gamification and r/place

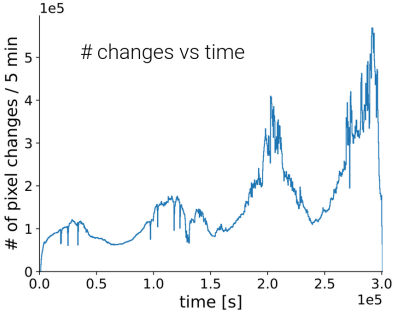
- Real-life and experimental ecosystems are costly to monitor, measure, and control
- "Gamified" experiments with human players can provide large amounts of data and diverse experimental settings!
- What if a game gave us 10,000 complex subsystems with homogeneous data to study EWS and how cooperation emerges?
- **r/place** on reddit in 2022:
  - 160 million pixel changes
  - 3.5 days
  - 10.6 million users, changing pixels at *maximum 1 pixel / 5 minutes / user*
    → collaboration is essential!

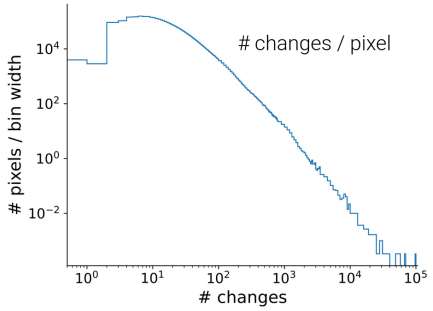


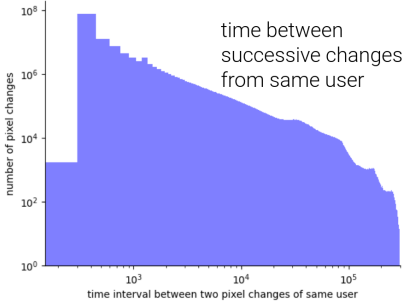
Some dynamics

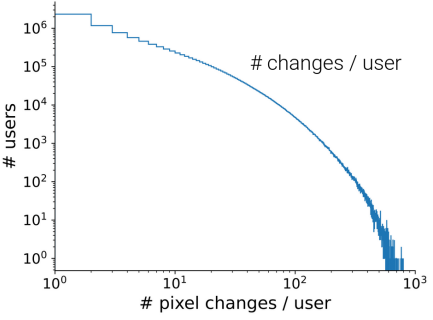
Heat map





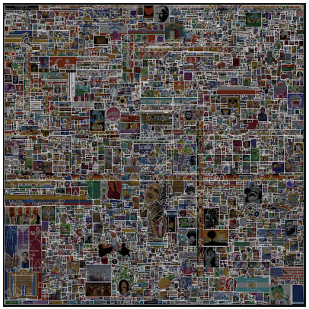


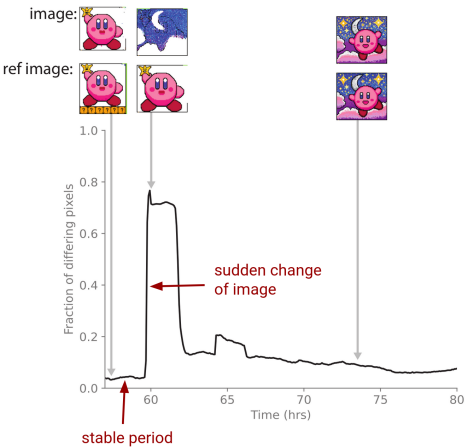




10000 subsystems with transitions

- Atlas of $>$ 10k "compositions" annotated by reddit users
- Many transitions between drawings... identified with a threshold on # pixels differing from a sliding-window-averaged image (+ a preceding stable period)





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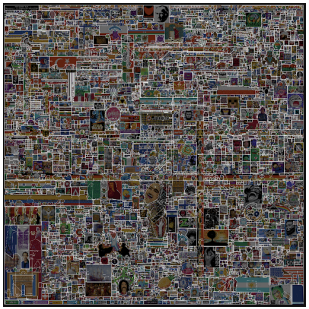
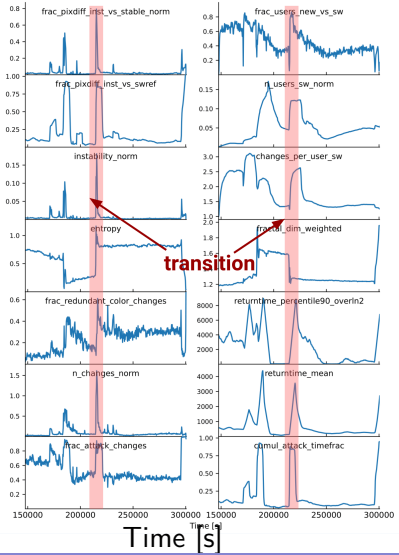
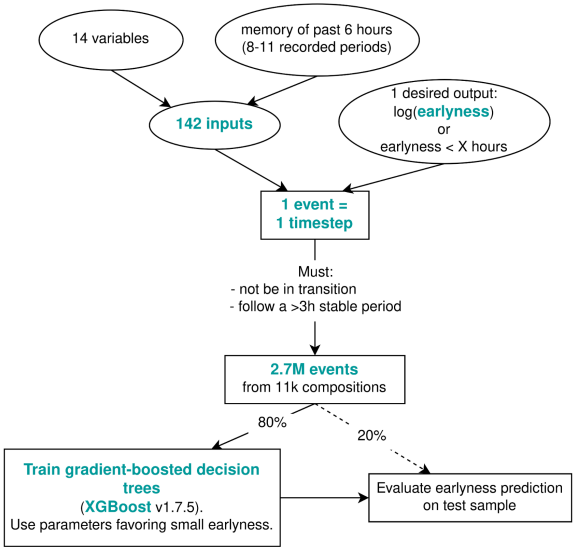


- 14 time-dependent variables describing a composition



Warning signals with XGBoost

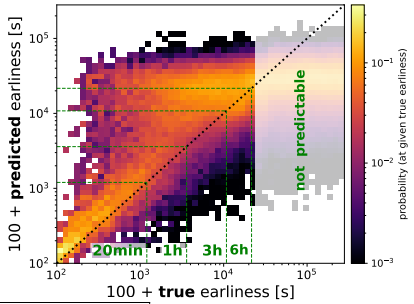
- At each time point, we intend to:
  - Use only past 6 hours
    on all 14 variables ...
  - ... to predict how close a future
    transition might be – named "earliness"
- Use XGBoost: gradient-boosted decision trees
  → 142 input features
  1 output (earliness or 'earliness $< X$')
  2.7M time points



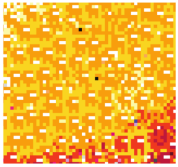
Learning early warning signals

- We obtain predictive power for coming transitions, up to a few hours before they arrive!
- Predict half of "earliness $<$ 20 minutes" events with only 0.5% background efficiency!
- Can use SHAPley additive values to determine what variables bring the most predictive power

earlyness condition	**true positive** rate	**false positive** rate
$<$ 20 min	50%	0.48%
$<$ 1 hour	50%	4.2%
$<$ 6 hours	50%	15%

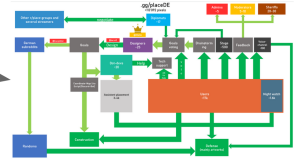


Related project: structure and emergence of cooperation



Observed organizational structure to build compositions:

- **Twitch streamer** with an "army" of followers
- More horizontal through **subreddit/discord forums**
- **Bottom-up** only through **indirect interactions** on the canvas?
- "**Democratic**" with emerging hierarchy on forums? Or mix?



Top-down/hierarchical

⇨ What shape of **organizational networks** are best to promote **cooperation / solve the prisoner's dilemma**?

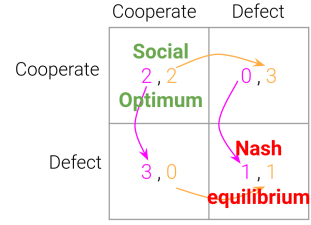
Bottom-up/distributed

Ideas:

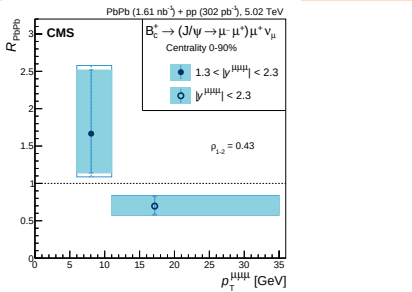
Polycentric governance
Multi-layered networks
Spatial **homogeneity** (breaking echo chambers)
Self-organization vs top-down policies

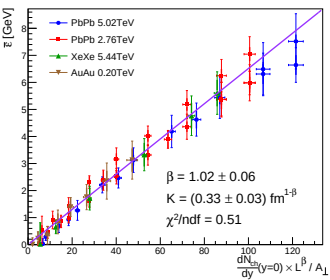
Possible methods:

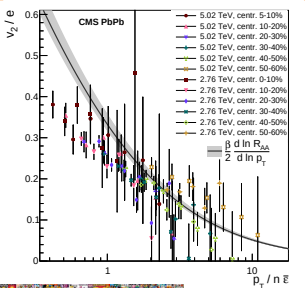
Spread of **simple drawings**
Network of users in external communication
Use **NLP** on subreddits
Currently circulating a **survey** to players

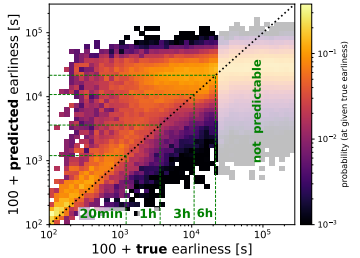


Thank you!


PbPb (1.61 nb^{-1}) + pp (302 pb^{-1}), 5.02 TeV
CMS
$B_c^+ \to (J/\psi \to \mu^-\mu^+)\mu^+\nu_\mu$
Centrality 0-90%
1.3 < |y$^{\mu\mu\mu}$| < 2.3
|y$^{\mu\mu\mu}$| < 2.3
$\rho_{1\text{-}2}$ = 0.43
R_{PbPb}
$p_T^{\mu\mu\mu}$ [GeV]


PbPb 5.02TeV
PbPb 2.76TeV
XeXe 5.44TeV
AuAu 0.20TeV
$\beta = 1.02 \pm 0.06$
$K = (0.33 \pm 0.03)$ fm$^{1-\beta}$
χ^2/ndf = 0.51
$\bar{\varepsilon}$ [GeV]
$\frac{dN_{ch}}{d\eta}(\eta=0) \times L^{\beta} / A_{\perp}$


CMS PbPb
5.02 TeV, centr. 5-10%
5.02 TeV, centr. 10-20%
5.02 TeV, centr. 20-30%
5.02 TeV, centr. 30-40%
5.02 TeV, centr. 40-50%
5.02 TeV, centr. 50-60%
2.76 TeV, centr. 0-10%
2.76 TeV, centr. 10-20%
2.76 TeV, centr. 20-30%
2.76 TeV, centr. 30-40%
2.76 TeV, centr. 40-50%
2.76 TeV, centr. 50-60%
$\frac{\beta}{2}\frac{d \ln R_{AA}}{d \ln p_T}$
v_2 / e
p_T / n $\bar{\varepsilon}$


100 + **predicted** earliness [s]
100 + **true** earliness [s]
not predictable
20min
1h
3h
6h
probability (at given true earliness)