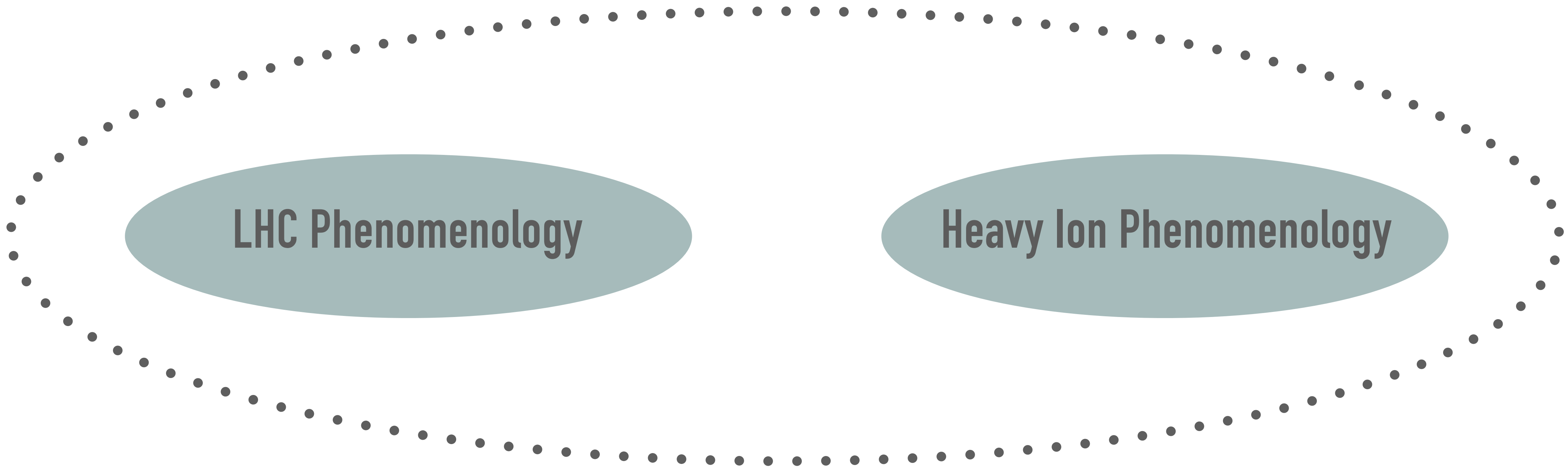
Phenomenology at LIP

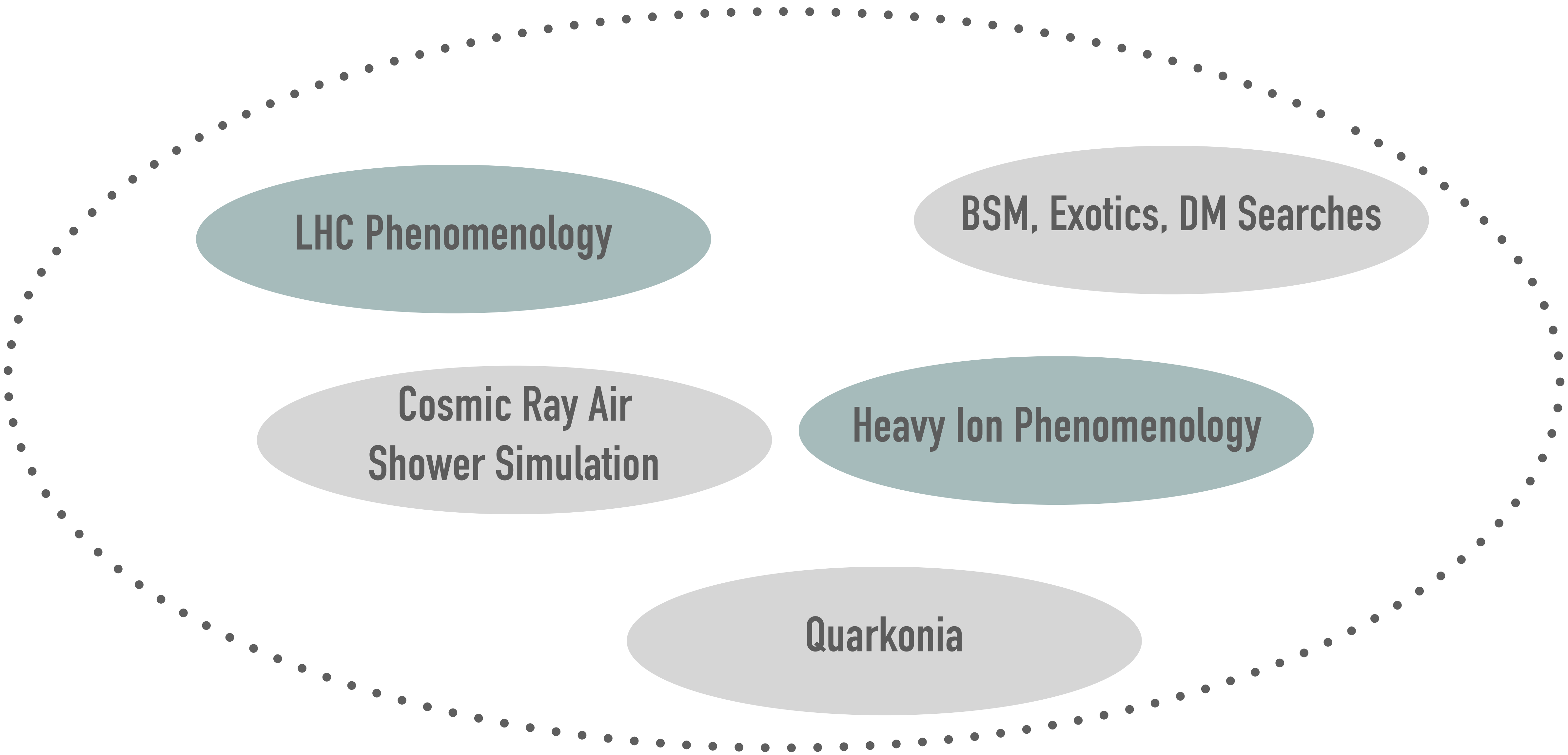
Guilherme Milhano

LIP Lisboa & IST & CERN

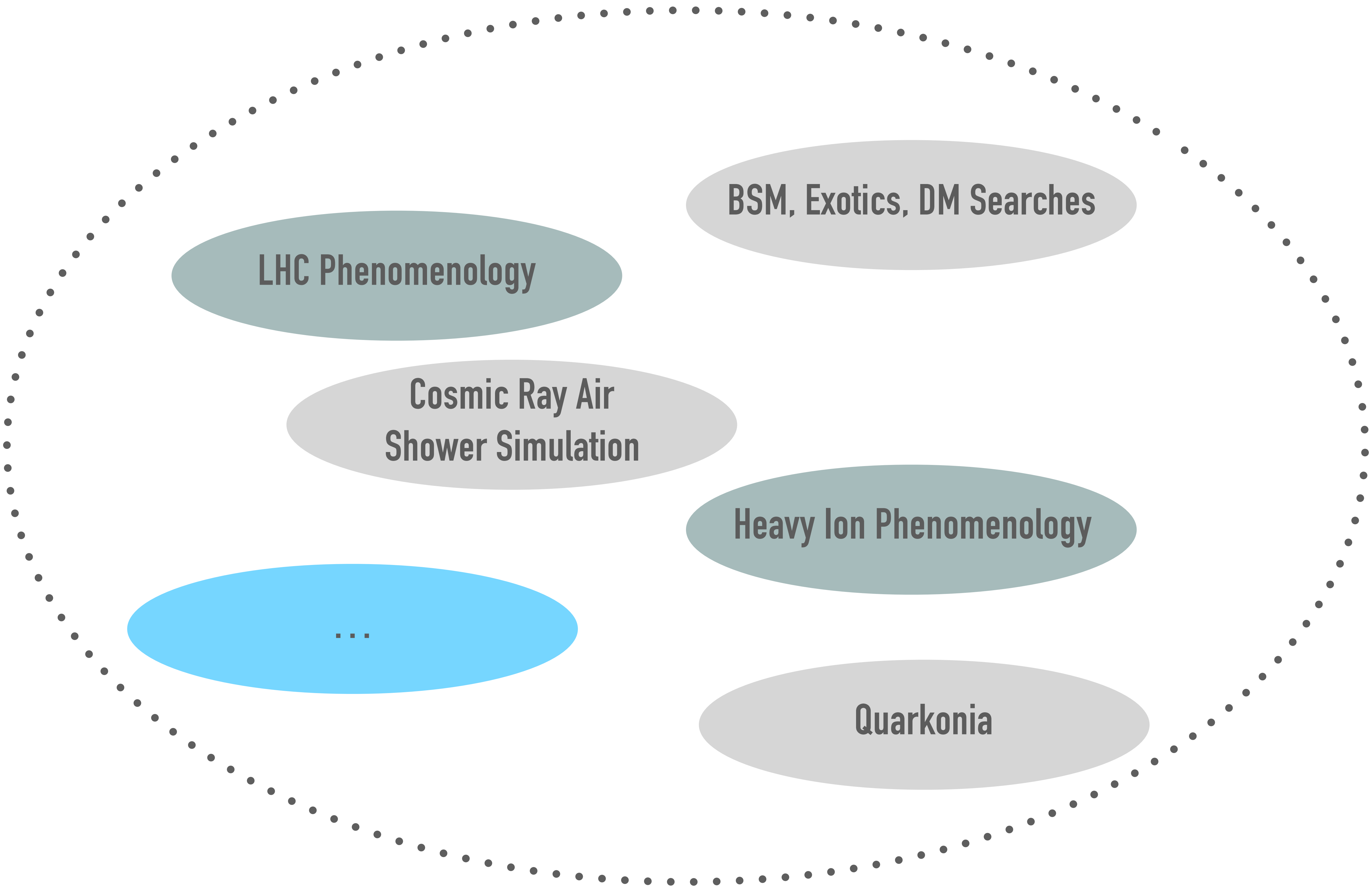
THE FUSION OF TWO EXISTING GROUPS



AND AGGREGATION OF OTHER LIP PHENO ACTIVITIES



INTO FUTURE FULL PHENO COVERAGE



IN A SINGLE GROUP SPREAD OVER BRAGA-COIMBRA-LISBOA

Collider Phenomenology

Astro-particle Phenomenomenology

LIP-Pheno

future facilities and opportunities

as of 30 Jan 2018

START-UP TEAM

researchers:

António Onofre, Guilherme Milhano, Juan Pedro Araque, Korinna Zapp, Liliana Apolinário, Miguel Fiolhais, Nuno Castro, Ricardo Gonçalo, Rúben Conceição, Pietro Faccioli

students:

André Reigoto, Artur Amorim, Duarte Azevedo, João Barata, João Gonçalves, Maria Ramos, Pedro Lagarelhos, Ricardo Faria, Rui Martins

SNAPSHOTS

EFTfitter

Castro, Erdmann, Grunwald, Kröninger, Rosien :: Eur.Phys.J. C76 (2016) 432

The EFT approach

- Extend the SM electroweak Lagrangian:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda_{\text{NP}}^2} O_i + \mathcal{O}\left(\frac{1}{\Lambda_{\text{NP}}^3}\right)$$

- Searches for BSM physics: what if $\Lambda_{\text{NP}} \gg \sqrt{s_{\text{LHC}}}$?

- EFT: → indirect search for new physics
  → can test whole classes of BSM models at once
  → widen search radius by increasing the energy frontier

EFT in the top-quark sector

Four-quark operators

$$O_{qq}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l),$$
$$O_{qq}^{3(ijkl)} = (\bar{q}_i \gamma^\mu \tau^I q_j)(\bar{q}_k \gamma_\mu \tau^I q_l),$$
$$O_{qu}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{u}_k \gamma_\mu u_l),$$
$$O_{qu}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{u}_k \gamma_\mu T^A u_l),$$
$$O_{qd}^{1(ijkl)} = (\bar{q}_i \gamma^\mu q_j)(\bar{d}_k \gamma_\mu d_l),$$
$$O_{qd}^{8(ijkl)} = (\bar{q}_i \gamma^\mu T^A q_j)(\bar{d}_k \gamma_\mu T^A d_l),$$
$$O_{uu}^{(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{u}_k \gamma_\mu u_l),$$
$$O_{ud}^{1(ijkl)} = (\bar{u}_i \gamma^\mu u_j)(\bar{d}_k \gamma_\mu d_l),$$
$$O_{ud}^{8(ijkl)} = (\bar{u}_i \gamma^\mu T^A u_j)(\bar{d}_k \gamma_\mu T^A d_l),$$
$$O_{quqd}^{1(ijkl)} = (\bar{q}_i u_j)\,\varepsilon\,(\bar{q}_k d_l),$$
$$O_{quqd}^{8(ijkl)} = (\bar{q}_i T^A u_j)\,\varepsilon\,(\bar{q}_k T^A d_l),$$

Two-quark operators

$$O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{\varphi}\,(\varphi^\dagger \varphi),$$
$$O_{\varphi q}^{1(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_i \gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_i \gamma^\mu \tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j),$$
$$O_{\varphi ud}^{(ij)} = (\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}_i \gamma^\mu d_j),$$
$$O_{uW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\,\tilde{\varphi}\, g_W W^I_{\mu\nu},$$
$$O_{dW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I d_j)\,\varphi\, g_W W^I_{\mu\nu},$$
$$O_{uB}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} u_j)\,\tilde{\varphi}\, g_Y B_{\mu\nu},$$
$$O_{uG}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} T^A u_j)\,\tilde{\varphi}\, g_S G^A_{\mu\nu},$$

Two-quark-two-lepton operators

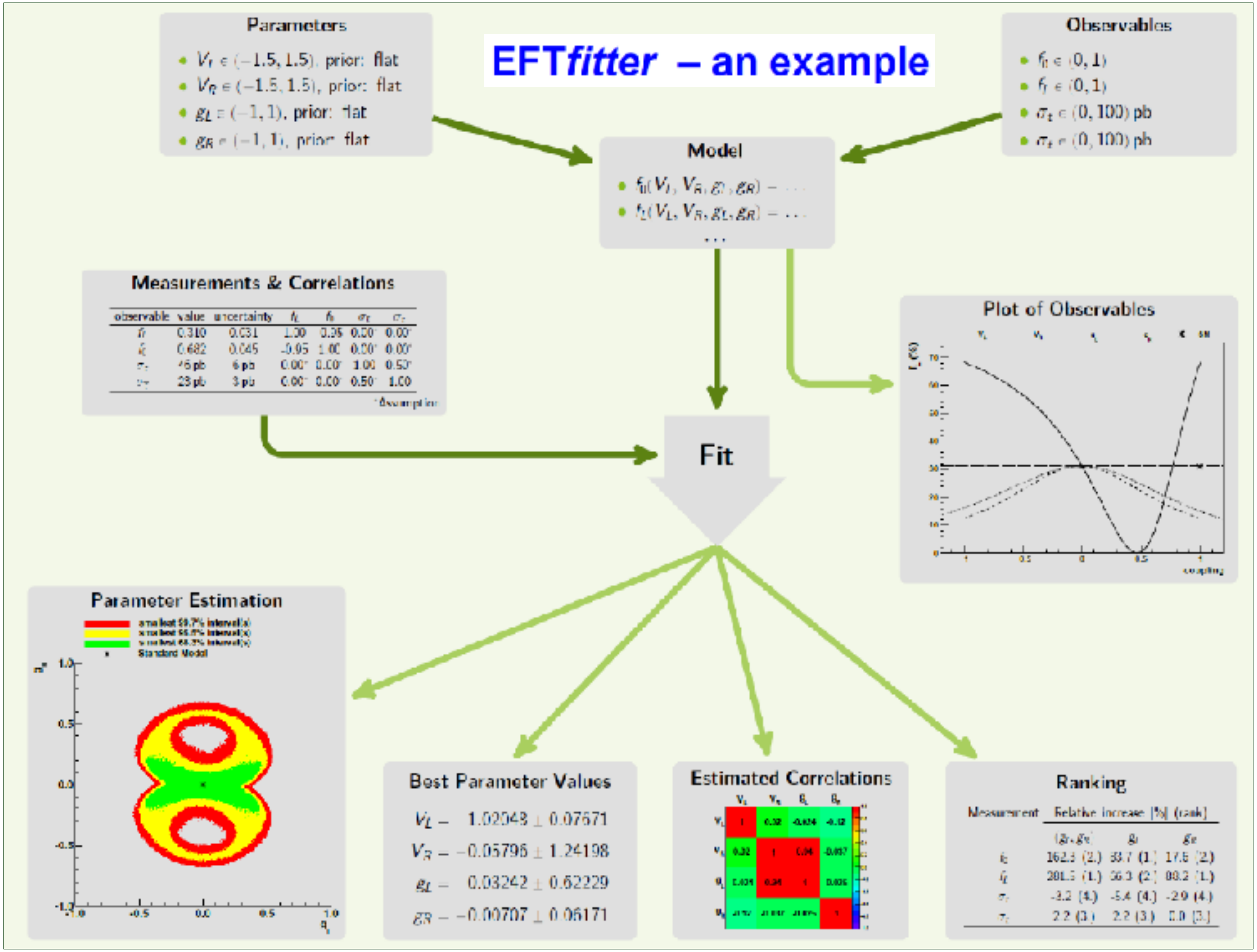
$$O_{lq}^{1(ijkl)} = (\bar{l}_i \gamma^\mu l_j)(\bar{q}_k \gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_i \gamma^\mu \tau^I l_j)(\bar{q}_k \gamma^\mu \tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_i \gamma^\mu l_j)(\bar{u}_k \gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_i \gamma^\mu e_j)(\bar{q}_k \gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_i \gamma^\mu e_j)(\bar{u}_k \gamma^\mu u_l),$$
$$O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_k u_l),$$
$$O_{lequ}^{1(ijkl)} = (\bar{l}_i \sigma^{\mu\nu} e_j)\,\varepsilon\,(\bar{q}_k \sigma_{\mu\nu} u_l).$$

$+\ \not{B}$ and $\not{L}$ operators

- Common effort ongoing at the LHCtopWG
  - (G. Durieux, J.A. Aguilar-Saavedra, C. Degrande, F. Maltoni, E. Vryonidou, C. Zhang)
  - Effective field theory contacts
    - Nuno Castro and Oliver Maria Kind (ATLAS), Nadjieh Jafari and Alexander Groshjean (CMS)

EFT*fitter*

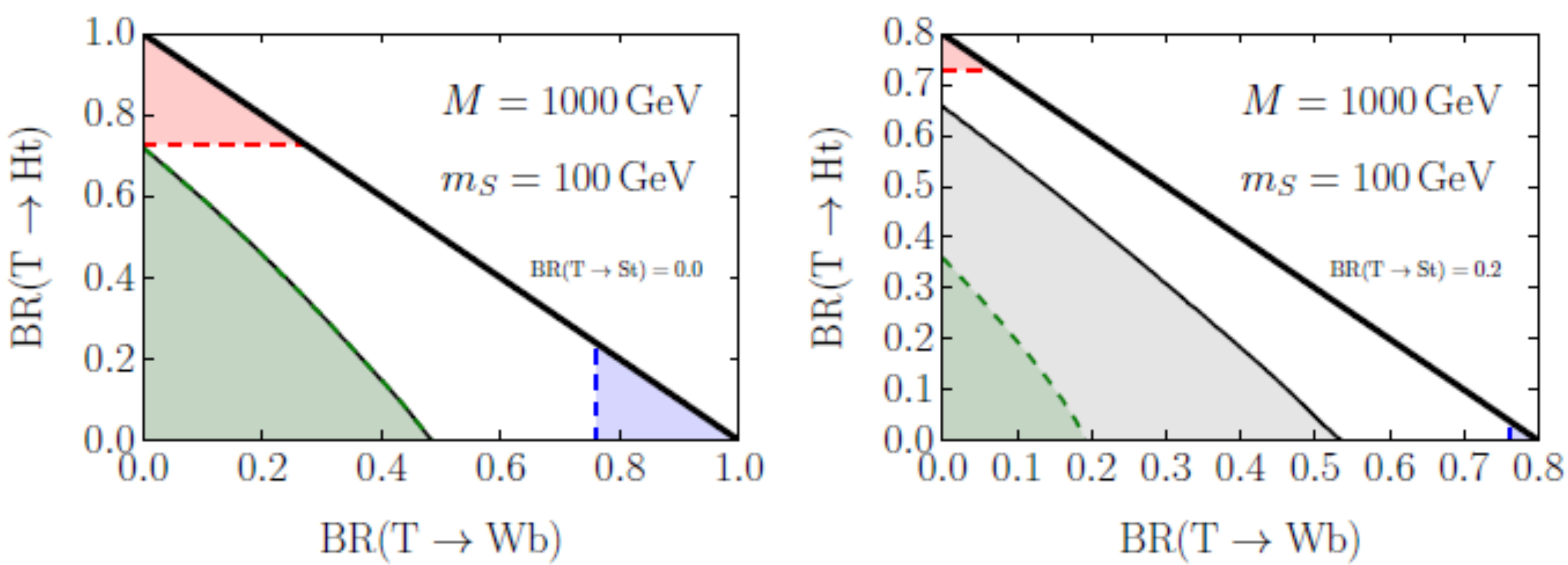
Developed by a team from Dortmund and LIP
https://github.com/tudo-physik-e4/EFTfitterRelease



Composite Higgs Models

Composite Higgs models

- Collaboration between LIP, IPPP-Durham and Granada
  - These models often predict new vector-like quarks
    - (ongoing searches under LIP responsibility in ATLAS)
  - Important to fully explore the full parameter space
    - Alternative production and decay mechanisms
      - → new interpretations and analysis strategies



[PRD96 (2017) 015028]

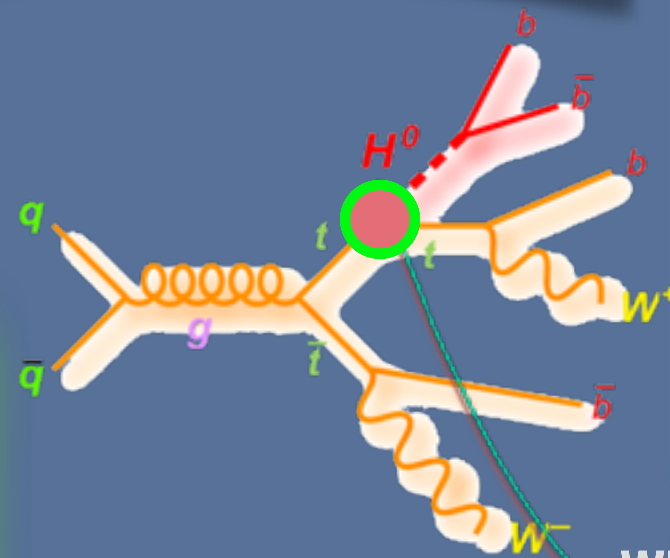
- Maria Ramos started her PhD at LIP-Minho (and IPPP-Durham) and will focus on collider phenomenology of CHM, as well as their potential astrophysical signals
  - Study of viable dark mater candidates at the LHC

Higgs production and couplings

Amor Dos Santos et al. :: Phys. Rev. D 96 013004 (2017)
Broggio, Ferroglia, Fiolhais, Onofre :: Phys. Rev. D 96 073005 (2017)
Azevedo, Filthaut, Gonçalo, Onofre :: arXiv:1711.05292 [hep-ph]

TOP QUARK HIGGS BOSON ASSOCIATED PRODUCTION @ LHC:

$$\mathcal{L} = \kappa\, y_t\, \bar{t}\,(\cos\alpha + i\gamma_5 \sin\alpha)\, t\, h$$



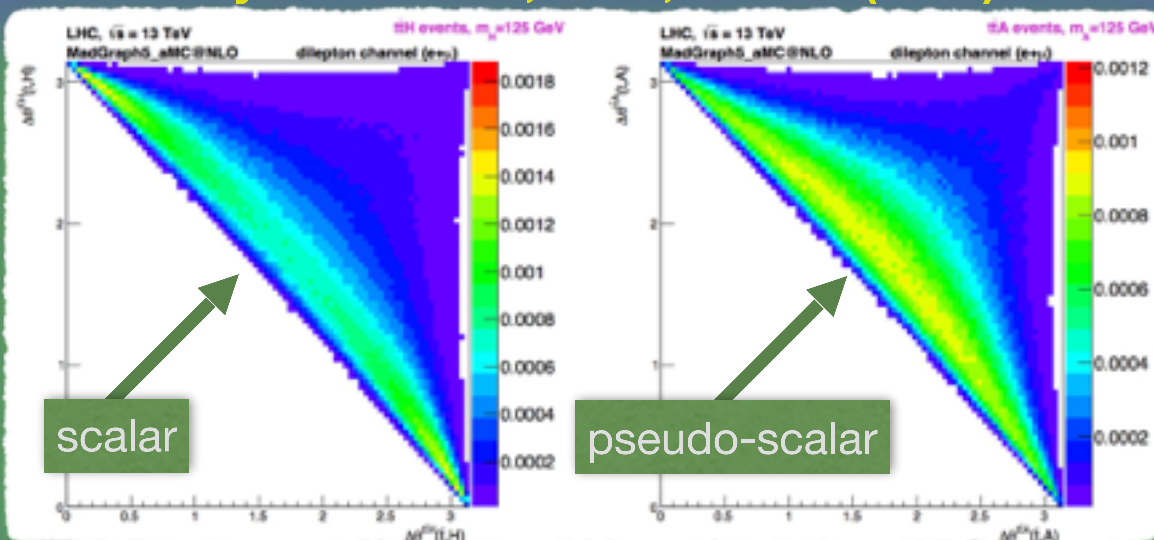
WHY STUDYING THE COUPLING?

IT JUST HAPPENS WE WANT TO KNOW WHERE WE LIVE…!

1) ttH dileptonic channel:

NEW ANGULAR DISTRIBUTIONS EXPLORED

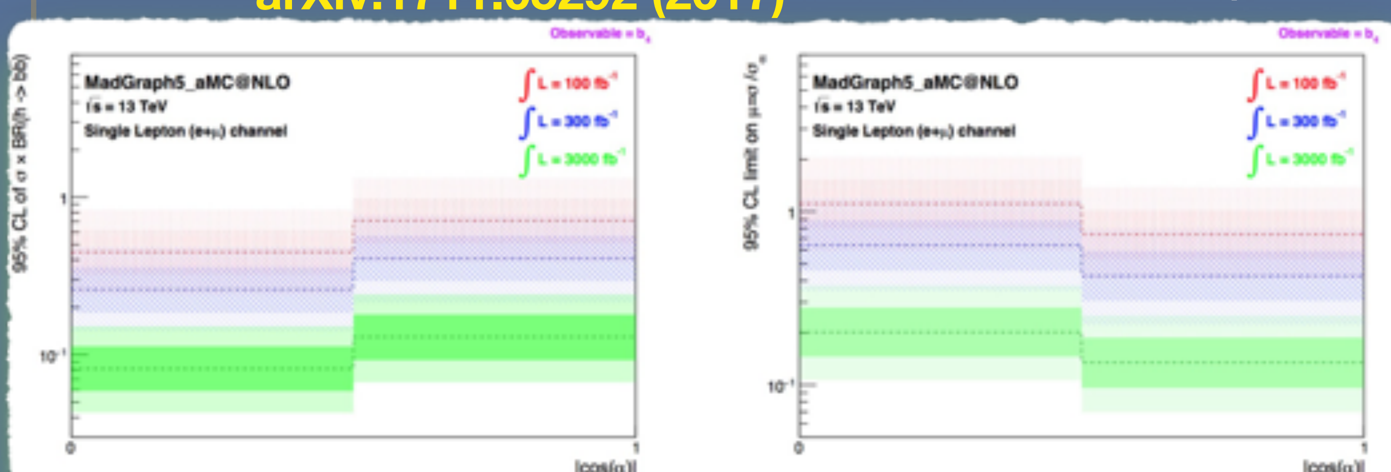
Phys. Rev. D 96, no. 1, 013004 (2017)



2) ttH semileptonic channel:

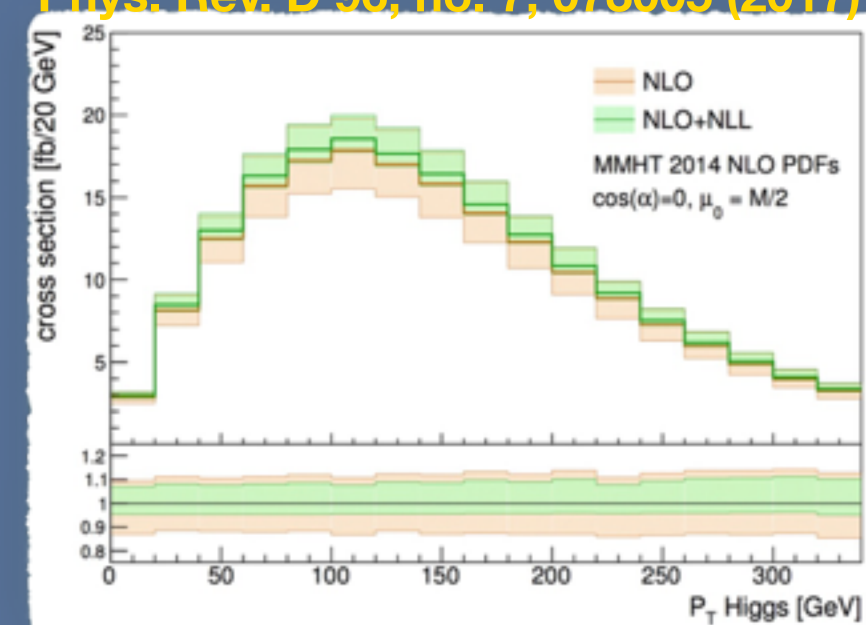
arXiv:1711.05292 (2017)

LIMITS @ 95% CL



3) NLO vs NLO+NLL @ LHC

Phys. Rev. D 96, no. 7, 073005 (2017)



WORK PLAN (2018): STUDY THE NATURE OF THE COUPLING @ HL-LHC, HE-LHC AND FCC-HH

A.ONOFRE (UM)

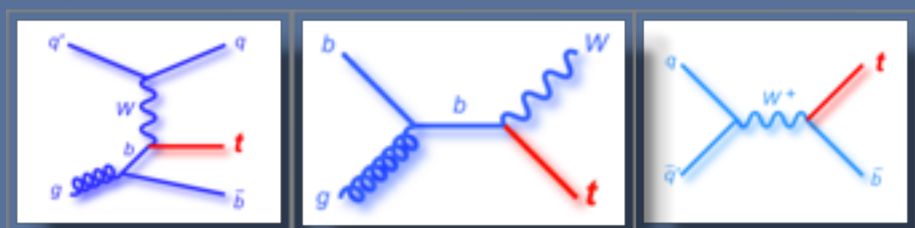
Anomalous top quark couplings

Déliot, Faria, Fiolhais, Lagarelhos, Onofre, Pease, Vasconcelos :: Phys. Rev. D97 (2018) 013007

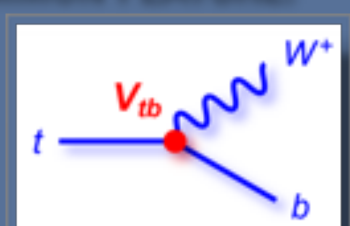
CHOICE OF PHYSICS CHANNELS:

1) DOUBLE TOP QUARK PRODUCTION:

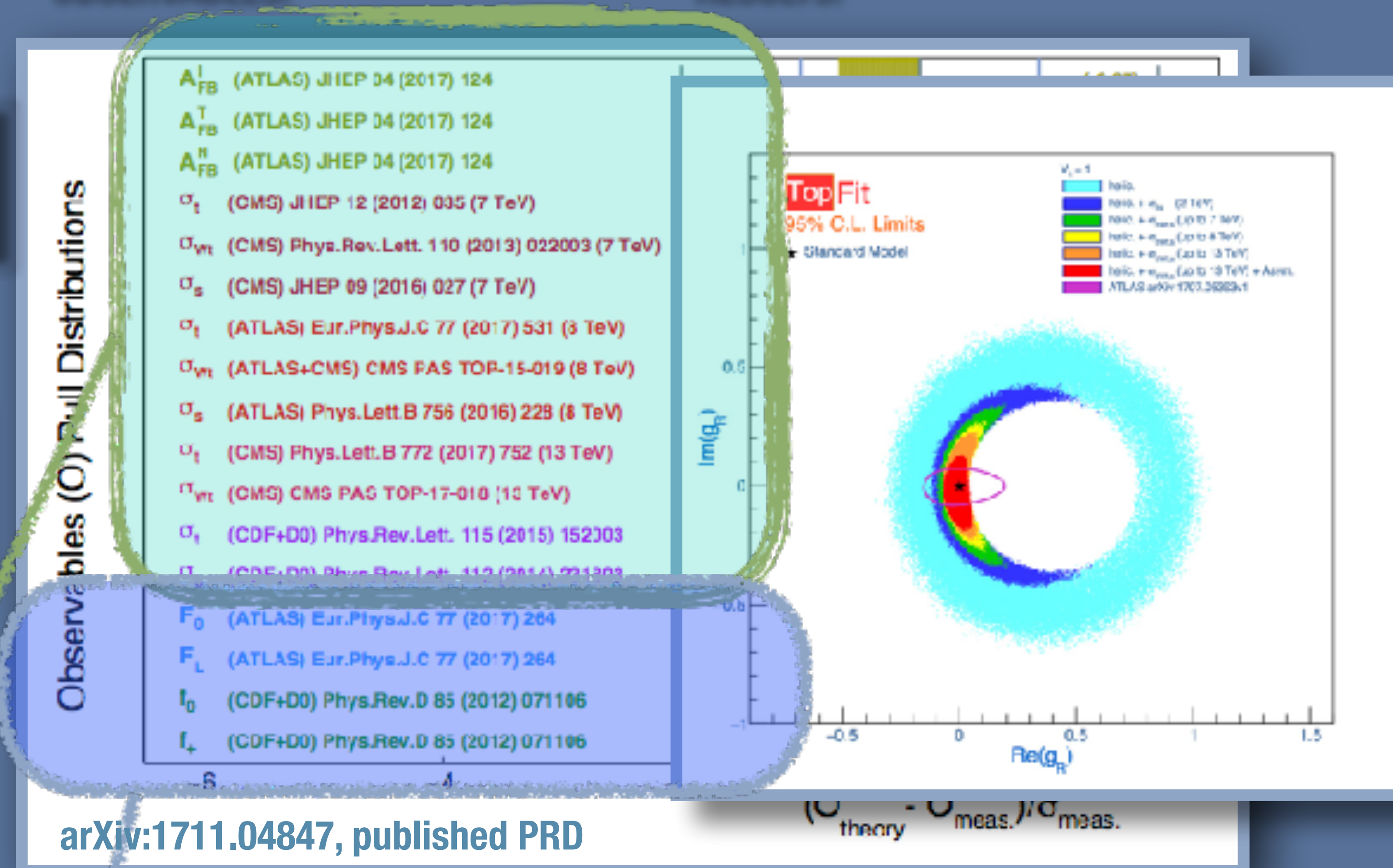
2) SINGLE TOP QUARK PRODUCTION:



COMMON FEATURE:



OBSERVABLES: RESULTS:



arXiv:1711.04847, published PRD

FROM THE EXPERIMENTAL SIDE:

(INTEGRATED APPROACH)

1) USE SINGLE TOP QUARK OBSERVABLES
2) USE DOUBLE TOP QUARK PRODUCTION OBSERVABLES
3) DO THIS STEP BY STEP INCREASING THE NUMBER OF OBSERVABLES EACH STEP, AS THEY BECOME AVAILABLE
4) PERFORM A GLOBAL FIT OF ALL OBSERVABLES AT THE SAME TIME (HIGGS LIKE)
5) RANK THE OBSERVABLES, CHOOSE TOP10…..

FROM THE THEORY SIDE:

1) MAKE SURE DEPENDENCES ARE AVAILABLE
2) USE GLOBAL FITTERS AS TOOLS (TOPFIT,…)
3) INCLUDE PROGRESSIVELY NEW OBSERVABLES DEPENDENCES
4) MAKE SURE ALL REAL AND IMAGINARY COMPONENTS IN

MONTE CARLO SAMPLES AND TOOLS NEEDED:

1) FOR HL-LHC:

★ TTBAR OBSERVABLES:
SIGN = TTBAR (SM) SAMPLES (PROTOS SAMPLES ?) AND
BCK = SINGLE TOP (ALL 3 CHANNELS), V+JETS (V=W,Z), DI-BOSON

★ SINGLE TOP OBSERVABLES:
SIGN = SINGLE TOP (SM) SAMPLES (ALL 3 CHANNELS) AND
BCK =TTBAR, V+JETS (V=W,Z), DI-BOSON

★ SCALING TO HIGH LUMINOSITY BASED ON STATISTICS PROBABLY USED

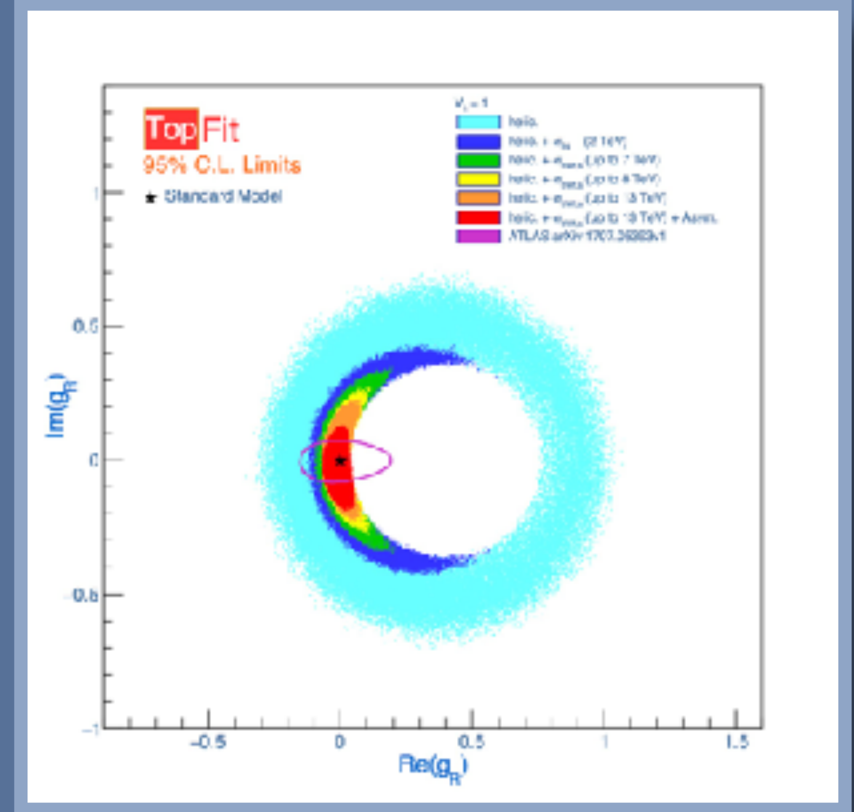
2) FOR HE-LHC (27 TEV) AND FCC-HH(100TEV):

WOULD NEED BASICALLY THE SAME THING FOR 27-100TEV

★ TTBAR OBSERVABLES:
SIGN = TTBAR (SM) SAMPLES AND
BCK = SINGLE TOP (ALL 3 CHANNELS), V+JETS (V=W,Z), DI-BOSON

★ SINGLE TOP OBSERVABLES:
SIGN = SINGLE TOP (SM) SAMPLES (ALL 3 CHANNELS) AND
BCK =TTBAR, V+JETS (V=W,Z), DI-BOSON

RESULTS:



3) TOOLS:

INPUT FROM THEORY MANDATORY !!!

★ FITTERS:
TOPFIT HAS BEEN USED
NEW TOOLS AVAILABLE

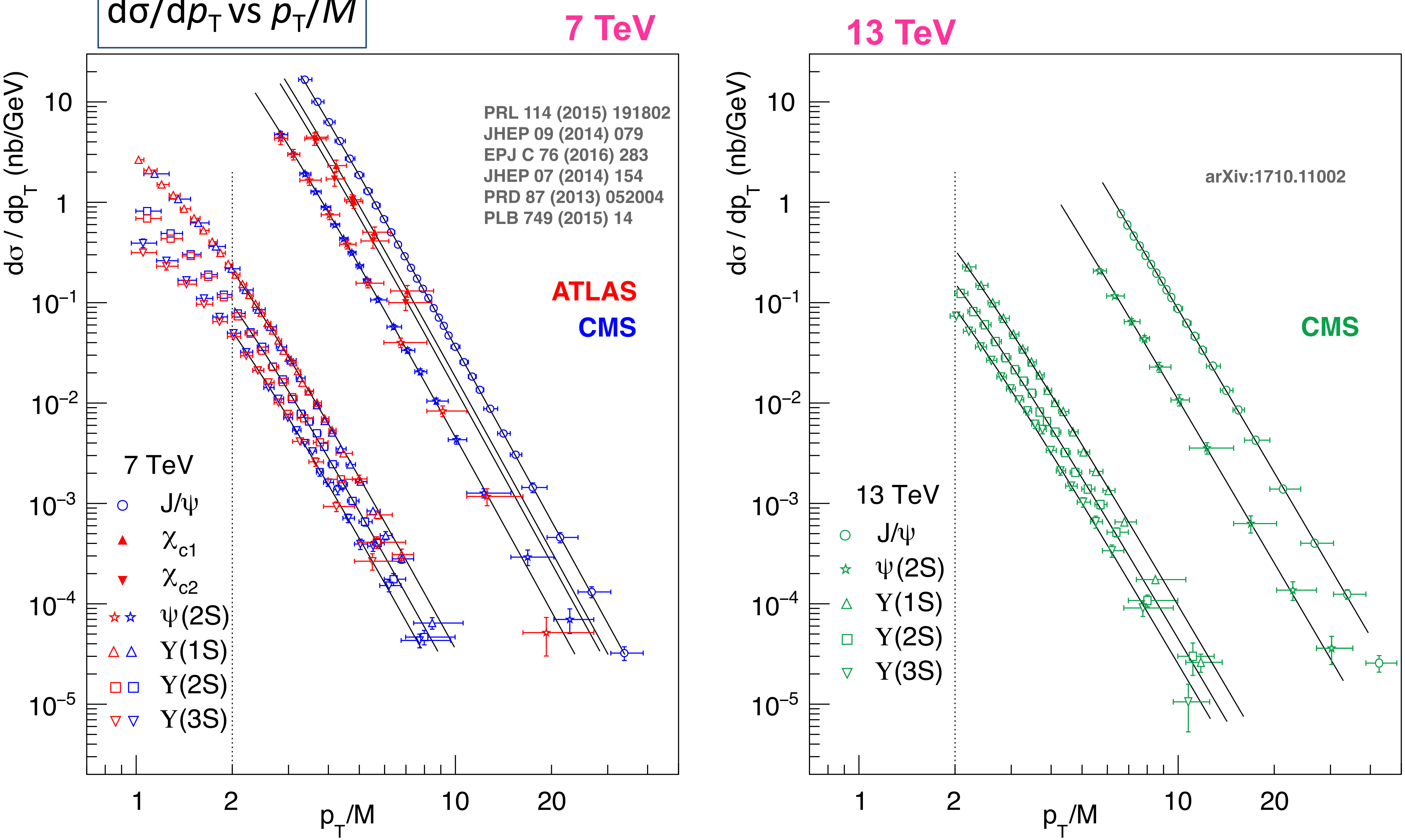
heavy quarkonium

Faccioli, Lourenço, Araújo, Knünz, Krätschmer, Seixas :: Phys. Lett. B 773, 476 (2017)
Faccioli, Lourenço, Araújo, Knünz, Krätschmer, Seixas :: arXiv:1802.01106 [hep-ph]
Faccioli, Lourenço, Araújo, Seixas :: Eur. Phys. J. C 78, 118 (2018)

Unexpectedly simple data patterns

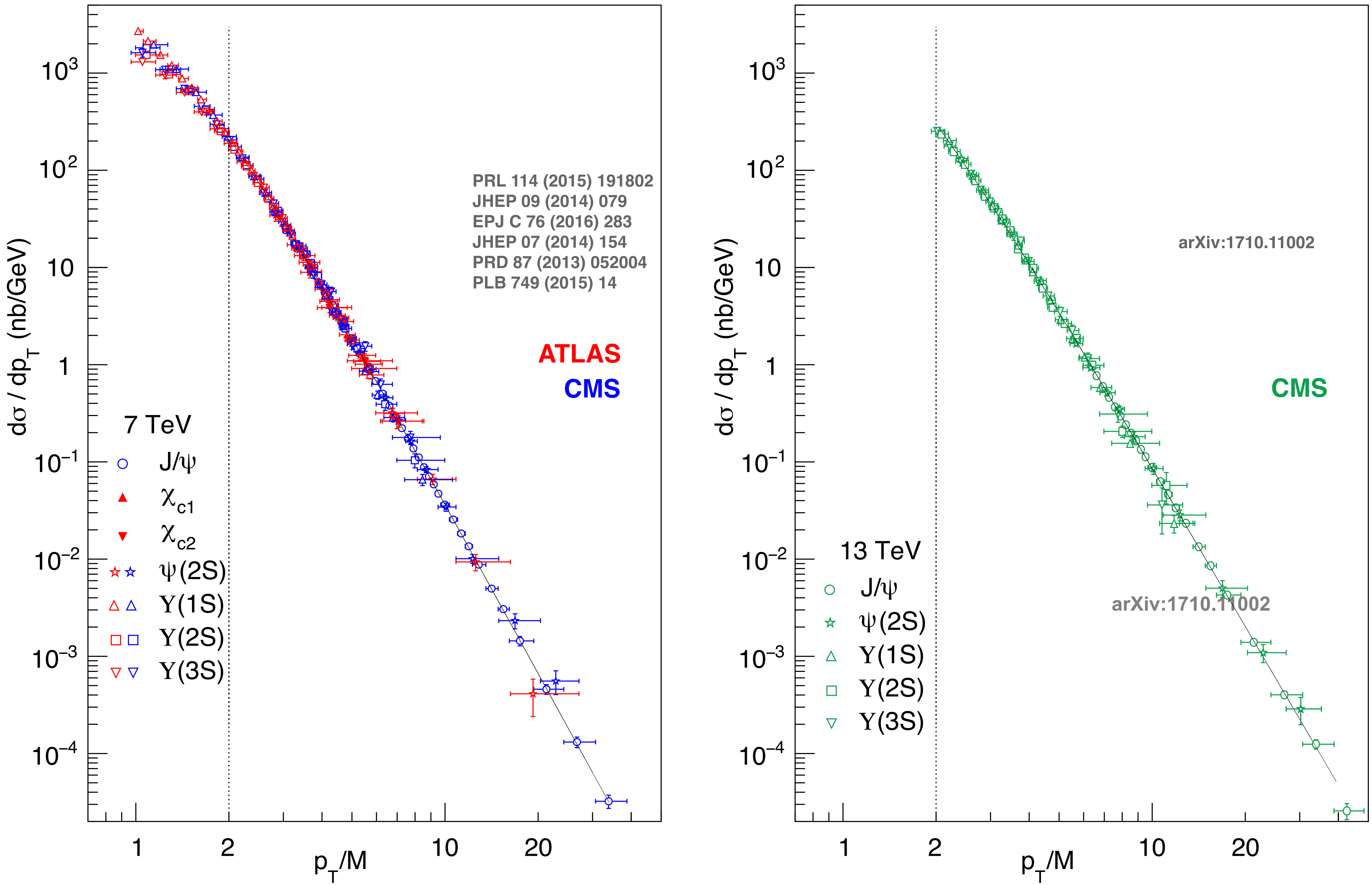
Mid-rapidity cross section measurements show a *common shape pattern* for ***$p_T/M \gtrsim 2$, independent of M and quantum numbers***

$d\sigma/dp_T$ vs p_T/M

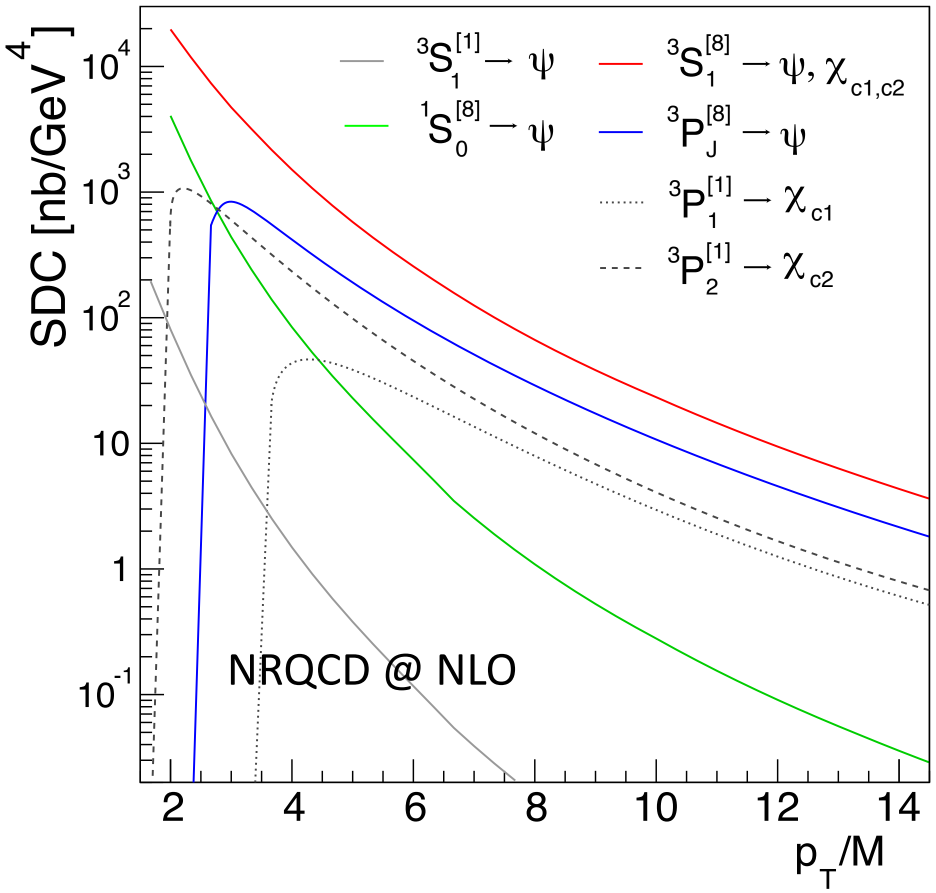


Unexpectedly simple data patterns

Scaling all data to match the J/ψ normalization



A "surprising" agreement with NRQCD



$^1S_0$ $^3S_1$ $^3P_{0|1|2}$ ⇨ **J/ψ, ψ(2S)** **ϒ(1,2,3S)**

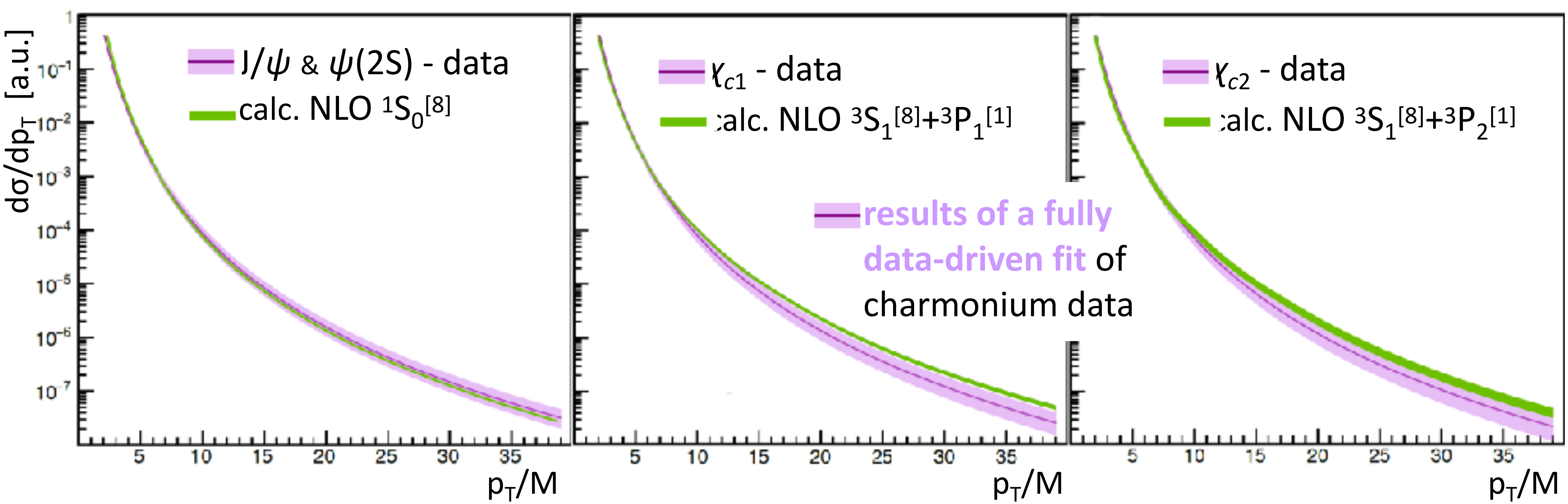
$^3P_1$ $^3S_1$ ⇨ χ_{c1} , χ_{b1}

$^3P_2$ $^3S_1$ ⇨ χ_{c2} , χ_{b2}

The variety of kinematic behaviours in NRQCD seems **redundant** with respect to the observed "universal" p_T/M scaling and lack of polarization

⇒ *cancellations* are needed to reproduce data....

...*and they actually happen*!



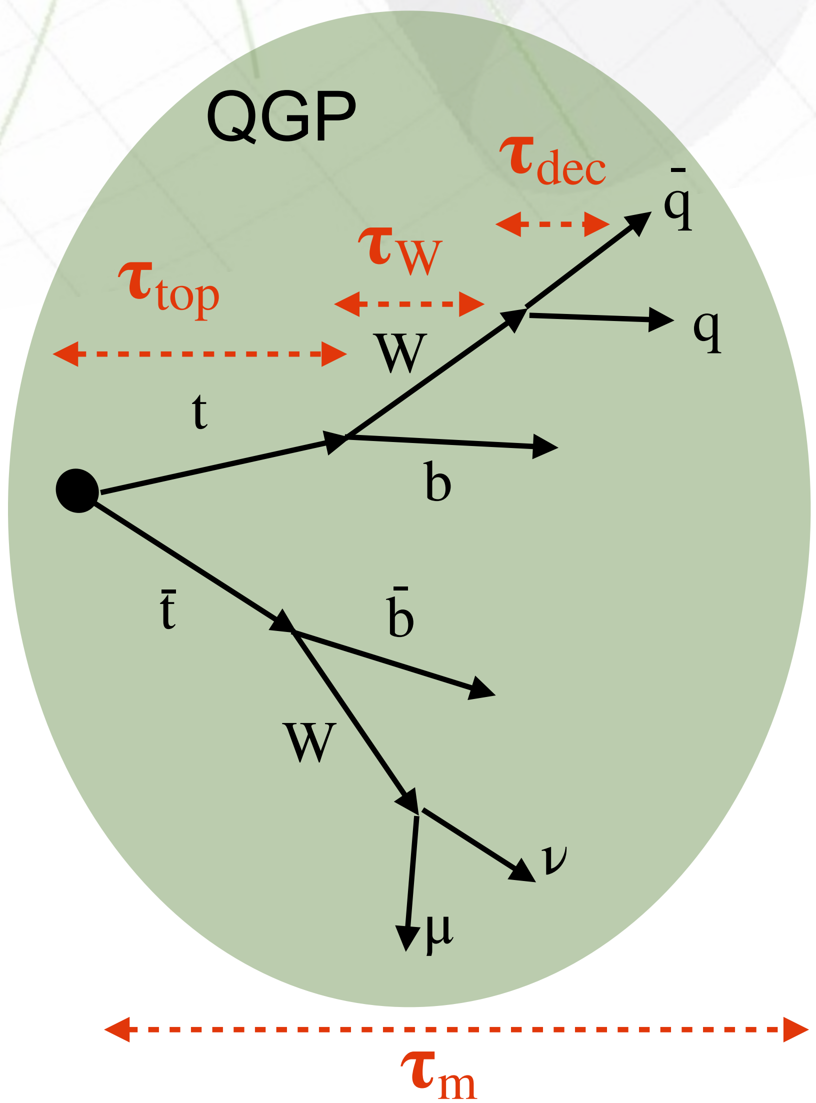
results of a fully data-driven fit of charmonium data

top quark as probe of QGP time structure

Apolinário, Milhano, Salam, Salgado :: arXiv:1711.03105 [hep-ph]

Tops in HIC

- Probing the QGP time structure with top quarks:
  - Total time delay = top decay + W decay + decoherence time



τ_{top}=0.15 fm/c

τ_W=0.10 fm/c

$$\tau_d = \left(\frac{12}{\hat{q}\theta^2_{q\bar{q}}}\right)^{1/3} \quad , \quad \hat{q} = \text{“medium density”}$$

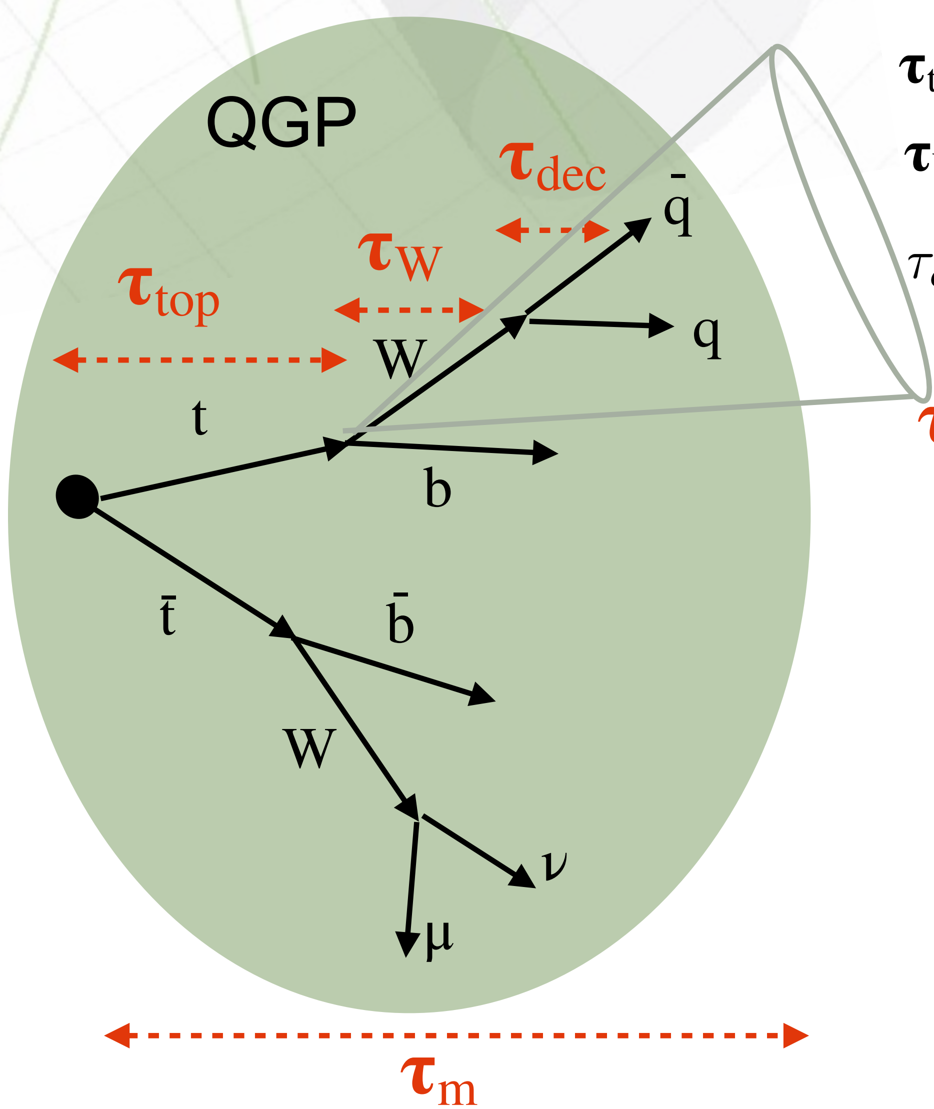
$$\tau_{tot} = \tau_{top} + \tau_W + \tau_{dec}$$

Jets from the W decay will only start los at *later* times:

$$\left.\frac{\Delta E}{E}\right|_{\substack{\text{W decay}\\ \text{products}}} = -\omega \left(\frac{\tau_m - \tau_{tot}}{\tau_m}\right) \; 0 \leq \tau_{tot} \leq \tau_m$$

Tops in HIC

- Probing the QGP time structure with top quarks:
  - Total time delay = top decay + W decay + decoherence time



τ_{top}=0.15 fm/c

τ_W=0.10 fm/c

$$\tau_d = \left(\frac{12}{\hat{q}\theta^2_{q\bar{q}}}\right)^{1/3} \quad , \quad \hat{q} = \text{“medium density”}$$

$$\tau_{tot} = \tau_{top} + \tau_W + \tau_{dec}$$

Jets from the W decay will undergo jet energy loss at *later* times:

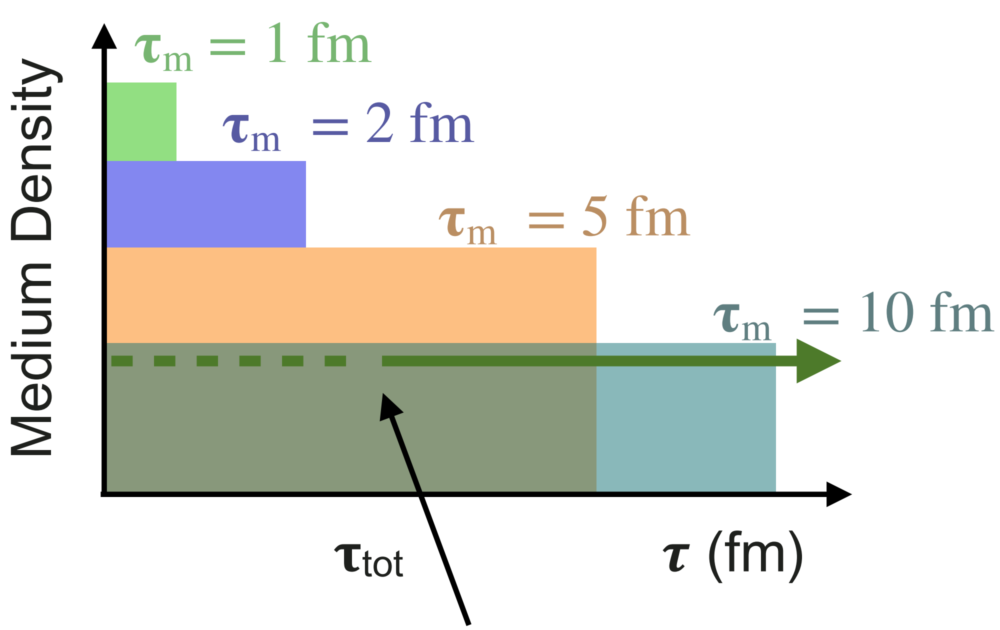
$$\left.\frac{\Delta E}{E}\right|_{\substack{\text{W decay}\\\text{products}}} = -\omega\left(\frac{\tau_m - \tau_{tot}}{\tau_m}\right) \quad 0 \leq \tau_{tot} \leq \tau_m$$

Jet energy loss ⇒ change in W mass

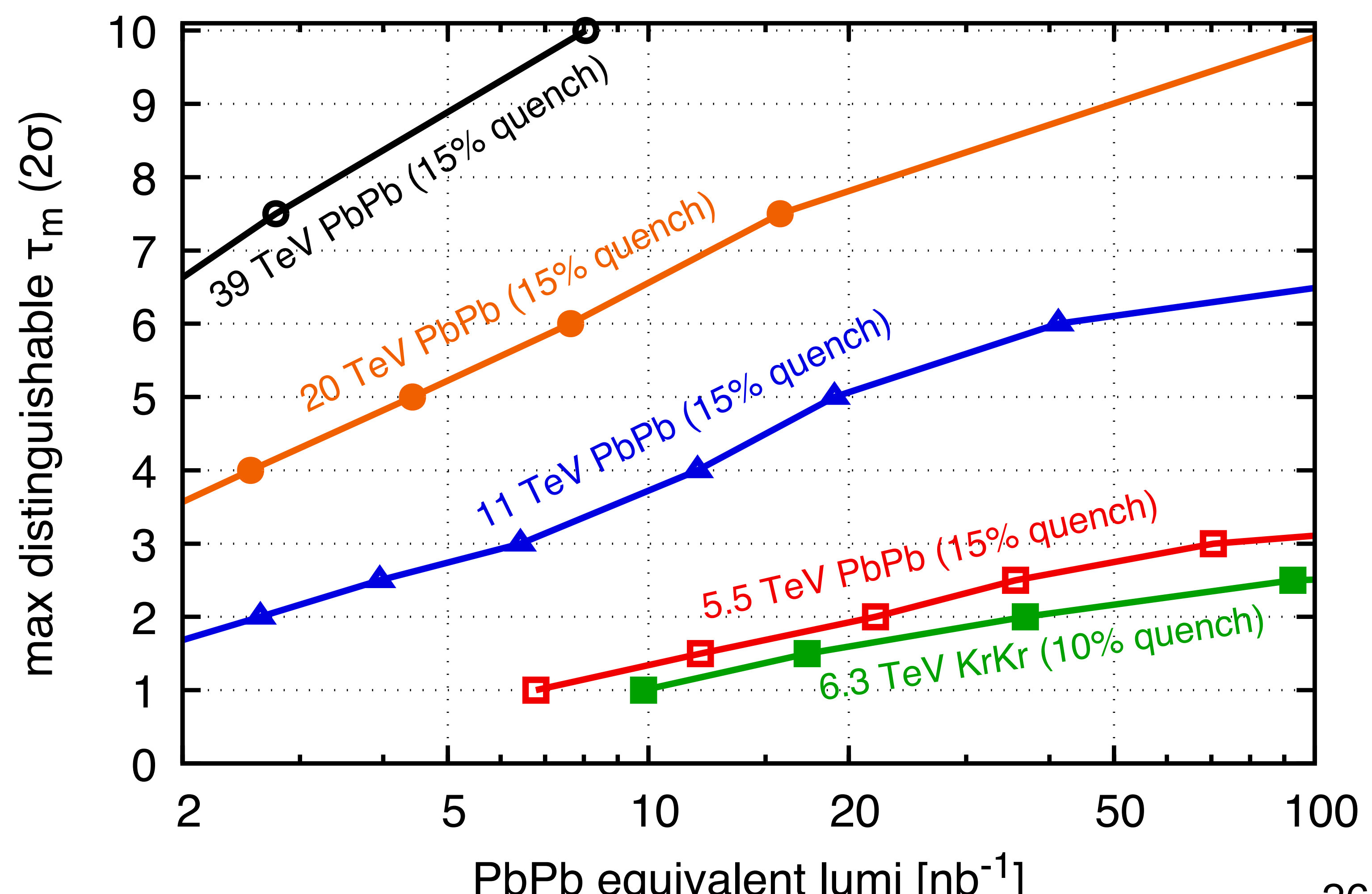
W mass can be used as an observable to probe different timescales of the QGP

Tops in HIC

- Probing the QGP time structure with top quarks:
  - Total time delay = top decay + W decay + decoherence time
  - Maximum time, τ_m that can be distintinguished with 2σ for a given $\mathcal{L}_{equiv}^{PbPb}$:



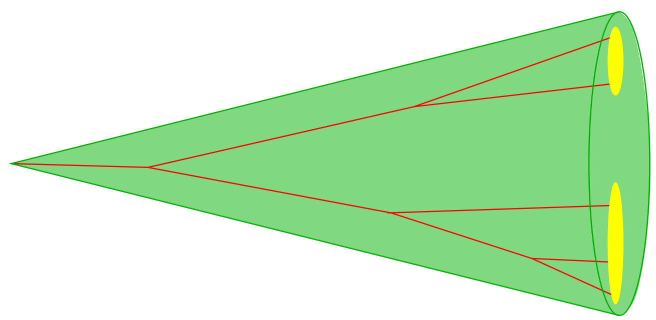
Time that it starts to interact with the medium



jet substructure and QGP response

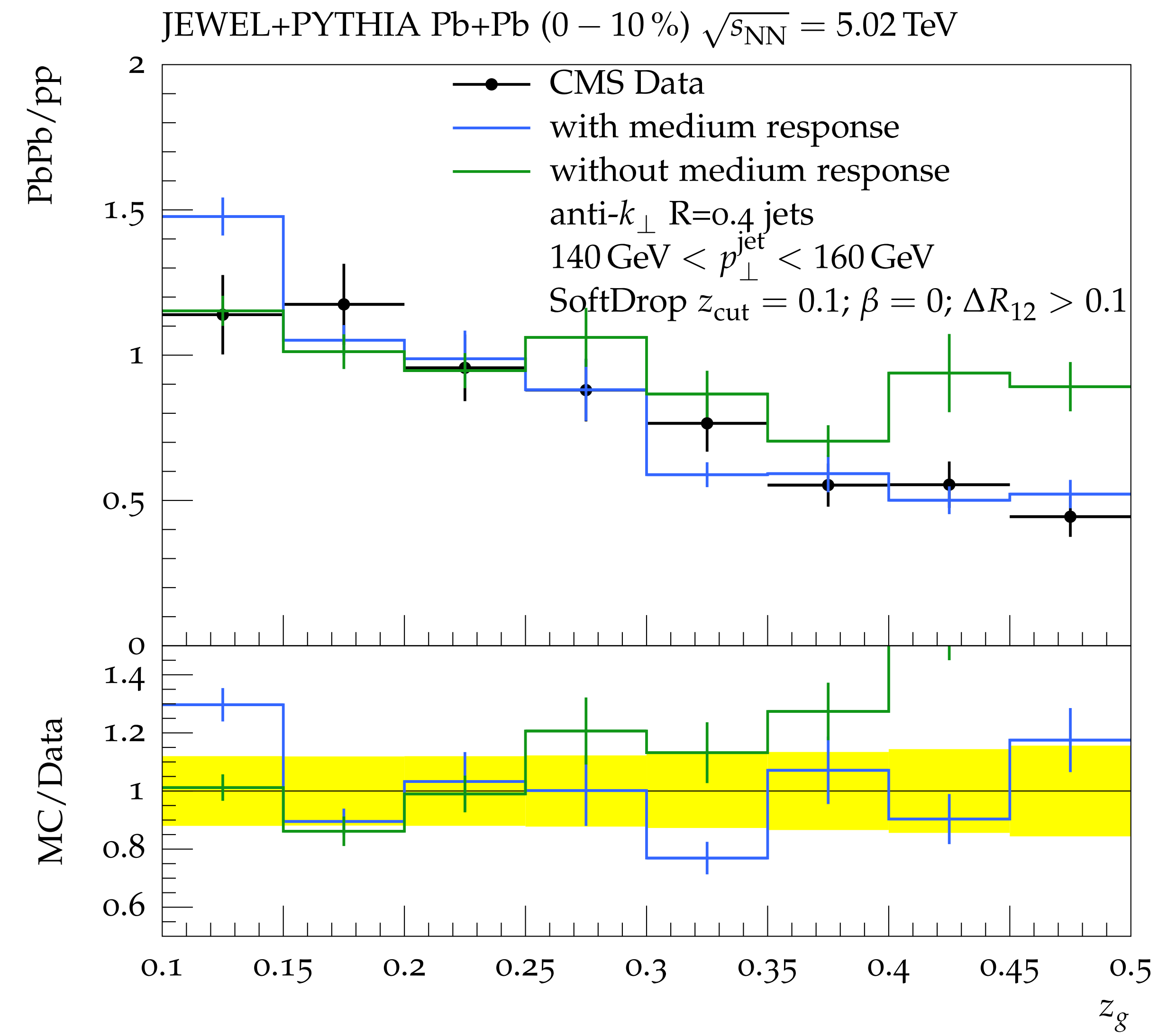
Kunnawalkam Elayavalli, Zapp :: JHEP 1707 (2017) 141
Apolinário, Milhano, Ploskon, Zhang :: arXiv:1710.07607 [hep-ph]
Milhano, Wiedemann, Zapp :: Phys.Lett. B (in press)

SUB-JET MOMENTUM SHARING



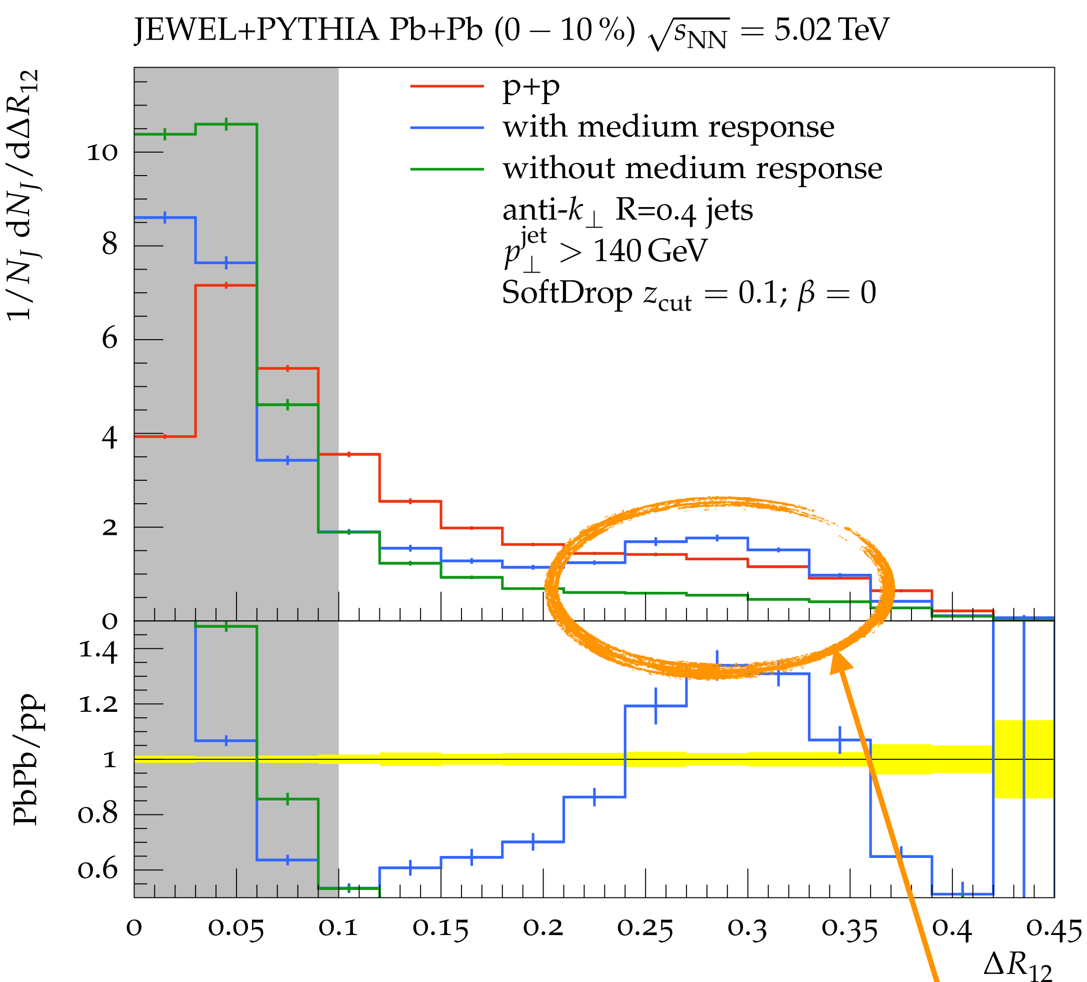
$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}$$

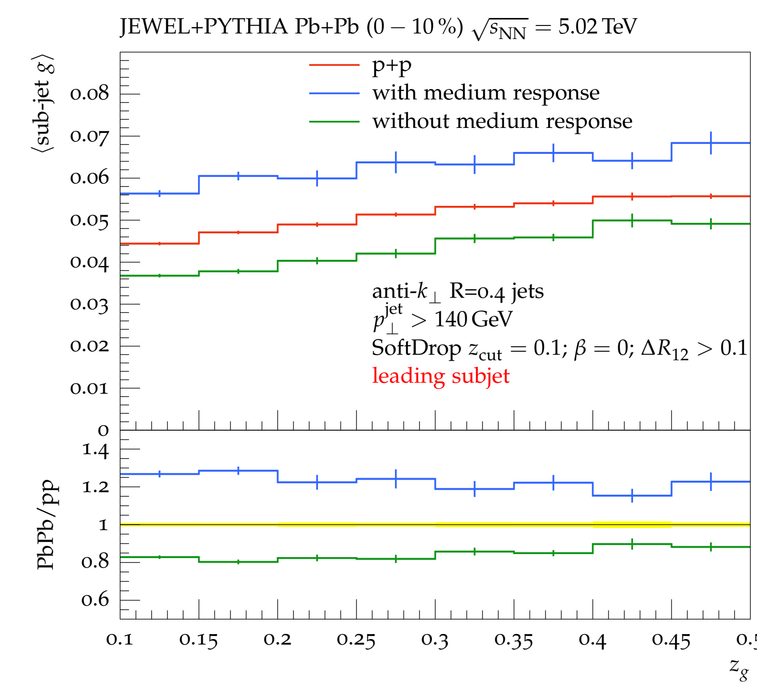
$z_g > z_{cut}$

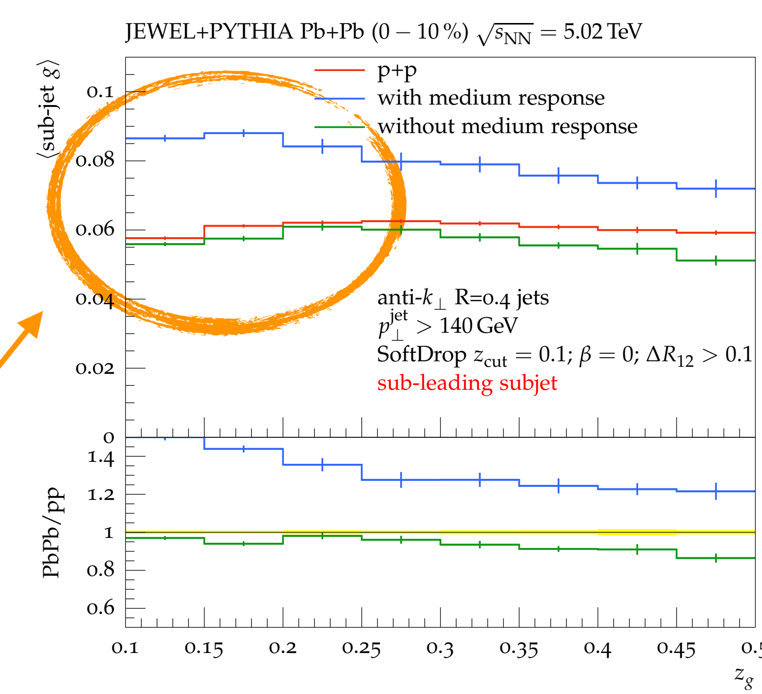


- small modification of z_g distribution from 'additional splittings' and 'energy loss'
- medium response essential to reproduce data

MEASURABLE TELL-TALES OF QGP RESPONSE







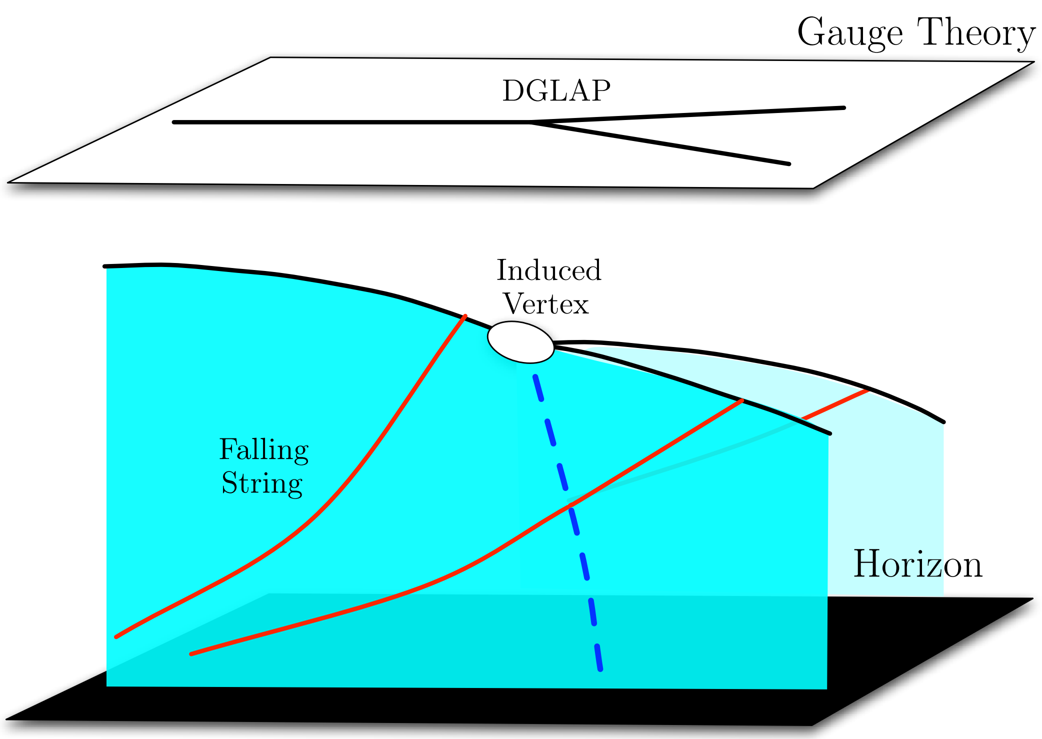
- additional component at large angular separation
- z_g dependent modification of sub-leading jet girth

$$g = \sum_i \frac{p_{\perp,i}\, \Delta R_{ij}}{p_\perp^J}$$

hybrid approach to jet quenching

Can Gulan, Casalderrey, Milhano, Pablos, Rajagopal :: JHEP 1603 (2016) 053
:: JHEP 1703 (2017) 135

HYBRID STRONG/WEAK COUPLING MODEL

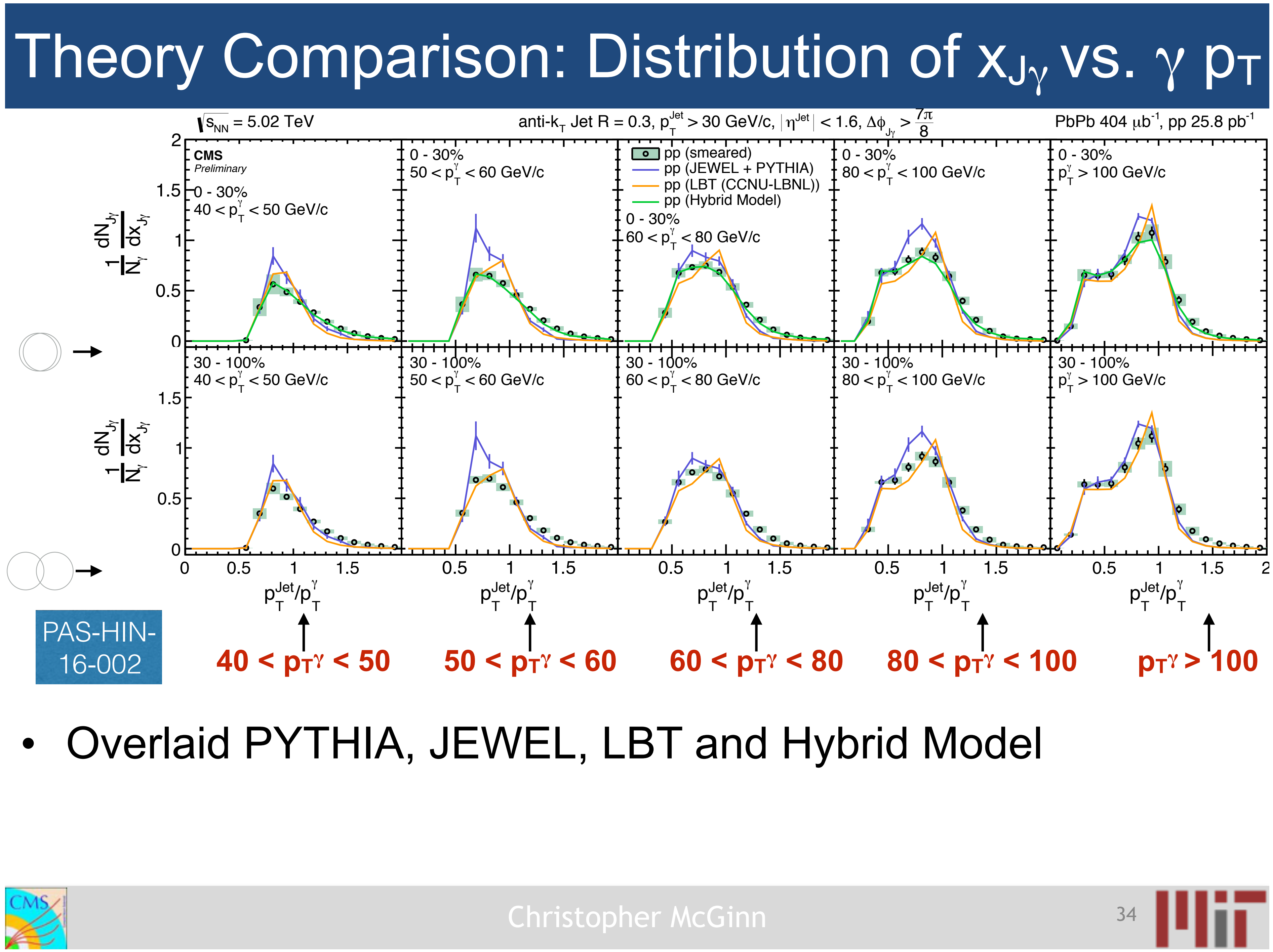


- physics at different scales merit different treatments
  - vacuum jets where each parton loses energy non-perturbatively [as given by a holographic AdS-CFT calculation]
- lost energy becomes a wake [QGP response], part of which will belong to the jet

$$\left.\frac{dE}{dx}\right|_{\text{strongly coupled}} = -\frac{4}{\pi} E_{\text{in}} \frac{x^2}{x_{\text{stop}}^2} \frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}}, \qquad x_{\text{stop}} = \frac{1}{2\kappa_{\text{sc}}} \frac{E_{\text{in}}^{1/3}}{T^{4/3}}$$

single free parameter
[accounts for QCD/N=4 SYM differences]

SUCCESSFUL IMPLEMENTATION OF NonPert Jet Eloss



✓ *overall excellent agreement with data and strong predictive power*

FUTURE PLANS

FOR THE NEXT TWO YEARS AND BEYOND

- ✓ strengthen efforts on existing activities
- ✓ identify synergies within the group for potentially high-impact projects
- ✓ identify further complementarity with LIP's experimental groups for in-house thematic task forces
- ✓ seek to expand, benefiting from available external funding, the scope of the group :: the aim is to match the breadth of LIP's experimental endeavours and have the ability to play a leading role in the definition of future projects
- ✓ seek points of contact with other researchers/groups in Portugal for collaboration
- ✓ strengthen existing international collaborations and foster new ones